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Malleable Media

Tangible Interfaces for Musical Interaction

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Abstract

This thesis addresses the possibility of using material properties such as malleability as a way for enriching physical representation and expression in musical interfaces. The contemporary attention in the materiality of the interface is pushing designers, artists and researchers to look at the interface as a material, rather then a group of sensors or a gesture acquisition system. In the area of Tangible User Interfaces (TUIs) dynamic and engineered physical materials are explored as a way for merging together the physical properties of those materials with digital processes and models. One of the most interesting area of application of the principles of TUIs is musical interaction. Already some musicians, performers and designers have tried to sketch and prototype interfaces for live performances inspired by the possibility of using direct physical manipulation as a way to give expression to computational sound models and algorithms.
Through description and discussion of the project SculpTon, I will explore those aspects in relation with a Malleable Tangible Interface for sound sculpting.

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Introduction

"*Viaggi di mani* (*Hand journeys*)"

F. T. Marinetti [1921]

This thesis addresses the possibility of using material properties such as *malleability* as a way for enriching physical representation and expression in musical interfaces. The contemporary attention in the materiality of the interface is pushing designers, artists and researchers to look at the interface as a material, rather then a group of sensors or a gesture acquisition system. In the area of Tangible User Interfaces (TUIs) dynamic and engineered physical materials are explored as a way for merging together the physical properties of those materials with digital processes and models. One of the most interesting area of application of the principles of TUIs is musical interaction. Already some musicians, performers and designers have tried to sketch and prototype interfaces for live performances inspired by the possibility of using direct physical manipulation as a way to give expression to computational sound models and algorithms.

The main idea behind this thesis is to try to explore the possibility of applying the recent acquisitions in the area of TUIs – such as the idea of "Digital Clay"- in music interface design. The creation of an interface for musical expression is a very delicate task, because is not based only on engineering and scientific principles, but have to take into account elements such as expressivity, engagement, and communication that are difficult to formulate, define and even to

solve.

If there is something in common between music making and interfaces based on the idea TUIs is the use of hands. With their hands musicians express themselves through the instrument, acoustic, electronic or digital it is. But, human hands have been also shaping human culture and its products. From bread to pottery the list of what the hands have formed is almost infinite. As Hermann von Helmholtz noticed "*'everything is an event on the skin*" [Von Helmholtz 1878], then human hands and the relative sense of touch have profound implications and many expressive, aesthetic and cognitive possibilities. According to Erkki Huhtamo the idea of interactive art is "*intimately linked with the act of touching*" [Huhtamo 2005]. From the futurist manifest of the "Tactilism" to the "non-retinal art" envisioned by Marcel Duchamp, the sense of touch and active manipulation have played a subversive role, and opened electronic and digital media to the spectator. The importance of touch [MacLean 2008] and direct manipulation [Lederman and Klatzky 1987] have been already explored in Human Computer Interaction (HCI) as a powerful way of performing multiple degrees of freedom input tasks [Zhai et a.l 1996]. In those fields *haptics* (from the greek ἅπτω = 'I fasten onto, I touch') has become an important notion and a vast territory of experimentation [Hara 2004].

Beyond the pure touch, this work will explore how sculpting, as creative process, can be employed for provoking complex, creative and engaging interactions with what I defined as *Malleable Tangible Interfaces*. The idea of sculpting sound, manipulate it as a piece of clay has captivated the imaginations of many composers and musicians, especially in the electronic and digital era.

The work presented in this thesis expresses the tentative of developing further this idea, and contributing in the creation of a stronger link between the current focus of Tangible Interfaces with interfaces for performance. In this manuscript I will present and analyze SculpTon, a

malleable tangible interface for sound sculpting through it's conception, implementation and utilization. Different theoretical and historical aspects will be discussed in order to propose *malleability* as a sort of paradigm for addressing and developing more expressive, embodied and embedded interactions in musical interfaces. SculpTon represents also a novel approach of sensing deformations in tangible interfaces, and a complete and tested interface for live performances. Malleability will be analyzed not only as a quality of certain materials, but also as an element where the hands, the mind, computation and sound production are conflating, in a new material.

The discussed topics are the following:

- **Chapter 1**: This chapter introduces the idea of sculpting, not only as a technique but as a space for creation, expression and cognition. Drawing from different studies in areas such as anthropology, archeology, cognitive science and education I will explore why malleable materials started to be employed by human beings and why today are still successful.

  Sculpting have been also related to the idea of music making. Beyond the use of clay for the creation of musical instruments, I will describe how the concept of *sound sculpting* emerged through the writings and visions of many artists, composers, and musicians since the beginning of the last Century.

- **Chapter 2**: Through this chapter the development of the state of what is known as New Interfaces for Musical Expression (NIME) will be introduced. The first part of the chapter will be dedicated to the historical steps and milestones that have led to the

contemporary practice and definition of the field. The second will highlights some relevant issues in the design of NIME instruments, with a special attention to the problem of expression. Then some relevant examples will be analyzed and some open questions and issues in the crowded world of interfaces for musical expression will be discussed.

- **Chapter 3**: In this chapter the main ideas and concepts behind the development of Tangible User Interfaces (TUIs) will be introduced. A consistent part of this chapter will describe the main aspects and examples of projects that inspired the design of SculpTon. After a brief survey of the foundations and characteristics of Tangible User Interfaces, the most recent and contemporary research questions and directions of the field will be presented. Special attention will be given to the analysis and vision of the possible role of new malleable and digitally augmented materials.. Finally some projects that are exploring the idea of "Digital Clay" in the context of Tangible User Interfaces will be discussed under the lens of the vision of Radical Atoms.

- **Chapter 4**: Through the analysis of many recent projects, this chapter will discuss why the combination between the idea of TUIs and NIME is possible, desirable and meaningful.

  After a brief illustration of some relevant projects in this area, the possibility of combining the idea of Malleable Tangible Interfaces with musical interaction will be introduced. Then some possible benefits, limitations, perspectives and limitations of this approach will be discussed.

- **Chapter 5**: This chapter will describes the background and the development of SculpTon, a malleable tangible interface for sound sculpting. Within this project some possible applications of the idea of Radical Atoms will be discussed in the context of NIME.

  The discussion will be followed by a detailed description and evaluation of the interface in different live performances and presentations. Then, some qualities and limitations will be analyzed and discussed.

Chapter 1

Form giving : towards sculpting as a creative process

This chapter presents the concept of *sound sculpting* and what in this thesis is meant with the verb *sculpting*. Drawing from different studies in areas such as anthropology, archeology, cognitive science and education I will explore why malleable materials started to be employed by human beings and why today are still successful. Through this survey I will define what *sculpting* represents in relation with malleable materials, such as natural clay or compound materials. Sculpting is not only a specific action, but also a broad idea that expresses a more complex social and cultural relation with the matter and the mind: a joint process of form giving and modeling. Sculpting have been also related to music making since prehistoric times. Besides the use of clay as a material for musical instruments creation, I will describe how the concept of *sound sculpting* emerged through the writings and visions of many artists, composers and musicians from the XXth Century.

1. The emergence of sculpture as a cultural and social product

Since their appearance on planet Earth, human beings started to use natural materials for creating artifacts of different types and for many purposes. Those materials founded in their environment have suggested humans to create since the early days what today we know as

sculpture.

The first examples of sculptures produced by humans are dated from the Stone Age period, beginning around 40,000 years ago. They comprise figures and monuments made out of stone, bone, antler and ivory. During the Neolithic period pottery originates in different parts of the world. From this point humans started to develop techniques and tools for give form to inherent and physical matter found in nature. Wood, marble, clay, bronze, and later iron, plastics, and artificial resins became part of the materials used to be sculpted by humans.

Sculpture is a very old art form, which had a different evolution depending on geographic and cultural conditions. During the centuries different styles, techniques and aesthetics emerged.

If the different genres of sculptures have been analyzed in details by art historians, art critics, archeologists and anthropologists, the techniques and actions involved belongs to artists and craftsmen. Also nowadays it's easy to found them in art schools, artists studios or academic books about crafting and artistic creation.

In this thesis I will talk about *sculpting* and not *sculpture*. Sculpting is a verb, which stands for an action that refers "*to form, shape or manipulate, as in the manner of sculpture*" [Collins 2009].

I'm not interested in the result (the sculpture, doesn't matter which kind of sculpture) but in the process, the actions involved in the act of sculpting.

This verb refers to a vast body of techniques, gestures and knowledge deeply connected with several cultures and traditions and obviously, to different materials.

Sculpting marble is totally different to sculpting wood: the gestures, tools and techniques employed are very different. Due mainly to their affordances some materials can be sculpted directly by hands others only with specific tools.

1.2 Manipulating the matter: techniques

Looking to traditional classification in art history, we can find two main branches of approaches, such as *tutto tondo* and *relief*.

Usually with *tutto tondo* we refer to three dimensional sculptures, and for *relief* everything that emerges from a flat surface. If the former usually describes objects, vessels the latter is normally

used for decorations.
Depending on the material, different techniques can be employed by artists. The repertoire is vast and depends also to what is the final result that an artist wants to achieve. Sculpting a piece of clay for creating a vessel involves totally different techniques and approaches than make a pottery relief.
For the sake of clarity we can distinguish between two ways of sculpting:

- Direct manipulation, such as hand's forming, building, and shaping;
- Manipulation with tools, such as carving.

Usually direct manipulation is used with malleable materials, or materials that allow this kind of affordances. Hard materials are usually manipulated and sculpted with the help of other tools.
Along with these basic techniques, we can find other processes that are typical of later stages; for instance lost-wax casting or burning. Those processes are not involving any type of manipulation by they are activating some chemical processes present in the materials.
As the title of this thesis suggests, I will focus my attention on sculpting with malleable materials.

2. Clay, the matter that matters

Clay was one of the first material employed by humans that affords direct manipulation. Especially with the development of techniques such as pottery, this material became one of the most used for creating house supplies such as vessels and pots, but also religious objects, small statues and even musical instruments.
Clay is a fine-grained soil that combines one or more clay minerals with traces of metal oxides and organic matter. Geologic clay deposits are mostly composed of phyllosilicate minerals containing variable amounts of water trapped in the mineral structure [Guggenheim and Martin 1995].
There are many reasons why this clay became a common material for different cultures. The most

important was the availability in nature of the raw clay, another one might be the nomadic and pre-literate cultures, which has contributed to the exchange of artifacts and techniques.
Pottery put the use of clay as a prominent technique for producing artifacts. Pottery is produced by forming clay body into objects of a required shape and heating them to high temperatures in a kiln which removes all the water from the clay, which includes reactions that lead to permanent changes including increasing their strength and hardening and setting their shape.
But the history of pottery is believed to have begun in the period 29.000 BC to 25.000 BC. This period is known as the Upper Paleolithic period, sometimes referred to as the Late Stone Age.
The oldest examples of pottery (molded of clay and fired) have been founded in Southern China and dated around 20.000 BC, at the height of the ice age, long before the beginning of agriculture [Wu et al. 2012], or the Venus figure of Willendorf [Otte 1990].
Clay is also recognized as one of the oldest building material on Earth. Compared to pottery and sculptures this practice emerged later, when humans became sedentary and other techniques for working with clay have been discovered, such as the pottery wheel in Mesopotamia between 6.000 BC and 4.000 BC [Rado 1988].
During the last century -due especially with advancement of material studies- archeologists have developed a growing interest in studying pottery [Van der Leeuw 1993]. According to van der Leeuw [Van der Leeuw 1994] archeology is not interested in the mere description of artifacts, but through the analysis of them it tries to move closer to an understanding of the individuals who created and used them.

2.1 Shaping musical experiences: from pottery to music making

Pottery involves different elements from environmental (where the clay is coming) to technological and even social aspects. Claude Lévi-Strauss in one his famous anthropological studies defines the line between pre-history and history as a passage from the period of the *raw* and the period of the *cooked* [Lévi-Strauss 1964]. Caused by the invention of the fire humans started to cook raw food (this helped for preventing natural diseases and intoxications). This also let them to build houses by cooking clay in the form of bricks. This was a big cultural and

social change, which opened the doors to a new chapter of human history. Later, as attested by Mycenaean and later Babylonians tablets, clay became also the first medium used for storying memory outside the biological brain [Malafouris 2008] .

A particular branch of research known as *archeoacoustics* [Devereux and Richardson 2001] assumes that through the analysis of the surface of ancient pottery it's possible to retrieve auditory informations about the environment where a particular vessel was made.

Due to its characteristics of creating three dimensional artifacts with cavities and empty spaces since earliest time clay have been used as a material for creating musical instruments. Probably many of them originates as domestic pots, acting as primitive resonators.

Most of clay instruments are aerophones (such as whistles and flutes), and clearly derived from bones, horns, conch shells and wood. Some of them resembles the idea of whistles and flutes, but we can find also some made with a non-representational shape, more like modern ocarinas. One of the oldest clay instrument is a chinese cross-blown flute called *hsuan*. Some whistling jars, called *sillbador* have been found in South America. Globular flutes with zoomorphic shapes are known from Mexico and Malaya. Many different clay panpipes have been also found, but they seems to be unique to South America [Baxter 2001].

Together with flute and ocarina-like instruments we can find many clay trumpets. Although they are in a small number, they were quite distributed in Mayan cities in Central america, India, Western Europe and some parts of Africa. Probably the first trumpets were probably conch shells, so it is not surprising that clay imitations have been founded in South America, such as the *potuto* from Perù [Baxter 2001]. The famous artist Jean Dubuffet was a collector and player of clay trumpets from all around the world [Fundation Dubuffet 2006].

Rhythmic and percussive instruments have been also made with clay since the Neolithic, and have been founded in central african regions. The Ancient Romans had pottery clappers called *crotalum*, used in theatrical performances. Some percussions especially kettledrums, are still made with clay in the islamic and indian world.

Clay was also employed in the modern times for making musical instruments. One of the most notable example is the ocarina, designed by Donati in Italy around 1860 [Baxter 2001].

3. The emergence of sculpting as a cultural and social process

Since now we have been talking about artifacts created with clay, the sculptures, and the discussion about the verb, the action of sculpting, was left behind. One of the reasons is that, from the point of view of this research, an historical and archeological look to what malleable materials (such as clay) can probably reveal that, besides the chemical properties and the natural availability, there is something more. The actions and the engagement that these malleable materials affords probably have a profound meaning in the development of our culture and cognition.

Before trying to sketch some possible answers, I will describe some techniques, pointed out by the archeological and anthropological research about sculpting clay, mainly used for shaping pottery.

3.1 Direct manipulation: from bread to industrial clay

The goal of this chapter is not to describe or analyze what is possible to make with (*sculptures*), but the focus is on the action, on *sculpting*.

As we know clay can be shaped by using a different range of tecniques. Some of the most common techniques are defined as hand building and modeling, with tools such as the potter's wheel, granulate pressing, injection moulding, jiggering and jolleying, and slipcasting. Some important references and descriptions can be founded in [Rado 1988].

Since my attention is on direct manipulation, hand building and modeling can be viewed as the earliest and most common forming methods employed by humans. For instance, wares can be constructed by hand from coils of clay, combining flat slabs of clay, or pinching solid balls of clay or some combination of these. Parts of hand-built objects (especially vessels) are often joined together with the aid of slip, an aqueous suspension of clay body and water. A clay body can be decorated before or after firing. Prior to some shaping processes, clay must be prepared such as tablewares although, some studio potters find hand-building more conducive to create one-of-a-kind works of art. Direct hand-work with clay represents also the main attraction and afforded

interaction with this material.

Malleable materials are not common only in prehistorical periods, but they had also an evolution. If we think about bread dough -which represents the preparation for one of the most common, oldest and basic food in the world- it require also direct manipulation, and in some way a process similar to sculpting clay. Objects and products made for different usages, from feeding to aesthetic, are sharing similar actions, gestures, processes; mainly because they are based on materials with similar physical behavior.

With the advent of the industrial revolution and chemical manufacturing other clay-like substances have been developed. The success and the wide usage of those materials (from artisans to children) prove the relevance of malleable material for human expression.

In the modern times we can find different types of industrial malleable compounds:

1. *Modeling Clay*: with this term we connote a group of malleable substances used in building and sculpting. There are three main types:

a) *Oil-based clay* is made from various combinations of oils, waxes, and clay minerals. Because the oils do not evaporate as does water, oil-based clays remain malleable even when left for long periods in dry environments. Articles made from oil-based clays cannot be fired, and therefore are not ceramics. Because the viscosity of oils decreases as temperature rises, the malleability is influenced by heating or cooling the clay. Oil-based clay is not soluble in water. It can be re-used and so is a popular material for animation artists who need to bend and move their models. It is available in a multitude of colors and is non-toxic.

Being readily worked in fine detail, oil-based clays are also suitable for the creation of detailed sculptures from which a mold can be made. Castings and reproductions in a much more durable material can then be produced. Cars and airplanes may be created using industrial design-grade modeling clay. Oil-based clays are referred to by a number of trademarks.

One of the most famous modeling clay is *plasticine*. Plasticine, a brand of modeling clay, is a putty-like modeling material made from calcium salts, petroleum jelly and aliphatic acids. The name is a registered trademark of Flair Leisure Products plc. Plasticine is used extensively for children's play, but also as a modeling medium for more formal or permanent structures.

Plasticine was formulated by art teacher William Harbutt of Bathampton, in Bath, England, in 1897. He wanted a non-drying clay for his sculpture students. The original Plasticine was grey,

but the product initially sold to the public came in several colors. Plasticine was popular with children, widely used in schools for teaching art, and has found a wide variety of other uses; for instance moulding casts for plaster, and plastics.
We can find similar products in various countries, such as the "Kunst-Modellierthon" (known as Plastilin) invented by Franz Kolb of Munich, Germany in 1880. This product is still availablewith the name of "Münchner Künstler Plastilin" (Munich artists' plasticine). In Italy, the product Pongo is also marketed as *plasticine*.

b) *Polymer clay* is a modeling material that cures when heated from 265 °F (129 °C) to 275 °F (135 °C) for 15 minutes per 1⁄4 inch (6.4 mm) of thickness, and does not significantly shrink or change shape during the process. Despite being called "clay", it generally contains no clay minerals. Polymer clay is sold in craft, hobby and art stores, and is used by artists, hobbyists, and children. This material is also popular in animation since it allows static forms to be manipulated frame after frame. Leading brands of polymer clay include Fimo, Kato Polyclay, Sculpey, and Modello.

c) *Paperclay* is also another variant. Paperclays are cellulose based substances which air dry firm. Thanks to this property the finished sculpture is extremely lightweight. We can notice that commercial air drying paperclay does not shrink noticeably when drying.
Paper clay is hand made or commercially available clay to which a small percentage of processed cellulose fibre is added, to increase the tensile strength of dry clay, enable dry to dry and soft (wet) to dry joins.
There are two major groups of paperclay users: those that are using paperclay as an unfired body predominately for recreational use or doll making, and those using paper clay in the ceramic art studio to make sculptural and functional studio pottery.

2. *Modeling compounds*: As showed in the previous examples, some other compounds emerged from industrial research. Since the 1950s some clay-like materials started to be produced and commercialized. Some of them had slowly a big impact in the post-war popular culture, especially in the area of games and education.

a) One of the most famous example is *Play-Doh*. This is a modeling compound used by young

children for art and craft projects at home and in school. It's a non toxic material, composed of flour, water, salt, boric acid, and mineral oil, the product was first manufactured in Cincinnati, Ohio, U.S., as a wallpaper cleaner in the 1930s. When a classroom of children began using the wallpaper cleaner as a modeling compound, the product was reworked and marketed in the mid-1950s. Play-Doh was demonstrated at an educational convention in 1956 and prominent department stores opened retail accounts. Since its launch on the toy market in the mid-1950s, Play-Doh has generated a considerable amount of ancillary merchandise. In 2003, the Toy Industry Association named Play-Doh in its "Century of Toys List".
A similar material called Didò was produced and commercialized by FILA in 1985, for children from 2 to 5 years old. Didò it's also a compound material, not toxic made with natural ingredients (flour, water and salt), and apple-flavored.
More recently, in 2010, the japanese company BorneLund launched on the market Kanten Clay, a highly safe compound modeling material. Kanten Clay is composed of kanten (commonly know as agar, or agar-agar), a gelatinous substance derived from seaweed, natural food coloring and brine.

b) Another material called DAS, which shares a many characteristics with clay, is a synthetic paste. It's interesting to note that this material was invented in the 1950s by an italian poet called Dario Sala. With a light gray appearance, the DAS has a self-hardening properties. This differs from clay, because it doesn't need to be fired for becoming hard.

4. Clay as a neuro-compatible material

The mere description of the different malleable materials (both natural or compound) together with the gestures and techniques used for manipulating and sculpting them, is not enough for understand why such materials have been successfully employed by humans, and also, why *malleability* seems to represent something more than an action or a quality of some particular materials. As we noticed before, there is probably something in common between manipulative gesture, and malleable materials, and why the qualities of the latter have been so attractive for

humans.

I have to notice that there are no structural studies about this aspect; different disciplines have been tackling some related issues by merging different approaches.

One of the most interesting body of work -because it refers also explicitly to sculpting and clay- is the research developed by Lanfrod Malofouris, which focuses on the relation between archeology and cognitive science, asking for "*a new alliance between material and cognitive science must be establish in the field of archeology*" [Malafouris 2010]. For Malafouris the study of the artifacts and the material used by ancient humans can reveal the cognitive process used by those people and societies. From his point of view It can also help the study of the evolution of the human brain.

Malafouris have been developing his research together with the idea of Brain-Artifact Interface (BAI), a conceptual framework for the analysis of the cognitive aspects of agency from the human perspective but also from the material one, and their relationships [Malafouris 2010] [Malafouris 2013].

In his article "*At potter's wheel*" [Malafouris 2010], Malafouris describes in details the process of pottery making. For him, this activity became the main example for starting an analysis about agency and for illustrating his idea of BAI. Beside the description of the act and process itself, Malafouris as a cognitive scientist working in the field of archeology, points out some interesting ideas that became very useful for trying to answer to our questions.

Malafouris said that "*my choice of the potting process as the focus of my discussion* […] *I consider pottery making as a prototypical exemplar and one of the best diachronic models of the active mind*" [Malafouris 2008].

Already in this passage Malafouris explains that the act of sculpting, that is form giving, is intended not only has a crafting technique but also a cross-cultural model of the development of decision-making processes of humans in front of an action [Malafouris 2008].

According to him the process of pottery making, in the framework of the Brain-Artifact Interface is something similar to what for others is a "*Turing machine or centrifugal governor*" [Malafouris 2008]. If these last considerations can be arguable, the analysis of Malafouris is interesting because it to looks at the process of sculpting through a particular perspective. For Malafouris not only the process of sculpting must be analyzed, but also the materials employed in this action: clay matters. Malleability seems to be for him a fundamental quality to include in this discussion. For instance, wood carving can't be a "*diachronic model of the active brain*"

[Malafouris 2008], not only for the technique that is employed but also for the properties of the material. "*I* […] *consider clay to be one of the earliest truly neuro-compatible materials in the history of humanity. Neuro-compatible here refers to materials that afford the flow of the noetic activity beyond skin and skull thus bridging neural and cultural plasticity*" [Malafouris 2008].
Even if those words sounds metaphysical, they formalize that there is something that connects humans and materials through characteristics such as malleability, form giving, and exploration. Clay became not only a material but a symbol of a relation between what is happening not only in the neuronal but also at the cultural level, "*beyond skin and skull*" [Malafouris 2008].
Malfouris is proposing that by analyzing the actions made by the potter we can face a "*residual component of the prehistoric mind*" [Malafouris 2008].
This is a discussion goes beyond the scope of this thesis and of this chapter. However, we can start to delineate that there is also a cognitive, historical, social and cultural relation between humans and malleable materials.

4.1 Malleable materials as a media for education

In todays society beside the fine arts (where especially clay is used in ceramic) malleable materials are almost used by children.
The use of those kind of materials, especially the non-toxic and commercial types of plasticine and modeling clay, are used and encouraged by educators in early period of life. Malleable materials have been studied in areas such as learning and education.
Modeling clay, or similar materials, seems to be for children a very familiar and appealing action. For instance, the soft feeling of Play-Doh makes it very friendly to them. The physicality makes it intuitive and easily understandable; for example by changing the shape of the clay and observing the effects in real-time. The malleable nature of materials such as clay or plasticine frees children from rigid constraints and stimulates thinking and creativity.
Very young children (from 0 to 3 years old) are exploring objects and environments by touching, mouthing tossing, banging and squeezing. Sensory play appears in children an early attempts to feed themselves. This type of play is defined as *exploratory*, *sensory*, or *object play*. It was also

observed that as children are getting older (from 3 to 8 years), materials like play-dough and clay add to sensory-play experiences activities such as building and construction.

If we cannot find clear and extensive studies about this aspect, seems that malleable and modeling media are supporting an *enactive learning* [Bruner 1966]. In his/her early years knowledge is what the child can manipulate or do with his/her movements.

Developmental psychology research has shown the benefits of manipulating tangible objects, such as clay or plasticine [Piaget 1962] together with the importance of play in learning [Mandryk and Maranan 2002].

Especially the Swiss developmental Jean Piaget have illustrated in his influential book "Play, Dreams and Imitation in Childhood" [Piaget 1962] how clay-like materials are fundamental for early development stages of children.

His assumption that knowledge is a process in continuous evolution, which involves a conception that the driving force of intelligence is it's manifestation through action. Piaget includes many examples of activities for children using malleable materials for learning physical laws such as conservation, weight and other characteristics of the material world.

Educators such as Sonstroem [Sonstroem et al. 1966] employed malleable media, such as plasticine, in their experiments on children's learning. One of the most notable is a reworking of the famous experiment called “conservation task” developed by Piaget. In the version of Sonstroem children were asked to roll out a ball of plasticine so it was longer and thinner. They were also asked to watch their own actions and describe what they were doing. For the researchers this example suggests that *enactive* processes help's children in the development of abstract thinking [Sonstroem et al. 1966].

Besides those considerations, we can notice that malleable materials and media seems to play a significant role in the development and expression of humans in their young stage, that is prehistoric age or first years of a little child. Piaget and Sonstroem were not the only one that have linked malleable materials to education.

The italian designer Bruno Munari was suggesting the use of plasticine for experimenting with unconventional topologies. For instance, transforming a sphere made with plasticine into a pyramid and vice versa, was as a way to understand the passage between a form into another one [Munari 1997].

This educational practice commonly known as “*learning by doing*”, was then developed and in relation with computer technology by constructivists such as Seymour Papert at MIT in the

middle of the 1970s. According to Papert the process of learning is process in which a person is constructing more or less functional representations of the world with which he / her is going to interact [Papert 1994]. For Papert the human mind need some appropriate building materials, that he defines as *cognitive artifacts*. Those ideas have been very influential especially for introducing children to computer programming. Nowadays the "Lifelong Kindergarten" project at MIT Media Lab is carrying forward the idea of Papert in the contemporary society.

Molding compounds such as play dough have been used also to teach intuitive electrical concepts. As Johnson and Thomas [2010] noticed many introductory physics classes have used commercial molding compounds in labs to teach electrical resistance, and application of Ohm's Law [Herrenkohl 2007]. These educational experiments have also showed the electrical properties of malleable materials.

Most commercial and homemade molding compounds (such as play-doughs) are semisolid, ionic substances. Usually the recipe for these materials is employing salt, tap water, and additional ingredients that became ionic in aqueous solutions. Those properties have been exploited in high school physics classrooms to teach students how to measure resistance [Jones 1993]. Some results have shown that the electrical resistance of a commercial compound can even change with respect to its color. By running some currents to a piece of play-dough is possible to see that exist a relation between the length of the dough and the value of the resistance.

Despite to some limitations -such as the non predictability and stability in the electrical properties, and the state of oxidation that they can reach when current is injected- researchers such as Johnson and Thomas [2010] tried to introduce this element in Human-Computer Interaction and as a possible environment for teaching electronics and robotics principles.

Through their concept of "Squishy circuits", Johnson and Thomas [2010] have been noticed that these can be very interesting to apply this idea for controlling sound. This is the next step that we are going to take.

5. Sound sculpting

Starting from the idea of *sculpting* we have seen that when interacting with highly malleable and deformable materials, such as clay, several possibilities for input are emerging.
Sculptors use their hands to shape and deform, not just their fingertips, providing nuanced control. When sculptors deform clay, they also feel the feedback of the clay pressing back. This enables sculptors to accurately gauge how much material they are removing or the manner in which they are shaping the medium. By combining these various inputs, sculptors transform blocks of clay into expressive and meaningful forms. What if we could combine the expressivity of clay with the benefits of digital interaction to allow for input from hands, tools and arbitrary objects with co-located visual feedback ? They could use their hands to explore and deform a piece of inert matter to a new form. Users could also feel the deformations while producing them, because of the immediate feedback.
What happened also if this is coupled to music production? What will be the relationship between deformation and music expression ?
Merging together *malleability*, *sculpting* and music making is not a new idea. Through the last century, several artists and composers have tried to propose a concept that we can define as *sound sculpting*. As we will see in the next section, despite the recurrent recall, this idea was never theorized as a particular practice or method for sound control and music creation.

5.1 Forming sound through shaping

Sound sculpting is a concept that I borrowed directly from the homonymous work of Mulder and Fels [1998a] [1998b] that I'm going to describe later. With *sound sculpting* I refer to the metaphor of sculpting used in relation to sound production: sculpting an object is an equivalent of sculpting sounds.
In this context the verb *sculpting* is used to describe actions, such as hand gestures, used to manipulate and actively shaping physical matter. The action of sculpting involves a direct manipulation and engagement with physical matter, such as clay or doh.
When this action is related to sound production, it implies a direct connection between gestures and sound, through a material that became the interface.

It's important to don't confuse this idea of *sound sculpting* to the one of *sound sculpture*. As Licht [2007] noticed "*sound sculpture is the oldest form of sound art* (...) *from chinese stone chimes* (…) *to the works of Jean Tinguely* (…)" and it comprise everything (installations, sculptures, environments) "*that is not instrument making*" [Licht 2007].
By following this definitions I propose to think to *sound sculpting* as a metaphor and a methodology for creating new musical interfaces, where the sound is produced by actively sculpting a material, an artifact, that exhibits some specific properties such as malleability, and allowing direct and continuous manipulation.
Though the starting point was the already mentioned work of Mulder and Fels [1998a] [1998b], they were not the first and the only that tried to explore this metaphor.
Already in 1922, the avant-garde artist and theoretician Lazlo Moholy-Nagy [1922] tried to imagine a direct connection between human agency and sound creation, by turning the gramophone from an instrument for reproduction to an instrument for musical performance:

"*So far it has been the job of the phonograph to reproduce already existing acoustic phenomena. The tonal oscillations to be reproduced were incised on a wax plate by means of a needle and then retranslated into sound. An extension of this apparatus for productive purposes could be achieved as follows: the grooves are incised by human agency into the wax plate, without any external mechanical means, which then produce sound effects which would signify – without new instruments would have to take into account the technology of radio, electric recording and broadcasting. and without an orchestra – a fundamental innovation in sound production (of new, hitherto unknown sounds and tonal relations) both in composition and in musical performance*." [Moholy-Nagy 1922].

Some years later, the french composer Edgar Varèse envisioned the possibility of creating musical instruments that will physically follow the continuous flow of musical ideas:

"*When new instruments will allow me to write music as I conceive it, taking the place of the linear counterpoint, the movement of sound-masses, of shifting planes, will be clearly perceived. When these sound-masses collide the phenomena of penetration or repulsion will seem to occur. Certain transmutations taking place on certain planes will seem to be projected onto other planes, moving at different speeds and at different angles. There will no longer be the old conception of melody or interplay of melodies. The entire work will be a melodic totality. The entire work will flow as a river flows*".

[Varèse 1936].

As Jordà [2005] noticed, several authors have also described metaphorical sculptural approaches to music creation, especially through dedicated software, such as Bischoff [1991] and Rowlands [1998]. This is also highlighted by the name chosen for some commercial softwares such as AudioSculpt[1] from IRCAM.
These approaches are going from composition and real-time sound generation to direct manipulation of digital sounds through filters and effects.

For instance, in the area of musical interfaces Atau Tanaka points out that "*with computer generated sound, a musical event in the classical sense does not have to be articulated for the sound to be modified. One could imagine a system that is comprised simply of an ongoing stream of sound that is sculpted by performer's gestures*" [Tanaka 2000].

Composer and electronic musician David Rosenboom have recently expressed to The Wire magazine his idea of electronic music : "*I taught it (the synthesizer a/n.) as a plastic medium, like clay, ready to be moulded to serve artistic ideas*" [Rosenboom 2014].

Summary

This recurrent idea of *sound sculpting* have never found a real application. In the following chapters I will explore how this can be achieved now in the area of musical interfaces through the application of the most recent research about computational materials and Radical Atoms developed in the framework of Tangible User Interfaces (TUIs). Through my project SculpTon I will present one possible approach for applying this idea to music expression, and discuss which are the possible advantages and limitations.

1 http://anasynth.ircam.fr/home/english/software/audiosculpt

Chapter 2

New Interfaces for Musical Expression : the complex art and science of creating music in the digital age

This chapter introduces the development and the state of the art of a field known as New Interfaces for Musical Expression (NIME). The first part of the chapter will be dedicated to the historical development and the main milestones that have led to the contemporary practice and definition of the field. The second part will highlights some relevant issues in the design of new musical interfaces, with a special attention to the problem of expressivity. Then the state of the art, the different genres and some open questions and issues in the crowded world of interfaces for musical expression will be analyzed.

1. Music and technology

"*Musical ideas are prisoners, more than one might believe, of musical devices*."
[Schaeffer 1966]

Music instruments are used to play and to produce music, transforming the actions of one or more performers into sound. Music was probably one of the earliest applications of human toolmaking, after hunting, shelter, and survival. One of the first example was a 43.100 old bone-flute founded in Slovenia in 1995. As toolmaking evolved into mechanical and electrical technology over the last centuries, inventors and musicians have been driven to apply new concepts and idea into improving musical instruments or creating entirely new ways of controlling and generating musical sounds.

Until the end of the 19th century, the design of musical instruments relied upon mechanical systems and the acoustic properties of tubes, strings and membranes. The classical acoustic instruments have been with us for centuries, thus have settled into a near-optimal design and only slowly yielding to gradual change and improvements. For hundreds of years, the art of music instruments making (luthery) has remained a mysterious activity. Only few specialized artisans were holding the knowledge of treating materials, especially wood and brass, to form them into musical sound producers.

More then one hundred years ago, with the advent of electricity, instrument designers started to experiment with the new possibilities offered by electrical, electronic and digital means.

According to Joel Chadabe [1997] the development of electronic musical instruments through the twentieth century has involved a multitude of composers, engineers, scientists, and entrepreneurs. With different personalities, backgrounds, skills, and goals, they composed music, build instruments, conducted research, formed companies and, in general, contributed to the cumulative body of concepts, artistry, and techniques that defines the electronic musical instrument in its current forms.

Some composers contributed by using existing technology in such creative way that their compositions led to the invention of new instruments "*We need new instruments very badly* (…) *Musicians should take up this question in deep earnest with the help of machinery specialists." In the absence of "new instruments*" [Varèse 1922].

Engineers contributed also, by designing and building instruments, albeit sometimes they disagreed on basic issues viewed by designers as a quality.

Scientists contributed through research in psychoacoustics and other related fields, by publishing theories, even nonmusical theories, that shed light on the issues raised by new musical technologies.

Entrepreneurs contributed by forming companies, turning ideas into products, and making those products available to the public.

1.1 Three milestones

In his fundamental historical essay called “Electric Sounds” Chadabe noticed that the history of electronic and digital musical instrument, is the result of a complexity of many stories. Each of those stories are describing a coherent step-by-step progression of work along a certain path. And the paths often run along parallel lines [Chadabe 1997].

Along this road made of different paths, Chadabe identifies three milestones that mark an overall chronology that can be consider the history of electronic music from the origin until now.

According to him, the first milestone marks the development of the early electronic instruments, build by pioneering individuals during the first half of the twentieth century- from Thaddeus Cahill's Telharmonium in 1906 to the Theremin in 1920, and the RCA Mark II Electronic Music Catalog in 1957 [Chabade 1997] [Paradiso 1999] [Smirnov 2013].

The second milestone marks "the opening up to all sounds". This begins with John Cage's early work in the mid-1930s and continuing into the first round of tape studios in the 1950s. At that time, tape music became the first technology based music overcoming the music studios and spread into society.

The third milestone was the growth of synthesizers from their roots in mainframe computers and analog systems in the 1960s, with systems such as the Buchla and the Moog [Paradiso 1999]. They become commercially successful electronic musical instruments in the 1970s and 1980s.

As electronic technology evolved from vacuum tubes to transistors in the 1960s, from transistors to integrated circuits in the 1970s, and from integrated circuits to microprocessors in the 1980s, so evolved the technology of electronic musical instruments from large, expensive, institutional systems to small, relatively inexpensive, and personal system. Additionally, the so-called open software, hardware and DIY movement made the rest in terms of divulgation, openness,

collaboration and shared creation.

The fourth milestone for Chadabe is on a path that paralleled the development of the hardware instruments, was the formulation of new ideas for making music and playing instruments. Those ideas, which dealt ultimately with the concept of interaction, challenge "*the very nature of way we've traditionally thought about music and musical instruments*" [Chadabe 1997].

I'm starting my discussion about musical interfaces from the fourth milestone described by Chadabe, which identifies the period that we are facing, and the contemporary state of the art of the field.

The idea of interaction is now a fundamental and accepted term or quality with which musicians, composers, designers and engineers are relating nowadays. When we are talking about 'controllers' or 'interfaces' we are implicitly talking about musical or sonic interaction. This area of development growth very rapidly in a multidisciplinary research community. Composers and researchers of in the area of sound synthesis algorithms, music information retrieval, and digital signal processing are coupled together with the community of Human-Computer Interaction (HCI).

By developing dedicated interfaces, sound artists and interaction designer are nowadays working in the development of new and different forms of interaction with sound.

The two most common ways to generate sound are through the use of a synthesizer and by means of a general-purpose computer. With the advent of digital technologies, the connection possibilities afforded by data communication protocols (such as MIDI or OSC), powerful and low power microntrollers, together with the development of embedded computing, every complex sound can be generated in real-time. Also the use of mobile phones as a musical instrument is pushing the possibility of creating music with personal, portable and multipurpose devices [Tanaka 2010]. Collaborative practices emerged with the development of internet networks and wireless systems. Through new musical interfaces, electronic and digital music became invested with new social meanings [Chadabe 1997].

2. Defining the instrument

One of the main differences between acoustic and electronic instruments, is that the latter are characterized by a strong separation between the sound synthesis and the physical human interaction [Miranda and Wanderley 2006]. Trevor Wishart, one of the leading figures in the development of electronic music, add that electronic -and later, computer based- music can be defined as a "*music for loudspeakers*" [Wishart 1996]. If for Paradiso [1999], interposing a computer in the loop between physical action and musical response, allows essentially any imaginable sonic response to a given set of actions, Bongers [2000] notices that the distance between the control surface and the sound generator with digital technologies became even bigger. Due to this decoupling of the control surface and the sound source, a lot of feedback of the entire process is lost. Then, one of the main research in the field of electronic music instruments and musical interfaces address the sense of touch, and how it can restore the characteristic haptic feedback provided by acoustic instruments.

This issue was related by composers and researchers to the problem of "*expressivity*" [Dobrian and Koppelman 2006]. During the last three decades in the field of musical interfaces, musical *expression* with machines was constantly related to *control* [Wanderley and Orio 2002]. The first is a desiderable achievement, the second represents only a starting point, and must be overtaken by designers and performers. If we consider that the main academic conference in this field is called New Interface for Musical Expression (NIME)[2], we can see how expression represents an open and widely discussed issue in the community. Where expression lies in music made with machines ? It's a matter of the interface ? Of the hardware ? Or of the software ? It is a problem of the performer ? Acoustic and traditional instruments are more expressive than a gestural controlled digital synthesizer ?

2.1 Interfaces, controllers or instruments : a question of terminology ?

Before going into the analysis of the aspects that are composing a musical interface, it's important to discuss some terminology: we are talking about instruments, controller or interfaces ? For the purposes of this thesis I'm adopting the term musical interfaces.

2 http://www.nime.org/

Different terminologies have been discussed in the last twenty years. Miranda and Wanderley [2006] use the term Digital Musical Instruments (DMI) to denote an instrument that contains a control surface (also referred to as a gestural or performance controller, an input device or a hardware interface) and a sound generation units. If [Mulder 2000] tried to use a more descriptive term such as *control surface*, on the other hand, Tanaka [2000] and Bongers [2000] introduce the possibility of define those instruments as *sensor-based*. Jordà [2004] is very critical about the use of the term "musical instrument" in this context. If it's true that in the research field defined as NIME, the term interface is often employed for referring only to input devices, it's also true that researchers in the field of sound synthesis are invoking this term for themselves [Jordà 2004]. For this reason, Jordà introduces the idea of *digital liutherie* [Jordà 2004], which is an attempt to define the design of new musical instruments as a whole concept: from the input device to the sound synthesis and control; a sort of of craftsmanship of the digital era.

With the establishment of NIME in 2001 as a workshop at the Computer Human Interaction (CHI) conference [Blaine 2005], and established as a full conference in 2002 the term of interfaces for musical expression (or simply musical interfaces) became an established research field, *interface* became an accepted definition.

Tanaka [2010] highlights the fact that in NIME community two themes are predominant: the definition of the instrument and the study of approaches to mapping gestures to sound. Because the focus on this chapter is on input devices and interfaces, my choice of employing a specif term like "interface" is motivated by this discussion around the terminology. In the last twenty years this field has developed very fast, and different approaches emerged, but like in music, there are no inviolable rules. For Tanaka [2010] the use of the word "interface" instead of "instrument", reflects the desire to open up the field of research, but also it describe the challenge in arriving to a single vision of what a NIME instrument could be.

This can be viewed also as an attempt to leave room for new developments, and identify federating characteristics. Tanaka [2010] tries to define these musical interfaces as an autonomous and open-ended system. By autonomous he means self-contained and self sufficient. By open-ended he means extensible systems, in the technical and sonic characteristics of the interface.

In a contemporary context musical interfaces are not only artifacts or systems that can be played by a performer, but also interactive environments like the "Very Nervous System" by David Rokeby [1998], mobile systems [Wang and Essl 2008], musical robots [Kapur 2005], or

networked [Tanaka and Bongers 2001] and shared instruments [Fels and Vogt 2002].
Music interfaces are also shifting into the more general idea of *sonic interaction design* [Franinovic and Serafin 2013], which means that the music production became embedded and embodied in our environment in most different contexts suchas education, rehabilitation, video games, commodities.
Some concepts and artistic methodologies such as the Reed Ghazala's "circuit bending" [Ghazala 1993] or the "hardware hacking" of Nicolas Collins [Collins 2006] became very influential not only in the community of researchers and artists, but also in hobbyists and beginners.
Apart from NIME and the International Computer Music Conference (ICMC)[3], an increasing number of conferences, undergraduate and post-graduate university courses, workshops, books, websites and international competitions have proved that the research on musical interfaces is one of the most active areas that stands between art, science, music and technology.

2.2 Real-time interaction and multidimensional control

As Chadabe [1997] observed the idea of 'interaction' changed forever the idea of a musical instrument from the emergence of computer based music.
Nowadays real-time interaction is a concept that defines the characteristics of most of the common computational processes. Jordà [2008] argues that real-time interaction is not about getting something 'instantaneous', that is the fastest response to our actions. It's not only about the perception of 'instantaneity', but it's more related to perception of 'continuity' in time and space. In this time continuum, the user's actions do not need to wait for each system answer (like in a real conversation), but there are no fixed turns and "*everyone is free to say anything at any time*" [Jordà 2008]. If we are talking about computer based works, in several video games and interactive art installations the user can sense the 'real' time passing outside of the computer, where decision are taken and actions performed in space and time, also by different users. Jordà [2008] stresses the point that real-time interaction is not only conveying time continuity but

3 http://www.computermusic.org/page/23/

also space continuity, which is a clear consequence of this interaction paradigm.
Then, for Jordà [2008] musical and audiovisual performances that are executed in real-time are representing some of the most paradigmatic genres of real-time interaction.
Traditional music performance is also continuos and multi-dimensional: a violinist continuously controls the position of the fingers on the strings as well as the position, inclination, pressure and speed of the bow. Digital music performance is, conceptually, nothing different. Since the implementation of MIDI computer music practice has cohabited with multidimensional and continuous control. The only problem is the resolution, the temporal granularity and precision that consists of very few milliseconds. These issues can be viewed in two different ways: as a technical problem or as an artistic problem. Artists such as Atau Tanaka [2000] have been proposing to look at resolution and latency as a characteristic, a quality of the computer based instruments and musical interfaces, so it must be used by performers in an artistic way.

3. Design musical interfaces: issues, problems and perspectives

"*Musical interface construction proceeds as more art than science,*
and possibly this is the only way it can be done "
Perry Cook [2001]

Similar to the development of electronic music, also the development of musical interface is based on different approaches, mixed backgrounds and interdisciplinary research.
Describing musical interfaces as an abstract or general category seems to be a very difficult task. We can analyze them by drawing a parallel between acoustic and electronic instruments, or using methods and categories developed in Human-Computer Interaction.
In this section I will describe some common approaches adopted by artists and engineers during the last forty years that became part of the common knowledge for the community devoted the development of musical interfaces.
The design of new digital musical interfaces involves two main aspects: the first one is the design of appropriate interface, the second one the development of new methods of sound generation.

These two aspects are evolving together and one is driven by the other: new synthesis techniques such as physical modeling enables and require expression and control over new degrees of freedom.
In this chapter I'm going to explore the development and the idea of the input interface as such, and leaving the discussion about real-time synthesis algorithms. Since electronic instruments became digital, the field of musical interface research has merged with the broader field of Human-Computer Interaction.

3.1 Expression and control: a difficult balance

As Johan Sundberg suggests, the voice organ, possibly the most expressive instrument ever, can be considered as one of the most badly designed instrument from an engineering point of view, if we took into account the complex relationship between articulator movement and formant frequency changes that makes articulation/formant frequency a one-to-many system [Sundberg 1987].
The development and the design process of musical interfaces is characterized by a continuous research of a balance between good design, robust and precise technology and musical expression.
Expression is a highly discussed but fundamental term in the design and analysis of musical interfaces [Dobrian and Koppelman 2006].
Apart some general-purpose and commercial available devices, most of the musical interfaces that have been developed by composers and artists are not 'stable' and are constantly changing their balance. If in a first prototype the author wants to express some possibilities, in a second version maybe some technical issues need to be solved. Nowadays we know that in musical interfaces good engineering is not a synonymous of good expressivity, since the contrary is also valid [Bongers 2000] [Jordà 2005a].
Musical interfaces is a field of research and experimentation full of incomplete, sketched and highly mutable hardware and software elements.
Usually the musical idea, the desired musical expression, can be achieved only through some

several adjustments, that are made in order to fully obtain the desired functionalities. Furthermore, it is likely that this refinement process will be extensive and span a number of years, such as most of the interfaces that I'm going to discuss in this chapter have gone through various refinements.

Most of these refinements may have been made in order to solve inherent design problems. Others may be made owing the availability of newer components and technologies in order to make interfaces more robust and precise. One of the most typical procedure involves the replacement of original sensors with higher-performance and/or lower cost ones [Bongers 2000].

If technical refinements are sometimes physiological, another important reason for new implementations, is that the artist may realize, after a period of practice, that extra functionalities could be added to the original device or some changes can be made in terms of ergonomic. Conversely, initial functionalities may have to be removed from the controller if they do not fulfill design expectations when put in practice.

This is the famous case of “The Hands”, a musical interface developed by Michael Waisvisz through twenty years [Waisvisz 1985]. Working with different designers and engineers, Waisvisz developed and explored different versions of the interface. Most of those iterations and implementations are not entirely driven only by technical or ergonomic problems. They can also be driven by artistic and compositional ideas. Waisvisz noticed that in his personal experience he found useful to 'freeze' the technical development for some years, in order to develop the musical and expressive side of the instrument [Wanderley and Battier 2000].

3.2 Composing the instrument

We can say that the design of a musical interface may involve a lengthly trial-and-error process before a stable version is achieved.

I mean “stable” not only from a technological point of view, but also from an artistic point of view.

It's very important at this point, to stress the idea that the design and development of a musical

interface is not only a matter of design or computation, but involves a lot of artistic decisions.

"*Musical interfaces that we construct are influenced greatly by the type of music we like, the music we set out to make, the instruments we already know to play, the artists we choose to work with, as well the available sensors, computers, networks, etc. But the music we create and enable with our new instruments can be even more greatly influenced by our initial design decisions and techniques*." [Cook 2001].

This aspect highlighted by Cook is particularly evident in the different consequences on music development caused by the invention of the electronic synthesizers by Moog and Buchla. According to Pinch [2003], due to their different idea of 'control' behind their interfaces, Robert Moog and Don Buchla led to different musical directions. With its keyboard based synthesizers, the Moog attracted musicians already familiar with traditional instruments, and made it very successful in pop, rock and jazz music. On the contrary the Buchla, characterized by the patching style and the absence of a standard interface, opened the doors of different experimental practices, such as the one explored by Morton Subotnick [Pinch 2003].

During the years various artists, composers and instrument builders have reflect on the process of design and create a musical interface, controller or installation that is.

"*My own electronic music equipment is designed as part of the process of composing my music*" states the composer Gordon Mumma [1967]. As one of the first composers who started to work directly with the idea of interface and interaction, Mumma consider his instruments as inseparable from the compositions themselves: his famous piece "Hornpipe" (1967) is a composition in the form of an instrument, or an interactive composition controlled by a modified acoustic musical instrument.

Composer Alvin Lucier explains how within many of the works produced by the Sonic Arts Union "*there were no scores to follow; the scores were inherent in the circuitry*" [Lucier 1998].

Circuits are configured in a specific way for their artistic use, containing enough structural elements to be used in a musical situation. The role of the composer, at an equidistant point among designers, composers and performers, starts with the configuration of the technical system behind the actual instrument.

With the advent of digital technologies this process start to affect not only the hardware side but also the software.

Computer programming started to be an indispensable skill for musician and composers.

David Tudor define his aesthetic as "*composing inside electronics*" [Kuivila 2004]. This anticipated

the concepts found withing the contemporary practice of circuit bending, DIY builders and sound hackers. But more importantly, he founded the principles of a new musical practice that was continued up to the contemporary use of digital instruments and interfaces [Kuivila 2004].
This connection between the idea of composing and building a composition, which can be an electronic circuit or a piece of software (or both), was also introduced twelve years ago in the area of musical interfaces by Schnell and Battier with the concept of *composed instruments* [Schnell and Battier 2002] .
They noticed that during the technical implementation of the instrument we often incorporate many ideas of composition into the programmed system. Also the choice of a sensor has some deep and relevant artistic consequences [Ryan 1991].
But just like in any traditional composition, many cultural, personal and idiosyncratic elements of the builder's personality impregnate each digital instrument design. As explained by Wanderley and Orio [2002], if a composer decides to build or take part in the design of a certain instrument, the vocabulary of gestures of an instrument is often created with a subjective artistic reason in mind.
"*I consider that my designing and building of circuits is really "composing"* (…) *I simply employing electronic technology in the achievement of my art*" [Mumma 1967].

3.3 Idiosyncratic music technology

However, due to hundreds of different approaches, it's very difficult to derive some unified guidelines for designing New Interfaces for Musical Expression. Most of the interfaces developed are usually prototypes or instruments developed for specific compositions or performances. Since most of them are often only used by their respective creators it's very difficult to identify a "new standard electronic instrument".
According to Sergi Jordà this situation is due to two main factors [Jordà 2004]. The first is that the list of new instrument virtuosi and professionals musicians who use new and 'alternative' musical interfaces as their main instrument is very small. We can insert in this category pioneers such as Michael Waisvisz, Laurie Anderson, Atau Tanaka, Nicolas Collins, Laetitia Sonami. In

the recent years, due to the big spread of the DIY culture, a lot of young artists started to develop their own interfaces, but if we are going out from the modular synthesizer, noise machine or keyboard paradigm, the list does not enlarges so much. From this last example we can derive the next factor: being that live electronics and laptop music is so widespread that most of the musicians and performers prefer still rely on the mouse or to generic midi fader boxes.

Idiosyncrasy is the most used term for describing the state of art of musical interfaces now.

By describing the design process, Jordà [2004] notice that when instruments' designers start to envisage a new interfaces they do not have to study their instruments' sonic capabilities, not even their algorithmic power. They must be especially careful about the instruments' conceptual capabilities. "[...] *One method for making truly new music might be to create an instrument that allows performers to experiment with new playing techniques*" [Rubin and McAvinney 1990].

Starting from this consideration Joel Ryan [1992] insists that the most important part to take into account also on a conceptual level in the design of musical interfaces is the relation between effort and expression. "*Too often controllers are selected to minimize the physical, selected because they are effortless* (...) *Effortlessness in fact is one of the cardinal virtues in the mythology of the computer* (...) *we continue to think of the computer as essentially a labor saving device*" [Ryan 1992]. The link between expression and effort developed by Ryan represents a sort of unique and original contribution to the field.

By considering something really human such as physical and / or mental effort, takes the problem of expression in musical interfaces from a mere technical problem to a cultural and social issue: "*Physical effort is a characteristic of the playing of all musical instruments. Though traditional instruments have been greatly refined over the centuries the main motivation has been to increase ranges, accuracy and subtlety of sound and not to minimize the physical. Effort is so closely related to expression in the playing of traditional instruments. It is the element of energy and desire, of attraction and repulsion in the movement of music*" [Ryan 1992].

But for Ryan, effort is not only something physical but it's closely related to music in its essence: "*effort is just as important in the formal construction of music as for it's expression: effort maps complex territories onto the simple grid of pitch and harmony. And it is upon such territories that much of modern musical invention is founded*" [Ryan 1992].

3.4 The art and science of musical interface design

As we can see, designing a musical interface is a task that involves different issues, both technical and artistic, conceptual and technological. From the perspective of an instrument builder, Perry Cook [2001] wrote some interesting remarks based on his experience. He identifies some basic principles, both artistic and technological: "*smart instruments are often not smart*", "*copying an instrument is dumb, leveraging expert technique is smart*", "*some players have spare bandwidth, some do not*", "*make a piece, not an instrument or controller*".

Cook described also which are the challenges and motivations behind the development of new musical interfaces. Such as: "*new algorithms suggest new controllers*" and "*new controllers suggest new algorithms*"; "*existing instruments suggest new controllers*", "*everyday objects suggest amusing controllers*".

Many researchers have been stressing the point that musical interfaces can be evaluated only in live performances. Only when playing and using an interface an artist can ultimately feel its flexibility, potentials but also limitations. This was particularly the case of some famous interfaces like the "Hands", the BioMuse or the Lady's Glove, probably some of the most 'played' electronic and digital interfaces in the last twenty years. All of these instruments went through a process of modifications and improvements. Instrument and interface designer Bert Bongers points out, if the engineer wants to correct the mistakes immediately, the artist find these as potentially musical [Bongers 2007]. As we said before most of the time the designer , the engineer and the artist is the same person. This situation creates a pool filled with different personal tastes and ideas, but without a common basis of evaluation, became very difficult to provide useful informations for potentials users and designers[Miranda and Wanderley 2006].

For Leonardo Tarabella the main issue is that is not easy to define how to use the computer as an instrument the way it can be done with traditional instruments [Barbosa 2001]. This fact for the italian musician is a clear proof that we are at the "Stone Age" of computer music live performance.

4. What makes an interface 'musical' ?

As we said before, in contrast to acoustic instruments, digital musical interfaces can always be divided into a gesture controller or input device that takes the control information from the performer(s) and a sound generator that produce the synthesized sound. In acoustic instruments this separation in fuzzy and unclear due to the fact that (apart from organs and several other key instruments) the control surface interact with the performer's body gestures for the creation of the sound through physical oscillation and vibrations.
This separation was standardized by MIDI and it sprouted the creation and the development of new alternative controllers with which to explore new creative possibilities. First MIDI and after Open Sound Control became the standard cross point between input gestures and sound generation.

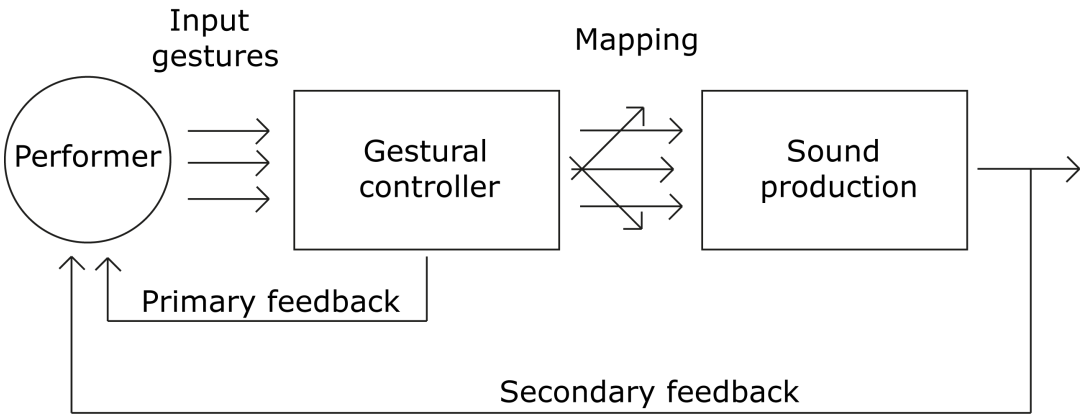


Figure 2.1: *Model of a Digital Musical Instrument.*

Miranda and Wanderley [2006] propose a model (Fig. 2.1) for describing an interactive digital musical instrument as a system comprised of three basic subsystems:

a) Gestural input;
b) Mapping;
c) Sound production.

We can define the gestural controller as a piece of equipment, a device, that provides the inputs

for the instrument. It is where the interaction between the performer and the sound generation happen. The sound generation unit involves the synthesis algorithm and its controls. The mapping is commonly defined as a translation layer that is responsible of the correlation between gestures and sound.

4.1 Gestures

For understanding the nature of musical interfaces it is important to start by analyzing the characteristics of the actions that will be captured by the sensors. In computer music such actions are commonly referred as *gestures*.

The term gesture may be used to refer to a number of actions such as empty-handed movements (together with speech or not), movements that involve the manipulation of an object, genera body movements, and even the sensation of touch, taste and smell.

The study of gesture is a vast and complex field of research, and it's going beyond the scope of this thesis. Various research communities have been exploring gestures in different contexts and the definition of what a gesture is are different.

In the field of computer music Mulder defines gestures as the opposite of postures [Mulder 2000]. Gestures are dynamic, postures are static. Other authors consider gestures to be hand movements that contain information [Kurtenbach and Hulteen 1990]. More generally, gestures are movements that convey meaning to oneself or to a partner in communication [Hummels et al. 1998].

In this thesis with term gesture I mean any human action used to generate sound. According to Miranda and Wanderley [2006] the term refers to actions such as grasping, manipulation, and non-contact movements, as well as to general voluntary body movements.

4.1.1 Gestures in music

In music, with the term gesture we refer to different means: to musical gesture, performance gesture, or instrumental gesture. The study of gesture in music is an important area of research that raises many issues about perception, performance and emotional communication [Miranda and Wanderley 2006]. One of the most significative and clear formulations of the role of gestures in music is from Francoise Delalande. "*The question of gesture is...crucial in music. It lies in the intersection of two axes: one that binds together an observable action (the gesture of the instrumentalist) and a mental representation (the fictive movements evoked by sound forms), and another one that establishes a link between the interpreter (that produces the gestures) and the listener (who guesses, symbolizes and transforms them on an imaginary plane). The latter is established through a recording of the music*" [Delalande 1988]. In the context of this thesis, for a better understanding of what a musical interface is, I'm focusing on those gestures that performers make in order to generate sounds. Such movements have been defined by Claude Cadoz as "*instrumental gestures*" [Cadoz 1988]. These gestures are usually applied to a concrete (material) object with which there is a physical interaction, and specific (physical) phenomena are produced during a physical interaction whose forms and dynamics can be mastered by the subject. For Cadoz [1988] these phenomena may become the support for communicational messages and/or be the basis for the production of a material action.

Together with these gestures we can identify also "ancillary gestures", which are some gestures that are part of a music performance but are not produced in order to generate sound. Ancillary movements are known to convey expressiveness in musical performance and therefore can be thought of as extra variables for sound generation and control [Wanderley et al. 2005]. It's important to notice that in the context of musical interfaces any body movement or signal can be used as a variable to control a musical performance. Define which gestures will be used to control the system is one of the crucial point in the creation of a musical interface [Miranda and Wanderlay 2006)] [Wanderley and Depalle 2004]. For instance, actions like walking [Choi 2000], facial expression [Ng 2004], mouth [Lyons and Tetsutani 2001] and eye movements [Rubine and McAvinney 1991], dance movements [Camurri 1995], muscular tension [Lusted and Knapp 1996], motionless signals such as brainwaves [Lucier 1976], and even audio signals [Jo 2009] have been studied and employed as effective means for sound control. For Bongers

[2000] looking at the gestures and manipulations that humans use in traditional instruments or in other means of conveying information is one the most valid approach for answer at the question : "[...] *How to deal with the total freedom of being able to design an instrument based on the human (in)capabilities instead of a traditional instrument form ?*" [Bongers 2000].
Another important aspect that comes with gestures is the kind of feedback that is available to the performer, which can be visual [Jordà 2005] [Fels and Mase 1999], auditory [Vertegaalet al. 1996], tactile or haptic [Bongers 1998] [Verplank et al. 2002] [Berdahl et al 2008]. These feedback modalities are for example crucial in performing on acoustic instruments and are necessary in interfaces that aim to simulate the control surface of such instruments [Cadoz et al. 1984], but maybe not in gestures that does not involve a direct contact with a physical device [Rovan and Hayward 2000].

4.1.2 Gesture acquisition

Once the gesture characteristics has been defined and analyzed, the next step is design an acquisition system that will capture these characteristics and translate them into electric signals.
For many years, the keyboard and a number of knobs and slider were the standard interface object for making electronic and digital music. Nowadays there is a wide variety of sensors available on the market[4] that can, virtually, transfer any real-world action into a control signal for a electronic or digital system [Bongers 2000].
An acquisition system can very substantially, since the design of the interface it's based on the gestures employed for control and play. Certain gestures can manipulate sound synthesis directly, while others articulate note-like events, while other actions can be directed to the structural progress of a composition [Tanaka 2000]. Especially in the area of totally new interfaces, not based on a traditional instrument as referent, new gestural acquisition systems -based on a particular gestural vocabulary- must be developed.
Miranda and Wanderley [2006] have identified three main different ways of gesture acquisition: *direct*, *indirect* and *physiological*.

4 http://www.sensorwiki.org/doku.php

In *direct acquisition*, one or more sensors are used to monitor the actions of the performer. According to Bongers [2000]: "Sensors are the sense organs of a machine. Sensors convert physical energy (from the outside world) into electricity (in to the machine world). There are sensors available for all known physical quantities, including the ones humans use and often with a greater range". The signal from those sensors presents individual basic physical features of a gesture, such as pressure, acceleration, light level, proximity, angular displacement. Depending on the type of sensor and their combinations in various systems, different movements can be traced. For a more complete survey on sensors and their use I refer to [Horowitz and Hill 1980] [Mims III 1996] [Sinclair 1998].

Unlike direct acquisition, *indirect acquisition* provides information about performer actions from the structural properties of sound being produced by an instrument. In this case the only sensor is a microphone. Due to the complexity of the information available from the sound produced by the instrument, different real-time signal processing techniques are used in order to distinguish the effect of a performer's action from environmental features [Miranda and Wanderlay 2006]. These systems identify some sound parameters to be extracted in real-time, in order to recognize a gesture.

Normally parameters are related to the sound's melodic profile (fundamental frequency), the dynamic profile of the signal (short-time energy), the distribution of sound partial amplitudes (spectral envelope), amplitude and pitch.

Examples of indirect acquisition of performer actions can be found in applications like score following [Vercoe 1984], augmentation of acoustic instruments like clarinet [Egozy 1995] and voice following [De Götzen et al. 1998]. For a more accurate discussion of the topic I refer to [Wanderley and Depalle 2004].

The third method is the *physiological signal acquisition*. This method includes signals such as electromyogram (EMG), electroencephalogram (EEG), electrooculogram (EOG), and galvanic skin response (GSR), are also referred as *biosignals*. Unlike the previous methods, physiological signal acquisition is potentially hard to master because signals are weak and contaminated by noise [Miranda and Wanderley 2006].

At this point it's important also to highlight some critical aspects regarding the acquisition of musical gestures in a real-time system. One of the first researcher who started to problematize those aspects was Moore by relating gesture acquisition to the issues and problems of encoding complex gestures and meaning into binary representation of events in digital audio [Moore

1988]. His observations are still relevant, even if was relating these issues to the MIDI protocol in the end of the 1980s. For Moore, *resolution* and *rapidity* are two fundamental aspects of a gestural acquisition system in musical interfaces, but also some very critical elements that, if not treated carefully, can seriously limiting the whole instrument [Moore 1988].

4.2 Mapping: characteristics, issues and limitations

Once the gesture's data are available, ones needs to relate those variables onto the parameters of a synthesizer or an algorithm that will be used to produce the sounds. This relationship between input gestures data and control data is commonly known in computer music as *mapping*.
As I said before, unlike with acoustic instruments, in musical interfaces the control surface is usually completely separated from the sound generator. This means that the relationship between them has to be established from scratch. For this reason often *mapping* is defined as a intermediate layer where the correlation of gesture to sound happen [Hunt et al. 2002].
But, far from being a simple stage between two processes, this aspect of the design of musical interfaces needs careful consideration because the relation between gesture and sound is not an obvious or easy task to tackle [Miranda and Wanderley 2006]. The *mapping* 'layer' is not only a mere correlation of different variables, it's also what '*brings the interface to life*' [Hunt et al. 2002]. It's important to stress the fact that in this 'layer' a lot of artistic and musical decision are taken. According to Michael Waisvisz "*This area* (the translation of gestural parameters to sound, a/n) *is often considered as a technical area. I believe that algorithm for the translation of sensor data into music control data is the major artistic area; the definition of these relationships is part of the composition of a piece. Here is where one defines the expression field for the performer, which is of great influence on how the piece will be perceived*" [Wanderley and Battier 2000].
The number of characteristics of the interfaces may vary enormously depending on which sound synthesis technique is employed, and even which kind of musical events or structures of a composition one wants to control. From a frequency modulation to a live sampling and looping routine, to an articulated physical model, the relation between a gesture and a sound can led to a lot of complex decisions. For Jordà it becomes hard -if not impossible- to design highly

sophisticated control interfaces without a profound prior knowledge of how the sound or music generators will work [Jordà 2004].

Hunt and Wanderley [2002] that have been conducting one of the earliest literature review on the topic, consider mapping to be an integral part of a musical interface, something that strongly define its musical essence. They emphasize the 'dramatic effect' that the style of mapping can have on the artistic and musical success of the interface [Hunt and Wanderlay 2002], because the mapping strategy chosen affects the way the interface will be played and its artistic effectiveness. With a different terminology Moore refer to this moment placed between the real-time capture of a performer's gesture and the sound synthesis as the "*control transmission*" problem [Moore 1988]. We don't have to forget that all of these technical aspects in the design of a musical interface have a musical and audible meaning. A delay between the two layers (gesture acquisition and sound generation) can be a critical moment for the performer but also for the audience. Moore stressed the importance of taking into the account the "[...] *vulnerability of the expressive aspects of musical sound to low bandwidth transmission rates*" [Moore 1988].

But, how does one relate a gesture to a particular sound control parameter? There is not a unique or agreed answer. According to Miranda and Wanderley [2006] we can devise two main directions in the existing literature about what we define as mapping:

a) The use of Neural Networks, feature extraction, or pattern recognition. These tools can provide mapping strategies characterized by the internal adaptation of the system through training or selection of the most important features in a given signal. In the last twenty years a variety of research was devoted on the development of frameworks and tools for real-time gesture recognition and mapping. The common approach is to identify and apply algorithms and methods derived from research areas such as Artificial Intelligence (AI) and Machine Learning (ML). The use of Neural Networks (NNs) for this purpose was one of the first methods that has been investigated for real-time applications [Lee at al. 1991] [Fels and Hinton 1992] [Rowe 2001]. The recent advances in machine learning has brought real-time performance, robustness and invariance in modeling data, making ML increasingly capable of analyze live and expressive gestural inputs [Caramiaux and Tanaka 2013]. With NNs and ML algorithms the mapping is less deterministic and can be adaptable by the performer based on his/her personal gestural vocabulary [Merrill and Paradiso, 2005] [Friebrink and Cook 2009]. Nowadays different toolkits

for expressive gesture recognition, developed especially for musical applications, are available for researchers and artists, They include the MnM [Bevilacqua et al. 2005], Wekinator [Fiebrink et al. 2009] and SEC [Gillian et al. 2011].

b) The use of a explicitly defined mapping strategies, where the relations between a gesture and the sound synthesis are defined and hard-coded in the system. In the literature available on this topic we can notice that this relation in the mapping layer is generally considered as a few-to-many relationship [Miranda and Wanderley 2006].
Hunt and Wanderley [2002] have identified four main types of mapping strategies:

- *One to one*, where one synthesis parameter is correlated to one gestural parameter.
- *One-to-many,* where one gestural parameter influence many synthesis parameters at the same time.
- *Many-to-one*, where one parameter of the synthesizer is driven by various gestural parameters.
- *Many-to-many*, which is the combination of the previous strategies.

This categorization is still valid for analyze the main styles of mapping in order to provide a reference framework for addressing this delicate task.
The design of a particular mapping strategy can be simple or complex. A particular mapping strategy can also be chosen to reflect other expressive needs, such as an interaction metaphor [Fels et al. 2002].
Hunt et al. [2000] noticed that often designers has the tendency of making a one-to-one mapping, but the use of different layers of simple mapping can led to more interesting and provide more degrees of expressivity to an interface [Hunt et al. 2002].
This represents also one of the most criticized aspects in literature. As I said before, independently from the strategy used, mapping is still a critical element while designing a musical interface. The complexity (input data and sound control parameters) of an instrument can led to an abstract mapping that is not describing the complex reality of a musical interface [Chadabe 2002].
Some of the still open question are: is that is possible to move from a pure 1 to 1 gesture-sound

correlation to a much more wide idea of expression? How much expressivity we can derive from gestures?
In the last ten years many researchers and artists tried to explore and answer to these questions throughout an increasing number of papers that have been published and presented in conferences such as ICMC, NIME, and in specialized publications [Wanderley 2002].

4.3 Sound production

The last element, sound production, can be seen as the reason why the previous elements are existing. If in electronic music the sound is generated by electrical energy, voltages and frequencies, in computer music this is done through algorithms and computer code. Domain such as sound synthesis represents some of the fundamental and vast area of investigation in the realm of computer music.
During the last fifty years, many researchers, scientists and musicians have been experimenting and implementing many techniques for synthesizing digital sounds.
Most common methods are ranging from combining basic waveforms to complex algorithms that mathematically reconstruct a real instrument's physical attributes.
Since the focus of this dissertation is not on sound synthesis techniques, I will only list some of the most common. The following descriptions are simple introductions to the different types of synthesis, meant to present a short review of how the common types of sound synthesis work.

Additive synthesis:

additive synthesis constructs sounds from the ground up by building a complex waveform from it's basic elements. It works by mixing (or summing) one or more simple waveforms, such as sine waves, together to create a more complex waveform. his method of synthesis is theoretically capable of reproducing any sound. This is true because every sound can be broken down into a collection of sine waves. Unfortunately, natural sounds are extremely complex and require a great

amount of processing to be recreated accurately.

Subtractive synthesis:

Subtractive synthesis takes a reverse approach to generating sound. It starts out with a waveform rich with harmonics (such as a saw or square wave) and filters it to produce the desired output. This method can be used to effectively recreate natural instrument sounds as well as textured surreal sounds.

Granular synthesis:

Granular Synthesis uses a sequence of short sound grains to form a final longer output sound. Sound grains are relatively short segments of audio (usually from 10 to 100ms) that consist of frequency information in the form of a group of samples. The sound grains can be simple sine waves or complex sampled sound textures. The sound grains are played in a variable sequence with different variations on the amplitude, individual sound grain durations and total duration of the sequence of sound grains to form a final output sound/instrument. These variations define the output sound's envelope, pitch and length, while the contents of the sound grains define the output sound's "texture".
Forms of granular synthesis are commonly used to independently change the pitch/frequency or duration attributes of digital audio without effecting the other.

Amplitude Modulation (AM) *synthesis*:

Amplitude Modulation Synthesis is performed by combining two signals together. A source audio signal, the carrier, is multiplied by an unipolar modulation signal. A unipolar signal is simply a signal that contains only positive values (usually between 0 and 1). This process is typically used to alter the carrier signal in one of two ways.
The modulation signal can be used as an envelope which is applied to the carrier signal to

determine the audio signals amplitude over time. AM synthesis used to apply an amplitude envelope.
The modulation signal can be also be used to quickly cycle the carrier signal's amplitude to form two additional frequencies known as sidebands, forming harmonic or non-harmonic sounds.

Ring Modulation (RM) *synthesis*:

Ring Modulation Synthesis is almost identical to AM synthesis (described above) with the exception that it uses a bipolar modulation signal. A bipolar signal is simply a signal that has positive and negative values. An audio waveform is an example of a bipolar signal and can in-fact be used for the modulation signal to alter another audio waveform used as the carrier. The use of a bipolar signal causes an interesting difference in the output signal when compared to AM synthesis. When the modulation signal is used to quickly cycle the carrier signal's amplitude, like AM synthesis it forms two additional sidebands, but the carrier signal is cancelled out and disappears.
One of the most common application of Ring Modulation synthesis is in Vocoders.

Frequency Modulation (FM) *synthesis*:

Frequency Modulation (FM) Synthesis produces an output signal by oscillating the frequency of a source oscillator's signal. This process can generate fairly complex output containing multiple frequencies/sidebands with only two oscillators, requiring minimal computations. This computational efficiency is the reason for it's invention and great popularity in earlier synthesizers and sound cards.

Wavetable synthesis:

This type of synthesis is carried out by simply playing segments of digital audio to produce a realistic instrument or synthetic sound. The digital audio segments are stored as a table of

waveforms in memory and played back at different speeds to produce output of a different pitch for each musical note. One common addition to wavetable synthesis is that each instrument waveform contains a loop region. This region is starts after the attack segment of the digital audio has played and repeats while the instrument's note is sustained (i.e. while a note is held). Then the release segment of digital audio finishes off the note. Wavetable synthesis in the form of envelopes and modulators are often combined with AM synthesis to add some variation to otherwise repetitive sounding output.

Physical Modelling (PhM):

Physical Modeling (PhM) takes a unique and complex, but more intuitive approach to synthesizing sounds. Synthesis is accomplished by simulating the physical properties of a real or fictitious musical instrument mathematically by defining exciters and resonators. Exciters are what trigger the physical model to start generating sound. Real examples include the hit of a drum, stroke of a bow, or pluck of a string. An input (such as a key press and the strength/velocity of the press) is translated into the appropriate parameters for simulating physical properties of instrument's input (such as blowing, amount of air, etc.). Resonators simulate the instruments response to the exciter which usually defines how the instrument's physical elements vibrate. Examples include, a plucked string, struck drum membrane, blown reed or even vibrating vocal chords. This type of sound generation can be extremely complex and require heavy computation, so many currently available physical modeling synths use short-cuts or watered-down methods which enable them to respond in real-time.

The previous synthesis methods are not exclusive, several other techniques exists and have been developed during the decades. Most of the contemporary hardware and software synthesizers are using a combination of these techniques to produce new, more realistic and / or interesting sounds.
For a better understanding of sound synthesis and related techniques I refer to [Roads 1996] [Cook 2002][Puckette 2006] .

5. Musical interfaces : a possible classification

"*The world is multidimensional in its essence. Mental processes are also multidimensional. Why not demand that models of musical thinking be multidimensional?*"

L. Theremin, 1965 [Smirnov 2013]

After the exploration of the concepts, ideas and issues behind the design of musical interfaces is now the moment of analyze some examples of interfaces created by researchers, engineers and artists in the last twenty years and more. Although several examples of electronic musical instruments have been proposed in the past century, in the las two decades musical interfaces has increased dramatically. This fact is mostly due to the emergence of the MIDI and then OSC protocol, to the widespread availability of powerful, embeddable and low-cost computers.
The actual crowded world of musical interfaces can be studied from different points of view. Different classifications and grouping methods have been proposed, based on various factors. One of the most straightforward method would be to compare musical interfaces in terms of the resemblance to existing acoustic instruments. By doing this, Manning [2004] proposes a range of possibilities: from traditional instruments augmented by sensors and controllers imitating or inspired by existing acoustic instruments to totally new designs, which are bearing little or no resemblance to existing instruments, and based on different musical and interaction concepts.
Miranda and Wanderley [2006] proposed one of the most clear classification based on this principles. They identify four different types of musical interfaces:

a) **Augmented instruments**. These are acoustic instruments augmented by the use of different sensors. We can devise some examples in the Meta-Trumpet (Fig. 2.2) by Jonathan Impett [1994], the "hyper" family instruments developed by Todd Machover and collaborators at MIT [Machover 1992] or the "Tape Bow Violin" (Fig. 2.3) used by Laurie Anderson [Collins 2006].

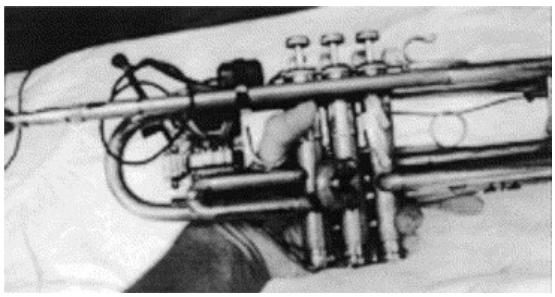


Figure 2.2 : *Meta-Trumpet*.

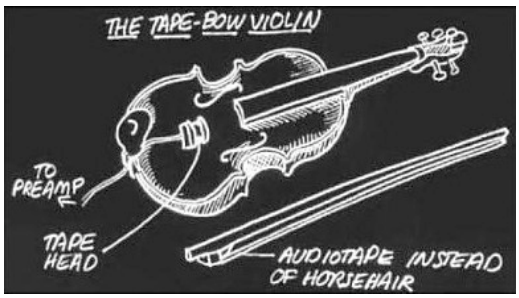


Figure 2.3 : *Tape Bow Violin*.

b) Controllers and interfaces that are **modeled on traditional musical instruments**. The goal of this type of musical interfaces is to completely reproducing the control features of these instruments. Keyboard type of instruments are the most represented one with the most famous models commercialized by Yamaha and Akai. One of the most popular in popular culture is probably the Roland AX Synth (Fig. 2.4). Several wind instrument interfaces have been also developed, such as the Yamaha WX series (Fig. 2.5) .



Figure 2.4 : *Roland AX synthesizer*.



Fig. 2.5 : *Yamaha WX synthesizer*.

c) **Instrument-inspired interfaces**. These interfaces are inspired by existing instruments or that intend to overcome some intrinsic limitation of the original models, but the do not seek to reproduce them exactly. The design can be substantially different from its original acoustic model. Some well-known examples are the "VideoHarp" by Dean Rubine and Paul McAvinney [1991] an the "Trombone-Propelled Electronics" (Fig. 2.6) developed by Nicolas Collins [1991].

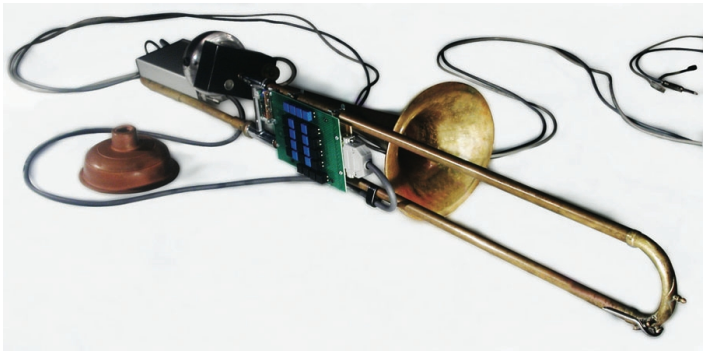


Figure 2.6 : Trombone-Propelled Electronics

d) **Alternate controllers**, which are interfaces that do not bear strong resemblance to existing acoustic or electronic instruments. They can take any shape and form, can be a total new design, augment every-day like objects or use plants and vegetables.

Obviously this classification is not exhaustive or intended to be definitive, since boundaries may overlap and one interface may satisfy more then one criterion. For instance, some instrument-inspired interfaces can be seen as alternate controllers. Hundred of classifications and comparisons have been devised in literature: for instance, Atau Tanaka [2000] proposed to classify musical interfaces into the categories of physical and non-physical, and into mechanical and non-mechanical controllers. If some applied analytical tools from Human-Computer Interaction in the context of musical interfaces [Orio et al. 2002], others have been compared interfaces starting from some features like expressivity, immersion and feedback [Pringer 2001], or based on the study of the efficiency of musical instruments [Jordà 2004]. One can also compare different interfaces from a purely technological perspective by looking at the sensor technologies that is adopted [Bongers 2000], the mapping strategies and the synthesis algorithms [Wanderley and Depalle 2004], or looking through the perspective of the interaction involved [Birnbaum et al. 2005].

For the purpose of this thesis I'm not going into the details of different classification methods for musical interfaces, and I will not introduce a new framework, or a methodology. Such classifications can provide a useful means to make sense of the wide variety of developments in the area of musical interface design. For a more detailed analysis of other types of musical interfaces I remind at Roads [1996] [CMJ 1990a] [CMJ 1990b] [Miranda and Wanderley

2006] and the official proceedings of international conferences such as NIME and ICMC.
In the next section I'm going to explore and analyze some relevant examples of what Miranda and Wanderley [2006] defined as *alternative controllers*.

5.1 Alternative controllers

As I said before, the increasing numbers of musical interfaces developed in last ten-twenty years is composed of very different, hybrid and sometimes very unusual devices. According to Miranda and Wanderley [2006] we can insert in the category of alternate controllers any kind of interface that does not fit the other categories previously mentioned. In the computer music community these types of interfaces are known as *alternate* to mean alternative controllers. Probably, nowadays is very difficult to define what is an alternative controller. The question might be "alternative to what ?" As Blaine [2005] noticed we are facing an enormous numbers of alternate controllers which are being employed in game and toys industries. If we think about some gestural controllers such as the Microsoft Kinect, or the DataGloves in the 1990s, we can see how these interfaces were initially alternative and rapidly they became part of our environment.
However, I'm referring to all of the interfaces which are not directly inspired or modeled on already existing instruments, acoustic or electronic they are.
One of the first who tried to classify alternate controllers was Axel Mulder [2000]. He proposed a classification based on the features of those interfaces:

a) **Touch-based interfaces**: alternate controllers that still require the performer to touch a physical interface. They can be a surface or a device, and can be mobile or fixed in space. They also provide some forms tactile feedback to the performer. These controllers can allow direct touch but also manipulation. One example is the "PeebleBox" (Fig. 2.7) developed by O'Modhrain and Essl [2004]. In this interface real peebles are placed inside a foam-padded box and the collisions between rocks are sensed using a microphone. The control variables are

derived from the analysis of the collision sound (captured by the microphone) and are used to drive granular synthesis algorithms. Similar techniques are employed in other touch-based interfaces, such as the "Tangible Scores" by Enrique Tomás (Fig. 2.8), where some wooden plates are etched with different 'graphic scores' [Tomás and Kaltenbrunner 2014]. When the performer is exploring those textures with his fingers, several piezoelectric sensors are translating the sound produced by the performer's action to control variables used for driving a concatenative synthesis.

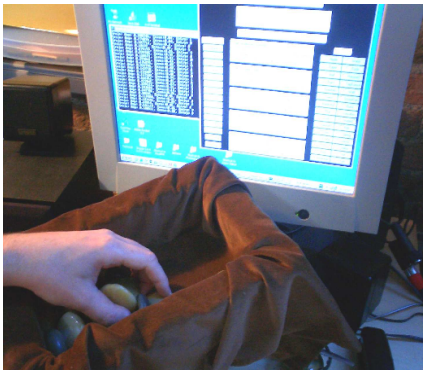


Figure 2.7 : *The PeebleBox*.

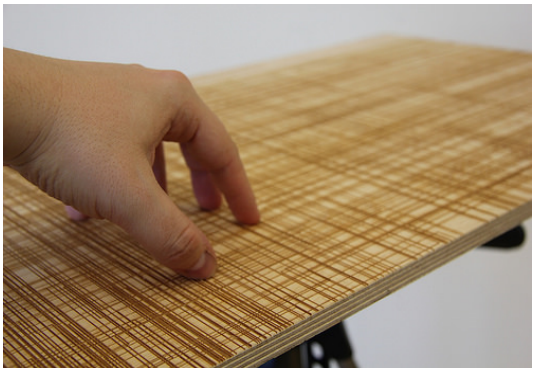


Figure 2.8 : *Tangible Scores*.

b) **Expanded-range interfaces**: this type of controllers require may physical contact in a limited form or even do not require physical contact at all. Their main characteristic is to have a limited range of effective gestures. According to Mulder [2006] in these type of controllers the performer can always "escape" the system, such as making movements without musical and sonic consequences. We can find two examples in the "Hands" (Fig. 2.9) and the "Mouthesizer" (Fig. 2.10). The former was created by Waisvisz [1985] for improving the use of hand and arm gestures, finger movements and pressures in sound control. It's composed of two ergonomically shaped controllers worn by the performer and providing sensing of distance between the hands, hand-tilt sensing, and various multifunctional switches and potentiometers. On the contrary, the "Mouthesizer" is a touchless interface. It uses the recognition of the mouth's shape for controlling audio effects and synthesizer parameters [Lyons and Tetsutani 2001].



Figure 2.9 : *The Hands.*



Figure 2.10 : *The Mouthesizer.*

c) Immersive controllers: alternate controllers with few or no restrictions on performers movements. The performer is the sensing field all the time and, differently from the previous one, she or he cannot "escape" the system. This type of controller can contain also what we nowadays term known as wearable interfaces [Paradiso 1999]. In this category we can list different interfaces, from a partially immersive controllers such as Laetitia Sonami's "Lady's Glove" [5] (Fig. 2.11), to fully immersive body suits like the one developed by Suguru Goto[6] (2000) . We can consider also as a immersive controllers all of the interfaces which are using biosignals for music purposes, such as the BioMuse (Fig. 2.12) explored by Tanaka [2000] or the open-source "Xth Sense" bio-physical interface developed by Donnarumma [2011]

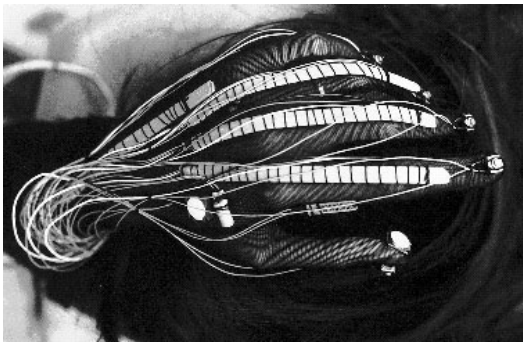


Figure 2.11 : *The Lady's Glove.*



Figure 2.12 : *Atau Tanaka performing with the BioMuse.*

5 http://www.sonami.net/works/ladys-glove/

6 http://suguru.goto.free.fr/Contents/Works/BodySuit/BodySuit-e.html

6. Haptics and force feedback

Up to know I was focusing on interfaces based on several sensing technologies and modes of interaction based on inputs, and that do not make use of actuators. Considering a musical interface not only as an input device, but also as something that can communicate something more to the user and the audience not only through auditory feedback (such as with loudspeakers) but also with tactile stimulators. Motors and various types of actuators opened the door for new significative artistic possibilities. This type of feedback is often referred as *haptic*. With this term we refer to tactile and kinesthetic sensations.

Usually in musical interfaces haptic properties are activated models of vibration and form patterns programmed in software and output by actuators.

We can define haptic musical interfaces as interfaces that exhibit active haptic feedback, in other words, interfaces whose haptic feedback behavior can be modified according to software models [Miranda and Wanderley 2006].

For Miranda and Wanderley [2006], tactile sensation is associated with discriminative touch such as the perception of surfaces. Receptors distributed unevenly on the skin and in subcutaneous tissues are sensitive to tactile information. Tactile sensation therefore comprises, among others, the sensations of vibration, pressure, texture, thermal properties, softness, wetness, and friction-induced phenomena

Kinesthetic sensation is related to awareness of the state of our body. It includes information on position, velocity, and forces supplied by muscles. Kinesthetic receptors are located mostly in the muscles and tendons.

In Human-Computer Interaction, tactile feedback therefore aims to stimulate tactile receptors distributed over the skin, while force feedback aims at creating forced to be sensed by the kinesthetic receptors in muscles and tendons [Miranda and Wanderley 2006].

Gillespie [1999a] [1999b] suggests that, in fact, all acoustic musical instruments have some form of acoustical and mechanical responses that are normally related to each other, and both responses are important for the performers. When performing on acoustic instruments, performers also receive information related to the instrument's mechanical behavior, such as the vibrating strings and resonance of the body of the guitar, the vibrating reed and body of the saxophone, the forces produced by the action mechanism of the piano keys, and so forth.

In other words, the mechanical behavior of acoustic instruments contributes to how performers feel their instruments [Jordà 2005a].

Materials also exhibit inherent passive feedback (mostly tactile) that might be important in performance. For instance, the body of an artifact built of plastic will feel different from a similar body made of wood in terms of temperature, texture, and weight. In other words, part of the feel of a controller is provided by its intrinsic characteristics (material, weight, etc.), which are constant for a given prototype.

In literature haptic musical interfaces are divided in two main types:

a) Tactile simulators that use mechanisms for skin sensation, vibrotactile devices that vibrate at given frequency, and thermal devices;

b) Force-feedback devices.

Force-feedback interfaces use mechanical systems with a wide bandwidth source of mechanical power, typically motors of several sizes. Tactile simulators use a matrix of pins, small vibrators, and loudspeakers. As Rovan and Hayward [2000] suggested, tactile simulators reproduce the effect of the skin touching a source, while force-feedback devices serve as mediating devices through which one explores or manipulates a virtual mechanical system.

Haptic interface technology is an important area of research in engineering, with applications to areas such as robotics and virtual reality. Several haptic devices have been proposed and many are commercially available. They range from small tactile stimulators to large exoskeletons to be worn by the user, such as the ones used by Marcel.lí Antúnez Roca[7].

Force-feedback input devices are common in general computer applications, mostly in games, rehabilitation systems and teleoperation. Examples include force-feedback joysticks, gamepads, driving wheels. The most notable examples of affordable and generic force-feedback devices are the Phantom Omni by SensAble Technologies[8] and the Falcon by Novit[9] (Fig. 2.13).

In the area of musical interfaces Cadoz et al. [2005] were some of the first investigators of force-feedback devices, and still are some of the leading researchers in this area (Fig. 2.14).

7 http://www.marceliantunez.com/work/afasia/
8 http://www.dentsable.com/haptic-phantom-omni.htm
9 http://www.novint.com/index.php/novintfalcon



Figure 2.13: *The Falcon haptic device by Novit.*



Figure 2.14: *A force-feedback device.*

The application of haptic devices for music expression is an active research topic which includes:

- The design of new haptic music interfaces using commercially available sensors and actuators;

- The design of new actuators to be used in new haptic music interfaces;

- The development of models used to simulate the haptic behavior of these interfaces.

Since the 1970s, thanks to the development of sophisticated, low power and low cost mechanical and electrical actuators, various interfaces using haptic feedback have been developed. Except the ones that are designed for accomplish the simulation the feel of acoustic instruments, we can find a various interfaces that explore the possibilities of tactile and force-feedback. For example, vibrotactile displays where loudspeakers or small actuators mounted on rings or embedded in surfaces on which the performer can stand [Rovan and Hayward 2000]. Experimental interfaces and prototypes were developed like The Plank, where an old computer disk drive was turned into an haptic controller for musical application [Verplank et al. 2001]. Recently at the Copenhagen Institute of Interaction Design (CIID) a framework of research called "Motors & Music" was developed in this direction [Verplank et al. 2013]. An interesting example of haptic interface for music is the Syntact by Ultrasonic[10], with which the user can feel in the mid-air the sound's temporal and harmonic texture through through a force field produced by an array of airborne ultrasound transducers.

10 http://www.ultrasonic-audio.com/products/syntact.html

Nowadays, with the development of nanotechnologies, piezoelectric and polymer actuators and Shape-Memory Alloys, this area became an interesting territory of experimentation also from an aesthetic point of view.
In this context Michael Waisvizs imagined in one of his visionary texts, which can be one of the possible future of musical interfaces:

"*The recent progress in development of electro active polymers (EAP) will drastically improve the physical qualities of gestural instruments.*
Instruments that vibrate through the sound.
Instruments that are sensors, processors and loudspeakers at the same time.
Control surfaces that change shape in coherence with the change of the sound it plays.
Think of instrument that vibrates electro-mechanically when you touch it.
Physical response of the instrument and resulting sound is inspiring the performer to touch and engage with touch/music.
Trapped in the sounding and haptic perceivable groove.
Deliberately trapped.
Excited by the excitement.
Exiting the excitement.
Performer and instrument merge together into one electro-mechanical circuit." [Waiszvisz, 2003].

Compared to input devices, haptic interfaces in musical expression are still in their infancy. Despite some experiments and prototypes it's not clear in which way haptic interfaces can 'solve' the problem of *expression* in computer and electronic music.
In the next chapter we are going to explore how and why actuations represent a contemporary frontier not only in musical interfaces but in interface and interaction design in general.

Summary

In this chapter I tried to summarize the development of a particular branch of research defined as NIME that stands between electronic and digital music, Human-Computer Interaction,

design, acoustic psychology and interactive art.

Due to the convergence of all these different topics I had to leave aside important area of music technology such as algorithmic composition and sound synthesis.

As an hybrid an relatively young field, the research of musical interfaces is deeply connected and aspire to be a continuation of the ancient tradition of music making and luthery in the digital age. Like in music also in interface design for musical expression there are no fixed rules and still there are no recipes for building a successful musical interface. Successful in this case, can be interchanged with expressive.

The problem of expression is still an open question, and there are no share methodologies for measure or evaluate this element in a scientific way. It's still valid the judgement with music in general, if a performance is touching, or if a particular composition is stimulating then, we can say that the performer and it's interface is *expressive*.

Apart from this, in absence of meaningful parameters for measuring the expression of a musical interface, we can look to which designs and concepts seems to be more promising.

One of these is the field of Tangible User Interfaces (TUIs), that I'm going to present in the next chapter.

Chapter 3

Hands, bits and atoms.
From graspable to malleable interfaces

"Where bits meet atoms, there is another kind of shoreline. Today, we live on this boundary between physical space and cyberspace. The constant pounding by waves of bits distorts our experience of space, challenging the boundaries of our physical bodies. Living on this edge is hard because our bodies remain in the physical world, even while we are immersed in digital information. However, this boundary marks a most interesting challenge for designers of media to bridge the gap between the worlds of bits and atoms. People tend to think of borders as separators, but it is important to understand borders as "interfaces" which actively promote exchange between adjoining worlds."

[Ishii 1997]

This chapter will introduces the main ideas and concepts behind the development of Tangible User Interfaces. A consistent part of this chapter is a review of the main aspects and projects that inspired the design of my work SculpTon. First of all, I will look at the foundations of Tangible User Interfaces, then I will concentrate the discussion on the most recent and contemporary research questions, especially where the use and the vision of new malleable and digitally augmented materials play a significant role. Finally I will analyze some projects that are exploring the idea of "Digital Clay" in the context of Tangible User Interfaces under the lens of

the vision of Radical Atoms.

1. Defining Tangible User Interfaces

The development of the notion of '*tangible interface*' is closely tied to the initial motivation for the development of Augmented Reality and Ubiquitous Computing in the context of Human Computer Interaction (HCI).

In 1991 Mark Weiser, from Xerox PARC, published an article called "The computer of the 21th Century" [Weiser 1991] about his vision of Ubiquitous Computing, which became one of the most influential vision in the field of HCI. In this paper Weiser illustrates his paradigm of computing and HCI which tries to push computers into the background and make them invisible. In his famous incipit Weiser wrote: "*The most profound technologies are those that disappear. They wave themselves into the fabric of everyday life until they are indistinguishable from it*" [Weiser 1991].

In the beginning of the 1990s, the debate around 'virtual reality' and internet networks was viewed as very promising and full of expectations. The claim of Weiser [1991] for an *embodied virtuality* was based on the observation that we are constantly wired, and so we can be here (physical space) and there (virtual space) simultaneously.

This research can be framed in a broad context of the development of interfaces and interaction with computers which tries to go beyond the GUI and the desktop metaphor, which involves not only the HCI community but also the media arts.

The development of head-mounted displays, datagloves and alternative interfaces for interacting with virtual worlds and environment were shifting the locus of computation from the desktop onto our skin, bodies and physical environment.

In 1993 a special issue of the Communications of the ACM titled "Back to the real world" [Wellner et al. 1993] argued that both computers and virtual reality estrange humans from their "natural environment". The different contributions to this issue were suggesting that rather than forcing the user to enter a virtual world, one should augment and enrich the real world with digital functionality. This approach was motivated by the desire to retain the richness and

situatedness of physical interaction, taking advantage of natural physical affordance and by the attempt to embed computing in existing environments and human practices to enable fluid transitions between the 'digital' and the 'virtual'.
In this context ideas from ethnography, situated cognition and phenomenology became influential for the development of new ways of interaction between people and information.
It's inside this debate that what we called now Tangible Interface emerged from. We have to wait some years from when this complex idea was formalized and evolved into an interaction style as such.

1.1 Graspable User Interface

In 1995 Fitzmaurice et al. [1995] introduced the concept of Graspable User Interface as a "[...] *conceptual shift in thinking about physical input devices not as graspable devices but instead as graspable functions*." [Fitzmaurice et al. 1995]. A graspable function consists of specialized physical input device which is bound to a virtual function and can serve as a functional manipulator. The core property of the Graspable User Interfaces is space-multiplexing, where input and output devices are distributed over space. For demonstrate this idea the authors used wooden blocks as graspable handles to manipulate digital objects. A block is anchored to a graphical object on the monitor by placing it on the top. Then, by moving and rotating the block the graphic was moving in synchrony. Placing two blocks on two corners of an object activates a zoom function. This implementation was allowing a kind of two-handed and two-fingered interactions that we nowadays knows from multitouch surfaces [Shaer and Hornecker 2009]. The aim of this research was to increase the directness and manipulability of graphical user interfaces where the aim of the use of some functional dedicated input tools were argued to distribute input in space instead of time, de-sequentializing interaction to support bimanual action and reduce the mediation between input devices and interaction objects.

1.2 Tangible Bits

The second important contribution for the development of a dedicated research field of Tangible Interfaces was the notion of Tangible Bits, introduced in 1997 by Ishii and Ullmer [1997]. The vision exposed in their article represent the base of a rich research agenda which became highly influential in the community. The authors define as TUIs an user interface that "*augment the real physical world by coupling digital information to everyday physical objects and environments*" [Ishii and Ullmer 1997]. Their aim was to make bits directly manipulable, using the real world as a display and as a medium for manipulation, as "*an attempt to bridge the gap between cyberspace and physical environments*" [Ishii and Ullmer 1997]. In their first explorations they show that data could be connected with physical artifacts and architectonic surfaces by coupling Bits and Atoms, by making bits tangible.

The meaning of "*tangible*" encompasses "*realness / sureness*", being able to be touched as well as the action of touching, leading to multi-sensory perception, where "*graspable*" meant the ability to manually manipulate objects [Shaer and Hornecker 2009].

"GUIs fall short of embracing the richness of human senses and skills people have developed through a lifetime of interaction with the physical world. Our attempt is to change "painted bits" into "tangible bits" by taking advantage of multiple senses and the multi- modality of human interactions with the real world. We believe the use of graspable objects and ambient media will lead us to a much richer multi-sensory experience of digital information." [Ishii and Ullmer 1997].

In their later work Ullmer and Ishii [2001] tried to narrowing the definition of TUIs and emphasize different characteristics like the possibility to eliminate the distinction between input device and output device.

2. Precursors

We can find several precursors to the work of Fitzmaurice and Ishii. The following examples addressed issues in different domains, like interactive art, product design, architecture and

educational technologies, and became highly influential for the development of TUIs as a research area as such.

2.1 The Slot Machine

In the 1970s Seymour Papert and his students at MIT AI lab began researching methods of introducing children to the world of computer science and bringing programming into their physical environment. This research led first to the development of the famous LOGO programming language and the LOGO Turtle, a little dome-shaped robot that moved across the floor in response to simple LOGO commands. The Turtle could be fitted with a pen and be used to draw pictures on a sheet of paper placed on the floor. One of the core idea was that children can learn abstract geometric forms more easily if they are modeling them in physical space. Instead of asking the children to immediately explain how can the robot can be instructed for drawing a square, the child was asked to explore the creation of the square by moving his / her body in the space, like "walking the square" [McNerney 2004].

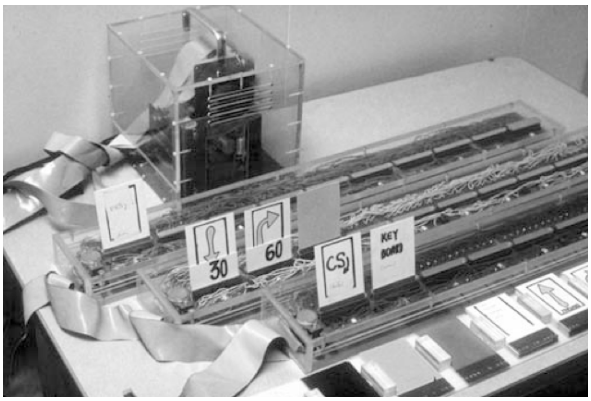


Figure 3.1 : *The Slot Machine*

A student of Papert, Radia Perlman argued that the big impediment for children for learn computer programming was not the language syntax, but the user interface. Then she came up with different input devices, one of them was the Slot Machine (Fig. 3.1), which is probably the first system that can be classified as a tangible interface. The Slot Machine uses physical plastic cards to represent language constructs used for programming the Turtle. The cards could be inserted into one of the three colored racks of a box, which was used as a remote controller for the robot. On the left side of each rack was a "Do it" button. When the child pressed the button,

the Turtle performed the actions pictured on each card in the rack, in sequence from left to right. This machine allows children manipulate a program directly by adding, rearranging and removing cards from each racks with their hands. Stacking cards of different types onto each other creates complex commands. Special colored cards -placed in a particular position- produces simple recursions and even infinite loops.

2.2 3D modeling system

The use of physical input devices for control and represent complex computational process invests also the area of Computer Aided Architecture systems.
Already in the beginning of the 1970s Aish [1979] implemented a building block system (BBS) for modeling physical-world buildings. Later John Frazer popularized this idea of using a network of physical building blocks to create digital architectural models [Frazer and Frazer 1980]. His concept behind was to involve inhabitants of buildings in the design discussion with architects, to simplify the dialog with CAD, and to support rapid prototyping and testing. Frazer and his team experimented with a variety of applications, but the most popular was the Three-Dimensional Intelligent Modeling System [Frazer and Frazer 1980].
This system (Fig. 3.2) was composed of different blocks, with their own internal circuitry, able to scan its connections, poll its neighbors, and pass messages. The user can assemble these blocks together and build a physical model. Then the computer scans the assembly, deduces location, orientation, the type of each component, and creates the digital model. At this point the user can configure the digital properties of each block and let the computer perform the calculations such as floor space or energy consumption. In the most advanced version the computer simulation could also provide suggestions on how improve the design through the use of evolutionary algorithms. Once the user is satisfied, the machine can produce plans and footprints. Further developments led to assembly which can organize themselves and perform autonomous spatial operations [Frazer 1995].

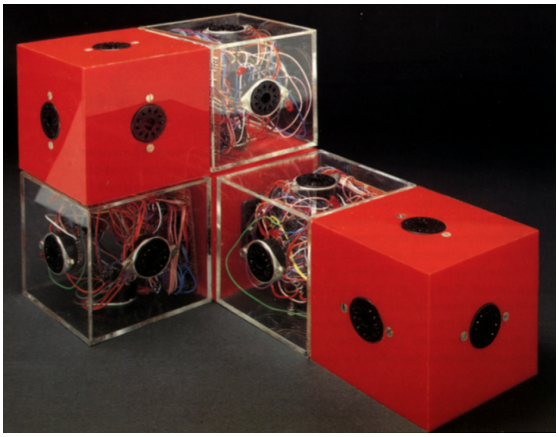


Figure 3.2 : *An example of the Three-Dimensional Intelligent Modeling System.*

2.3 Marble Answering Machine

Except the previous examples, the Marble Answering Machine [Abrams 1999] was explicitly mentioned by Ishii and Ullmer as an inspiration for the development of tangible interfaces. This was a conceptual sketch developed by the designer Durrell Bishop in 1992 during his studies at the Royal College of Art. With this work Bishop designed a prototype telephone answering machine to explore in which way computation can be embedded into everyday objects. In the Marble Answering Machine incoming voice messages are physically represented with colored marbles that roll into a bowl embedded in the machine (Fig. 3.3).The user can physically grasp the message (marble) and drop it into an indentation, then the correspondent message is played back. By putting the marble onto an augmented phone the user can also call automatically the number related to the call.

There are some aspects that makes this project an important foundation for tangible interfaces. The first is the design, which rely on physical affordance and the users' knowledge of everyday life actions used to interact with physical objects. The second is the object mapping, or how Bishop assign new meanings to objects, turning them into pointers to something else, into containers of digital data.

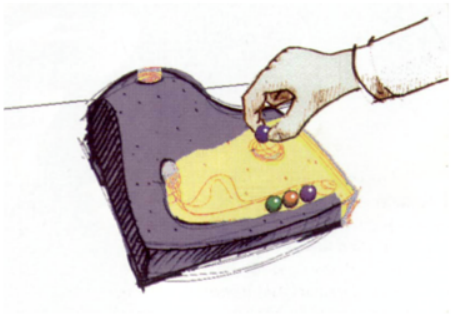


Figure 3.3 : *A sketch of the Marble Answering Machine by Bishop* (1992).

3. Concepts and foundations

In 2001 with their article "Emerging Frameworks for Tangible User Interfaces" Ullmer and Ishii [2001] presented an important step towards the identification of TUIs as a "*distinct and cohesive stream of research*" [Shaer and Hollnecker 2009]. After a period when the basic paradigm of TUIs was demonstrated trough some 'proof of concepts' examples, and few attempts for defining the research and application area has been made, different frameworks emerged. Not only the Tangible Media group at MIT, but also a growing number of academic and independent research in the field of HCI, design and interaction design became interested in the contribution and exploration of TUIs. Ishii defined Tangible User Interface as systems that are "[...] *build upon our dexterity by embodying digital information in physical space. Tangible design expands the affordances of physical objects so they can support direct engagement with the digital world.*" [Ishii et al. 2012]. Drawing from the model of GUI interaction defined as MVC (Model, View, Control), Ullmer and Ishii [2001] suggest a new interaction model called MCRit (Model-Control-Representation). While the MVC emphasize the separation between graphical representation and control, the MCRit model highlights the integration of physical representations and control in tangible user interfaces, which basically eliminates the distinction between input and output devices (Fig. 3.4).

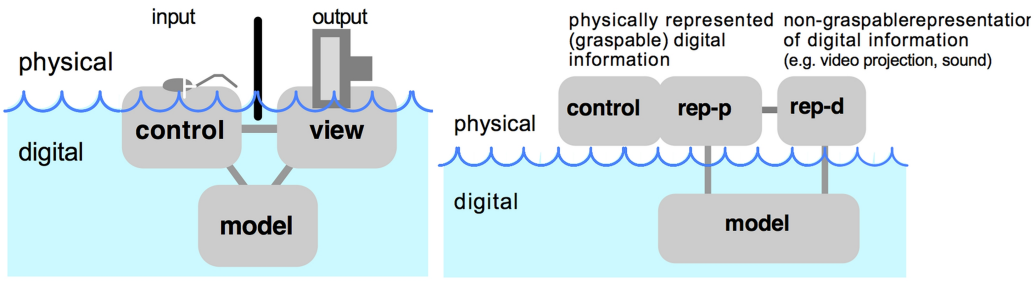


Figure 3.4 : *An illustration of the MVC (left) and MCRit model (right).*

3.1 Properties of TUIs

As the field matures, the concept of Tangible User Interfaces evolved, researchers have been developing several frameworks and taxonomies with the aim of providing to TUIs developers methods for analyzing, comparing, and guiding the design of tangible interfaces.

The function of a framework is to focus our view, providing us with concepts that systematize our thinking and allow our reflection. In this sense most of the frameworks do not intend to be all-encompassing or to provide rules. They can assist both in analysis and design, synthesizing and orienting to relevant issues. Designers, artists and researchers should use them as inspiration, provocation, or suggestion, triggering discussion and ideas. It's important to describe the properties that broadly distinguish tangible interfaces from other approaches.

During the last two decades since the field has developed, several frameworks emerged: some are relevant for the broader context, some are domain-specific, some others are focusing on the user experience.

In the early days of TUIs research such frameworks tended to focus on taxonomies and terminologies, analyzing open questions like mapping between the physical and the digital, investigating affordances and physical form [Fishkin 2004] [Djajadiningrat et al. 2007].

Since it's still difficult to find and define a unified perspective of the field, with the help of some of these frameworks we can distinguish some relevant properties of tangible interfaces. Ullmer [2002] was the first who articulated a classification of TUIs, it's still the most comprehensive and quoted one. According to Ullmer the physical and digital artifacts at the center of tangible interfaces – the tangibles – can be seen as having four distinguishing physical properties:

a) Physically embodied;

b) Physically representational;

c) Physically manipulable;

d) Spatially reconfigurable.

a) Physically embodied

The broadest property and criteria of tangible interfaces is that digital information or functionality is somehow embodied in physical form. Ullmer highlight that at some level, every computational device involves somehow some forms of physical artifact. The distinction concern the modalities by which people perceive and interact with digital information [Ullmer 2002].

With embodiment we refer to how the form of the human body and bodily activity shape cognitive processes, language, and the interaction of action and perception. Embodiment is strongly connected to phenomenology and cognitive science and philosophy,

In HCI this term is used in many different ways, where the simplest use refers to the physical embodiment of data and its control via physical body movement and devices. Fishking [2004] has developed one of first and most comprehensive analysis of TUIs through the lens of embodiment.

In his book "Where the action is – The foundations of Embodied Interaction", Paul Dourish [Dourish 2001] introduces the notion of *embodied interaction*, which became a common term within HCI. But we should not confuse the general idea of embodiment and the one proposed by Dourish, which denotes "*the way that physical and social phenomena unfold in the real time and real space as a part of the world in which we are situated*" [Dourish 2001]. This sense of embodiment incorporates all of TUIs as a small subset, and focusing more on the social functions of interaction in our world.

b) Physically representational

Physical representation is one of the most important properties of tangible interfaces. In our case, the term "representation" means that artifacts serve as a physical manifestations of particular kinds of digital associations. Examples include the use of objects as embodiments of specific data, as containers for data aggregates, or as specifiers of digital parameters. The physical form of the artifacts can vary very widely. They can be literally iconically representational, or symbolic representational. The physical artifacts can be designed as data containers or function specifiers, then it's very important to develop different physical forms which reflect these differences.

c) Physically manipulable

As we said before, tangible interfaces can be described as systems that are employing physical artifacts both as representations and both as controls for computational media. Within TUIs, this capacity for control derives from the direct manipulation of the interface artifact. Then an underlying sensory system is monitoring the changes and turn them into the corresponding digital representation.

The predominant property of TUIs artifacts is that they are graspable. We mentioned above the importance of physical affordances and the work of [Fitzmaurice et al. 1995] which underlying that objects can be taken within the hands, and physically manipulated by the user. We are going to talk in detail later about this aspect in sections 4 and 5 of this chapter.

d) Spatially reconfigurable

Spatial reconfiguration of physical elements is one of the central mode of interaction within tangible interfaces. Their physical placement and removal, translation and rotation are the most common features. Ullmer specifies this property of TUIs by saying that tangible elements "*work to discretize interfaces into multiple distinct physical elements with their own digital bindings*" [Ullmer 2002]. This definition must be extended for include characteristics like continuous interaction.

3.2 Examples and instances of TUIs

As discussed in the previous sections, except some common properties and characteristics of TUIs, there are many systems which are crossing categories and definitions.
TUIs is a research area that encompasses approaches from different fields such as HCI, computer science, design and interactive art.
While this thesis is not focusing on classification of TUIs, in this section I'm going to present a simple survey that introduces and briefly discusses examples of different instances of tangible interfaces. For a more complete survey on different classifications I refer to the works of [Fishkin 2004] [Shaer and Hoerneckner 2009].

3.2.1 Interactive surfaces

One of the most popular paradigm for tangible interfaces is based upon “interactive surfaces”, where physical objects are manipulated by user upon an augmented planar surfaces. The presence, identity, and configuration of these objects is then electronically tracked, computationally interpreted, and graphically mediated.
In the context of tangible interfaces, interactive surfaces have taken one of several major form. Ullmer [2002] noticed that 'interactive surface' is a term itself not entirely specific to tangible interfaces. Some of them have been based upon interactive walls like “Videoplace” (1977) of Myron Krueger, interactive floors like in “Boundary Functions” (1998) by Scott Snibbe, or on the specific use of surfaces like in “Composition for a table” (1999) by Toshio Iwai.
But, according to Ullmer [2002], for the most part these works do not employ any tangible interfaces techniques.

Case study: URP – Urban planning workbench

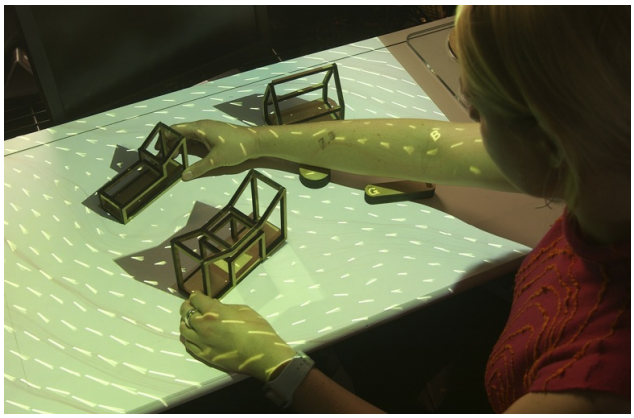


Figure 3.5 : *URP - Urban planning workbench.*

"Urp" (Fig. 3.5) is a project developed by John Underkoffler [Underkoffler and Ishii 1999] in 1999 at MIT, which employs the idea of a horizontal workbench for collaborative urban planning and design. The idea of the workbench is one of the most popular within tangible interfaces, especially in the early days. This interface uses simple physical models of architectural buildings to configure and control a urban simulation of shadow, light reflection and wind flows. Through a video projection the Urp's models cast digital shadows onto a workbench surface. The interface provides various interactive tools for querying and controlling the parameters of the urban simulation. A clock, which represent the sun, controls the time of the day, a material wand changes building surfaces between brick and glass, a compass changes wind direction and an anemometer measures wind speed. "Urp" is a tangible interface configured as a spatial system that provides visual feedback and promotes collaboration and group usage.

3.2.2 Token and Constraints

One of the peculiar characteristic of tangibles is the use physical objects as containers for digital media, and the use of these physical containers to transport these data [Ullmer 2002]. If we think about the precursors of Tangible Interfaces like the Slot Machine and the Marble Answering Machine (see 2.2) we can see how this concept was already present.
Ullmer [2002] has developed an approach called Token+Constraints, which describe this

particular structure and set of relationships between physical objects and digital informations.
A physical object in a TUI may enhance its physical properties with digital properties, such as graphics and sound. Ullmer define these objects *phycons*, some kind of physical icons. According to the author we can find two of these physical/digital objects: token and constraints. Each of these objects can be a token, a constraint, or both [Shaer and Hornecker 2009].
A token is a graspable physical object that is bound to digital information or a computational function. The user interacts with the token in order to access or manipulate digital information. The physical properties of a token may reflect the nature of the information it represents. Their physical properties may afford also how it is to be manipulated.
Differently, a constraint is a physical object that limits the behavior of a token with which it is associated. According to Shaer and Honecker [2009] we can define these kinds of limitations:

- the physical properties of the constraint are suggesting to the user how (or how not) manipulate the associated token;

- the constraint limits the physical interaction space of the token;

- the constraint serves as a reference frame for the interpretation of the token and constraint compositions.

We can then define a Token + Constraints system as relationship between a token and one or more constraints. This terminology comes from the analysis of board games, such as chess or backgammon, which shares some common properties with TUIs.

Case study: MediaBlocks



Figure 3.6 : *An image of the mediaBlocks interface.*

Developed by Ullmer [Ullmer et al. 1998] in 1998, "mediaBlocks" (Fig. 3.6) is a TUI that explores the idea of token and constraints. It consists of a set of small electronically tagged wooden blocks. These blocks serve as a 'physical icons' for the containment, transport and manipulation of online media. MediaBlocks interface with media input and output (such as a video cameras and a projectors), allowing digital media to be 'copied' from a source and 'pasted' into a media display. This is achieved through the use of RFID technology. If the wooden blocks represent a token, a tray sequencer act as a physical constraint. This physical tool allows the sequential rearrangement of media content.

3.2.3 Constructive assemblies

Another major approach in TUIs draws inspiration from popular building blocks kits such as Meccano and LEGO. As I mentioned at the beginning of the chapter, this approach was employed by some of the precursors of tangible interfaces. The concept of constructive assemblies refers to a set of primitives that can be used to model a more complex system, towards the end of providing modular, electronically instrumented artifacts for constructing models of physical-world systems. If architecture and CAD are some of the most popular applications for constructive assemblies, several tangible interfaces of this type have been developed for describing software programs inspired by the concept of "s*olid programming*" of

Maeda and McGee [1993], like the "AlgoBlock" by Suzuki and Kato [1993]. Other projects took the idea of film montage for collaborative video editing such as the "Tangible Video Editor" by Zigelbaum [2007]. One of the most interesting features of recent constructive assemblies are characterized by a coincidental input and output and the possibility to record and memorize kinetic movement and sequences of actions, like in "Topobo" [Raffle et al. 2004].

Case study: Triangles



Figure 3.7 : *Triangles.*

"Triangles" (Fig. 3.7) is a physical/digital modeling toolkit developed in 1998 by Gorbert and Orth [Gobert et al. 1998]. This is a system composed of uniformly shaped modular elements in the form of triangular electronics tiles. These modules allows the user to physically manipulate connections and relations between data elements. By physically connecting the triangles together, users can associate digital files and processes them to one another. Every triangle can be connected to another one through magnetic conductive connectors. The user can create both two and three-dimensional pattern. "Triangles" was used as a system for construct different applications, most of which related to sound and storytelling. The power of this system lies in its flexibility, because its capable of being reconfigured in both in hardware and software.

3.2.4 Physical actuated platforms

One of the relatively recent development in the area of TUIs concerns the exploration and the use of physical and mechanical actuation in combination with tangibles. Actuation had been a part of the vision of TUIs from the very beginning, but, due to technical difficulties only now actuation is emerging as a strong trend. With the development of new actuator technologies, microprocessors, and smart materials adding actuation to tangible interface as become easier then ever. Poupyrev et al. [2007] notice that in those kind of interfaces "*physical* [and] *tangible elements are not merely dynamically coupled to the digital attributes and information, but are themselves dynamic, self-reconfigurable devices that can change their physical properties depending on the state of the interfaces, the user, or the environment*". Usually TUIs input are explicit, and the user needs to manipulate a physical artifact and usually receives a tactile, visual or auditory feedback. Once the he/she knows how to address the system, the user can avoid unintended address and selection. Actuated TUIs are sharing many elements with research areas like robotics, making use of similar principles and hardware. Modern computers can handle very abstract and complex tasks, which are hidden and difficult to understand. A combination of the actuation and tangibility can expand and enhance the design of tangible interfaces. Pangaro et al. [2002] highlight that the coupling between tangible and digital has usually been in one direction and the digital had no effect on the tangible interface elements. For Poupyrev et al. [2007] actuation seems to be one of the natural direction for TUIs research to take. Actuation take into tangible interfaces not only mechanical kinetic movement and the possibility of behavioral expression, but also a renovated attention on haptic, and material properties. For Ishii actuation can helps to keep "*the physical and digital states in synch when the information changes dynamically, either by user's input (direct manipulation of tangibles) or results of underlying computation.*" [Ishii et al. 2012] and represents the current challenge for TUIs. In actuated tangible interfaces, movement became not only a feature but also a media for communication.

Case study: Pico platform



Figure 3.8 : *The Pico platform.*

Actuation can be employed in TUIs not only for expressive and aesthetic reasons, but also for support the solving of complex problems. The Physical Intervention in Computational Optimization (Pico) developed by Patten and Ishii [2007] is a tangible interface based on a tabletop surface that can track and move small objects in top of it (Fig. 3.8). The aim of this interface is to merge software-based computation with dynamic processes that are exposed to and modified by the user in order to accomplish his/her task. In this system a group of objects are placed on a surface and moving under software control using electromagnets. They can also be modified by the users standing around the table. The Pico interface was used to control an application for optimizing the configuration of cellular telephone network radio tower. In this context the users can physically intervene in the computational optimization process of determining cellphone tower placement. Additional physical interface elements became natural constraints for the placement of the tokens.

4. From graspable bits to radical atoms

"*The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could be literally be the Wonderland into which Alice walked*"

I. Sutherland [1965]

As TUIs an emerging and evolving field of research, several recent approaches attempt to move this field from a collection of rigid discrete objects to more organic and dynamic interfaces. Driven by the advances in new smart material technologies [Addington and Schodek 2005], such as electrophoretic ink (E-Ink), conductive fabrics, flexible and conductive polymers, OLED displays, and shape-memory alloys, researchers and designers started to concentrate on the materiality of the interface as key aspect.

In interface design, materiality connotes a variety of qualities that can be the source of rich sensory experiences and occasion for numerous action modalities. Engaging and manipulating the material qualities inherent in the physicality of Tangible Interfaces rapidly become a new and emerging research focus. Some relevant theoretical works have been developed for helping designers and artists to face this new issue [Fuchsberger et al. 2013].

Robles and Robles and Wiberg identify this as a 'material turn' in Human-Computer Interaction [Robles and Wiberg 2010]. This 'turn' manifests under the rubric of tangibility, and has helped inspire the re-examination of computation in more material terms or as just another material operating "*on the same level as paper, cardboard, and other materials found in design shops*" [Bdeir 2009]. Wiberg [2012] noticed that in this context also "*physical materials are being re-imagined as substrates invested with computational properties. The result is an activation of material properties, always already there, that can be interacted with and experienced in wholly new ways. In a sense,* [Wiberg 2012].

In this context, the interface is not identified as an object, a piece of software but as a sort of new compound material, or using the definition of Blaine Brownell a *transmaterial* [Brownell 2006] .

In 2005 Brownell compiled one of the first survey of those new materials that are coupling computational processed and physical properties for modifying their physical properties, or material produced by digital processes and technologies. He define them as *interfacial materials* as "[...] *products and systems* (that) *navigate between the physical and the virtual realms*." [Brownell 2006]. Brownell also noted that "[...] *interfacial materials are not infallible* [...]" and like glitches in hardware and software these materials can reflect in the physical world some digital processes.

Vallgårda and Redstrom [2007] have been developing further this notion with the one of 'computational composites', by highlighting that computers became a material itself in design and architecture. According to Vallgårda and Sokoler a computational composite is "*a composite*

material where at least one of the materials has computational capabilities" [Vallgårda and Sokoler 2010].

Nowadays we are facing the development of new materials with embedded and embodied interactions and computational processes which are becoming widely used like other 'traditional' composites, especially in architecture and design [Vallgårda and Redstöm 2007].

In 2011 a Special Issue of ACM was centered on 'material computing' [Buechley and Coelho 2001]. With this term Buechley and Coelho [2001] refer to "*works that blurs the boundary between materials and computers – between an object's material composition, its computational functionality and its form*". This research theme is including a number of different areas such as material science, interface design and architecture.

Smart materials, can significantly alter their physical properties in response to a controlled stimulus. Composite materials interleave distinct materials to achieve properties unavailable in their constituents. Through 'transitive materials' Coelho et al. [2009] are investigating the emerging process of integration between materials and computationally-driven behaviors.

Tangible Interfaces became rapidly the main catalyst of these investigations and experiments in HCI.

All of these definitions such as *interfacial materials*, *computational composites*, *material interactions, material computing* have contributed to the definition of a framework and opening a debate in HCI and interaction design.

Those definitions became quickly common keywords in publications of international conferences such as TEI[11], UIST[12], CHI[13] and journals like ACM INTERACTIONs[14].

4.1 Shape-Changing Interfaces

The interest in new and dynamic materials is deeply intertwined with the development of Shape-Changing Interfaces [Coelho and Zigelbaum 2009]. This particular and hybrid branch of TUIs is exploring the impact of computationally-enabled materials and soft mechanics for the

11 http://www.tei-conf.org
12 http://www.sigchi.org/communities/uist
13 http://www.sigchi.org/conferences/chi
14 http://interactions.acm.org/

creation of transformable surfaces. In recent years, Tangible User Interfaces have started to make use of shape change as a way to embody digital information. For Poupyrev et al. [2007] this represents a 'logical step' in TUIs, where "*physical, tangible elements are not merely dynamically coupled to the digital attributes and information, but are themselves dynamic, self-reconfigurable devices that can change their physical properties depending on the state of the interfaces, the user, or the environment*" [Poupyrev et al. 2007].

In the last century, developments in material science, fabrication processes, and electronic miniaturization have dramatically altered the types of objects and environments we can construct. More recently, materials that exhibit electromechanical properties are paving the way for the seamless integration of sensors and actuators into the environment, expanding the limits of where computation can be found and reshaping the ways in which we interact and communicate.

Nowadays the combination of the actuation, self-configuration, and tangibility have expand and enhance the design of tangible interfaces. Poupyrev et al. [2007] noticed that actuation is used in tangible interfaces to "*preserve consistency between digital and tangible representations. The inconsistency occurs when there is more than one way to change digital information*". As we saw in projects such as "Pico" [Patten and Ishii 2007] or the "Actuated Workbench" [Pangaro et al. 2002], the tangible interface element would move to reflect changes that are remotely controlled. According to Poupyrev et al. [2007] "*the problem of consistency is an old one and has already been addressed using actuation. For example, some high-end studio sound mixers change the position of their sliders when controlled sound parameters are changed from outside using MIDI*".

However, even if this is becoming an hot topic as Coelho and Zigelbaum noticed "*while a lot of headway has been made in controlling light to deploy information all around us through visual displays, there is still much to be done to make physical form equally mutable and controllable*" [Coelho and Zigelbaum 2009].

The idea of Shape-Changing Interfaces is coming directly from the research and availability of shape-changing materials. We can define shape-changing materials as materials that undergo a mechanical deformation under the influence of direct or indirect electrical stimuli. They are by nature dynamic, in addition to the static properties that we find in other conventional polymers or alloys. While materials science literature is replete with examples of shape-changing materials, which promise one day to revolutionize the way we build things, most of these materials are in the early stages of development and only a few are sufficiently mature today to

be reliably implemented [Coelho et al. 2009].

The main functional purpose of applying shape-change is to communicate informations [Coelho and Zigelbaum 2009], and as Rasmussen et al. [2012] noticed, to encode information in a more expressive or efficient manner.

Shape-changing Mobiles [Hemmert et al. 2010], for instance, uses changes in thickness of the phone to guide users to move in a particular direction, by making the phone slightly thinner in the direction in which to move. In other cases, changes in shape are used as "information displays" [Coelho and Maes 2009] or to "visualize information" [Horev 2006].

Some projects such as the installation "Protrude, Flow" by Kodama and Takedo [2001] is one of the most famous notable in this direction. In this work a ferromagnetic liquid is actuated by an array of magnets that reacts to the environmental sound. This create a variety of organic-looking shapes in the form of a never ending shape-changing sculpture.

Other materials have been investigated in the works of Marcelo Coelho such as shape-memory alloys in his project "Shutters" [Coelho and Maes 2009] for building reactive displays made out of fabric.

As a forefront research in TUIs, Shape-Changing Interfaces started also to be analyzed and classified. After a period of experimentation nowadays the necessity of a vocabulary started to emerge. Through some user studies, researchers started to explored the potentials and the limitations of Shape-Changing Interfaces. Rasmussen et al. [2012] proposed recently a significant contribution in the analysis of the state of the art in Shape-Changing Interfaces. They identify four basic functional aims of Shape-Changing Interfaces:

- *dynamic affordances*, which is used to communicate possibilities for action, allowing for dynamic affordances depending on digital content;

- *haptic feedback*, which provides tactility to touch displays. For example Lumen [Poupyrev et al. 2004] uses haptic feedback for an explorative purposes. Here, haptic feedback is used to create social presence by recording the interactions of one user and play them back either locally or on remotely placed device;

- for *construction*, where the user can assemble a dynamic form and manipulate it. Both

Kinematics [Oschuetz 2010] and Topobo [Raffle et al. 2004] allow users to construct different shape-changing kinetic structures through assembling parts;

- as a *design solution*: when shape-changing represents a practical solution to a problem. One example of this is the Inflatable Mouse [Kim et al. 2008] that can be inflated to the size of a regular mouse and deflated in order to fit inside a PC card slot.

This survey of Rasmussen et al. [2012] became particularly useful not only for a better understanding of Shape-Changing Interfaces but also for my work about Malleable Tangible Interfaces.
They identify different types of changes explored in Shape-Changing Interfaces, are not limited only to kinetic movements, but are including also changes in: orientation, form, volume, texture, viscosity, spatiality, adding/subtracting, and permeability.

- Changes in *orientation* distort the original shape through rotations or changes in direction, while preserving the recognisability of the original form. Orientation is a widely used means to establish shape change [Parkes and Ishii 2010] [Slyper et al. 2011]. The Thrifty Faucet [Togler 2009] communicates information on water consumption and hygiene to the user through deforming its shape into various postures, using changes in rotation and direction.

- *Form* changes are defined by transformations that preserve the approximate volume of the shape while changing its overall form [Coelho et al. 2008] [Kim et al. 2008] [Thomsen 2009]. Horev's Morphing Harddisk concept [Horev. 2006] changes form by sucking in or blowing up a cube shape, thereby hiding or revealing the cube's skeleton structure. The concept applies the form change to visualize information about harddisk activity, synchronization, and the remaining space on the harddisk.

- Changes in *volume* maintain the approximate form and are used in some shape-changing interfaces.

- *Textural* changes are small changes on the surface of the shape that add visual and tactile properties without affecting the overall form [Bau et al. 2009] [Hyunjung and Woohun 2009] [Rozin 2007]. The inFORM interface [Follmer et al. 2013] is actuated by an array motorized pins, which allow users to create and experience digital models of, for instance, a geographical terrain. A 3d scanner is used for acquiring movement and depth of people gestures for controlling this deformable surface.

- Changes in *viscosity* can result in both physical shape changes and in the illusion of shape change, where the viscosity changes while the original form is maintained. Mudpad [Jansen 2010] uses changes in viscosity as haptic output for a multi-touch surface. The change in viscosity is for instance used for the play button feedback: When the play button is pressed it becomes fluid and the user's finger sinks in. As the music starts playing, a tactile representation of the music's amplitude can be felt on the button.

- Changes in *spatiality* do not automatically create the illusion of shape change. A change of one element's position in space does not create the illusion of shape change, as the change is typically seen as a repositioning in space. The illusion of shape change through spatial repositioning depends on individual elements being seen as part of a collective structure. When multiple elements are repositioned spatially, they may be perceived as part of the same structure. One of the few examples of shape-changing through spatial repositioning in the sample of papers is the Kinetic sculpture at the BMW museum in Munich [Art+Com 2008]. The sculpture consists of 714 metal spheres that can be repositioned vertically and thereby lead to perception of a composite form, rather than of individual elements.

Rasmussen et al. [2012] noticed that changes in *viscosity* and *spatiality* do not necessarily deform objects (i.e., change shape in a strong sense), but they can be included because they may lead to the experience of shape change.

Apart of the types of shape change mentioned above are topological equivalent, meaning shapes that can pass from one form to another through continuous deformation, without dividing or joining elements. There are changes that are not topologically equivalent, for instance when

shapes are being split, united, or perforated. However, interfaces rarely use such changes because few materials are capable of producing them [Rasmussen et al. 2012].

- *Adding* or *subtracting*: this shape-changing is achieved by transformations that unite or divide elements, while being able to return to the initial shape or shapes. Blob Motility [Wakita et al. 2011b] is an example of an interface that explores the possibilities of creating shape changes that break homeomorphism, through using a magnetic fluid as an interface that is able to split, merged, and moulded into organic shapes through changes in the magnetic field.

- Changes in *permeability* are defined by transformations, where the shape is perforated, but it's also able to return to its initial shape. Permeable transformations offer interesting design possibilities, for creating architecture that allows regulation of ventilation flow, daylight intake, or visual privacy. However, current materials are not able to realize this ideal. Shutters [Coelho and Zigelbaum 2009] imitates a permeable transformation, where parts of a surface can open and close to regulate the flow of air and light. Although the example does not break the homeomorphism of the surface, the imitation exemplifies the potential of permeable transformations.

- In a recent project of Niijama et al. [2014] the changes in volume are coupled with changes in *weight*. They use liquid metal (Ga-In-Tin eutectic) and a bi-directional pump to control a mass that is injected into or removed from a target object. The liquid metal has a density of 6.44g/cm , which is about six times heavier than water, and is thus suitable for effective mass transfer. One of the interesting aspect of this project is the combination of this device with a dynamic volume-changing function to achieve programmable mass and volume at the same time. This project explores three potential applications enabled by weight-changing devices: density simulation of different materials, miniature representation of planets with scaled size and mass, and motion control by changing gravity force.

Shape-Changing materials and interfaces are opening new design spaces in the context of

Tangible User Interfaces. The projects and the classification presented above are an important contribution in the development of a new step in tangible interfaces and computational materials. The levels of interaction with Shape-Changing Interfaces can be of different types, and not only by direct user input. They can be used only as a display of digital informations, such as weather data (wind display) or environmental sound (ferrofluid).
I'm not interested in actuated or shape-changing physical displays but when a direct action of the user through the manipulation of the interface occur. This led to the vision of "Radical Atoms" developed by Ishii et al. [2012], which represents a sum of the systems and ideas described above through the lens of Tangible Interaction and the idea of Digital Clay.

4.2 Radical Atoms

In 2012 Ishii proposed a new framework called "Radical Atoms" [Ishii et al. 2012], which represents the next step in Tangible Interfaces vision after the one of Tangible Bits. Radical Atoms represent a vision for human interactions with hypothetical dynamic physical materials that are computationally transformable and reconfigurable, conform to constraints, and inform the users to their affordances.
This idea has his roots in the idea of Organic User Interfaces (OUIs) introduced in 2008 with a special issue of the ACM [Vertegaal and Poupyrev 2008]. Encompassing TUIs, the vision of Organic User Interfaces refers to the use of interfaces with non-planar displays that may actively or passively change shape via continuos physical inputs. The term 'organic' was selected because of the organic technology and as a reference to the inspiration drawn from flexible, transformable, and evolvable organic shapes.
"*Organic interface design represents a less literal approach which, rather than focusing on physical objects or metaphors, emphasizes the analog, continuous and transitional nature of physical reality and human experience. By combining sensitive analog input devices with responsive graphics, we can create user experiences that acknowledge the subtleties of physical interaction*." [Schwesig et al. 2004]. Organic User Interfaces are then exploring mainly non-flat, flexible, potentially arbitrary and even fluid display devices.

According to Holman and Verteegal [2008] the aim of OUIs is to support several design goals that transcend traditional usability to more explorative and creative engagement with materials. The emphasis on flexibility and malleability makes affordances a crucial element in the interaction with organic user interfaces. In this context bending and stretching are explored as a means for input with flexible devices.

"*An Organic User Interface is a computer interface that uses a non-planar display as a primary means of output, as well as input. While flexible, OUIs have the ability to become the data on display through deformation, either via manipulation or actuation. Their fluid physics-based graphics are shaped through multitouch and bimanual gestures*" [Holman and Vertegaal 2008].

For Vertegaal and Poupyrev [Vertegaal and Poupyrev 2008] there are identifies three fundamental aspects of OUIs which describe the possible interactions and design rules:

- Input Equals Output;
- Function Equals Form;
- Form Follows Flow.

Those characteristics, if not explicitly, were present since the beginning of TUIs. But the reflection on Organic User interfaces pointed the attentions to different input gestures, such as bending and stretching, which were not fully explored in the context of TUIs.

Even if the vision of Ishii shares some characteristics and challenges with the agenda of the OUIs, it's strongly developed inside the discussion of Tangible Interfaces. The idea of "Radical Atoms" is intended as a direct continuation of the one of "Tangible Bits" after the 'material turn' we discussed before. This not represent only a technology driven research (inspired by new materials and sensors) but a vision-driven research. For Ishii "*Radical Atoms envisions a change in the paradigm of human-computer/material interaction in which we no longer think of designing the interface, but rather of the interface itself as a material*" [Ishii et al. 2012].

This last sentence explain really well the direction that Ishii and his colleagues wants to develop, and in general what we are facing now.

What makes interesting Radical Atoms is the focus on the development of possible interactions

with hypothetical dynamic materials, rather then on the technological difficulties in developing such a materials. In the vision of Ishii these materials will be characterized by dynamic affordance, which became a medium for representation.
Ishii identifies three main requirements for Radical Atoms:

- Transform it's shape, to reflect underlying computational state and user input;
- Conform to constraints imposed by the environment and user input;
- Inform users of its transformational capabilities, dynamic affordances.

The main question which arise from this vision is: which kind of interactions are possible with new type of matter capable of changing form dynamically ?
In the context of "Radical Atoms" Ishii envisioned "Digital Clay", which is an hypothetical physically represented, malleable material that is synched with a coupled digital model. "*Direct manipulation by user's hand of a sensor-rich objects and materials should be translated into an underlying digital model immediately to update the internal digital states*" [Ishii et al. 2012]. As I have been explaining in the first chapter, direct manipulation is one of the oldest interaction techniques for form giving. Ishii et al. [2012] noticed that direct touch offers high-precision manipulation with direct haptic feedback from the operand, but it constrains the user to reshape the material only at the scale of his of her hand. In the vision of Ishii, direct manipulation must be coupled with gestural interaction.
Since there are not existing examples of Radical Atoms, Ishii and his students proposed a fictional material called "Perfect Red" (Fig. 3.9). This is described as a clay-like material preprogrammed to have many of the features of computer-aided design softwares (CAD). "Perfect Red" can be sculpted like clay and responds according to rules inspired by CAD operations. A user can start by taking a piece of "Perfect Red" a roll it as a perfect sphere, like a primary solid. When we join two pieces together we are performing a boolean addition.

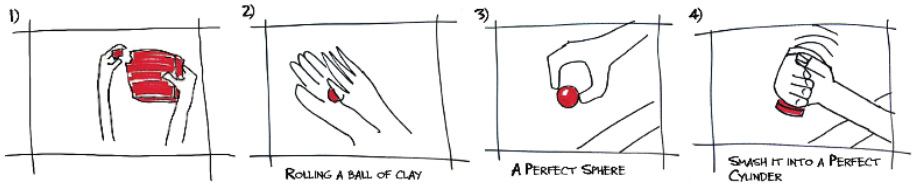


Figure 3.9 : *A conceptual sketch of the Perfect Red system*.

The vision of "Radical Atoms" represents an important step towards the possibility of looking and designing interfaces as a 'materials', which are embedding and embodying intuition, improvisation, and from where new interactions can arise. This can represent not only a new technological achievement but also an aesthetic and social challenge. One of the other projects developed within this framework was the interface called "inFORM" [Follmer et al. 2013] which is the base of the "TRANSFORM" a tangible input/output interface oriented in furniture design[15].

By envisioning "Radical Atoms" Ishii et al have summarized and problematized the last developments not only in TUIs but in HCI and interaction design in general, demonstrating that Tangible Interfaces is an active area of exploration open to a multidisciplinary work and contributions.

As a "vision", it opens and suggests different research fields which only few of them have been explored.

5. Malleable Tangible Interfaces

Poupyrev et al. [2007] have identified *malleability* as the most attractive property of the digital world and one of most promising idea for the development of Tangible Interfaces.

Malleable and organic tangible interfaces have the potential to enable radically new forms of interactions and expressiveness through flexible, free-form and computationally controlled shapes and displays [LeClerc et al. 2007].

15 http://tangible.media.mit.edu/project/transform/

In this thesis I'm interested to explore the idea of *malleability* as a way for enabling and promoting direct and continuous exploration, and form giving of the interface itself.
Several recent approaches have attempt to bring human manipulation skills to human computer interactions, that we are going to describe later.
The passage from rigid to malleable interfaces was described by Jun Rekimoto [2008] as a shift similar to the one from stone to skin. Traditionally TUIs systems often employ physical objects as tool for manipulation. As we describe above, these objects are graspable and often have a concrete meaning in the application, and many TUIs systems are domain-specific. For Rekimoto these are tools, like stones, but in these new TUIs there are no intermediate objects between the user and the system. The user directly interact with the object, which possess some key characteristics of human bodies, such as *malleability* [Rekimoto 2008] .
I propose to call this sub-genre of TUIs as Malleable Tangible Interfaces. Instead of using predefined discrete objects with fixed forms, malleable TUIs employ continuous tangible materials that couples sensing and display, visual, auditory and haptic. Output and input are then coupled and integrated into a soft rather then hard physical/digital artifact.

5.1 Digital clay – A conceptual framework for Malleable Tangible Interfaces

In the last twenty years with the development of nanotechnologies, new embedded sensors, and conductive actuated materials the idea of "Digital Clay" emerge in different forms in HCI. For example [Zhu and Book 2006] propose in 2005 a prototype of a interface device based on a morphing, tangible and haptic surface, called "Digital Clay", which make this idea explicit.
Both [Ishii et al. 2012] and [Vertegaal and Poupyrev 2008] refer to *Claytronics*, a system proposed by Goldstein et al. [2005]. This system uses micro-sized robots whose shapes and colors change for dynamic shape design. These robots are in the size of few millimeters and are defined as *catoms* (claytronics atoms), and are programmed to self-assemble themselves into arbitrary 3D shapes. Goldstein highlight that "the idea behind claytronics is neither to transport an object's original instance nor to recreate its chemical composition, but rather to create a physical artifact using programmable matter that will eventually be able to mimic the original

object's shape, movement, visual appearance, sound and tactile qualities." [Goldstein et al. 2005]. For Rekimoto [2008] the possibility of getting engaged with materials and interfaces with deformable and organic characteristics are making the interaction with malleable interfaces more emotional compare with other TUIs. Then, the main references are becoming materials such as clay, plasticine and other malleable and sculptable materials. For instance, in this context, LeClerc introduces the idea of "*sculptable computer*" [LeClerc 2006].

When interacting with highly malleable and deformable physical surfaces and forms in the real world there are diverse possibilities for input. For Rekimoto [2008] the possibility of getting engaged with materials and interfaces with deformable and organic characteristics are making the interaction with malleable interfaces more emotional compare with other TUIs.

As we can easily notice, clay became immediately a reference for a possible interface material with full tangible, embedded and embodied interactions. Works such as "Illumiated Clay" [Piper et al. 2002], "ClayStation" [Wang and Cheok 2011], "Digital Clay" [Reed 2009] employing real clay as a tangible media, an input/output material for interaction. In his book "Analog In, Digital Out" [Dawes 2006] interaction designer Brendan Dawes proposes a simple interface for controlling video playback using a piece of plasticine.

Also particle-based materials, such as beads [Savary et al. 2013], or sand [Ishii et al. 2004], as well as fluids [Niiyama 2014], have been previously explored as malleable interfaces.

In Malleable Tangible Interface the quality of the material and its affordances became two crucial elements. If we compare those kind of interfaces to the Graspable User Interface we can notice that in this context users could use their fingers and hands to pinch and depress the form. They could also feel the deformations while producing them, because of the immediate feedback from an elastic input surface. Malleable objects have a compliant material quality that invites users to multiple levels of tactile exploration and control. LeClerc et al. [2007] notice that the physical act of deforming a malleable tangible interface can be mapped to a continuos of meanings.

What is going to happen if we could combine the expressivity of clay with the benefits of digital interaction to allow for input from hands, and maybe tools and other objects with co-located visual and haptic feedback?

5.2 Malleable input – malleable output

The research on malleable interfaces in the context of TUIs has been taken different ways, by merging the development of new embedded sensor technologies with materials capable of being stretch, squeezed and formed. In this context, the most notable research concerns the development of non-planar and deformable-curved displays. In this context the attention is pointed on the more general interest of TUIs of turning an arbitrary surface into an interface: flexible e-paper and OLED displays are been explored as the most promising technologies for general-purpose displays. Projection is still playing an important role especially through the visual augmentation of physical objects.

An interesting early example in this area is the "Khronos Projector" developed by Cassinelli and Ishikawa [2005]. In this project a stretchable lycra fabric is used as a surface and as an input interface at the same time. By pushing the surface the user can navigate a digital video. The deformation of the surface is measured with a camera which is tracking the intensity of the reflected pixels.

It's very important in malleable devices to sense user's freeform deformations, interaction on and above surfaces, including 3D shapes. In this context depth cameras and IR light scanners are, especially in the recent years, the most used sensor technology for detecting deformation in combination with flexible and highly manipulable surfaces. For instance, Vogt et al. [2004] have developed an interesting input device made with flexible rubber. A camera placed under the surface detect the different deformations and connect the physical surface with a digital virtual structure.

In a recent work called "deForm" by Follmer et al. [2012], a 3D light scanner was employed in combination with a malleable surface made with thermo-plastic elastomer for the detection of arbitrary objects and tools.

Passive feedback became an other important aspect and it can be provided by exploiting the inherent properties of deformable materials: gels and silicone have been employed by Vlack et al. [2005], along with polyethylene [Sato et al. 2009], foam [Smith et al. 2008] or more complex mixtures such as the one used for "The Haptic Lens" [Sinclair 1997], where liquid bladder and pigments are employed.

The surface and the properties of the object can be sensed not only with external sensors, but

also with a direct instrumentation of the material. In this context malleable interfaces became a territory of experimentation that merge new sensors technology, embedded interactions and tangible interfaces. For example, measuring stretching and bending became crucial. Sugiura et al. [2012] has developed "Metaskin", a skin-like stretchable sensor which combine IR LED and phototransistor with an elastic fabric, which is a smaller and stand alone version of the "Smart Skin" developed by Rekimoto [2002]. Apart from input characteristics, malleable interfaces includes also Shape-Changing Interfaces and became rapidly a territory of experimentation for haptic feedback, passive or active it can be.

Many designers refer to the haptic quality of clay as a material that "*instantly responds to pressure and changes its shape*" characterized with "*immediate tactile and visual feedback*" [Wang and Cheok 2011], which relates to the sensations pressure and the deformation perceived by the sculptor with his/her hands. In most of the cases elasticity is the quality that is highlighted and explored. Most of the malleable interfaces are employing inert materials (i.e. clay, plasticine, silicone, rubber) and have a static modulus of elasticity, which provides passive feedback to the user.

Some projects such as "RoCuModel" [Shen et al. 2014] tried to adapt tools and techniques used in pottery in the context of digital fabrication.

In contrast, Shape-Changing Interfaces can easily change their material stiffness to emulate interaction with different materials, or to increase the degree of control over the material. Different recent researchers have explored and emphasize this aspect, such as "JamSheets" [Ou et al. 2014], "Blob Manipulation" [Wakita et al. 2011], "PneUI" [Yao et al. 2013]. This represent the contemporary frontier of malleable tangible interfaces.

5.3 Examples

At this point it became crucial to define the main characteristics and features of malleable tangible interfaces. I will propose a classification of relevant projects that can be described as Malleable Tangible Interfaces, by defining some main gestures and interaction employed.

Already in the previous section some characteristics emerge from different examples and the analysis of malleable materials and the idea of "Digital Clay" developed inside the framework of

Radical Atoms. We can describe Malleable Tangible Interfaces as interfaces that are:

- suitable for a whole-hand interaction that involves both hands at the same time;
- promoting a continuos interaction and an active engagement with materials qualities inherent in the physicality of the interface;
- detecting deformation of the material as a way to accept arbitrary and multiple gestures and input modalities;
- promoting physical play and playful activities and learning;
- taking advantages of embedded and embodied interactions and computational composites for creating an environment capable of sensing forces such as squeezing, stretching and pressing;
- stand-alone or used within the constraints of other interactive surfaces or artifacts;
- must be able to switch between soft and rigid material states, allowing different types of manipulations and deformations.

Not all of the existing malleable TUIs are satisfying all of these requirements and they invite the user to different levels of interaction.
Another characteristic highlighted in several works is that there are no existing taxonomies or classifications of these kind of interfaces, and, since this is an hybrid and very experimental field of research it's not possible to identify exactly every single property. The nature itself of Malleable Tangible Interfaces is to accept different typologies of inputs, coupled with a great freedom. Due to those properties is very difficult to find an interface that is exploring only one type of interaction.
Many approaches are possible, such as creating a classification based on the sensing techniques implied. For instance we can identify interfaces based on external sensing (such as depth

cameras), one that uses its own surface as an input, or some of them make use of internal sensing mechanisms.

Inspired by the classification made by Ullmer [2002], and the one of Rasmussen et al. [2012], I will try to propose a classification of Malleable TUIs based on five types of interaction with such interfaces. Most of these works are using *malleability* as way of creating dynamic input devices, but can be found also as an output since malleable interfaces are suitable for direct physical actuation for input/output 'displays'.

5.3.1 Continuous TUIs

Ishii et al. [2004] defines *Continuous TUIs* as interfaces where the material itself became the interface and the user interact with it, directly. This imply that there is no undo function, and the action, the transformations (not only of the digital output), are continuous.



Figure 3.10 : *A demonstration of "Illuminated clay".*

One of the early example in this direction is “Illuminated clay” [Piper et al. 2002], and it can be considered also one of the early examples of TUIs that employs malleability and material affordance as key aspects and direct manipulation as the main way of interaction. This interface (Fig. 3.10) was conceived in 2002 for the designing and understanding landscapes through realtime analysis. “Illuminated Clay” utilizes materials that can be physically manipulated (in this case plasticine) for supporting form giving, through rapid sculpting actions. As a sort of

continuation of “Urp” (see 3.2.1), this project is focused on exploratory tasks: a laser scanner is capturing from above the geometry of the model made with plasticine. The user can alter the form of the landscape model by manipulating clay while seeing the resultant effects of computational analysis generated and projected on the surface of clay in real-time.
“Illuminated Clay” was followed in 2003 by a similar project called “SandScape” [Ishii et al. 2004] which uses sand in a similar way (Fig. 3.11). The only difference is in the sensing techniques, here the authors use an array of infra-red lights placed under a glass beads.

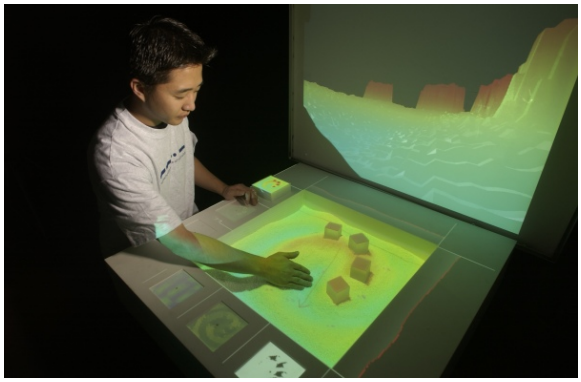


Figure 3.11 : *The "SandScape" system.*

5.3.2 Form giving / form destroying - Add and Remove

Similarly to what was noticed by Rasmussen et al. [2012], there are not so many interfaces (and materials) that enables the user to change radically the topology of an object, or to build a new one by adding and subtracting pieces of the same material. Due to its properties and and the techniques used in pottery making, clay seems to be a valid, natural and easily exploitable material. The use of computationally augmented clay as an input material for tangible interaction led to a prototype of a shape input device called “Digital Clay” [Reed 2009].

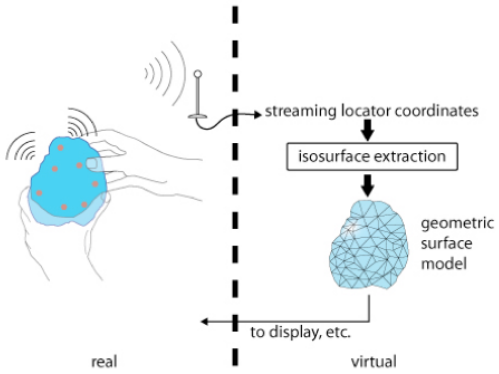


Figure 3.12 : *An illustration of the "Digital Clay" interface.*

Differently form the previous example, this work employ a direct instrumentation of the medium (Fig. 3.12). This approach tries to extend the clay modeling metaphor and perform complete shape capture, based on a literal interpretation of the idea of Tangible Bits of "coupling bits and atoms" [Ishii and Ullmer 1997]. "Digital Clay" is implemented by embedding a number of independent wireless locators[16] in a sculpting clay (Fig. 24). Those locators communicates their position to a computational model that capture and reconstruct the geometry of the entire shape. This method allows arbitrary deformations as well as shape alterations that change volume by addition or subtraction. "Digital Clay" represent an attempt to create a malleable and sculptable computational composite [Vallgårda and Redstöm 2007] for capturing shape deformations, and oriented to augmented reality applications.

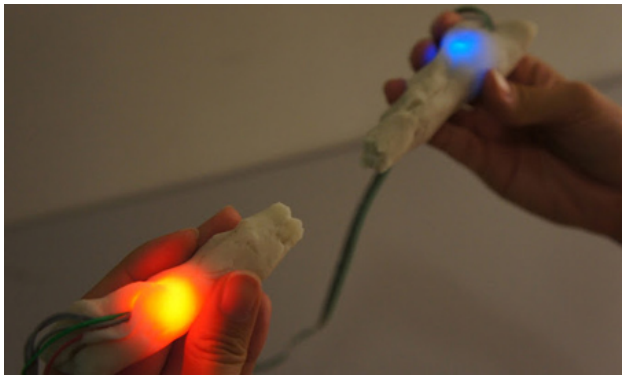


Figure 3.13 : *An image of "NeonDough".*

http://polhemus.com/motion-tracking/all-trackers/liberty-latus/

A project in the same direction was developed by Yamaoka and Kakehi [2011]. “NeonDough” (Fig. 3.13) is a prototype for a clay interface which enables crafting with pieces of glowing clay. Each piece of clay contains a module composed of two electrodes and LEDs. When two pieces of clay are combined the system detects different user's actions such as tearing, stretching apart. In response to this the different clay elements are changing in color and brightness dynamically and based on the clay states.

5.3.3 Augmented Physical Modeling TUIs

Not all of the possibilities of malleability can be achieved by using materials such as clay or plasticine. Sometimes some interactions for certain applications can be achieved only through some specific computational materials designed ad hoc. This is the case of "Senspectra" (Fig. 23). This project was developed by Vincent LeClerc [LeClerc et al. 2007], that is a computationally augmented physical modeling toolkit for sensing and visualization of structural strain. This interface incorporates the malleable properties of it's own material into a digital manipulative. The system functions as a decentralize sensor network consisting of nodes, embedded with computational capabilities and a full spectrum LED, and flexible joints. Each joint functions as an omnidirectional bend sensing mechanism to sense and communicate mechanical strain between neighboring nodes. This interface offers direct manipulation augmented with visual feedback for an intuitive approach to physical real-time analysis of organic forms.

"Senspectra" is particularly interesting because it address some of the main characteristics of a malleable tangible interface. First of all, the system incorporates the material quality of malleable elements of the interface into its digital control structure. It uses texture, plasticity and elasticity to inform the user about the functionalities of the physical interface. Also, the material affordances of the tangible interface are mapped in order to inform and manipulate its control structure.



Figure 3.14 : *A demonstration of "Senspectra".*

5.3.4 Physical actuated interfaces

As we already saw, malleable interfaces can be suitable not only as input surfaces but also as physical displays. The SMAAD (Smart Material Aided Architectural Design) is a fabric input/output device for intuitive shape creation (Fig. 3.15). This project developed by Wakita et al. [2011a] it's an interesting example on how it can be possible to combine the idea of malleable interfaces not only as an input device, but also as a dynamic and physical display. The SMAAD surface is a morphologically-variable smart material interlock with a 3D CAD system. The user can modify its shape through manual operations on the free form material. As we can see in Fig. 3.15 the SMAAD is a fabric device where sensors and actuators are embedded. Four flex sensors are grasping the textile shape and four actuators are changing the surface's shape. It's also possible to modify the virtual digital model and the command is sent back to the fabric device so that the physical shape can be modified to follow the digital data. This is made through the use of fibrous Shape-Memory Alloys (SMA). This fabric device can be also combined together with others for obtaining a bigger , manipulative and reactive surface.
This interface represents a good example on how can synchronize the physical world (atom) and the digital world (bit) through a malleable and deformable surface, which can be molded not only directly by humans but also from the digital.

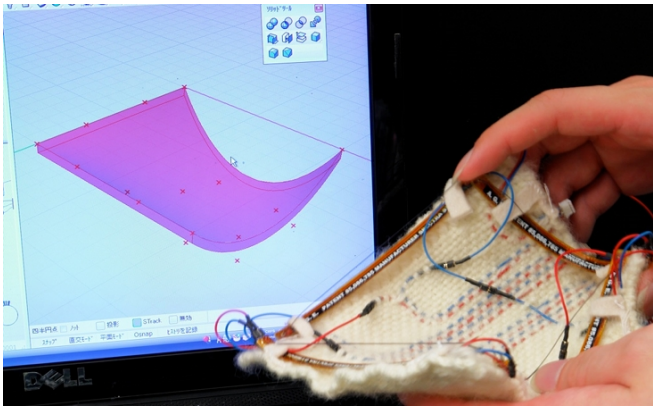


Figure 3.15 : The SMAAD surface.

5.3.5 Dynamic manipulative

One of the most recent studies on the use of a malleable input interface in the context of TUIs was conducted by Follmer et al. [2012].

Through different projects they tried to apply the technique of particle jamming for creative dynamic manipulative interfaces. This work represent another step into the idea that malleable interfaces can be either input and output devices, allowing different types of physical/digital interactions. Shape-Changing interfaces can provide users with more affordances for different tasks, allowing great tactile manipulability, and haptic feedback by changing their physical form [Coelho and Zigelbaum 2009].

In this series of prototypes the authors were exploring the use of particle jamming as a simple and effective method for flexible, shape-changing user interfaces where programmatic control of material stiffness enables haptic feedback, deformations, tunable affordances and control gain.



Figure 3.16 : *One of the prototypes developed by Follmer and colleagues*.

The authors apply the technique of particle jamming as a simple and effective method of stiffness control in Human-Computer Interaction. They defined those prototypes as 'granular media', characterized mainly by the ability to switch between soft and rigid materials.
Jamming became then an interesting way of developing deformable devices with haptic feedback and, again, clay-like interfaces. The authors combine this idea with a pneumatic system which can detect precisely a shape, record it and play it back (Fig. 3.16).

Summary

Through this survey on some of the contemporary trends in the area of Tangible User Interfaces. I tried to highlight how the importance of materiality, through the use of new dynamic materials, quickly became central in the development of what I defined as Malleable Tangible Interfaces. A turning point is the vision of Radical Atoms, where an interface is imagined as a new material rather then a an artifact.
The possibility of imagine highly malleable computational materials, opens different directions towards an unique interface material, which can couple the input and the output in a single compound material.
In the next chapter I will present how and why musical expression and performance represents one of the most successful and promising filed of application for TUIs. I will also introduce some previous examples that tried to explore the idea of malleable interfaces in this context.

But, which impact idea of "Radical Atoms" is going to have in the context of musical and sound interaction ? Conceiving an interface as a dynamic material is going to help designers, musicians and artists in the development of new and more expressive musical interfaces ?

Chapter 4

Trapped into the sounding and haptic groove : malleable interfaces for musical expression

In the previous chapters some of the main concepts behind the idea of New Interfaces for Musical Expression (NIME) and Tangible User Interfaces (TUIs) have been introduced.
Such frameworks have some points in common and in the recent years different projects showed the possibility of combining the idea of Tangible User Interfaces with musical expression. For instance, sound and musical expression were some of the first applications for TUIs.
This chapter discusses the state of the art of what we can call Tangible Musical Interfaces. This is a particular branch of interfaces for musical expression where not only direct manipulation and touch are the main ways of interaction, but also the whole concept of TUIs is developed into the realm of musical interactions. After a brief illustration of some relevant projects in this area, introduce the possibility of combining the idea of Malleable Tangible Interfaces for musical expression will be discussed, together with some possible benefits and limitations.

1. Tangible music

When the icelandic songstress Bjork picked up the ReacTable for her World Tour in 2007, both audience and musicians started to be aware of the potentials of tangible interfaces in musical performance. After this event we can say that we are facing a proliferation of Tangible Musical Interfaces. From prototypes to commercial products, several interfaces have been produced that it becomes difficult to keep track of every new proposal [Kaltenbrunner 2008].
Beside of being an intriguing application area for research projects, many tangible musical interfaces have been developed by professionals, such as electronic music artists. Specialized international conferences such as NIME[17] or ICMC[18] confirms the growing interest of TUIs in the community of digital musical instrument designers.
We can devise some main characteristics of tangible musical interfaces:

- The instrument is be perceived as such, not just only a controller;

- The performer can access all of the sound synthesis and control parameters simultaneously, at any time, through direct manipulation of whole components of the tangible interface;

- The instrument provides visual and/or haptic feedback in addition to the sonic one;

- Musical TUIs are either designed for novice where they provide an intuitive and easily accessible interface, or aim at the professionals that appreciates physical expressiveness, legibility, and visibility when performing electronic music in front of an audience.

- Most of these instruments support the collaboration of two or more musicians.

1.1 Some previous works

17 http://nime2014.sched.org/event/af817b6fc0f3a8e7e9523e7123a7119d#.VDQdyeeWSKo
18 http://www.eastn.eu/

According to Shaer and Hornecker [2009] music applications are one of the oldest and most popular areas of experimentation for TUIs. But it's around the year 2000 with projects such as the Jam-O-Drum [Blaine and Perkins 2000], AudioPad [Pattern et al. 2002] that we can notice a real interest in developing new musical interfaces within the framework of TUIs, rather then using sound as a simple and useful source of feedback for an interaction.
In 2004 the ReacTable [Jordà et al. 2004] was presented for the first time and, as we said before, became very rapidly as a sort of symbol of Tangible Musical Interfaces.
Jordà [2008] noticed that we can identify around 2007 the year of a sort of explosion of tangible musical interfaces, with devices such as the Jazz-Mutant's Lemur, and the Tenori-On designed for Yamaha by Toshio Iwai [Nishibori and Iwai 2008]. Since the roots of Tangible Musical Interfaces can be traced back in different areas such as experimental music, Human-Computer Interaction, performance, media and interactive art. I'm going now to introduce some early examples.

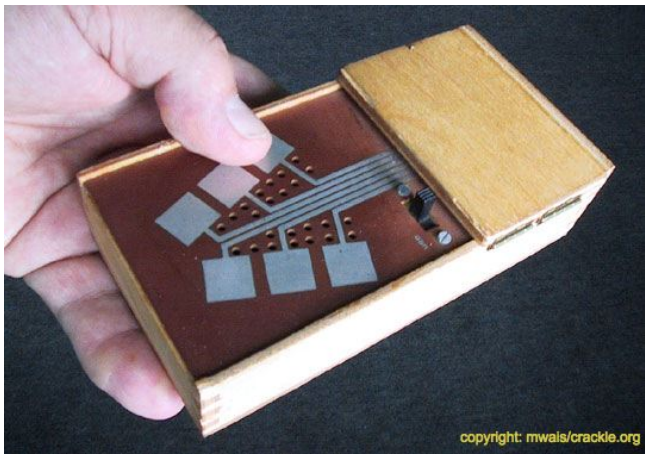


Figure 4.1 : *The Kraakdoos by Michael Waisvisz.*

1.1.1 Kraakdoos

Direct touch is a common way of interaction that musical instruments tangible interfaces are sharing. A musician that with his work tried since the 1960s to explore the expressive power of intuitive touch [Norman et al. 1998] in electronic music was Michael Waisvisz, one of the pioneer of alternative analog and digital musical instruments. The materialization of his vision of

getting physically engaged with a synthesizer was the "Kraakdoos"[19] (in english, Cracklebox). This is a custom made battery-powered noise-making electronic device (Fig. 4.1) developed in 1975 at STEIM in collaboration with engineer Geert Hamelberg. It is a small wooden box with and internal speaker and six metal contacts on the top, which when pressed by fingers will generate all manner of unusual sounds and tones. With the Kraakdoos the human body -through the active finger's touch- becomes a part of the circuit and determines the range of possible sounds [Krefeld 1990]. As Nicolas Collins noticed, if touch circuits had been employed before in the expressive keyboard controllers by Donald Buchla and Serge Tcherepnin in their synthesizers, the Cracklebox was the first mass-produced electronic musical instrument that incorporated the player's skin as the primary variable component in a sound generating circuit [Collins 2009].

1.1.3 Augmented Groove

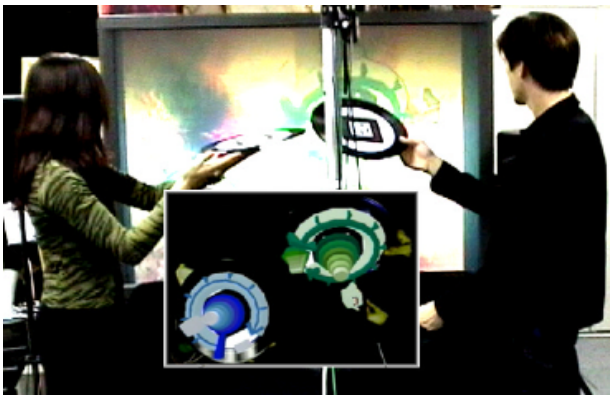


Figure 4.2 : *A demonstration of the Augmented Groove interface.*

Tangible interaction seems to be very appealing for electronic musician because it can exploit the power of direct and physical manipulation of artifacts. For instance, DJs and 'turntabolists' [Markski 2002] have developed a repertoire of gestures and techniques that became useless with CDs or digital audio files.

19 http://www.crackle.org/CrackleBox.htm

As we said before, one of the research fields where the idea of TUIs emerged was Augmented Reality. “Augmented Groove” (Fig. 4.2) is a musical interface designed especially for techno dance music, developed in 2000 at Sony CSL Tokyo [Poupyrev et al. 2000]. “Augmented Groove” uses augmented reality, head-mounted display, and a physical, tangible interface to allow performers to conduct multimedia musical performances. The performer modulates and mixes compositions by manipulating real LP records. The motions of the records control filters, effects and samples dynamically mixed in and out of the groove. A composer can assign any element of composition to any record and the song progression is controlled simply by removing one record and bringing in another.

1.1.4 Audiopad

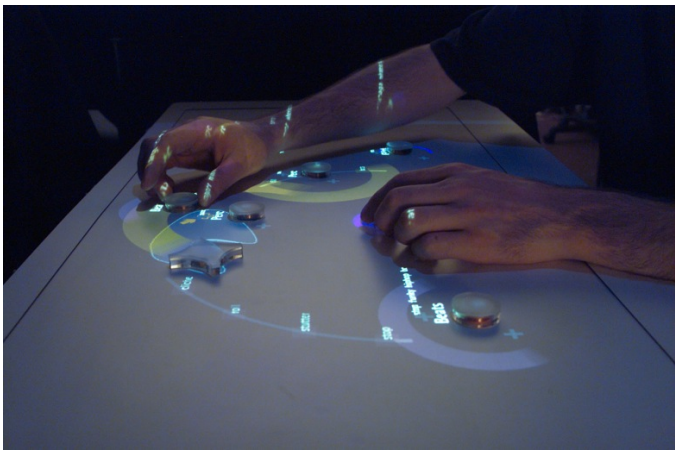


Figure 4.3 : *An image of the Audiopad tangible surface.*

The digital world, together with laptop performances and live mixing softwares, opened the door to different styles of music making. Looping, sampling and mixing became some of the most common terms in the new generation of Djs and live performers. Those tasks were (and still they are) executed by the performer on a laptop, by looking in front of a screen, with the aid of mouse and keyboard interfaces, or together with MIDI controllers, pads and mixers. In this context Tangible User Interfaces appeared to be an interesting a powerful approach to enrich the

interaction in this context.

Developed in 2002 at MIT Media Lab by James Pattern and Ben Recht, the “Audiopad” [Pattern et al. 2002] it's a tabletop interface for musical composition and live performance that aims to combine the modularity of knob based controllers with the expressive character of multidimensional tracking interfaces (Fig. 3.4). The “Audiopad” interface keep tracks of the positions of some objects on a tabletop surface and converts their motion into music. Different actions are possible, such as: navigating through archived recordings and samples, creating beats, and appling digital processing. This interface has a matrix of antenna elements which track the positions of electronically tagged objects on a tabletop surface. A software translates the position information into music and graphical feedback on the tabletop. Each object represents either a musical track or a microphone.

1.1.5 Lemur



Figure 4.4 : *The Lemur by Jazz-Mutant.*

According to William Buxton [2008] the Lemur (Fig. 4.4), developed by Jazz-Mutant in 2004, was the first multi-touch device to be offered as a commercial product to the general public.
This input device is a modular touch panel based controller designed for audio and multimedia real-time applications, using MIDI and OSC for communication with external devices and softwares. The Lemur comes with its own proprietary software with which the users can build their interfaces using a selection of fifteen different objects (which are graphic abstractions of

elements such as fader, knobs, sliders), group them into modules and arrange them in different pages as needed. One of the particular characteristics of the Lemur is the ability to modify the physical behavior of each objects, for instance adding or removing friction on faders. This input device became very popular and has been used by several famous artists such as Nine Inch Nails, Bjork, Daft Punk and Ryuichi Sakamoto. Jazz-Mutant stops the production of the Lemur in 2010, mostly due to the invasion of cheap and general purpose multi-touch tables and devices, such as the Apple iPad. Nowadays Lemur is available as an application for iOS.

2. Tangible Musical Interfaces

In the previous chapters some of main concepts, frameworks and issues of different areas of research such as Tangible User Interfaces and NIME were introduced.

If we take as a reference two of the main academic conferences of the fields mentioned above, we can ascertain an increasing overlap between the research questions of TUIs and NIME. In the past ten years a lot of Tangible Musical Interfaces arises, from both communities of interface designers and musicians. Although the goals they pursue can be different, the methodology and theoretical groundwork started to be shared. Especially musicians and instrument designers are taking into account the terminology and descriptive taxonomies developed in TUIs [Tanaka 2010].

This situation poses some questions on why Tangible Interfaces are becoming so popular in digital music and especially in live performance. Someone can argue that musical instruments have always been 'tangible', but only in the concreteness and physicality of the artifacts. There are other aspects that have contribute to popularize the idea of TUIs in musical interface design.

We have to observe that, a part of few examples [Jordà 2008] [Tanaka 2010], there are no relevant works that are analyzing Tangible Musical Interfaces as a separate category. Probably because this is not a genre, but still represents "*a promising and exiting field of multidisciplinary research*" [Jordà 2008]. The ReacTable is probably one of the few examples of Tangible Musical Interfaces developed by a team composed of musicians, designers and engineers that passed many different tests, especially when it came on stage. This demonstrates that it's possible to

think about Tangible Musical Interfaces not only as prototypes, but fully functional interfaces for live performance, also from an artistic point of view.
I have to notice that usually the community of TUIs designers is more concerned on using music and sound as an immediate form of feedback, where instead a musician or a live performer is approaching the framework of Tangible Interfaces from the point of view of an instrument builder and / or player. A performer, due to his/her practice and background, is more concentrated on issues such as 'expressivity' more then 'usability'
One of the main study that tries to answer the question "*why musical performance constitutes a promising application domain for tangible and tabletop interaction?*" was made by Sergi Jordà [2008]. In this work he proposes some representative topics for explaining why music performance turned to be a promising test bed for tangible applications. The two main topics are:

- collaboration and control sharing;

- complex, skilled and explorative interaction.

Even if this work is focused on tabletop interfaces, Jordà is one of the few that tries to find, either theoretically and empirically, the common features and the possible future directions that arise from the marriage of TUIs and digital musical interfaces.

2.1 Collaboration and control sharing

As we know traditional musical instruments have been mostly designed for an individual use. Multi-user musical instruments have been truly scarce in history [Jordà 2005]. On the other hand, musical performance is still one of the more archetypical group activities and, probably one of the densest from human communication. Cognitive scientists have addressed the perceptual aspects of interdependent group playing, by defining music as "*a medium through which individual brains are coupled together in a shared activity*" [Benzon 2001], where especially

playing live music for humans is like playing with the full bandwidth of communication [Bischoff et al.1978].

As I mentioned in Chapter 3, many researchers believes that the principle values of Tangible Interfaces may lie in their potentials for facilitating collaborative activities that are not possible, or are poorly supported by single user technologies [Marshall et al. 2007]. If we look at some of the most noticeable examples of Tangible Interfaces we can see that collaboration is one of the main characteristics that researchers tried to pursue [Ullmer and Ishii 2001] [Ishii et al. 2004]. Tabletop and interactive surfaces have been successfully exploited for exploration of photo archives, map navigation and urban planning, and now we can find them in museums and exhibitions. The social affordances associated with Tangible Interfaces have showed the potentials of concepts such as *social interaction and collaboration* [Hornecker and Buur 2006] and *sharable interfaces*, especially in context like learning activities for kids [Shaer and Hornecker 2009]. This interest in sharable activities and control is grounded in contemporary cognitive science research [Fernaus et al. 2007], and it's supposed to help moving Human-Computer Interaction from a data-centric view of interaction to a view focusing on representational forms and resources for action. Instead of relying on the transmission and sharing of data, the action centric perspective is looking for solutions that emphasis user control, creativity and social action with interactive tools [Shaer and Hornecker 2009].

Jordà [2008] noticed that music performance is also an activity that involves collaboration and sharing, but in an essentially different way.

Collective music performance with digital systems is thus better understood as a matter of sharing control over computational actions, rather than sharing datas among users. From "The League of Automatic Composers" [Bischoff et al. 1978] to the "SoundNet" created by the Sensorband [Bongers 1998] [Tanaka 2000], to laptop and live coding performances [Cascone 2004], musicians working in interactive music developed different interfaces for sharing control between different performers. The jazz musician and improviser George Lewis was talking about sharing the control on musical actions not only between musicians, but between the performer and the computer, in a collective and mutual improvisation [Lewis 2000].

This concept became very influent, and it's present in different Tangible Musical Interfaces such as the already cited ReacTable, BlockJam [Newton-Dunn et al. 2003], but also in most of the tabletop and token based interfaces, together with alternative devices such as the Squeezables [Weinberg and Gan 2001] and the LittleBits [Bdeir 2009].

2.2 Complex and explorative interactions

Human control bandwidth is hard to evaluate objectively, but musical instruments (which are among the most complex and sophisticated machinery humans have managed to design, construct and master) can give us some clues.

Traditional monophonic instruments frequently have three or four degrees of control. Polyphonic ones have two or three per voice while always showing limited continuous control possibilities. The reason for these restrictions are to be found in the physical and cognitive limitations of humans [Fitts 1951] [Cook 2001]. According to Robert Moog, a flute player is able to control amplitude with 6-bit resolution with a temporal resolution of about 100 Hz, while a drummer can play with a maximum frequency of 10 Hz controlling three parameters and an approximate resolution of 4 bit per parameter [Moog 2004]. This is showing that a very precise temporal control over several and multi-dimensional and continuous parameters, sometimes over simultaneous parallel processes is specially required in the interaction dialogue that takes place between the performer and the instrument. Moog [2004] estimates that the maximum meaningful information a skilled musician is able to generate is about 1000 bits sec.

If those numbers seems not to be related to tangible interaction, for Jordà [2008] they bring interesting subjects to debate in HCI. Usually, Human-computer Interaction has mostly focused on making things more efficient, and has discovered quite recently that not only efficiency is relevant, but perhaps also beauty and fun [Norman 2004]. This was an attitude that musicians and designers of musical interfaces have always criticized.

"I have recently been arguing that HCI and ergonomics are "failed sciences". Why? If we look at the design of the Personal Computer, it can be argued that there has been virtually no significant change in the design since the introduction of the Xerox Star in 1982. Now note, that this product (which commercially introduced, widows, icons, GUI, the mouse...) came into being with the benefit of virtually NO HCI or ergonomics literature. Yet, since then, you could pile the accumulated literature over 10 metres high, and yet virtually NONE OF IT has had any impact on design in practice. In a still photograph, a Xerox Star is indistinguishable from a modern PC. The science has failed. Why? Because it is not a design-based discipline. Virtually all of the people who made contributions to

electronic music instrument design were actively involved with musicians, or performers themselves, and they took the approach of a designer, not of a scientist. Yes, they benefited by science, but the approach was not scientific. It was far more closely rooted in the practice of industrial design or architecture."
William Buxton [Wanderley and Battier 2000].

"(...) *like music composition, instrument and controller design is a creative art and doesn't easily follow prescriptions. The danger with prescriptive sciences is that they tend to define a territory where things are supposed to happen, a kind of normalcy. Good, integrated designs – whether of artworks or of great tools – tend to push past what was assumed to be possible, tend to arrive at startlingly simple syntheses, and just plain to propose solutions for problems that no one may have even considered. One of the most exciting things about the current development of gestural controllers for music is that it is so often driven by creative individuals who have something unique and important to express as artists, and will grapple and bend materials and rules incessantly until that vision is realized. The results may not be so easy to standardize, but this process does lead to unpredicted scientific developments (since no one else would have asked such crazy and demanding questions), to surprises for the human factors community, and to very exciting controllers that are art works in themselves and often an inspiration for interface designers in other fields.*"
Todd Machover [Wanderley and Battier 2000].

Also Jordà (2008) underline that HCI is devoting much effort in making task-solving simpler. When complex and rich interactive processes are oversimplified, by definition, control can be degraded or lost. Buxton [1997] points out that seems that computer devices and tools have almost never been conceived for the skilled user in mind: for instance, a musician. One of the main reason behind the 'success' of tangible interface for music is that the field of TUIs have tried to exploit human skills of interacting with digital systems. As Ishii and Ullmer said "*people have developed sophisticated skills for sensing and manipulating our physical environments. However, most of these skills are not employed by traditional GUI* (…)*The goal is to change the painted bits of GUIs to tangible bits, taking advantage of the richness of multimodal human senses and skills developed through our lifetime of interaction with the physical world.*" [Ullmer and Ishii 1997].
If we look at music performance we can noticed that skilled and complex interactions (such as with a musical instrument) can also be enormously fun and rewarding for every one, even

novices. It's also for these considerations that tangible interfaces seem ideal for exploratory and expressive activities, allowing the users to create constructions that might not be possible with other media [Marshall, et al. 2007]. But, Jordà [2008] noticed that those interfaces should not be scared of complexity, when such complexity is needed. He proposes that the study of performing arts and music performance in particular constitutes some excellent realms for deeply understanding, exploring and fully exploiting the potential of tangible interaction.

If we can see the debate on the friction between usability and expression, common in musical interfaces (see Chapter 2) is still present in the ones who are employing the framework of Tangible User Interfaces. In the next section I'm going to present, through some projects, why the approach of tangible interaction can be an interesting framework for address those kind of problems.

3. A classification of Tangible Musical Interfaces

Since the year 2000, from prototypes to real products, many Tangible Musical Interfaces have been created. Thanks to the availability of open hardwares and softwares such as Arduino[20], RaspberryPI[21], Processing[22], OpenFrameworks[23], Pure Data [Puckette 1996], and specialized toolkits developed for Tangible Interfaces and gestural interfaces, such as TUIO[24], or OpenNI[25], and the availability of cheaper and little embedded sensors, actuators, interfaces and protocols for communication (i.e. Zigbee, RFID, Bluetooth).

If we are taking the perspective of musical interfaces we can try to classify Tangible Musical Interfaces as *touch interfaces* and in some cases *collaborative interfaces* . But this can be a limited approach, because TUIs have already developed its own vocabulary and taxonomy (See Chapter 3).

From many point of views the perspective of TUIs can describe better the diversity of the

20 http://www.arduino.cc/
21 http://www.raspberrypi.org/
22 http://www.processing.org/
23 http://www.openframeworks.cc/
24 http://www.tuio.org/
25 https://github.com/OpenNI/OpenNI

interfaces, because we don't need concentrate our attention on which gesture is capture, but which metaphor and strategy is implemented in the design of the interface.
According to Shaer and Hornecker [2009] we can distinguish between four high-level approaches in Tangible Musical Interfaces: *instruments*, that are fully controllable sound generators or synthesizers such as the ReacTable, *sequencers*, that mix and play audio samples, *sound toys* with limited user control, and *controllers* that remotely control an arbitrary synthesizer.
Kaltenbrunner [2008] proposes a more specific classification of Tangible Musical Interfaces inspired by the one made by Ullmer [2002], previously introduced in Chapter 2.
In his classification Kaltenbrunner distinguishes seven different types of TUIs oriented to music and live performance: *tangibles*, *blocks*, *tokens*, *artifacts*, *toys*, *touch*, and *alternative controllers*.
In this section I'm going to introduce and describe in details some relevant examples of Tangible Musical Interfaces by following this classification.

3.1 Tangibles

With *tangibles* we refer to Tangible Musical Interfaces that are fully conceived as a full musical instrument. They are not simple controllers, rhythm generators or sequencers, but they embed all of the functions of a complex synthesizer in a unique interface. Those interfaces are also using, exploiting and integrating different characteristics of tangible interfaces such as tokens and interactive tabletop surfaces.

Case study: The Reactable

The ReacTable [Jordà et al. 2004] is a tangible musical interface that allows expressive and collaborative live performances, oriented to professional musicians and amateurs, by surpassing the limits of many screen-baed interfaces for electronic music (Fig. 4.5). This interface was developed between 2003 and 2007 at the Music Technology Group of the Pompeu Fabra University in Barcelona (SP), by a multidisciplinary team composed by the Sergi Jordà, Martin

Kaltenbrunner, Gunter Giger, Marcos Alonso and Ross Bencina.



Figure 4.5 : *An image of the ReacTable.*

According to the creators "*the foremost goal was to design an attractive, intuitive and non-intimidating musical instrument for multi-user electronic music performance*" [Jordà 2008]. As the its name suggests the ReacTable is a table-based instrument that can be played by manipulating a set of objects distributed on the top of an interactive table surface. Each of these objects has its own dedicated function for the generation, modification or control of sound. By bringing those objects into proximity with each other, the user can constructs and plays the instrument at the same time. In addition to the sound, which is obviously produced while playing, the ReacTable also provides additional visual feedback by projecting a visualization of the sound-flow onto the table surface.

3.2 Blocks

Tangible musical *blocks* consist of physical elements that continuously generate or manipulate sound. They can be stacked, attached, or simply placed in each other's vicinity. With some systems, blocks are working independently of each other, with others the spatial arrangement modifies sound, which is transmitted and processed through sequencing blocks.

Case study: BlockJam

BlockJam (Fig. 4.6) is a tangible interface developed in 2002 at Sony CSL in Tokyo [Newton-Dunn, et al. 2003]. The interface is a "constructive assembly" [Ullmer 2002] composed by 26 physical artifacts that are controlling a dynamic polyrhythmic sequencer.
These physical artifacts, called blocks, have their own functional and topological status tightly coupled to an ad hoc sequencer, which is interpreting the user's arrangement of the blocks into meaningful musical phrases and structures. Users can take advantage of their explorative and intuitive abilities for creating musical structures in real-time. The function of each block is represented on the top through a small LED matrix, used for providing a visual feedback. One of the main motivations behind BlockJam was promoting face-to-face collaboration and social interaction within a single musical system.

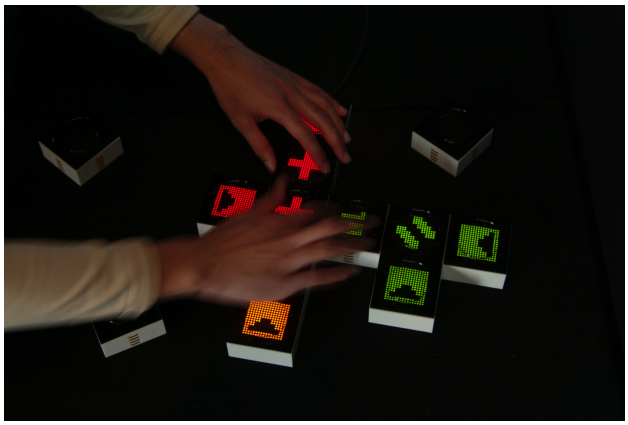


Figure 4.6 : *BlockJam*.

3.3 Tokens

Tangible systems based on *tokens* are often used for controlling sequencers. In this case a surface is repeatedly scanned and each slice of the scan generates sound. The location of a token, or other attributes (such as color) determine the note or the rhythm played.

Case study: Beat Blocks

Developed by Jeff Hoefslinked and Stijn Schiffeleers in 2006, Beat Blocks[26] is a tangible interface for a rhythmic sequencer (Fig. 4.7). The user can create and manipulate a four track drum loop by physically re-arranging wooden blocks within a 4x4 grid. Each block has a pattern of vertical stripes that represents a sequence of drum hits for a 1/4 measure time duration. The sequence plays in a continuous loop and is updated instantly as blocks are added and re-arranged so that the composition is constantly changing as people are interacting with the system. This Beat Blocks system functions as a MIDI controller, and it can be attached to a drum machine, sampler or other sound modules. One of the main purposes of this project was the creation of a simple and intuitive interface, where the only things required for the user is the basic act of re-arranging objects in a physical grid.

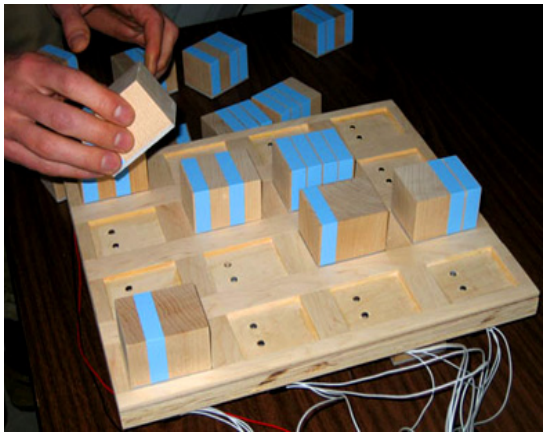


Figure 4.7 : *The Beat Blocks tangible interface*.

3.4 Artifacts

With tangible musical artifacts we refer to particular tangible interfaces where the music is "contained" within a sensorized object, and different interactions, such as rubbing, squeezing, shaking are producing or modifying different sounds. The interfaces that belong to this category are characterized by an high or full level of embodiment [Fishkin 2004] between the sound's

26 http://www.beatblocks.com

content and the container.

Case study: Audio Shaker



Figure 4.8: *An image of the AudioShaker.*

As its title suggests Audio Shaker [Franinović and Serafin 2013, p. 47] is an interface that uses the metaphor of the cocktail shaker for processing live recorded sounds (Fig. 4.8). As the authors said "*Anything sung, spoken, clapped, whistled or played near it is trapped inside, where it takes on an imagined yet tangible physicality. Sounds caught in this void are transformed, given weight and permanence, reacting directly to the shaker's movements, subtle or violent. Shaken sounds have to settle down before becoming still and silent, behaving more like fluid than transient energy. The linear timescale of sound is broken, a conversation is split into words and mixed up in the shaker, and can be poured out separately, tipped out in a simultaneous splash or added to and shaken up further*"[27].
Developed in 2004 by Mark Hauenstein and Tom Jenkins, this interface is showing the potentials of embodied interactions and tangible interfaces that are exploiting common gestures and actions, by investing them with new meanings.

3.5 Toys

27 http://www.tom-jenkins.net/projects/audioshaker.htm

This category represents a particular range of commercial tangible music toys for children. Those toys usually allow selection and placement of tangible objects into slots, activating associated sounds that are modified by the position and overall configuration of elements. Though the goal of most of these interfaces is not music making, they are going into a direction that belongs also to TUIs in general that is education and entertaining.

Case study: Music Blocks



Figure 4.9: T*he Music Blocks by Neurosmith*.

Music Blocks (Fig. 4.9) is an educational tangible musical instrument for children. It was produced and commercialized by Neurosmith [Sosoka et al. 2002] in 2000. With this interface children can explore the creation of melodies through the use of five cubes in a row. Each side of these five blocks plays a different phrase of music, chosen from three musical themes. The variety of phrasing allows children to compose many different sound combinations and patterns. Aside from the pure enjoyment in creating musical compositions, one of the main motivation behind Music Blocks was the stimulation of cognitive development in children through the use of a tangible interface.

From my point of view the last two categories proposed by Kaltenbrunner [2008], that are *touch based music tables* and t*ouch controllers* are not so relevant anymore. Touch panels, tables and surfaces are nowadays part of our environment in the form of tablets and smartphones. Even if they are using direct touch as a form of interaction they are not exploiting none of the potentials of TUIs, and we can say that they characterize some of the first works in the area of tabletops

musical interfaces. We can find some contemporary examples in some apps developed for platforms such as iOS and Android, but this is going beyond the scope of this thesis. Touch controllers for sound performance have already been introduced in chapter 2. Anyway, there are some relevant examples of alternative musical interfaces based on direct touch and manipulation that will be presented in the following section.

4. Malleable Tangible Musical Interfaces

In Chapter 3 I introduced the idea of *malleable interfaces* in the context of Tangible User Interfaces through some theoretical frameworks, such as the one of "Radical Atoms" and some examples of relevant works. Here I will concentrate my attention on the presentation and description of some interfaces that are exploring the qualities possessed by malleable objects for musical interaction, through the use of direct touch and manipulation.

In the physical world the action of deforming a material is often coupled to sound, as when wooden beams creak as they bend, or when string is bent by plucking motions.

In the context of electronic and digital music *malleability* is often employed for describing some features of those media.

Already the middle of the 1970s, Brian Eno was describing tape as a "malleable" material for recording, editing and processing music [Licht 2007]. In digital sound editing softwares actions such as "stretching" are often used for describing the increasing the duration or the pitch of an audio track.

Though there are not proper malleable acoustic musical instruments, excepts the bellows present in the accordion, the Shruti box, or a bagpipe, this seems a suggestion that a lot digital instrument designers tried to explore. We can identify some recurrent motivations behind the development of Malleable Tangible Musical Interfaces.

The first one regards the simplicity and intuitive interaction with those interfaces: malleable objects possess a natural affordances that every human being knows and has already experienced .

Several research noticed that *malleability* is a quality that promotes playfulness when its coupled

with musical creation [Weinberg and Gan 2001] [Jensenius and Voldsund 2012].
A third reason is that malleable objects allows some direct manipulation and engagement with the materiality of an object that, for some musicians, recall the experience with acoustic instruments [Marier 2010].
There also some technical challenges in the design of a Malleable Tangible Musical Interface. In 'conventional' musical interfaces (such as in any rigid gestural controller) the fragility of the components often distract the hands from their exploratory movements. Additionally, the specific localization of touch sensors and buttons often diminishes the freedom of interactivity, as performers must focus on targeting instead of being able to expressively interact with a surface or an artifact [Chang and Ishii 2007].
Haptics and tactile feeling are also some relevant topics. As I described in section 6 of Chapter 4, hapticity in musical interfaces has been implemented through the use of force-feedback and tactile stimulators, by exploiting the hands as another organ that must be stimulate.
In the next section I'm going to present some examples of Malleable Tangible Musical Interfaces, together with an analysis of their main characteristics. They will be presented in chronological order, this can help us to develop some considerations on recurrent themes and solutions.

4.1 GraspMIDI

One of the first example we can devise in literature is the “GraspMIDI” interface developed by Hideyaki Sawada [1999]. This first prototype of a malleable tangible musical interface was created with the aim of studying the "*emotional feelings presented in hand gestures*" represented by "*emotional twiddling gestures*" [Sawada et al. 1997].

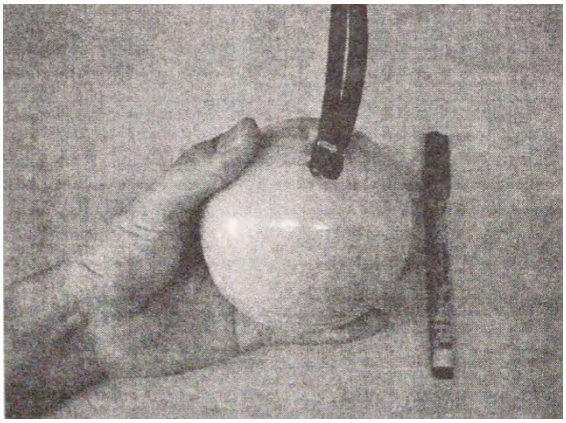


Figure 4.10 : *An image of the GraspMIDI interface.*

According to Sawada the design of the interface is inspired by the "*softness of human skin*" [Sawada 1999]. The goal of the GraspMIDI is to measure the squeezing force applied on the interface, which reacts to the force applied to the device body.

As a results of different iterations The GraspMIDI is composed of an array of six pressure sensors (especially developed for this work) and a three axis accelerometer molded into a silicon rubber body [Sawada 1999].

Sensor outputs are then fed to a personal computer through an A/D board. The values coming from each sensors are associated with six MIDI events, which are generated by a custom made sound to gesture mapping using a pattern recognition algorithms [Sawada et al. 1997].

Several musical applications have been tested by the author, such as controlling different effects, pitch and volume [Sawada 1999].

The GraspMIDI was conceived in the framework of the *kansei* [Harada 1998], which is a japanese word that covers the meaning of *sensitivity*, *sensibility* and *intuition* [Harada 1998]. This discipline intends to understand what *kansei* is and how this concept can be applied in the design of new products and services in engineering [Schütte 2006].

4.2 Squeezables

The Squeezables (Fig. 4.11) is a computer music instrument for collaborative music

performances. It allows a group of players to perform and improvise musical compositions by using a set of squeezing and pulling gestures. This instrument is probably one of the first interfaces that tries to explore the potentials of soft and malleable objects in music performance. The Squeezables was developed in 2001 by Gil Weinberg and Seum-Lim Gan [2001].



Figure 4.11 : *The Squeezables*.

The whole instrument comprised of six squeezable mounted on a small podium. Each player around the podium can simultaneously squeeze and pull the balls and control a set of musical parameters based on a algorithm developed on purpose [Weinberg and Gan 2001]. The combination of pulling and squeezing allows players to employ familiar and expressive gestures to manipulate multiple synchronous and continuous musical channels.

Each input device of the Squeezables is composed of a soft gel ball, inside a small plastic box covered with five pressure sensors that are protected from the gel with an elastic membrane. Detection of pressing and pulling gestures is performed in two ways: the analog pressure values from these sensors are transmitted to an Infusion System I-Cube digitizer and converted into MIDI format. The pulling actions are sensed by a set of six variable resistors that are installed under the table. An elastic band connected to each ball adds opposing force to the pulling gesture and helps retract the ball back onto the tabletop. Then the datas are converted through a digitizer to MIDI and transmits to a Macintosh computer running a Max patch. In this project particular attention was given to the mapping strategies. As a collaborative instrument each ball was mapped to a different synthesizer with a different function: Melody, Theremin, Arpeggio, Voice, Synth and Rhythm.

One of the main goal of this instrument was the exploration of interconnected group playing by

providing an infrastructure for the development of interdependent, yet coherent, multi-player interactions. As a test case for a particular high level control and interdependent mapping scheme, the authors composed a short musical composition for the instrument and was performed by a group of three players. By playing the Squeezables the users reports an high grade of satisfaction and engagement, due mainly to the particular qualities of malleable materials when they are employed in interfaces for musical expression [Weinberg and Gan 2001].

4.3 The MATRIX



Figure 4.12 : *The MATRIX.*

Around the same period Dan Overholt from MIT developed the MATRIX [Overholt 2001], a 3-dimensional tactile interface for musical expression (Fig. 4.12). The MATRIX (that stands for Multipurpose Array of Tactile Rods for Interactive eXpression) provides to the user a sculptable tangible surface for controlling and generating sound through an array of flexible push roads. This interface can be used either as a standalone instrument or in conjunction with a keyboard or microphone. According to the author the MATRIX generates musical output by mapping a

performer's expressive gestures to a variety of sonic parameters.
By pushing the rods, the user is changing the shape of the interactive surface and directly manipulating the parameters of a synthesis engine (eg. additive, granular, wave-terrain) or an effect algorithm (eg. delay, reverb, filter banks). The interface is composed of 144 rods on a grid, with a density of about 4 rods per square inch, covering an area of 36 squares inches. Each rod is connected to a spring, and the movement is sensed with a quadrature encoder. The metal springs are used also for providing a sort of haptic feedback. Then the sensors are connected to a custom circuit board that calculates the 3-D topology of the surface using an FPGA (Field Programmable Gate Array), a PIC microcontroller and a serial line driver to transmit the data to a computer running a Max/Msp patch.
Overholt was also experimenting with different mappings and musical compositions. One of those, which seems to be the most successful, each rods of the interface is controlling the individual grains of a granular synthesizer and "*thereby sonically sculpting the timbre of the sound*" [Overholt 2001].

4.4 Sonic Banana

Developed in 2003 by the musician and inventor Eric Singer, the Sonic Banana [Singer 2003] is an alternative MIDI controller in the form of a 2 foot flexible rubber tube (Fig. 4.13).
As Singer said "*The Sonic Banana is an attempt to create an expressive instrument with an unusual performance interface using a "less is more" approach – to create a rich musical output from a limited set of control streams. After the mapping and generation algorithm has been set, the interface encourages experimentation to explore what sort of bending and twisting gestures produce interesting musical effects*" [Singer 2003].
This interface is composed internally of four bend sensors, each 5" long, mounted in a row. A single pushbutton switch is mounted at the end of the tube. These sensors are then connected to a BX24 microcontroller which converts data from these inputs into MIDI messages. The four bend sensors send continuous MIDI control messages, 1 to 4 respectively. Bending the tube in different locations changes the control value corresponding to the sensor in that location. The

pushbutton sends a MIDI note when pressed.
Data from the Sonic Banana are sent to a computer running a Max/Msp patch and then processed.

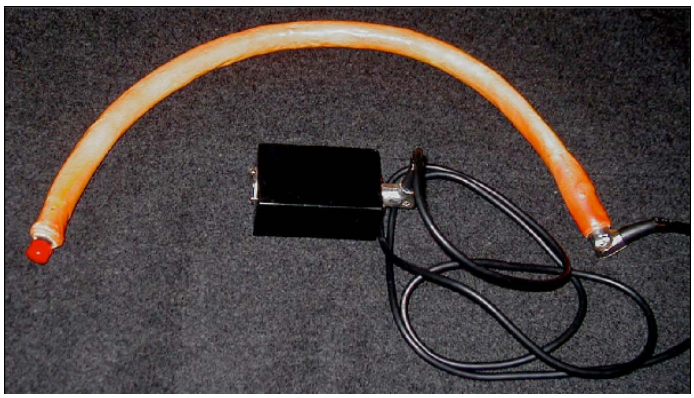


Figure 4.13 : *An image of the Sonic Banana.*

Similar to the previous examples, also Singer was experiments with several mappings and variety of algorithmic improvisational instruments. The author implements and describes [Singer 2003] two main performance patches. One is an arpeggiator and the other is a physical model of an harmonica.
This is highlighting that those kind of interfaces are open to many possibilities and seems very appealing for experimenting with mapping and dynamic control sound synthesis algorithms.

4.5 Zstretch

Zstretch (Fig. 4.14) is prototype for a textile music controller that supports expressive haptic interaction with stretchable fabric. It was developed in 2007 by Angela Chang [Chang and Ishii 2007]. This interface takes advantage of the fabric's topology and constrains to enable proportional control of musical parameters.
The intention of the author was to demonstrates how the use of a simple sensing mechanisms can support routine tactile interactions, such as with a piece of fabric. Zstretch tries also to exploit the physical properties of fabric for altering musical events and parameters.

For Chang and Ishii the action of stretching a piece of fabric can provide rich and dynamic expression, by allowing a wider range of interactions such as grasping, pulling, scrunching, twisting and stretching [Chang and Ishii 2007].

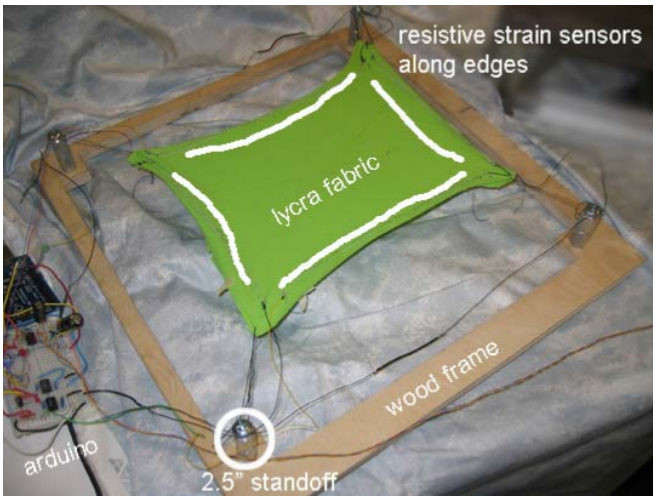


Figure 4.14 : *An illustration of the ZStretch prototype.*

The Zstretch controller is made out of a piece of lycra fabric mounted on a portable wooden frame, and connected through four elastic threads on each corner. This configuration allows the user to access and manipulate the edges of the surface of the fabric. Different gestures are sensed through four resistive strain sensors stitched along the edges of the fabric. These sensors are then connected through a voltage divider to an Arduino board, and mapped to a patch made in Pure Data. Two sensors are controlling the volume and the pitch of a sound sample, and the other two are doing the same but for another sample. When the stretch increase the pitch or the volume of the sound sample increase. One of the main problems encountered by the author was the fragility of the whole system [Chang and Ishii 2007]. Especially the stitches and the wires connected to the microcontroller tended to shear off. After a few weeks of use the author reports that the fabric started to tear, the strain sensors are drifting or time, and the entire interfaces need a constant maintenance and fixations. This represents a common problem within those kind of interfaces.

4.6 Clay Tone

Clay Tone [Watanabe et al. 2007] is a playful tangible interface that uses clay as the main input material for real-time musical creation (Fig. 4.15). This work represents one of the few examples that employs physical malleable materials such as clay or plasticine in the context of Tangible Musical Interfaces.

With this interface the user physically interacts with bodies of clay, where the shapes freely deformable lumps, and the user's physical movements against them, can affect the manner in which sounds are generated from the system.

Clay Tone senses color, shape, area and force of kneading to control the mode of interaction, tone and pitch. As we can see in Fig. 4.15, it uses pressure sensors and a small video camera to sense the body interaction of clay kneading. Pre recorded audio files are used, and they can be modified by using different pieces of clay of various colors.

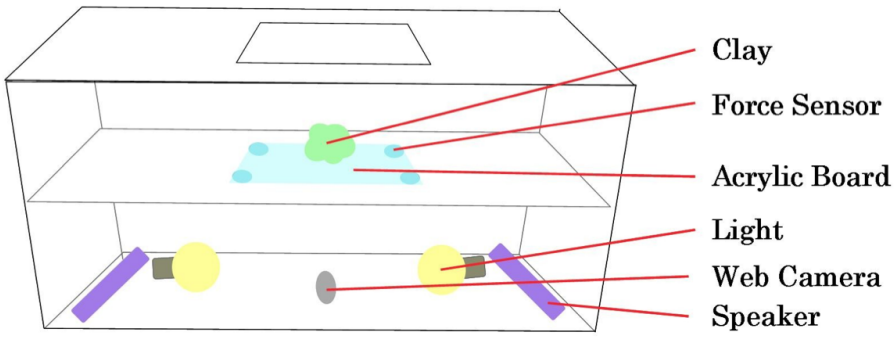


Figure 4.15 : *A representation of the Clay Tone interface.*

For instance, when the user plays with a piece of green clay, the speed of kneading influences the sound. The faster the user squeezes, the higher the tone gets. When the user spreads a piece purple clay changes the pitch. Big area of clay results in high pitch, where small clay area results in low pitch. A different function is assigned to blue clay that changes rhythms. The rhythmic patterns depend on where the user kneads clay on the board.

4.7 The Sponge



Figure 4.16 : *Martin Marier performing with his Sponge.*

Similar to the previous example, the Sponge (Fig. 4.16) can be described as a computational augmented material for musical expression. This interface, created by the canadian composer Martin Marier in 2010, is a piece of foam equipped with different sensors which can detect when it is squeezed, twisted or shaken [Marier 2010]. The Sponge is used by the author in live performances to control different sound synthesis algorithms and digital processing.

According to the Marier, the main motivation behind the creation of this interface was to regain "*the the natural gesture-sound link that is inherent to the practice of playing an acoustic instrument* […] *the playful aspect of it, and the interaction with the audience that it allows*" [Marier, 2010].

This need of getting physically engaged with digital music drove him to the exploration of the properties of malleable materials such as foam.

The deformations and gestures applied on the foam are sensed through an array of two force sensing resistors. Also, the force applied on to the material is sensed with a three axis accelerometer. Seven small buttons are also implemented. Then the data coming from these sensors are connected to an Arduino Fio board and sent to a computer through an Xbee module. The different gestures performed by the user are mapped to different physical models of musical instruments implemented by the author in SuperCollider[28].

Marier describes the mapping strategies developed for a composition made for the Sponge called *Cymbale*, that is divided in two main layers [Marier 2010]. The first layer combines data from multiple sensors to extract torsion, flexion, vibration and squeeze. The second is a many-to-many mapping which using a 2D preset interpolation system. If for the author this complex

28 http://supercollider.sourceforge.net/

mapping is more expressive, he experiments also with a one-to-one mapping, and observes that it keeps the expressivity but also its establish a clear gesture-sound link. But, according to Marier, this will require a more evolved playing technique [Marier 2010]. A documentation of the entire project and a tutorial for building The Sponge is available on Marier's website[29].
I have anyway to notice that a similar interface was prototyped by Zadel et al. [2004] for exploring interface physicality and intertial sensing by using a piece of foam as musical controller.

4.8 EchoFoam

The EchoFoam (Fig. 4.17) is malleable foam controller designed with the aim of enabling nuanced and intuitive musical control [Kiefer 2010]. The device was designed by Chris Kiefer in 2010 and improved through different iterations and applied as an interface for disabled children [Grierson and Kiefer 2013].

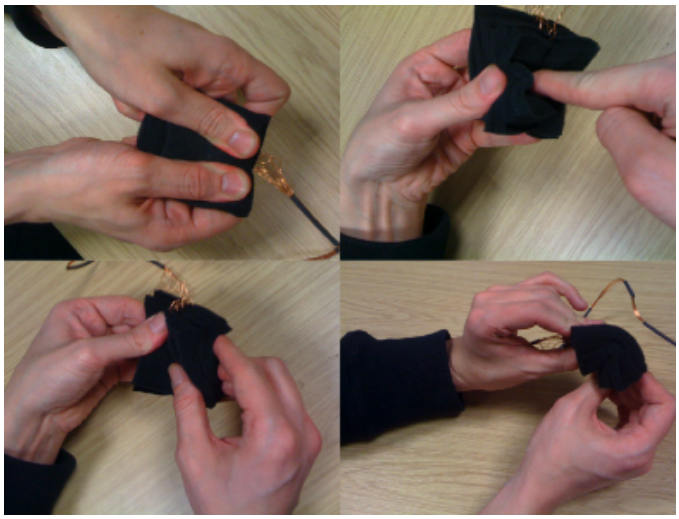


Figure 4.17 : *The foam input device developed by Chris Kiefer*.

EchoFoam is constructed from conductive foam, and exploits the properties of this material, such as changes electrical resistance when deformed. Those properties are employed in order to

29 http://www.martinmarier.com/

track the shape of the foam. Rather then using separate sensors (like the previous examples), this interface is made from one continuos piece of foam, with embedded contact wires that are measuring the resistance between different points.
The interface is constructed from foam squares that are glued together into a cube. Contact wires are placed in the top and bottom squares, in the four corners and in the centre. These two sets of wires are connected to two separate 74HC4051 multiplexer chips on a circuit board controller by an Arduino. As the author explains [Kiefer 2010] these two sets are divided into live and sensor wires; a program on the Arduino sequences the multiplexers so that a single wire is made live on one side of the foam while the five wires on the other side are scanned to measure resistance between these contacts and the live point. In this way, ten contacts can be used to take twenty-five resistance readings from the foam.
This system is tightly coupled with the use of Echo State Networks (ESNs), a class of recurrent Neural Networks, used as mapping engines to create control streams from the sensor data. Given the interdependent nature of the output of the foam controller, ESNs are used for reduce the dimension of the input data for matching the number of parameter of the synthesis engine. According to Kiefer [2007] the mapping produced after the training of the network is arbitrary.
This work represents an interesting attempt of using the properties of malleable materials, especially together with the use of Neural Networks for performing the mapping. This represents an interesting solution, mainly because it tries to create a sort of malleable mapping that is coupled together with the properties of the foam.

4.9 The music ball project

The *Music Ball Project* (Fig. 4.18) represents an attempt of developing musical interfaces that are "*inexpensive, simple, fun, human-oriented and with no corners*" [Jensenius and Voldsund 2012]. Since 2005 Alexander Refsum Jensenius and Arve Voldsund have created various interfaces based on the ball shape/metaphor.



Figure 4.18 : *Two squeezable interfaces from the Music Ball Project.*

The first one is a Microphone-based music ball, where a hollow toy ball was stuffed with materials having different sonic qualities (eg. paper, peas, steel wool, fabrics). Then a contact microphone is placed in the middle of the ball, and the sound is picked-up when the ball is squeezed. The second type is the Sensor-based music balls. As the title suggests, different types of balls are equipped with two types of sensors, according on which gesture - sound relation is wanted. Various flex or pressure sensors are placed inside a ball for detecting squeeze and pressure, in another one an accelerometer is integrated for a shaking-types of interaction.
According to the authors the microphone-based ball seems more expressive, conversely the sensors-based ones are more responsive and intuitive [Jensenius and Voldsund 2012].
They have also combined these two versions into an "Electroacoustic Music Ball", which consists in a small hardshell buoy equipped with one contact microphone and two pressure sensors fastened to the surface.
The Music Ball Project represents a collection of different simple interfaces for the exploration of natural affordances in music expression. The authors highlight the playfulness that emerge from these ball-interfaces that can also be thrown, bounced, squeezed and shaken [Jensenius and Voldsund 2012].

4.10 The Spine

The Spine [Hattwik et al. 2014] is a “prosthetic” digital musical instrument developed in 2014 for the dance project Les Gestes (Fig. 4.19). According to the authors they "*endeavoured to design new instruments for dancers extrapolating from the T-Stick used in the performance Duo pour un violoncelle et un danseur. Starting with foam prototypes, the Spine and its companion instruments the Rib and the Visor were developed iteratively using participatory design through frequent workshops, parallel problem solving, and digital fabrication methods. The current models are fabricated from laser-cut transparent acrylic, transparent PVC tubing, and PETg rods. The entire structure is assembled using interference fitting rather than any glues or fasteners*"[Hattwik et al. 2014] .
The Spine tracks and reports it's orientation and shape deformation in real-time, accomplished through the use of inertial and magnetic-field sensing at each end of the structure. Though this is not a malleable interface, “The Spine” represents an interesting interface for sensing complex deformations of a structure coupled with the human body.

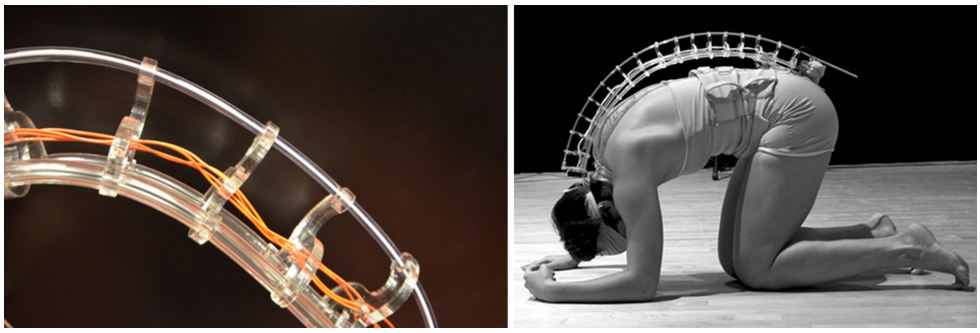


Figure 4.19 : The Spine.

Summary

Through this chapter I discussed the main reasons that are making the framework of TUIs very successful when applied to musical interaction. Especially I tried to explore how several tangible interfaces addressed positively and successfully some of the open issues in the design of musical interfaces. Those issues are including multi-dimensional control, gesture to sound mapping, expression and even collaboration and haptic feedback.
But it's not only a matter of solving a problem or finding the ultimate design: the idea itself of Tangible User Interfaces adds and opens some new possibilities in music interface design, and in

electronic and digital music practice, oriented to live performances.

Some of the projects presented in this chapter have been very influential and even commercially successful. This what Jordà defined as a new wave of "*tangible music*" [Jordà 2008].

Drawing from the conclusions discussed in Chapter 3, I tried to explore how especially the contemporary attention on direct interaction with highly manipulable artifacts, shape-changing interfaces and computational materials can add to musical expression. I define this sub category as Malleable Tangible Interfaces.

This is not an entirely new branch of research, since we can recognize different projects that have been exploring malleability as a key feature in interfaces for music expression.

Due to their intrinsic properties malleable materials seems to be appealing for musicians and performers. As we observed those kind of interfaces are embodying better then hard tangibles the complexity of contemporary digital sound models. They are also enhancing expressivity better because Malleable Tangible Interfaces are designed for accepting actions such as pressing, bending, squeezing, stretching and transforming them into expressive and complex musical gestures.

By exploring the physical qualities inherent in a particular material, producing a musical event is more a question of getting engaged with a material. Most of the projects presented as Malleable Tangible Musical Interfaces tried (at least as an aspiration) to overcome the limitations of mapping, through moving from a 'one to one' relation between gestures and sound to exploration and manipulation.

Then, if we have on one hand a material capable of accepting arbitrary inputs, deformations and forces, and on the other a complex sound model, expression is a result from a relation between the physical actions of the performer and the characteristics of the material: the material itself became the interface. It's interesting also to recall that *malleability* was related by Segawa [1999] to the ideas of *sensitivity*, *sensibility* and *intuition*. Those terms are not belonging to music making but related to human feelings and actions. Probably this is what *malleability* can add and reinforce in musical interaction and interface design.

Chapter 1 had already introduced the idea of *sound sculpting*, which is something different from controlling sound, because it implies a set of actions traditionally related with the practice and idea of artistic expression through a physical media.

If we consider this point we can see which are the unexplored potentials of Malleable Tangible Musical Interfaces. But, how can we design interfaces that embodies all of these features ?

In the next chapter I will go to present my project SculpTon, which tries to elaborate these issues in a functional Malleable Tangible Interface for Musical Expression.

Chapter 5

SculpTon : a Malleable Tangible Interface for Sound Sculpting

This chapter describes the background and the development of SculpTon, a malleable tangible interface for sound sculpting. Within this project I will try to delineate a possible application of the idea of "Radical Atoms" in the context of New Interfaces for Musical Expression.
The entire process behind the implementation of SculpTon will be described in details, either from a conceptual and technical point of view. Special attention will be given to the sensing technique developed for SculpTon and the main artistic, methodological and technical references will be discussed.
Then, the discussion will be followed by a detailed description and evaluation of the interface through different live performances and presentations. Then, some qualities and limitations will be analyzed.

1. Brief description

SculpTon is a malleable tangible interface for music expression oriented to live performance (Fig. 5.1) and it embodies a digital model of the human voice.

Within this project I introduce a framework for exploring the question of expression in musical interfaces (see Chapter 2) by looking at this problem through the lens of materiality in interface design and the idea of "Digital clay" (see Chapter 3).

From a design point of view the goal was to build a tangible interface with malleable organic characteristics, capable to keep track of subtle and detailed physical manipulations, which combine many input attributes with multidimensional control.

SculpTon does not mimic any existing traditional acoustic or electronic instrument, but it has a peculiar and distinctive feel, characterized by its organic appearance and handling.

Due the the particular coupling of its physical appearance, affordances and sound, SculpTon is a quite unique interface. SculpTon is inspired by and incorporates some ideas from the agenda of TUIs and with a special emphasis on computational materials and embodied interactions.

The system's principles are self revealing, and users could quickly and easily make sense of the interface using only their experiences of the physical world, for example manipulative tasks.

SculpTon consists of a physical interface, a stompbox and a software. The physical controller is composed of an array of sensors (analog, digital and acoustic), 4 LED for visual feedback embedded in a malleable structure covered with an opaque latex hull. The stompbox represents an useful bridge between the physical interface and the software. The final version is a 30x30x20 cm MDF box that contains an Arduino Mega board and a low-power audio amplifier.

The software was developed with Pure Data, and it is managing different routines, data processing, mapping and sound synthesis, which is currently running on a Mac OSX Macbook Pro.

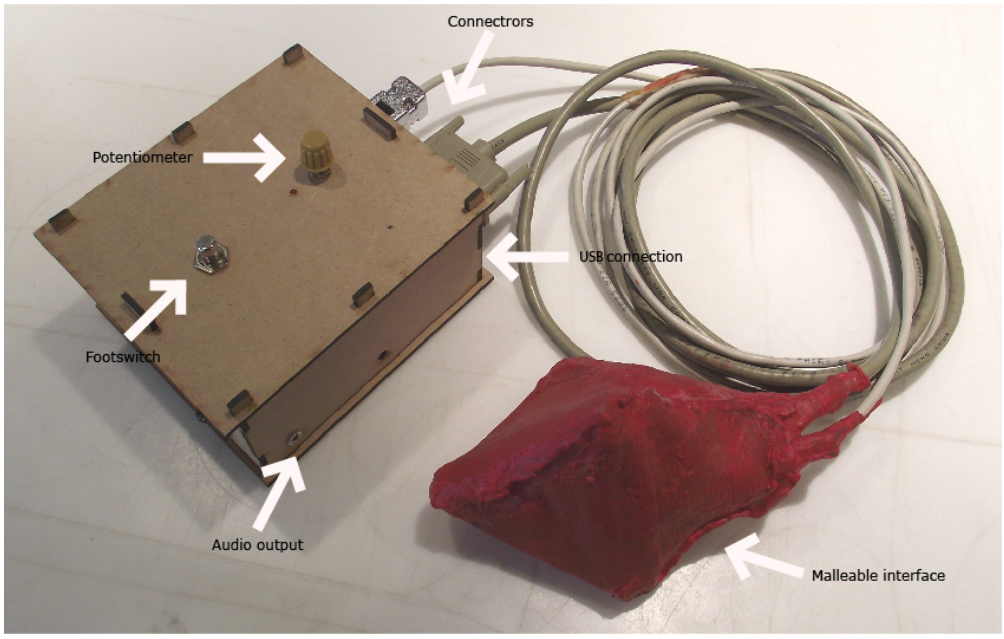


Figure 5.1: *An image of SculpTon, the malleable controller and the stompbox.*

2. Background and motivations

The main motivation of the project came from the idea that sculpting, such as the physical manipulation gestures used for changing object shape can be used as a powerful metaphor for designing tangible interfaces oriented to sound interaction.

As already mentioned in Chapter 1, within sculpting several techniques that involves the use of both hands -often without any additional tool- for modeling physical matter have been developed. If we think about modeling clay we can easily see that this action is characterized by touch manipulation and force feedback. The link between the process of sculpting and real-time sound production is not a new idea in contemporary music, it was already being applied and used for imagine and design musical instruments and digital musical systems (see Chapter 1).

But, still it is a simple and unarticulated metaphor that generally connects human gestures to music expression: by modifying the physical characteristics of a material / interface ones can modify the sound.

In this first section I will introduce four projects that were exploring (either technically and conceptually) the idea of *sound sculpting*. The first three can be classified in the area of gestural interfaces for musical expression, because they are relating hands' movements, manipulative gestures, malleable matter and sound interaction to the idea of sculpting.
In contrast, the last one is an installation that represents a more broad reflexion on the practice and theory of sculpting in the context of media art and digital technologies.

2.1 Manipulating sound through virtual sculpting

"Sound Sculpting" (Fig. 5.2) was a prototype interface for sound design developed in 1998 by Axel G. E. Mulder and Sidney Fels [Mulder and Fels 1998a] [Mulder and Fels 1998b].
The authors have implemented a system where the user can create, edit or perform sounds by changing parameters, such as position, orientation and shape of a virtual object, used as as an input device. As a virtual sculpture, the user can perceive this 'material' only through its visual and acoustic representation. Although sculpting in the physical world is most effective with touch and force feedback, the authors assumed that these forms of feedback could be replaced -together with some compromises- with an acoustic and visual feedback.

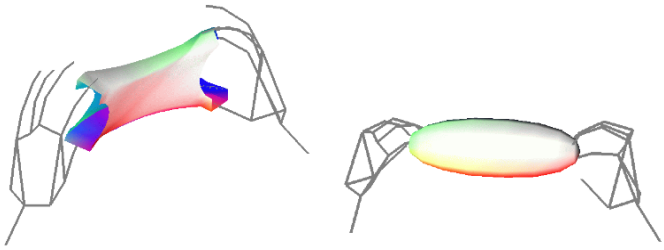


Figure 5.2: *Mulder and Fels "Sound Sculpting". The hands are shaping a sound-object.*

With this interface the user can literally 'sculpts' sound using a virtual sculpting interface, which is composed of a pair of Virtual Technologies CyberGloves, coupled together with a 6DOF motion sensor (Pollhemus Fastrak). These input devices are used to compute human movement

and virtual object features, and then connected to a program written in Max/FTS, which is responsible of the mapping and the real-time sound synthesis (Fig. 5.3).

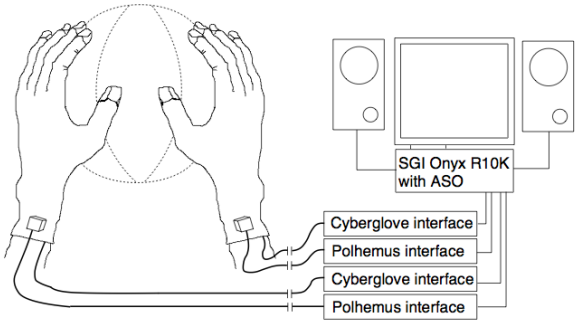


Figure 5.3: *A sketch of the "Sound Sculpting" interface*.

One of the most interesting aspects of this project is the exploration of physical manipulation gestures for multidimensional control of real-time sound synthesis, especially when the shape, position and orientation of the hands are changing simultaneously. Mulder and Fels [1998a] were suggesting that, instead of computing or analyzing any abstract symbolic representation of the gestures produced by the user, it's better to focus on the continuous changes represented by those gestures.

According to the authors this possibility of exploiting the continuous changes in materials caused by the continuous movement of the hands, is what connects gestures and object manipulation.

This is not only the main motivation behind the Mulder and Fels idea of *sound sculpting*, but we can devise two other crucial elements:.

- The first is that "*human hand is well-suited for multidimensional control due to its detailed articulation* (…) *most gestural interfaces, even those that use a dataglove-like interface do not fully exploit this capability due to a lack of understanding of the way humans produce their gestures as well as the lack of understanding what meaning can be inferred from these gestures*" [Mulder and Fels 1998b]. The authors highlighted that some previous works about hand gestures as a controller have mainly centered on formal gesture recognition. For instance, in [Fels and Hinton 1993] was noticed that since humans do not reproduce

their gestures very precisely, natural gesture recognition is rarely sufficiently accurate. Classification errors and segmentation ambiguity cause many of the problems connected with gesture recognition. Only when gestures are produced according to a well-defined formalisms, such as in sign language, automatic recognition will reach an acceptable precision and accuracy. However, for the authors a gesture formalism will require tedious learning by the user.

- The second motivation is concerning the embodiment of a sound metaphor in a virtual object for facilitating the comprehension of the mapping, especially in a system where haptic feedback is absent. According to Fels [2004] the use of metaphors can allows the player to hold a mental model of gesture space; a mental model constrains gestures to a meaningful space, if it is sufficiently strong. In fact, if the match between the metaphor and the gesture-sound relation is clear, this approach seems to be very successful. On the other hand, when the parameters of the sound are not matching those of the object, the entire metaphor just broke up. Again, for Fels [2004] the use of metaphors can also facilitate the development of intimacy in the context of musical interfaces [Wessel and Wright 2002].

These two considerations are representing the basis for the design of a gesture to sound system based on the metaphor of sculpting. But, according to the authors, this can be done only by applying some pragmatics.
For this, Mulder and Fels [1998a] have restricted the metaphor to the consideration that manipulative tasks are involving changes in the position, orientation and shape of an object. Then, orientation and position manipulation are simple and do not involve any tools. For achieving this the authors have developed an analysis of the methods employed by humans to edit shape with their hands. Through this they have identified three different stereotypical methods.

- *Claying*: The shape of objects made of material with low stiffness, like clay, is often changed by placing the object on a supporting surface and applying forces with the fingers of both hands.

- *Carving*: The shape of objects made of material with medium stiffness, like many wood materials, are often changed by holding the object in one hand and applying forces to the object using, a tool like a knife or a file.

- *Chiseling*: The shape of objects made of material with high stiffness, like many stone materials, are often changed by placing the object on a supporting surface and applying forces to the object using a tool a chisel held in one hand and a hammer held in the other.

Those methods have been applied by the authors for the creation of two virtual objects for controlling the parameters of an FM synthesis: a thick rectangular sheet and an elliptical balloon. Sound parameters such as panning and reverberation were mapped to the virtual positions of these objects. Other FM synthesis parameters (such as flange amplitude, chorus depth, modulation index) were mapped to object shape properties such as length, width and curvature. According to the authors pitch and duration of notes represent two parameters that is difficult to map to free gestures, even if they are fixed, and preprogrammed in a MIDI sequence [Mulder and Fels 1998a].

As input gestures, also *claying* and *stretching* have been implemented in Sound Sculpting, but with some limitations. Fels noticed that "*Claying is a compelling metaphor for shape manipulation, but is not useful without tactile feedback. Stretching, however, allows the player's frame of reference to remain attached to the object. The lack of tactile feedback is circumvented at the expense of the ability to vary contact position. This result indicates that it is important to choose a metaphor that can be supported by the input and output interfaces. Claying should be revisited if freehand tactile feedback becomes technically feasible*" [Fels 2004].

As I said before, for the authors the idea of working with a metaphor is a good way for design an interface like this, but has also its own limitations. They tried to overcome the absence of a tactile and haptic feedback through several solutions (for instance by reducing complex actions to defined abstract actions, such as from claying to elasticity) and the use of a real-time video projection. Even if the use of a mental model provides to the user the mental constrains on what actions make sense musically, however "*even with the clear mental model, the sound space still was*

difficult to explore inhibiting the embodiment of the interface. Further, while not explicitly created for real-time performance, the same metaphor strengthening the intimacy with the device also helps an audience understand the relationship between control and sound" [Fels 2004].

2.2 Virtual Sculpture

Along with the work of Mulder and Fels, in 2004 Mark T. Marshall proposes a prototype of an interface called "Virtual Sculpture" that aims to address similar issues [Marshall 2004]. Even if this work is not conceived as an interface for sound manipulation (but for a general use in interactive multimedia systems) it extends the idea of a gestural controller for sculpting a virtual object. According to Marshall the main goal of his interface was the creation a gestural controller "*which allows two-handed input in the form of both linguistic gesture, where the user's interaction is in the form of description of the action to be performed, and physically-based manipulation gestures, where the user directly grasps and manipulates a virtual object*" [Marshall 2004].

This interface exhibits a lot similar features with the "Sound Sculpting" system, especially in the gesture acquisition, recognition, and the use of a visual feedback. Marshall has implemented custom made data glove for tracking the position and the orientation of the user's hands along with the movement of the fingers. Differently from "Sound Sculpting" this system uses a simplified form of object creation and manipulation. Instead of creating a specific virtual material, "Virtual Sculpture" make uses of a small number of geometric primitives, such as sphere, cylinder, cone, torus and rectangular box. Those objects are manipulated by simple axial transformations, which include scaling, rotation, and shearing. One of the interesting feature of "Virtual Sculpture" is that different primitives can be joined together to create a composite objects. In this case objects are created by moving the hand over an icon representing the object at the top left of the display, creating a grasping posture, and "dragging" onto the display in the appropriate position.

Once an object is on the screen it can be manipulated through a combination of physically-based manipulation and linguistic gestures. This configuration allows the user to explore

different form of gestures. The most interesting type of manipulation is the physically-based one "*where the user appears to act directly on the object*" [Marshall 2004]. For instance, to rotate the object the user places a hand over the object and makes a grasping posture to indicate "grabbing" the object. The user then rotates their hand which causes the object to rotate through the same angles.

This system was tested as a public installation, and Marshall noticed that "*performing manipulation of virtual objects using two-handed gesture is a very natural method of interaction for the user*" [Marshall 2004]. In particular scaling an object seems to prove the naturalness of this type of interaction.

Apart from the interaction, "Virtual Sculpture" is also sharing with the work of Mulder and Fels [1998a] [1998b], limitations and problems. The most evident is the lack of haptic and tactile feedback. Marshall [2004] reports that some users have complained about the lack of any "*real feeling*" when using the system. Especially, some of them suggests that a form of haptic feedback can be useful for indicating when the hand is over an object, and for giving the impression of grasping an object.

2.3 The Manual Input Sessions

On the same direction -even if not explicitly related to the idea of sculpting- was also "The Manual Input Sessions" (Fig. 5.4), a system for audiovisual performance developed in 2004 by Golan Levin and Zachary Lieberman [2005]. Inspired by the work of Mulder and Fels [1998a] [1998b], the two artists tried to explore similar issues such as the relation between hand gestures and sound, especially when a virtual object is manipulated by the user. Partially inspired from the famous "Videoplace" of Myron Krueger [Krueger 1991] , "The Manual Input Sessions" is composed of a combination of custom interactive software, analog overhead projectors and digital video projectors.

The analog and digital projectors are aligned such that their projections overlap. Above the overhead projectors a video camera connected to a computer vision system analyses the silhouettes of the performer's hands as they move across the glass tops of the projectors. The hand gestures are then analyzed by a custom software. In response, it generates synthetic graphics and sounds that are tightly coupled to the forms and movements of the performer's actions. The synthetic responses are co-projected over the shadows produced by the overhead projector to form an "*augmented-reality shadow play*" [Levin and Lieberman 2005].

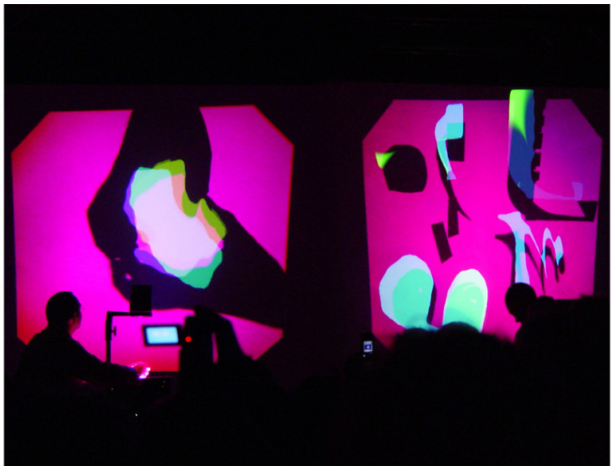


Figure 5.4: *Levin and Lieberman performing "The Manual Input Session".*

For the live performance the authors developed three different software instruments to use with this interface. Those instruments are using different types of mapping between gestures and sound. I'm going to introduce the first two.

The simplest instrument is called *NegDrop* and uses closed interior contours (i.e. holes or negative spaces) of the performer's hands, which are detected by a computer vision system and used as a visual representation of virtual sound-producing objects. When the performer breaks the contour of the hole by separating his fingers, the shape is released from his hand and falls downward as if pulled by gravity. When the virtual shape collides with the boundaries of the projection area, it bounces off the boundary and triggers the production of a MIDI sound whose properties are closely coupled to certain visual aspects of the dropped shape. For instance, the contour area is mapped to the pitch, the collision energy to the volume, the horizontal position to the stereo pan location and the compactness of the generated shape to the timbral brightness.

A second instrument called *InnerStamp* is also using negative contours but, instead of triggering

a sound event, the shape generated by user's hands creates a continuous drone. As long as the performer does not rupture the shape's contour, the sound can be continuously modified by changing various visual properties of the contour. Here the synthesized shape is coupled to an hybrid FM and granular synthesizer. The mapping is slightly different from *NegDrop*, except that a new variable -the amount of time since the hands departed- is mapped to the volume decay. A particular feature of this instrument is that when the performer 'releases' the shape (by opening the hands), the shape remains in the projection and plays back the 'recorded' manipulation. Those transformations replay endlessly, looping back-and-forth, until the user removes his hands from the projection, at which point the contour's sound and image gradually fades back.
This last module is probably the one that pursue the concept of *sound sculpting* as well as the one developed by Mulder and Fels. In the case of "The Manual Input Sessions" Levin and Lieberman are keeping the use of external sensing mechanisms for the detection of hands movement but they are less interested in a three dimensional representation since their visual result is flat and two dimensional. Another difference is that the virtual objects are generated in real-time from the shape of the user's hands.

2.4 Invisible Architecture

Outside from the specif area of gestural controllers and musical interfaces, Marcos Novak has been exploring the idea of manipulation of virtual sculptures through an installation called "Invisible Architecture" (Fig. 5.5). Novak is an architect and media artists, as well as the theoretician of "liquid architecture" or better known as "*the synthetic architecture in the cyberspace*" [Novak 1992]. Since the beginning of the 1990s he was one of the main investigators of the relationships between the virtual and the physical world in the context of generative architecture [Novak 2001].
This intsallation was presented in 2004 at La Biennale di Venezia and, according, to the artist it allows us to "*envision a time in the not-too distant future in which it will be feasible to build architectural form more complex than that of now* (…) t*he proposition of the invisible as the newest materials allows us to envision how virtuality could inhabit in the real city. This installation attempts*

to answer that question by peering into darkness if higher dimensions and the realm beyond our direct perceptions." [30] .

"Invisible Architecture" is composed of different interrelated elements of virtual and physical artifacts together with visible and invisible objects, which can be explored in different ways [Metamorph 2004].

At the top of the system there is core algorithms that generates: a) a series of virtual forms that are displayed on a large video display, accompanied by a b) interactive, navigable, spatialized audio controlled by a c) series of five small and two large invisible sculptures, actings as d) invisible interface to virtuality and placed in direct juxtaposition with e) four suspended 3D printed forms derived from the projections of f) a single four dimensional form created by extruding one of the virtual forms into a fourth spatial dimension.

Even if this work seems not so connected to the previous ones, it explicits address some conceptual topics behind the idea of virtual sculpture, and the relation between physical and virtual through objects that are generated and are even influencing each others.

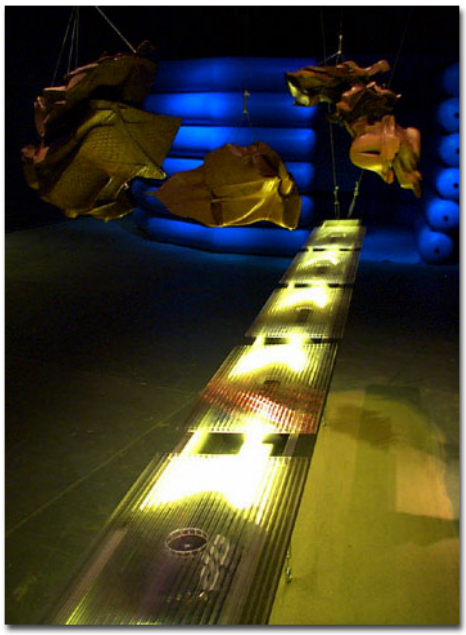


Figure 5.5: *An image of the installation "Invisible Architecture" at the Venice Biennale of Architecture (2004).*

30 http://www.kajima.co.jp/gallery/chronopolis/en/min/min02.html

2.5 Sculpting Sound

The works presented above are representing the conceptual and technical foundation of the idea of *sound sculpting*, and the starting point of my work SculpTon. Even if they are using virtual materials and objects as an interface between hand's gestures and sound, those projects are highlighting some important points that I tried to explore in my practice:

- human hands are very well suited for multidimensional control, that is what we are looking for in musical interfaces design;
- continuous and manipulative gestures do not belong to traditional musical instruments, even electronics;
- a well-designed material or artifact can allows the user to exploit these gestures;
- the key point is to establish a meaningful relation between gestures and modifications that their effects on sound;
- the choice of an appropriate sound model help the user to keep this relation.

Aside from those aspects, also some limitations are appearing:

- manipulative gestures seems to be not suitable for every sound model and backwards;
- the level of complexity of the sound model from one side, and of the hand's gestures on the other can lead to an high level of simplification, which is reducing the power of the whole concept of *sound sculpting;*
- this level of abstraction increases also for the lack of any tactile of haptic feedback.

Drawing from those considerations, I will start to introduce and describe my work SculpTon, which represents a possible bridge between the idea of *sound sculpting* and the vision of "Digital Clay" described in Chapter 3.

3. Previous work

Before exploring in details SculpTon, I will introduce some of my previous works developed at Interface Culture. These two projects "Poetry in Form of Movement" and "URSUPPE" are, in different ways, related to the work that I'm presenting in this dissertation.
The former one is an audio installation that explores the possible relations between sound poetry, gestures and space. The latter is a collaborative sound performance that uses raw edible materials (such as jelly, fruits and vegetables) as a collaborative electronic synthesizer.

3.1 Poetry in form of movement

"Poetry in form of movement" (Fig. 5.6) is an interactive sound installation developed by the author at Interface Culture in 2012.
In this installation visitors are invited to explore a virtual 'mine' of sounds and words to create a personal and intimate meaning and experience.
This system tried links orality and gestural performance, as an invisible and impalpable auditory interface for performing real-time sound poetry through body interaction [Leopoldseder et al. 2012].
This installation space consists of an empty area defined by four speakers displaced on the corners.
The movements and the position of the user is detected by a Microsoft Kinect camera[31] attached on the ceiling. The data coming from the camera are processed for detecting the position and

31 http://www.microsoft.com/en-us/kinectforwindows/

movements of body joints, known as 'skeleton'. This was made thanks to the OSCeleton[32] application, which is sending the position of each single joint as an OSC message to a custom made software made in Pure Data, for the real-time processing of the the sound. The whole software was running on a Mac OSX computer.

The sound space consists of an archive of prerecorded poetry that the users can modify and modulate through active participation with their body. Through the exploration of the different correspondences between body and space, the users are able to create their own new sound poetry compositions.

The installation must be experienced by a single person at time. When a visitor is entering the space of the installation his / her position is being recognized by the video sensor and a software assigns to him or her a specific piece of poetry.

An archive was build by using small samples of sound poetries publicly available and copyright free. Those includes pieces of Antonin Artaud, Vladimir Majakovski, Filippo T. Marinetti, Amiri Baraka, Augusto de Campos, Shuiji Terayama, and William Burroughs among the others. Additionally I includes some works from italian contemporary poets such as Lello Voce and Rosaria Lo Russo who gave me the right of using their recordings.



Figure 5.6: *An image of "Poetry in Form of Movement" at the Ars Electronica Festival 2012.*

Exhibitions

32 https://github.com/Sensebloom/OSCeleton

Center Eksperimentov Maribor - European Capital of Culture 2012, Maribor (SLO), 26.11 – 8.12.2012[33]

Tag der offenen Tür, Kunstuniversität Linz, Linz (AT), 12.11.2012.

Interface Cuisine, Ars Electronica Festival 2012, Linz (AT), 30.08 – 03.09.2012[34]

Media

DorfTV (AT), 04.09.2012 (Tv show, interview)[35]

Radio Fro (AT), 02.09.2012 (Radio show, interview)[36]

Best Of Ars Electronica, Fm4 (AT), 01.09.2012 (Featured)[37]

Wir scheißen uns ein Alphabet, Fm4 (AT), 01.09.2012 (Review)[38]

3.2 URSUPPE

"URSUPPE "(Fig. 5.7) is a sound performance that involves jelly made out of the seaweed "Agar agar", fruits, vegetables and hand-made analog oscillators and sound effects.

This project started in 2013 together with Davide Bevilacqua during the "Sound Studio" workshop conducted by Michael Schweiger. The main concept behind "URSUPPE" (in english, primordial soup) regards the possibility of getting engaged with an electronic synthesizer through the use of organic and edible materials. The title is also an ironic comment to the improvised electronic musical performances of the so-called 'noise music', which is very often described in a negative way, as a "soup of sound". It also refers to a performance called "Zuppa" (in english, Soup) of the group MEV – Musica Elettronica Viva from 1968, which involves the

33 http://www.napovednik.com/dogodek230397_maribor_2012_hisa_znanosti_center_eksperimentov
34 http://www.aec.at/thebigpicture/en/2012/08/08/interface-cultures-interface-cultures/
35 http://www.dorftv.at/video/5169?page=6
36 http://www.fro.at/article.php?id=5238
37 http://fm4.orf.at/stories/1704153/
38 http://fm4.orf.at/stories/1704155/

audience in a collective improvisation [Bernstein 2008].



Figure 5.7: p*erforming "URSUPPE" at MNAC-National Museum of Contemporary Art in Bucharest (RO).*

In the case of "URSUPPE" the use of edible materials is allowing every person – from children to adults – to menage a complex system (such as a modular synthesizer) through the manipulation of everyday elements.

When is cooked into jelly "Agar Agar" creates a semi-solid structure of proteins which can contain different substances that might give to the material particular characteristics. In this case, the salinity allows the flow of electricity. The resistance of the jelly modulates the oscillators and the sound produced by the latter is injected back into the mold. This create a feedback loop that is chemically modifying the material and its properties. These changes will then affect the way the electricity flows through the materials, creating an unstable and self-influencing process. In "URSUPPE" the performers are shaping a network of relations by a continuos modification of the flow of energy. The role of the musicians it's activating some electro-chemical process and boil the 'soup': corrosion, oxidation are phenomena characterized also by a strong smell and peculiar visual appearance. Something will emerge, like in a small universe. A physical, auditory and visual soup. Also the audience can participate and contribute at the creation of a more complex soup, a social soup.

"URSUPPE" was development through three main stages. The first one was a broad and empirical exploration of the possibilities of our idea. We experimented with different electronic

circuits and compositions of jelly and organic materials such as fruits (lemons, oranges) and vegetables (cucumbers, potatoes). In the second stage of the development we tried to develop further the idea of a modular organic synthesizer by casting the electronic circuits into a jelly like material.

As first possibility we tried transparent silicone. Each electronic circuit was placed inside a mold and covered with silicone. One of the most interesting features of this new configuration was possibility of incorporating a form of visual feedback with some LEDs. Since the silicone is translucent, the light produced by the LEDs can been diffused through the whole artifact.

Each module was independent, and equipped with audio input and output, probe connections, battery holder, and an on/off switch.

Based from this version we tried to make the process easily reproducible. After a brief research on different possibilities we replaced silicon with transparent epoxy resin. If this material is more expensive, it requires less effort for being injected in a mold and less time for drying off.

Due to the high transparency of the material, we worked more on the appearance of the circuits. Then we developed some molds designed with a CAD software and 3d printed.

One of the last feature that we add, was a video projection generated by the resistance produced by the 'soup' of edible materials. The image recorded by the videocamera was processed with a digital video mixer that was modified in order to substitute the sliders that are controlling different effects (ie. black and white, color mixing, equalization) with some additional probes connected to jelly, fruits and vegetables.

Performances and presentations

roBOTKidz, MAMBO, Bologna (IT), 5.10.2014[39]

roBOT Festival, Bologna (IT), 1-5.10.2014[40]

10 Years of Interface Cultures, Ars Electronica Festival, Linz (AT), 4-8.09.2014[41]

Sónar+D, Sónar Festival, Barcelona (SP), 12-14.06.2014[42]

39 http://www.robotfestival.it/2014/ita/news/100/robot-kids-.html
40 http://www.robotfestival.it/2014/ita/call4robot/19/alberto-boem-davide-bevilacqua.html
41 http://www.aec.at/c/en/interface-cultures/
42 http://sonar.es/en/2014/prg/sm/kunstuniversit%C3%A4t-linz-live!_146

MNAC - Museum of Contemporary Art, Bucharest (RO), 7.03.2014[43]

The Art of Vernissage, bb15, Linz (AT), 20.12.2013[44]

Rother Krebs, Linz (AT), 25.05.2013

The complete development of the project was documented with audio, video and photographic material, and its available on a dedicated website[45].

4. Description of the project

The starting point of SculpTon was the idea of creating a continuous tangible interface for musical interaction in the form of a three dimensional object, which represents a sort of bridge between the digital and the physical world.

This is made through a personal application of the method that in sound design is known as "physical modeling", such as the "CORDIS-ANIMA" system developed by Cadoz et al. [1993] or the PMPD developed by [Henry 2004] . This technique consists in the creation of a virtual dynamic structure with some physical characteristics that can be modified, moved and distorted by the user in order to generate sound. Already Cadoz [2002] has proposed to consider physical modeling as a metaphor for musical creation.

One of the aims of SculpTon was trying to materialize this idea in a playable musical interface oriented to live performance. We can describe SculpTon as malleable tangible interface that combines a deformable input surface and an embodied sound model. This interface is suitable for a whole-hand interaction that combines many attributes of conventional touch interfaces (such as pressure sensitivity) and new attributes like whole point interaction and multidimensional control. SculpTon offers also a passive haptic feedback that is one of the main characteristic of sculpting. As I described in the previous chapters, sculpting is an interesting reference frame for designing touch interaction for musical expression.

43 https://vimeo.com/90572896

44 http://www.ufg.ac.at/Newsdetail.1899+M51a8014d1a5.0.html?&tx_ttnews[pS]=1409433819

45 http://ursuppe-project.tumblr.com/

In this section I'm going to introduce the main topics behind the implementation of the interface.

4.1 Interaction

Within this framework I propose to use the idea of *sound sculpting* and *malleability* as the most expressive and promising metaphors for the design of new dynamic tangible musical interfaces. The vision of "Digital Clay" [Ishii et al. 2012] together with some existing examples of musical interfaces such as the "Squeezables" [Weinberg and Gan 2001] or "The Sponge" [Marier 2010], are attesting that this is not only a vision, but something already attempted by several researchers.

If we simply compare the use of a single wooden block and a piece of plasticine, it is simple to observe that the human hand can transfer and reinforce the expressiveness through more degrees of freedom comparing a malleable with a solid artifact. Especially those kind of surfaces are more suitable for a whole-hand interaction that involves both hands at the same time. With the term that Mulder and Fels [1998a] [1998b] defined as *claying* I refer to an action that transfer the bodily forces onto deformable matter or objects for modifying their shape. The idea of sculpting (going from a starting shape to another physical state) is the central concept that I employed for achieving my musical objectives.

4.2 Characteristics of the interface

The challenge of this work is to create an object equipped with internal sensors, which should allow a user or musician to:

• hold, grasp and manipulate the object with both hands and fingers from each side (top, bottom, laterals);

• apply forces, such as pressure, to allow squeezing, stretching and other deformations;

• stand - alone usage or within the constraints of other interactive surfaces or artifacts.

The interaction with the object must be intuitively improved by the dynamic binding to a creative and musical process. Every force and action applied to the object is reflected in real-time to the digital sound, which is synthesized through a virtual structure.

4.3 Object design

The idea of *sculpting sound* in real time through *sculpting* of a malleable object, not only requires research in appropriate technology and materials, but also the development of mapping strategies between an organic control interface and its sonic expression.
In Chapter 2 I introduced the approach that some musicians such as Mumma [1967], Tudor [Kuivila 2004], and Lucier [Lucier 1998] used to compose their music by designing their own instruments, which can be synthesized in the suggestion of Cook [2001] "*make a piece not an instrument*". In contrast with another relevant approach in musical interfaces that devoted to the creation of all-purpose instruments, the one proposed here is trying to embody the musical composition itself within the instrument physical characteristics. This represents one the most interesting approaches, especially if we are looking through the lenses of tangible interaction, and the relation between bits and atoms proposed by Ishii and Ullmer [2002]. In a similar way Mulder and Fels [1998a] [1998b] have been underlying the importance of linking the qualities of a material to a sound model.
For this work I designed a structure that involves the best possible precision of movement, while the physical design should also be easy to implement, build and expand. In that case the modularity of the different elements became an important issue, because the sound expression is based on the actual object structure. The challenge of SculpTon was to link the physical and the digital domain through a set of interdependent relations defined by this design space. The most

important approach to the problem was to define the internal structure and the external shape of that object.

4.3.1 Modularity

Modularity is a key concept for the structure and technical development of the malleable object. This idea not only embraces the structural design but also how can embody and connect digital elements within physical components. The "Triangles" by Gorbet and Orth [Gorbet et al. 1998] represents an important reference in the area of tangible interfaces, along with building blocks as a metaphor for information management. Another fundamental component of this project is the internal structure, which has to be self-sustainable and interdependent. For this I decided to adopt the physical mass-spring paradigm, considering the modularity and the mechanics of the object. Thinking about toy buildings kits such as the popular Meccano we can observe that they are basically composed of joints (such as magnetic spheres) and some structural parts (such as small iron tubes) that serve as connections. We can easily replicate such a system and consider that the connecting spheres are masses and the structural tubes are springs. The masses detect the position and receive the force applied from the springs (which act as a link) and in turn they receive the position of the two masses and output the forces between both of them. Then, the malleable object can be therefore composed with a series of masses and springs which reflects all actions and forces applied a) to the entire volume b) or in a single vertex c) and the relation between them, since each part is linked to the others.

4.3.2 Sensing through structure

Drawing from those conclusions I employed a methodology that seeks not to separate the object that the user deforms and the sensors used to measure it. Instead of adding sensing to already existing objects I started by designing an object with its own sensing capabilities. This approach

is based on three basic relations that explain the main concept of interaction:

- external manipulation – internal behavior;
- physical excitation – relaxation;
- spatial actuation – temporal response.

Then, I developed a physical representation of the sonic interactions in the form of three dimensional object. Through a method defined as "*sensing through structure*" I implement a way of monitoring continuous and subtle changes in a physical artifact. With "*sensing through structure*", I refer to the concept introduced by LeClerc [1997] and later formalized by Slyper [2012] [Slyper et al. 2011], which represents an approach for designing and integrating sensors into soft objects. This is also an interesting and efficient way of capturing the configuration of an arbitrary shape, which allows the detection of different gestures on malleable physical materials.
According to Slyper this methodology uses the "*physical changes in topology of a deforming material to suggest structures for simple multi-location sensing. These atomic sensing structures make up a sensing vocabulary, to be used as building blocks when a sensor is designed*" [Slyper 2012].
Most of the common sensors for monitoring position, motion, twist, bend, stretch and pressure work well with hard devices and objects, but when we try to embed them in soft and malleable objects they presents a number of difficulties. Most of today's sensors are either rigidly encapsulated in metal or hard plastic, or built on a thin plastic backing. Flexible sensors can be bend and twist, but not shear and stretch. Hence they do not conform well to soft materials such as human skin, textiles, and foam. These sensors are also somewhat fragile and cannot be creased, which limits their application and reliability [Slyper et al. 2011].
Also, embedding hard sensors into soft objects alters the tactile, malleable properties of these objects, which is their key characteristic that distinguish them from traditional hard devices.

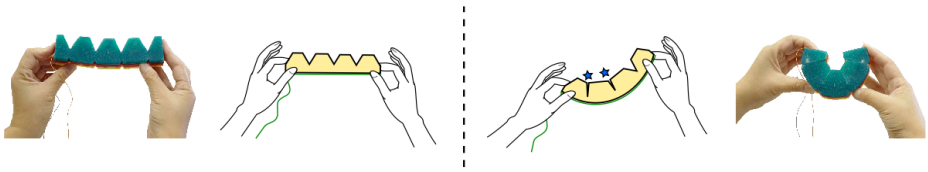


Figure 5.7: *A demonstration of the idea of "Sensing through structure"*.

The approach of "*sensing through structure*" (Fig. 5.7) is trying to solve those problems by focusing on the topological properties of materials, and most important, not to separate the object that the user deforms and the sensors used to measure it. Instead of adding sensing to pre-existing objects, Slyper et al. [2011] started by designing objects with "*their own sensing capabilities in mind*" [Slyper et al. 2011] In a broad sense, this approach can be described as "*form equals function*" [LeClerc et al. 2007] [Vertegaal and Poupyrev 2008] [Coelho et al. 2009], where "*the physical input, interactions, and device embodiment are designed in tandem, in harmony with its material construction*" [Slyper et al. 2011].

Some prototypes have been developed by Slyper et al. [2011] for demonstrating different applications and ways of "*sensing through structure*". They have been experimenting with some configurations of a bend, twist, pressure and stretch sensor with bases of both silicone and foam. For instance the authors have implement some "*multi-location sensors*" [Slyper et al. 2011] using an array of analogue magnetic distance sensors (whose values are transmitted over an I2C bus) in different configurations of normally open and close switches (Fig. 5.8).

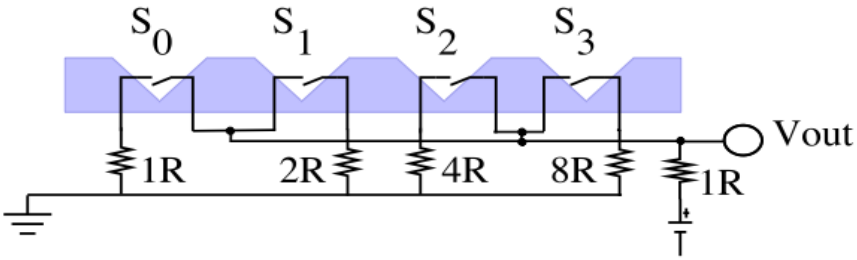


Figure 5.8: *A schematic of the soft silicone sensor by Slyper*.

Slyper et al. [2011] have explored different application scenarios in the area of interactive toys and personal electronics accessories, such as stuffed animals and mouth devices for kids.

The choice of an embedded system derive from its scope of operation, size and cost. An interface

characterized with a strong and specific relation between materials, gestures and sound -such as SculpTon- requires the development of a specific sensor arrangement.

4.4 Sound – Gesture

In section 3.2 I introduced the main characteristics of SculpTon and which input attributes and actions it should accept. Beside those elements, with SculpTon the users are required to employ their perceptual-motor skills. The use of perceptual motor skills is at the core of playing acoustic music where an embodied relationship with an instrument is fundamental to create music with it. In the context of music, Wanderley and Depalle [2004] propose multiparametric control as an efficient method that provides a more musical way of interacting with computers.
This was demonstrated by [Hunt and Wanderley 2002] through some user studies. Also they noticed that the complex mapping strategies are more engaging and even can enhance expressiveness better. SculpTon is embodying a digital model of the human voice, implemented through a formant synthesizer.
Within the concept of *sound sculpting* the coupling between the physical structure of the interface and the digital structure of the synthesis algorithms represents a key point for achieve a full embodiment of the interaction. The choice of using a formant synthesizer is first of all an artistic choice, justified through two relations:

- between the physical deformation of the human mouth and the physical deformation of an object;

- between the energy implied for producing speech and the physical energy, effort, and motor skills employed for playing the interface.

4.5 Interfaces for speech synthesis

Research in gestural control of speech and singings voice synthesis represent a small, but consistent, genre in musical interfaces. The history of artificial reproduction of speech started before the computer and the synthesizer with mechanical devices. It's interesting to noticed that, if mechanical electronic or digital, the idea of artificial speech was strongly linked to different objects, devices and interfaces.

In literature we can find since the Middle Ages the legendary "Brazen Heads", a sort of legendary automaton reputed to be able to answer to any question. This device was presented in the form of a human's head, casted in bronze or brass, which was invested by some magical and supernatural characteristics. In Miguel De Cervantes "Don Quixote" one of the character Don Antonio Moreno has a brazen head, that turns at the end to be a fake [Butler 1993].

Later, in the 18th Century started to emerge some of the first attempts of creating a mechanical artificial voice apparatus. In 1779, the Danish scientist Christian Kratzenstein built a model of the main five long vowels [aː], [eː], [iː], [oː] and [uː]. This experiment was followed by the bellow-operated "Speaking Machine" by Wolfgang Von Kempelen.

4.5.1 Speaking Machine

In his book "Mechanismus der menschlichen Sprache nebst Beschreibung einer sprechenden Maschine" (1791) [Pompino-Marschall 2005] Von Kempelen was presenting his "Speaking machine", his vision and a many sketches in order to divulge the device, the mechanism, and allowing other people to reconstruct it and make it more perfect (Fig. 5.9).

This machine was the first device that was allowing a single person to produce not only some speech sounds, but also whole words and even short sentences.

The machine (Fig. 5.10) uses a bellows to supply air to a reed which, in turn, excited a single, hand-varied resonator for producing voiced sounds. Consonants, including nasals, were simulated by four separate constricted passages, controlled by the fingers of the other hand.



Figure 5.9: *A replica of Kempelen's Speaking Machine, built 2007-09 at the Department of Phonetics, Saarland University, Saarbrücken (DE).*

According to Cater [1983] "*Von Kempelen had not been challenged with the replication of vowel sounds and, therefore, had aimed at a more complex traget of creating phrases and multiple word sounds. As with Kratzenstein's device, his system employed a bellows to supply air for a vibrating reed which served as the vocal cords. The resonators of the mouth were simulated by a flexible cylindrical leather tube which, through hand manipulation, could produced voiced sounds. The strange mechanical device also had openings to simulate the nasal resonators and two lever-operated whistle tubes to create the fricative sounds from the teeth and lips. The device was quite ingenious but required a considerable amount of skill and experience of the operator. As he "played" the device, he had to perform simultaneous actions not unlike those required to play the large musical organs of those times. Surprisingly enough, the talking machine had considerable human engineering built in so that a single operator could produce truly synthetic speech. As he sat beside the speaking machine with his right arm resting on the bellows, he controlled the nostril openings, the reed bypass pluynger, and the whistle levers with his right hand. His left hand was free to manipulate the leather speech tube to articulate the voiced sounds from the vibrating reed. According to von Kempelen, his machine produced 19 consonant sounds which could be understood*".

But, "*whether those sounds could be equally well understood by people other than von Kempelen might*

be questioned" [Cater 1983].

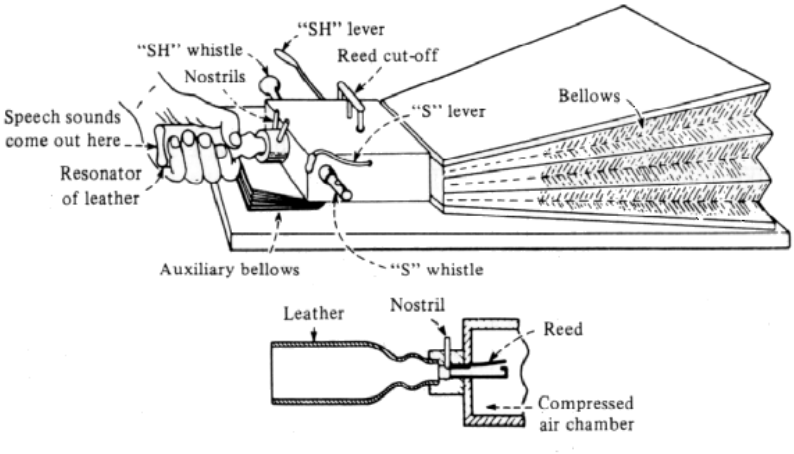


Figure 5.10: *A description of the improved version of the von Kempelen's speaking machine made by Wheatsone.*

The final version of von Kempelen's machine is preserved to this day. The only modification was made around 1830, when the famous english inventor Sir Charles Wheatstone made an improved version the original device [Flanagan 1965]. The original machine was kept at the K. K. Konservatorium für Musik in Vienna until 1906, before it was donated to the Deutsches Museum (von Meisterwerken der Naturwissenschaft und Technik) in Munich. In 2010 this machine was reissued for the exhibition "Roboter Träume" at the Kunsthalle Graz [Bucher Trantow 2010].

The "Speaking Machine" was conceived not only as a device for entertainment, but also as the main output of the von Kempelen's research about human speech production mechanism. He imagine also a therapeutic device, as an help for speechless people to communicate.

In the context of my investigation this device represents an interesting reference from different point points of views. This is a tangible device is embodying the human speech apparatus in a clear way through its mechanism. It can be operated by an user not only for producing some sounds, but also for adding an expressive layer to them.

Lately, this machine started to be discovered by artists and musicians and became an important source of inspiration for many installations and devices.

4.5.2 Some contemporary approaches

The device designed by Von Kempelen was for many decades an *unicum*. If we think about the "Voder" (developed by Homer Dudon in 1939), one of the earliest examples of electronic speech synthesis, and was operated through a keyboard like interface [Cater 1983]. With advent of portable synthesizer speech synthesis (in the form of formant synthesis) became accessible with devices such as the Moog series. But , people were 'talking' and 'singing' again with a keyboard.
Since the 1960s many artists and musicians started to use synthetic speech as a way of experimenting and composing in electronic music.
We can devise two main trends: one is from an engineering side, the other is from an artistic side.
If the former are concerned on the creation of the best interface for specific speech synthesis algorithms, the latter want to explore the relations between gestures and voice.
Perry Cook highlights some issues and problems in the creation of controllers and interfaces for computer voice models. From a technical point of view "*the sheer number of parameters that need to be controlled in an expressive voice model present daunting issues of sensors, bandwidth, systems and mapping*" [Cook 2005]. From a musical, linguistic and perceptual standpoint "*nearly all humans posses a voice, and have years of experience 'playing it'* (…) *further, humans closely attend to the voices of others, so we are extremely critical of synthesized voices*" [Cook 2005].
According to Cook as "*a wide variety of singing synthesis models and methods exist* (…) *there are remarkably few real-time controllers for these models*" [Cook 2005].
In this section I will not explore the history and techniques behind speech synthesis, but some works some previous works that are dealing with artificial voice through alternative interfaces will be introduced.

GloveTalk

The GloveTalk [Fels and Hinton 1992] [Fels and Hinton 1998] is one of the first attempts in the developedment of gestural interfaces for artificial speech in the area of music expression and

rehabilitation. This interface was developed in 1991 by Sidney Fels and Geoffrey Hinton.

The GloveTalk translates hand gestures to speech through an "*adaptive interface*" [Fels and Hinton 1992]. Hands gestures are mapped continuously to ten control parameters of a parallel formant synthesizer. The mapping allows the hand to act as an artificial vocal tract that produces speech in real- time. According to the authors "*this gives an unlimited vocabulary in addition to direct control of fundamental frequency and volume*" [Fels and Hinton 1998]. The GloveTalk interface went through a process of continuous development until 1998 with the GloveTalkII [Fels and Hinton 1998], which represents the most advanced version of the system. This last version includes different input devices such as a CyberGlove, a ContactGlove, a 3-space tracker, a foot-pedal, a parallel formant speech synthesizer and three Neural-Networks (Fig. 5.11).

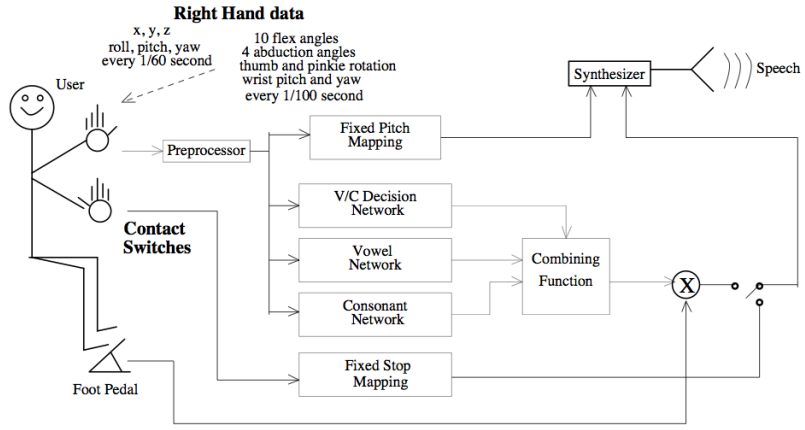


Figure 5.11: *A sketch of the "GloveTalkII" system.*

One of the most interesting feature of "GloveTalk" is the linkage between hand gestures and phonemes. At a first stage the system needs to be trained by the user. The consonant network is trained in order to produce consonant sounds based on user-generated examples based on an initial gesture vocabulary. Various consonants can be triggered by the user's left hand through the ContactGlove, which has nine contact points that correspond to the stop consonants (B,D,G,J,P,T,K,CH,NG). On the contrary, the vowel network implements a fixed mapping between hand positions and vowel phonemes defined by the user. This is made through the CyberGlove that was worn by the user on his/her right hand.

Then the foot-pedal provides a volume control by adjusting the speech amplitude.

Once trained, the user can initiate speech by forming the hand shape of the first sound she/he intends to produce. By depressing the foot-pedal the sound comes out of the synthesizer. Vowels and consonants of various qualities are produced in a continuous way through an appropriate coordination of hand and foot motion. But, the production of single vowels or consonants is not the ultimate goal of the GloveTalk system. Also, words can be formed by marking the correct motions. Fels and Hinton describe this element through an example: "*to say "hello" the user forms the 'h' sound, depresses the foot-pedal and quickly moves her hand to produce the 'e' sound, then the 'l' sound and finally the 'o' sound*" [Fels and Hinton 1998]. With this system the user has a complete control of the timing and quality of the individual sounds.
The authors had been testing the latest version of the GloveTalk with an accomplished pianist, because they expect that "*his pianistic skill in forming finger patterns and his musical training would help him learn to speak with GloveTalk*" [Fels and Hinton 1998]. They reported that after a long period of training with the system, the pianist was able to produce an intelligible and somewhat natural-sounding speech, but he still finds difficult to speak quickly, producing polysyllabic words, and speak spontaneously.

Three interfaces by Perry Cook

Perry Cook is one of the musician and researcher that was extensively exploring the possibilities of creating interfaces for computer voice models; first as a researcher on physical models for speech synthesis and after as in instrument builder [Cook 2005]. Through different prototypes and attempts he tried various combinations of sensors and input devices for achieving a better expressivity in synthesized speech control.
One of his first attempt is the "SqueezVox" [Cook 2005] made in collaboration with Colby Leider in 2000. The "SqueezeVox" (Fig. 5.12a) is a family of controllers used for controlling different variety of voice models (formant models, acoustic tube models, FOF synthesizers, tuva singing, etc.) based on some shared principles of operation. According to Cook the biggest issue for achieving a successful control of a vocal model an independent controls for pitch, breathing, and articulation is required [Cook 2005]. For this project the authors were using an accordion,

which is an instrument with components that "*map somewhat naturally to these requirements*" [Cook 2005]. If the pitch is controlled with the right hand keyboard, the "breathing" is provided in the bellows mechanism (a similar arrangement was employed by Von Kempelen), and the left hand provides an array of buttons. The authors have implemented many version of the same "SqueezVox" by augmenting the instrument with other sensors. For example, in a version called "Lisa" a linear FSR was located next to the keyboard to control fine pitch bend and vibrato. Two speakers are mounted inside, so the sound can be projected by the instrument itself. In Maggie, a smaller version based on a concertina, the right hand provides pitch control via four buttons (functioning as a brass instrument transposition valves), and a thumb slider selecting the overtone / octave. Another interface called Bart uses a two-axis accelerometer tilt sensor for controlling vowel space.

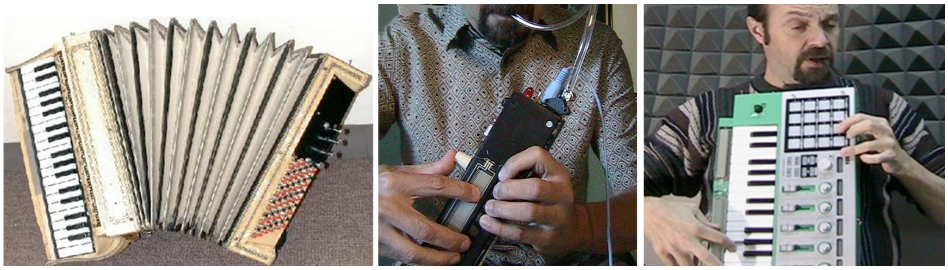


Figure 5.12: Some of the interfaces created by Perry Cook. From the left: The SqueezVox, the COWE, the VOMID.

In 2003 Cook developed another controller that was initially intended as a percussion and sound effects controller, but quickly he found an use as a new interface for vocal models. The name of this device is COWE (Fig. 5.12b) that stands for "Controller, One With Everything" and it contains various sensors, such as a breath-pressure sensor, linear FSR, thumb slider and a two-axis accelerometer. By touching the FSR sensor the user can overrides the vowel-space tilt control and activate pre-stored linear phoneme/word sequences, allowing the him / her to sing a text. Additional push buttons and rotary knobs are providing additional control. The breath-sensor was lately inserted into an exercise ball, which when inflated acts as an air reservoir. This arrangement allows the user to squeeze the ball under the arm to control breath pressure, similar to a bag-pipe.

The "COWE" differers from the "SqueezVox" family first of all for the absence of the piano keyboard. Cook noticed that configuration of the "COWE" proved difficult to maneuver, and

the keyboard was missed especially when trying to play rapid passages [Cook 2005].

Drawing from such conclusions, in 2004 Cook developed the "VOMID – Voice-Oriented Melodica Interface Device" [Cook 2005], based on the melodica, which is a small handheld reed keyboard instrument blown by the player. The "VOMID" was built on an highly modified Korg MicroKontrol device (Fig. 5.12c).

Aside from the note keyboard, touch-sensitive buttons, joystick, rotary and slide pots, the custom additions to the base controller include a breath pressure sensor mapped to phonation when blown, and breathing when sucked, and a linear FSR mapped to continuous pitch control, directly related to the discrete pitches of the keyboard. A three-axis accelerometer was also implemented for sensing leaning and shaking. The interface was then designed in a way to be suspended by a neck strap on the chest, thus played somewhat like an accordion.

All of these devices are generating MIDI values for controlling several programs written using different languages and systems, such as Synthesis ToolKit[46], Max/MSP[47] and ChucK [Wang and Cook 2003] .

The Formant Brothers

Established in 2000 as a "composition cooperative" between the composer Masahiro Miwa and the musician Nobuyasu Sakonda, The Formant Brothers[48] are pursuing a personal artistic research investigating "*the relation between voice and machines*" [Sakonda and Miwa 2009]. In 2003 they developed their own formant synthesis system called the Keyboard-to-Phoneme Transfer Standard for Japanese Language, which can be used with any conventional MIDI keyboard and "*allows anyone to perform speaking and singing with highly emotional expressions*" [Sakonda and Miwa 2009].

The Formant Brothers have produced several compositions using an ironic approach, like in "Ordering a Pizza de Brothers!" (2003)[49], which reminds to a famous demonstration of an early

46 https://ccrma.stanford.edu/software/stk/
47 http://cycling74.com/
48 http://formantbros.jp/e/works/works.html
49 https://www.youtube.com/watch?v=FFvFlpVjEjM

Text-to-Speech system.

They tried also to address some issues of the mediated apparatus through artificial voice. This is the case of "Le Tombeau de Freddy" (2009), where the voice of Freddy Mercury was digitally re-created through a custom made formant synthesizer and used for singing the japanese version of the "International" [Sakonda and Miwa 2009]. In "NEO DO-DO-I-TSU" (2009) they experiment the re-creation of six Japanese folk songs through their synthesis protocol.

In 2013 they started to experiment with a new system called "BROTHERS' Button to Phoneme Transfer Standard for International Language", a software implemented in Max/MSP that defines the of manipulation of button/keyboard/bellows of MIDI accordion (such as the Roland V-Accordion) to control their formant synthesis software[50].

Miwa and Sakonada explained that "i*t seemed to be the best choice to use the accordion as an interface device to control our vocal synthesis system because the player analogically and intuitively identifies it with a kind of externalized object of human speech mechanism - bellows as a human lugs and buttons and keyboard as the vocal tract*" [Sakonda and Miwa 2009]. The combination between this input device and their protocols allows the user to explore many possibilities of the formant synthesis software, such as pronouncing a single unvoiced consonant, diphthongs, ambiguous mixed/morphed vowels, breathing sound etc.

Miwa and Sakonada have published different videos on Youtube that clarify their approach and the results they want to achieve with this interface[51]. They played mostly japanese traditional songs, usually in public places, with an acoustic guitar and the accordion interface.

Beside this, the intent of the Formant Brothers is not merely the creation of a new interface but to explore the possible aesthetics of a disembodied artificial voice.

They noticed that "*the voice that emerged from this system is too realistic -it can breath erotically, whisper softly, shout roughly and scream crazily-, we delusionally begin to regard the MIDI accordion on our knees not as a mere object called "Man-Machine Interface" but some kind of flesh organ which leads us to manipulate it to realize the voice of someone who is absent. Finally we are thrown into philosophically/aestethically profound questions: What is the object? Who is the subject of this voice?*"[52].

Beyond the mere design and exploration of new interfaces for speech synthesis the work of the Formant Brothers started to tackle some issues about tangible and manipulative interfaces and

50 http://formantbros.jp/e/works/entori/2014/3/18_BROTHERS_Button_to_Phoneme_Transfer_Standard_for_International_Language.html

51 All are available here https://www.youtube.com/channel/UCPb1rhVpI7nYbf72lEIZ5xQ

52 http://formantbros.jp/e/profile.html

the effect of synthetic digital voice in contemporary society.

Maywa Denki : speaking devices

In middle of the 1990s another artists group from Japan started to explore artificial speech through different digital, electronic, and mechanical devices. Maywa Denki is an "art unit" founded by Novumichi Tosa in 1993 along with his brother Masamichi. They started their career as a design and research group at Sony Music Entertainment, and later in 1998 with Yoshito Kogyo Co. Ltd. Characterized by a peculiar style, they identifies themselves as a continuation of the small/medium-sized electronics enterprises that had once supported Japan's economy during its high-growth period. Working mostly with sound devices and alternative instruments they usually called every new piece a "product" and a live performance or an exhibition as a "product demonstration" [Hatanaka 2005] .

One of their most successful and acclaimed piece is the "Otamatone"[53] (Fig. 5.13). This is a singing device that states between an electronic musical instrument and a sound toy. Its body is shaped like an eight note, with sound emerging from a sort of mouth on the notehead. The "Otamatone" requires of the two hands: while one hand holds and squeezes the head, the other hands control the pitch of the voice by placing the finger on a bar on the stem, which contains a Touch slider sensor.

By varying the pressure on the head (that acts as an opening and closing of the mouth) the user can create a sort of wha-wha effect. By shaking the neck it's possible to creates a vibrato effect. Some switches on the back allow the user to change octave, turn it off and on, or changing the volume. Conceived as a commercial products (it exists in different versions such as Deluxe, Mini, Original) it's not a simple toy, but it's not only a musical instrument. This represents one of the most important examples of what Machiko Kusahara defines as "*device art*" [Kusahara 2007].

The "Otamatone" is probably not a proper musical instrument defined as such, but posses some interesting characteristics that are absent in other interfaces for artificial speech and make it

53 http://www.otamatone.com/about-otamatone/

unique. Firstly in the design, every trace of technology and reference to traditional instruments is abandoned in favor of a strange note-like creature. Adding eyes and a mouth the device started to posses some characteristic of a semi-living entity. Secondly, the speech and singing produced is very abstract and is not reproducing any language or particular singing style.



Figure 5.13: *Maywa Denki's "Otamatone".*

The "Otamatone" is not a unique piece in the catalogue of Maywa Denki's products that uses artificial voice. This famous device was actually produced by applying the research that the Tosa brothers made with their series of mechanical devices called "Voice Mechanics"[54]. This is a group of kinetic sculptures produced over the years that synthesizing speech and sing only with mechanical structures, without electronic components. According to Maywa Denki "*this project originally started by focusing on interesting points of 'functionality' and 'funny' aspects of an artificial* voice"[55]. They present those sculptures in exhibitions and as instruments in their live performances.

Chorus Digitalis

Chorus Digitalis is a quartet composed by four musicians leaded by Christophe d'Alessandro from the Audio and Acoustic Group from the LIMSI-CNRS of Orsay (FR). This quartet has

54 http://www.maywadenki.com/products/voice/what-is-voice-mechanics/
55 http://www.maywadenki.com/products/voice/what-is-voice-mechanics/

been played in different venues since 2011 with a repertoire of choral singing with their speech synthesis system and gestural controllers.

Musicians on the stage are equipped with a laptop computer (which is running the sound synthesis software), a customized Wacom tablet, a joystick used as a gestural controller, and a speaker that represents the individual sound source of each voice.

The speech synthesis is based on the CALM model, developed by d'Alessandro [D'Alessandro et al. 2006], which is an improved parallel real-time formant synthesizer with the name of "Cantor Digitalis". This model was then implemented in the The Méta-Mallette [D'Alessandro et al. 2006] environment, and allows precise spectral control of the sound source characteristics, and can reproduce specific voice categories, such as baritone, tenor, alto, soprano. "Cantor Digitalis" is then driven by four Wacom tablets augmented by a transparent keyboard, with lines and relief prints in order to indicate the true pitch scale. Each musician is playing with one hand the stylus and literally drawing the melody by controlling the pitch in the specific range of each voice using only the x-axis of the surface (the y-axis is free). According to Le Beux et al. [2011] this gives to the performer the possibility of realizing pitch ornaments by using different hand's gestures. The two extremities of the Wacom stylus are equipped with different points (a fine point and a thick point) and springs. The player feels the spring reaction when pressing on the point, and this effect is associated with vocal effort. Le Beux et al. [2011] define vocal effort as "*a mixture of sound intensity and voice source spectral tilt: increasing the effort increases the sound intensity and decreases the source spectral tilt (it enhances spectral richness)*".

With the other hand the musicians are controlling a joystick using a particular mapping. With the hat switch, which is controlled by the thumb, they are selecting different vowel presets, and sound volume is controlled by the throttle. An extra button on the base allows the musicians to set the different types of voice. Expressive parameters such as lax-tense dimension, aspiration noise, jitter and shimmer are controlled by the stick motion [Le Beaux et al. 2011].

Usually the repertoire of the Chorus Digitalis is composed of improvisational pieces and also polyphonic scores from the XVth and XVIth Century. Le Beaux et al. [2011] reported that this instrument seems playable and viable and that each musician was able to obtain reasonable results, only with a short amount of training. One of the main issues for the creators of this project was to achieve a good intonation, ornamentation and synchronization through the players that if from one side was solved on the performative side seems to reproduce the same problems of a 'real' choir singing [Le Beaux et al. 2011].

After this survey we saw that, despite from similar algorithmic models, different approaches have been explored in the design of interfaces for real-time speech synthesis.
SculpTon is sharing with those interfaces the ambiguity of working with artificial speech through alternative interfaces. By applying to a technological artifact the mechanics and functionalities of the human voice apparatus we are investing those devices with a sort of anthropomorphic qualities and attributes.
From an artistic point of view I'm not interested in using SculpTon as an interface for controlling and creating realistic simulations of human voice and speech, but to use it as an interesting, ambiguous and even funny sound space to explore and invests with new expressive meanings.

5. Implementation

The final version of SculpTon was the result of several iterations in the design of both hardware and software elements. In this section I will introduce the main steps and different prototypes developed for achieving the desired result. At the end, an evaluation made through several performances, live demonstrations, and public tests will be presented and discussed.

5.1 First prototype

The initial stage of the development was characterized by two parallel activities: the first one was the study of different topologies and the possible interactions; the second was the research on possible sensing techniques.



Figure 5.14: The first prototype of SculpTon (May 2012).

5.1.1 Topological studies and interaction

In order to embody a potential structure and experiment with some tangible interaction qualities, I developed two mockup prototypes without any electronics or sensors. In this first design step I tried to keep the initial statement clear and allow its verification through the experimentation with different possible solutions. Those objects should form a framework for the experimentation with the overall shape, the malleable surface and the structure and also allow to test the various configuration for different sensors.

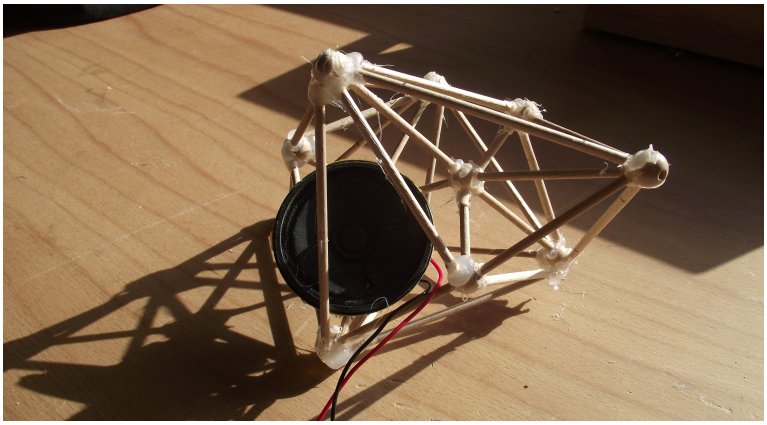


Figure 5.15: A conceptual model of SculpTon (May 2012).

The first prototype was a tetrahedron made of four wooden spheres and metal springs connect them together (Fig. 5.14). This structure can be broken down into different single sub-modules

made of a couple of masses and springs. Such configuration is very useful for attaching different sensors to be tested in a simple and effective way.
The second was a larger object composed of a larger number of those mass and springs modules. It was then covered with different materials for testing the surface qualities and its tactile responses (Fig. 5.15).

5.1.2 Sensors

The implementation of the sensors part reflects the current development stage of our project. In order to create a physical structure which sonically reverberates the physical actions by the user, the sensor implementation forms a key part of the development. The structure itself has to be composed from sensors with specific characteristics: they should detect stretching, pressure, distance, orientation and map this multidimensional data directly onto the virtual model for sound synthesis. Different topologies and configurations of of commercial sensors have been evaluated.
Those kind of sensors usually have mechanical, size and manufacturing requirements that limit their use in non- standard applications. Comparing this to the development of wearable and textile materials suitable for interactive and augmented usage scenarios to the rigid and plain surface of the standard sensors, pushed me into the direction of a combination of modified or custom-made sensors.

Light sensors

The first problem needed to be solved was how to get a virtual representation of the physical structure. Before thinking about the behavior and the malleable object characteristics, I had to determine how to get the most accurate measurement of the distance variation between each masses through the springs. One of the most simple and effective way to detect this kind of information was to measure the distance between two points with an LED and a Light

Dependent Resistor (LDR) This LED/LDR assembly was then connected to an Arduino microcontroller to collect the data (Fig. 5.16). By using the first module, described above, I attached these two elements on the opposite sides of each mass. Through this configuration one can obtain the real-time informations about the variations of the distance, and therefore a discrete image of the whole structure. The further way the LED is from the resistor smaller the is value of the detected by the LDR.

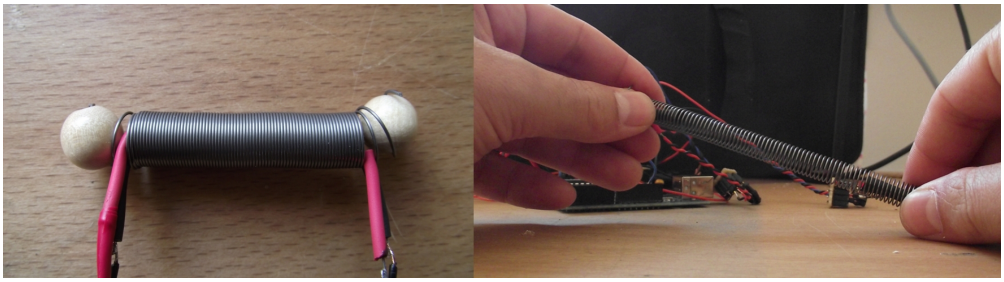


Figure 5.16: *First prototype of the sensor module.*

Stretch-sensor

A malleable object require a stretchable and moveable structure. At this point I was researching on sensors and materials which can track those kind of variations. The development of new conductive materials and electromechanical components -which are used now in robotics applications- were a good starting point.

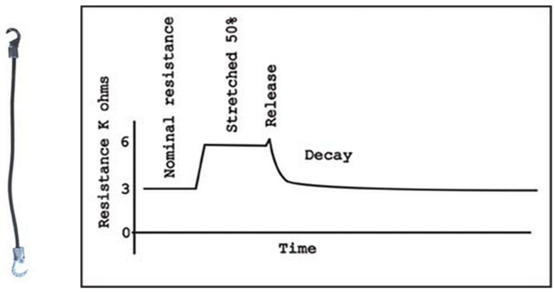


Figure 5.17: *On the left, the flexible stretch sensor from Image-Scientific Instruments; on the right the datasheet.*

The most interesting sensor available on the market was the Stretch Sensor by Images-Scientific

Instruments[56], a polymer cylindrical cord of .060-.070 diameter and 5mm of length (Fig. 5.17). This component change resistance when stretched, with a variation around the 50% more of the resistance. That curve is very rapid but we noticed that the relaxation part is very slow and it shows an high impedance. Then I add a 1M Ohm resistor in parallel for prevent this behavior, but the variation is far from consider this sensor for a continuous detection. The small dimension and the high price make this sensor not suitable for our project. Due also to the cost of such sensors, some experiment have been made in order to create a stretch-sensor from scratch (Fig. 5.18). I tried by mixing some corn starch with silicone (for making a kind of polymer) and finally add some graphite powder as a conductive element.

When this compost was ready, I sucked it into a syringe and then injected into a plastic tube of c.a. 2 mm of diameter. Even if this represents a simple and easy way to produce a stretch sensor the results were not that satisfactory. The impedance was still very high, and due to the continuous shifting of the particles of graphite, after some trials the sensor itself became unstable and then unreliable.



Figure 5.18: *Hand-made stretch sensors*.

Slide potentiometer

This third variation consists in detecting the distance between two masses by using a modified slide potentiometer. As we can see in Fig. 5.19, a standard slide potentiometer (10kΩ) was augmented with a plastic straw. On side was of the slider connected to one 'mass' and one side of the straw was connected to another 'mass'. With this configuration was possible to detect the gesture of stretching a joint in a simple and effective way. As I mentioned above this approach also contains several limitations, but provides sufficient stability and robustness. This kind of

56 http://www.imagesco.com/sensors/stretch.pdf

variable resistors are for example used in audio mixers and are generally designed to be manipulated by hand. Their design and appearance is very rigid, flat and of small size, therefore these elements can be easily fit into each of the individual connecting modules.

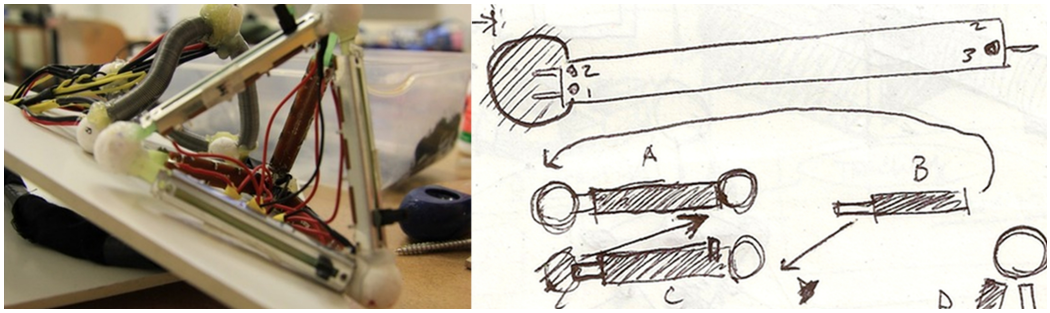


Figure 5.19: *Sensor modules with slider potentiometers*.

5.2 Second prototype

Drawing from these conclusions I opted for a custom made sensors array by improving the first implementation of the light sensors.
One of the main motivations regarding the use optical sensing mechanism, was mainly the reliability of such system and the economy in terms of money and time.
This type of sensing technique has been already successfully implemented in a variety of interfaces for sensing deformation and gestures such as bending and stretching.

5.2.1 Sensing structure

Drawing from those experiments I opted for a custom made sensor array, using light as a way to measure deformation.
The detection of gestures such as bending, stretching and squeezing was still an open question. After a survey on the sensors available on the market, was possible to notice that bend sensors and stretch sensors are normally decoupled. Apart from cost, one of the main limitations are the

size and the length of these elements.

This conclusion led me to the development of a another crucial step: instead of use a group of specific sensors for specific tasks (bend sensor for detect bending, and so on) I decide to build an array of sensors that, thanks to their physical configuration, can detect different gestures at the same time, by following the principle that form follows function.

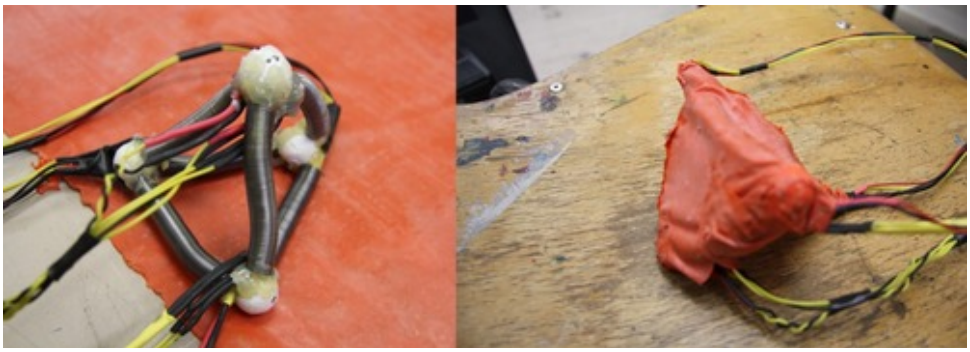


Figure 5.20: *One of the first version of the sensing structure*.

The idea of implementing a *sensing structure* started with the creation of six modules (Fig. 5.20). Each of these modules were composed of an optical sensing mechanism embedded in two opposed nodes connected with a stretchable joint. The masses (a this stage, some little wooden balls of a 3 mm of diameter) were joined with with an LED and an light dependent resistor (LDR) facing each other. Then, these modules have been arranged in the form of a tetrahedron. For providing a form of passive haptic feedback each couple of masses were joined with a metal spring. The mechanical properties of the springs helps to increase the sensation of deformation and elongation by applying a natural mechanical resistance. The spring were then covered with a latex tube. I choose latex for its interesting properties about deformation (Fig. 5.21).

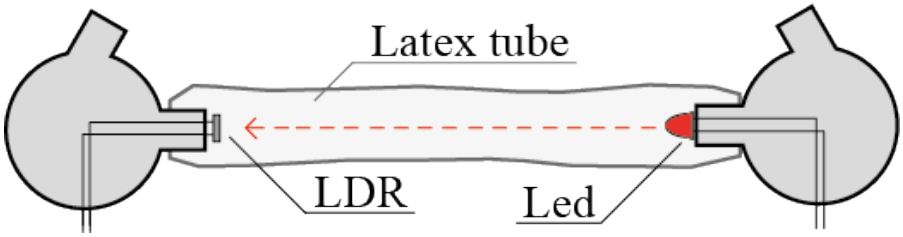


Figure 5.21: *A section of the sensor module*.

This configuration combines several characteristics of materials for creating an internal structure that is not only a sensing mechanism but it is influencing the whole interaction with the artifact itself (Fig. 5.22).

Before latex I tested other materials like fabrics such as Spandex, a stretchable fabric widely used in sport's wear. The results were not satisfactory, because the material was not supporting continuous deformations. Also, compared to latex the tactile feeling was very poor.

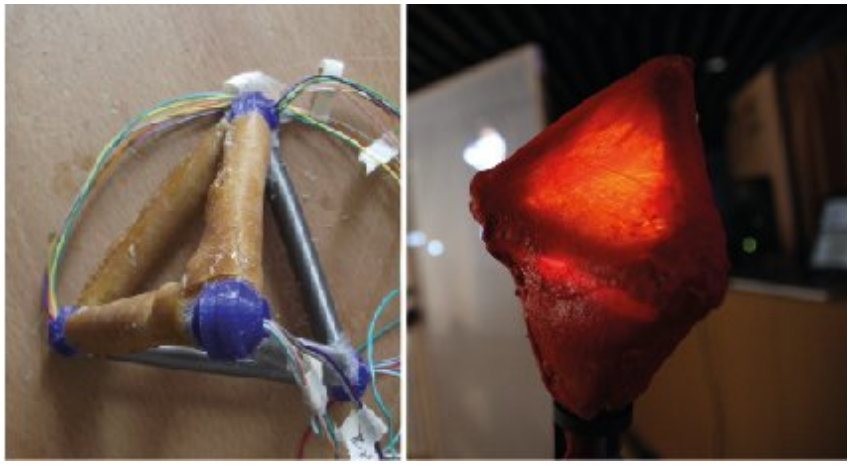


Figure 5.22: *An advanced version of the sensing structure, and the final one externally covered with latex.*

5.2.1.1 Organic Augmented Sensing Structure

These sensor modules have been created in order to measure deformation of the interface, including bending, twisting and stretching gestures. The tubing within the joints serves as an omnidirectional bending and stretching sensing mechanism. Its measuring the intensity of the light coming from an LED on one end of the joint with a matching light dependent resistor (LDR) placed on the other end.

When the joint is straight the intensity of the light is at its maximum. As the joint bends the tubing occludes the light to a point where the LDR cannot detect any light emitted from the LED. Otherwise, when the the joint stretches, the light perceived by the LDR slowly decrease according to how much the tube is elongated. I noticed also a relation between the decreasing of

the light and the time when this phenomena occurs.

When the joint bends the light decrease very rapidly, from the maximum to the minimum intensity. On the contrary, when the joint is stretched the light perceived by the LDR never reaches the minimum, but is very slowly dimmed. This behavior is a result from a combination of the optical sensing mechanism and the elastic property of the latex tube. This material applied a resistance when it's stretched, and thanks to the global configuration, makes this gesture recognizable respect to the other one (Fig. 5.23). For *organic augmented sensing modules* I mean of a combination of a sensing technique (in this case optical) and the 'organic' properties of the material that compose the compound sensor.

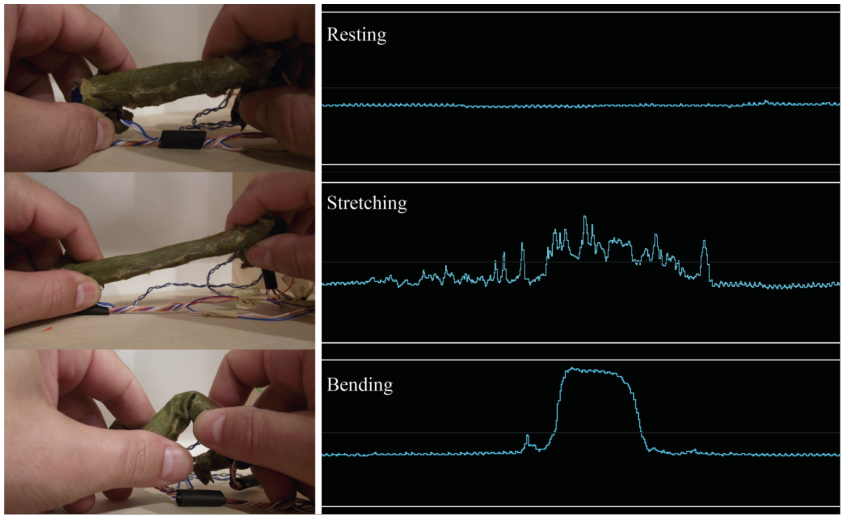


Figure 5.23: *Different gestures detected by the implemented sensor: resting, stretching, bending.*

The choice of a particular material can not only affect the haptic feedback of the entire interface, but must influence the interaction with the artifact itself.

Following the idea of employing latex, I decided to cover also the structure with a skin of hand-made Latex. Inside the structure I inserted also four white LEDs that are lighting the object from the inside.

Then, the sensors array and the LED were connected to an Arduino MEGA board, where the datas from the sensors were filtered first and then transferred through a serial protocol to a Mac OSX laptop computer.

5.2.1.2 Optical sensing for deformation

Optical sensing have been already successfully applied for sensing bending and stretching. For instance, Zimmerman [1982] created an optical flex sensor that senses bending by measuring the amount of light able to pass through a flexible light guide. He placed a light source and a photodiode on the opposite side of the light guide; when the guide was bent, the amount of light reaching the photodiode decrease. This technology was used in early data gloves.
Using the same concept, Measurand [2010] has built a fiber optic sensor to measure bend and twist continuously along its length. Kakehi and colleagues used reflected infrared light to measure the location and amount of compression in soft materials such as cotton stuffing [Kakehi et al. 2011].
We can also find some relevant examples of the use of optical sensing in TUIs for measuring structural strain in physical models [LeClerc et al. 2007], deformation [Shen et al. 2014], and also in musical interfaces [Hollinger et al. 2010] [Hattwick et al. 2014].

5.2.2 First application

The first application I developed was a simple and demonstrative patch made in Pure Data. The datas coming from each sensors were mapped to six different low-pass and high-pass filters for filtering an audio sample. This mapping was creating the effect that when the object was untouched, in a sort of resting position, no sound was coming, but when the object started to be operated a sound was emerging. In a very simple way, the user was sculpting the sound.

This second and more complete prototype was presented at the TEI Conference 2013[57] (Barcelona, Spain) in the "Work in Progress" Section with a poster and a live demonstration (Fig. 5.24). A paper was also produced for this conference, which was documenting the previous

57 http://www.tei-conf.org/13/

stages of the development [Boem 2013].

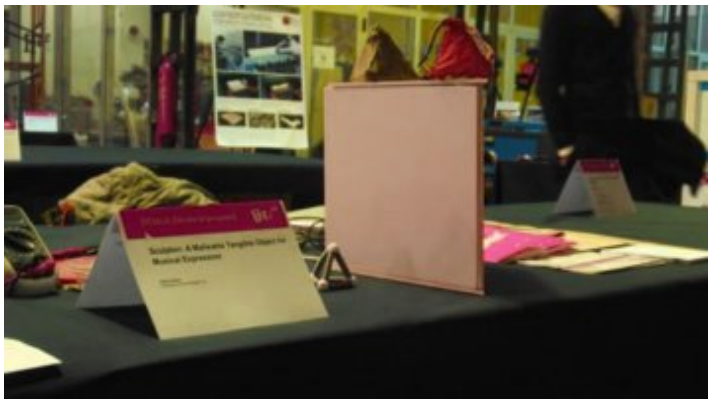


Figure 5.24: *Presenting SculpTon at the Demo Session of the TEI Conference 2013*.

5.3 Third prototype

In order to make SculpTon a complete and playable interface some improvements were needed. From the hardware side one of the first issues was to create a stable and scalable version of the bend/stretch sensor modules. Beside this other sensors will needed, such as accelerometer and gyroscope for detecting motion and orientation in space (Fig. 5.25).
Some more research and experimentation are needed especially with latex in order to create a more interesting surface, with a peculiar organic feeling, but also elastic and stable.

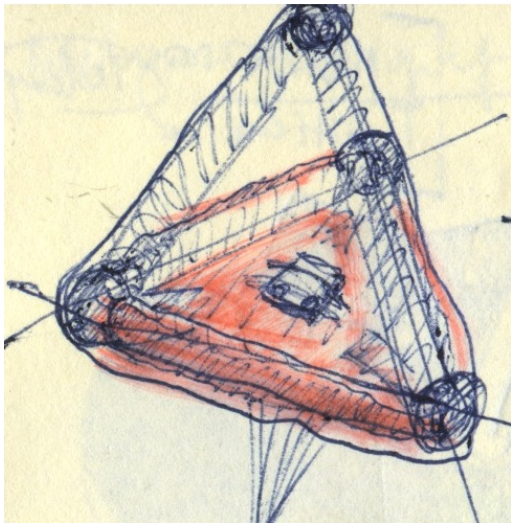


Figure 5.25: *Sketch for a third version of SculpTon.*

5.3.1 New sensor's adjustments

The main problem regarding the sensor modules was the stability and the modularity. For this I started to work with some cases for encapsulating the LED / LDR pairs. I experimented with several CAD models and 3D printed elements. The most successful design was the one showed in Fig. 5.26, which is a 3 mm ball with three apertures made with PLA plastic. The LDR or the LED are inserted inside and are pointing outside. On the bottom of each module there is a hole for the wiring. This configuration makes easy to assemble the final structure as a tetrahedron.
As a joint I kept the solution adopted in the previous version by using a metal spring covered with a latex tubing. With this configuration the structure was self sustaining and stable.

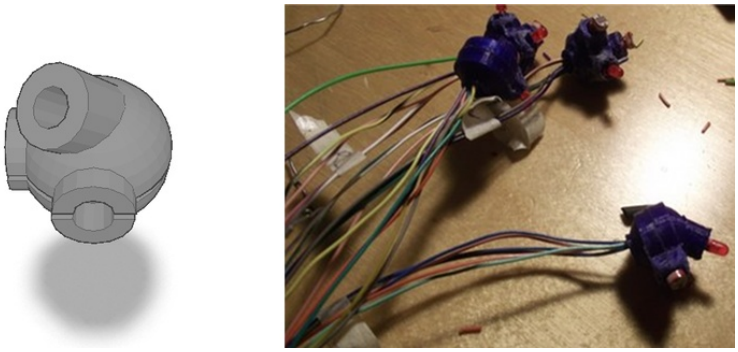


Figure 5.26: *The CAD model, and the final version of the 3D printed enclosures for the sensors.*

5.3.2 Additional sensors

The *sensing structure* provides a good way of monitoring constant deformation, but some others subtle and global events can occur in the interaction with an interface such as SculpTon (Fig. 5.27).

Air pressure and sound represent some interesting global parameters that can be employed. In the area of musical interfaces Kazuhiro Jo introduces the idea of *inaudible computing* [Jo 2009], which proposes to exploit audio capture devices for capturing sensor data, in contrast with the idea of physical computing that is based on standard microcontrollers.

Then I decide to place inside the structure an electret microphone, which represents an interesting sound source and a sensor for detecting additional gestures. The microphone was placed inside the *sensing structure* in order to capture the sound produced by the friction between the hands and the latex cover of the device. For preventing interferences and malfunctions the microphone was also incapsulated into a silicone holder and placed into an additional latex tube. By placing the microphone inside the structure was possible to prevent some phenomena such as feedback with other sound sources.

I will explain later how the sound captured by the microphone is processed in the software part.

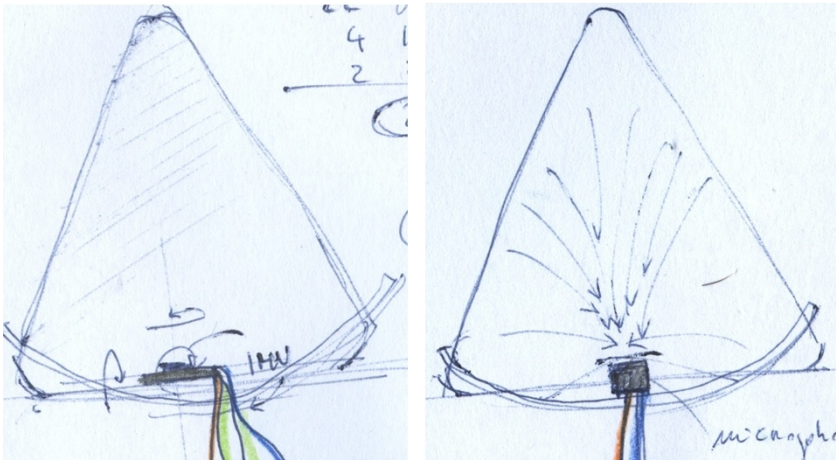


Figure 5.27: *Studies for the new sensors implementation. On the left the IMU, on the right the microphone.*

5.3.3 Detecting motion

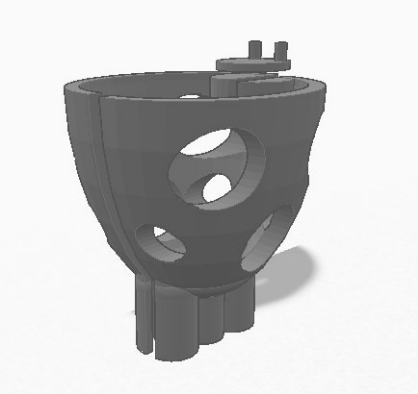


Figure 5.29: *CAD model for the vessel.*

SculpTon is not only composed of a malleable surface, but because it's conceived as a whole artifact, I encountered the need of sensing energy and movement in space. After some experimentation with different types of motion sensors I opted for a complete 10 DOF mems IMU board[58], which comprises a three axis accelerometer, gyroscope, pressure sensor and a compass on a single tiny, low power board, communicating through the I2C protocol. With the

58 http://www.dfrobot.com/index.php?route=product/product&product_id=818

help of some further calculations, thanks to the FreeIMU library[59] I was able to extract features such as acceleration, rotation, orientation, the yaw, pitch and roll of the artifact.

At this point one of the main problem that emerge was: where to place the motion sensor ?

It needs to be in a flat and stable position, fixed on an horizontal plane. After some trials I decide to add another structure, a sort of vessel, on the bottom of the sensing structure (Fig. 5.29).

This element was also designed with a CAD software and then fabricated with a 3D printer. As we can see in Fig. 5.29 on the top part there is a sort of shelf designed especially for hosting the specific sensor I'm using. For improving the stability the board was fixed on the bottom with some glue. This vessel became also a useful way for providing a base for the *sensing structure* and for housing the huge amount of wires coming from the different sensors.

The first version was printed with PLA plastic, but it was too solid and was breaking the idea of having a malleable interface. After a research on materials available for 3D printing I opted for the ELASTO plastic produced by Shapeways[60].

This is a a robust and rubber-like elastomer developed for 3D printers. It's very solid but also capable of being squeezed without falling apart. The end part of the vessel has two empty short tubes where two long cables are coming from. These cables are connecting the sensors to the microcontroller. Each single wire was soldered to the cable from the inside, and then covered with the vessel.



Figure 5.30: *The 3D printed vessel with the 10 dof motion sensor*.

5.3.4 Between the controller and the software: the stompbox solution

59 http://www.varesano.net/projects/hardware/FreeIMU

60 http://www.shapeways.com/materials/elasto-plastic

When SculpTon was getting more improved on the hardware side, some considerations emerged from a performative point of view.

In which way SculpTon will be played? How can I stabilize the connection between controller–microcontroller-laptop ?

One of my big concern was to keep the computer much far as I can from the stage. For achieving this I will need to connect the device to a microcontroller. Also, the motion sensor needs to be calibrated before every use, and the microphone inside the structure needs a little amplifier.

I was considering of embedding a micro-controller inside the device but, this was creating different problems from a design and usability point of view. The most important thing was to keep the feeling of an organic device much as possible. Having a fragile microcontroller inside the object that needs power was not a desirable solution.

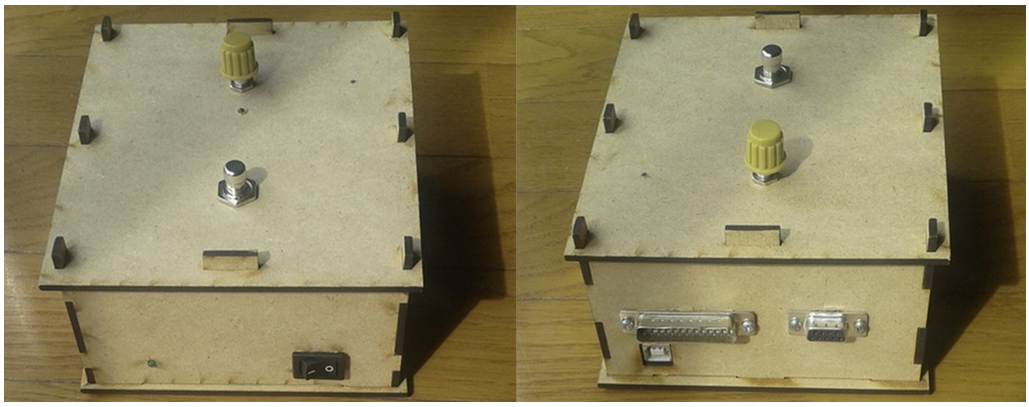


Figure 5.31: *The stompbox. On the left, the frontal part with the main switch. On the right the backside with the input and output connections.*

Inspired from my activity as a electric guitar player I decided to build a sort of stomp-box. I liked the fact of using foot-pedals for controlling and activating effects, which is makes an useful bridge between the input device (guitar) and the output (speakers).

As we can see in Fig. 5.31 the final version of the stompbox is composed of a light MDF structure (3 mm thickness) designed with a CAD software and fabricated with a laser cutter. This box contains an Arduino Mega micro-controller and a low power amplifier. On the top part there is a foot switch, an LED and a potentiometer.

By pressing the switch the performer can calibrate the motion sensor before playing. The LED

gives a simple visual feedback by blinking. The potentiometer is used for regulating the volume of the amplifier. On the right side of the box there is a female mono jack for the separate audio output.
On the front there is a switch, used for turning on and off the amplifier. On the back side there two serial connectors and a USB plug. Trough these connectors the performer can attach the malleable controller to the stomp box, while the USB is used for powering the micro-controller and send the data to the laptop. Internally all of those inputs and outputs are wired to the Arduino. For this purpose I designed a specific shield (Fig. 5.32). The micro-controller is not only processing the signal coming from the sensors, but also managing the functions of the elements of the box (eg. the push button) and the serial communication with the laptop.

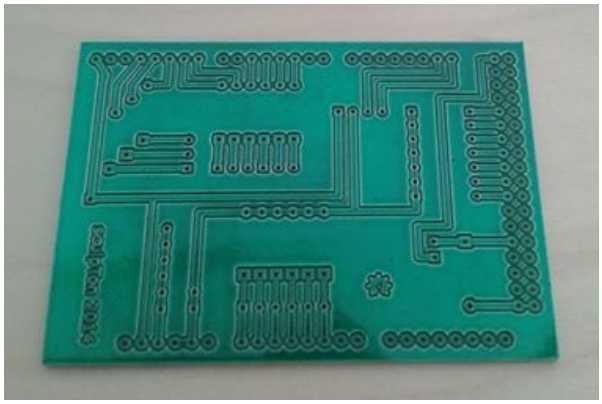


Figure 5.32: *The SculpTon PCB shield for the Arduino Mega*.

After several rehearsals and performances in various venues this configuration have demonstrated to be a good and convenient option for live performances. The chain composed of input device, stompbox and laptop became then a distributed, portable and stable system.
Since computational power and miniaturization are increasing it's not difficult to imagine a future development made by removing a laptop and embed the computation inside the stompbox. Already some trials were made in order to run the entire software on a Raspberry PI, which is an interesting little and low cost computer.

5.3.5 Fixing hardware

The tangible controller was then connected to it the stompbox two cables, one for the sensors (with a 25 pins serial connector) and a 9 pins one for the LEDs, used for the visual feedback.
Together with those sensors, the 25 pins connector is containing also the connections of the electret microphone. This element is treated separately and connected to a low-power audio amplifier, which is also hosted inside the stompbox. The gain of the amplifier is controllable with a potentiometer, then the audio output is provided through a 1/4 mono chas- sis jack socket, which is providing the connection to the sound card of the laptop. Four LED are embedded into the sensing structure. They are lighting the artifact from the inside. These elements are also providing a minimal visual feedback, by visualizing the acceleration measured by the motion sensor through a light pulsation. This configuration represents first of all, a compromise between the difficulty of embedding all of the electronics in a malleable object and secondly, the necessity of removing the computer from the stage.
In Figures 5.33 and 5.34 the components of the malleable controller and the stompbox are presented in their final implementation.

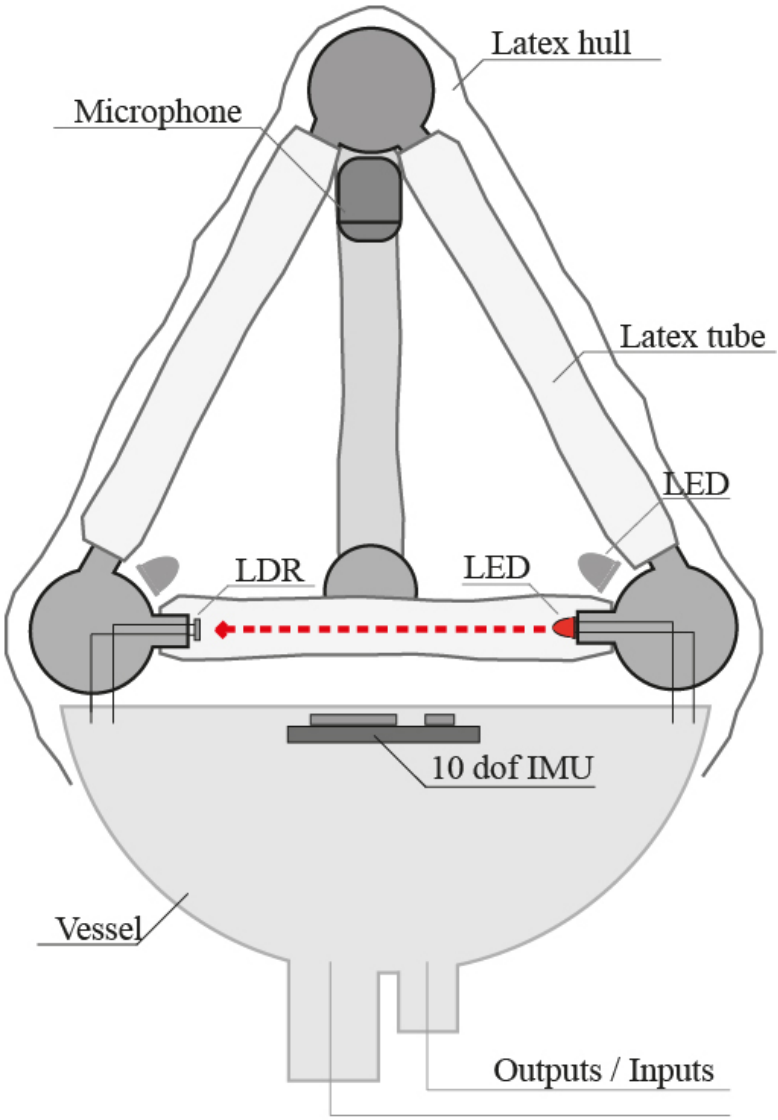


Fig. 5.33: *A section of the malleable controller.*

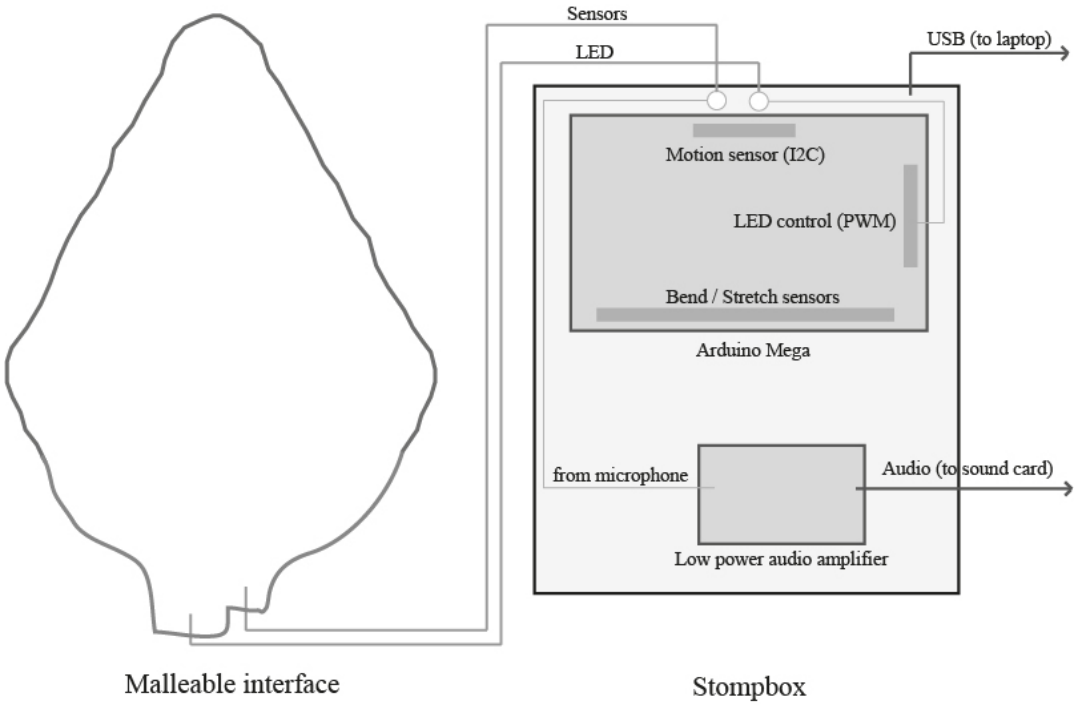


Figure 5.34: *A scheme of the elements placed inside the stompbox*.

5.4 The software

The end of the chain is the software. Here the sensors data coming from the micro-controller are processed, and the sound synthesis takes place. I developed a framework with Pure Data Extended, an open source and cross platform visual programming language oriented to real-time sound processing [Puckette 1996]. In order to monitoring in the data flow and adjust some parameters according to specific needs a graphical user interface was then developed (Fig. 5.35). The software developed for SculpTon is based on the following framework:

- *Sensor layer*: this layer is responsible of acquiring the data coming from the connected interface and perform some simple signal processing operations such as scaling and smoothing to remove jitter and noise and route them properly. The audio signal coming

from the microphone is also processed and can be additionally filtered and adjusted by the performer.

- *Gesture layer*: this layer combines and process the data coming from the different sensors for deriving some abstract gestures performed on the entire object, like stretching, squeezing, bending. For example at the level of the single joint these characteristics are extracted and have been put in relation with the others. Velocity and acceleration are some of the global gestures detected.

- *Sound layer*: this layer involves the detections of different sound gestures captured from the microphone. Different sound characteristics were extracted like amplitude, pitch, attack and a simple beat-tracker was implemented for capturing percussive gestures.

- *Mapping layer*: in this layer the musical interactions are determined and exhibited. I opted for a complex many to many mapping strategy.

- *Synthesis layer*: the last one is responsible for the generation of the audio signal. For this I employ a formant synthesizer implemented by the author.

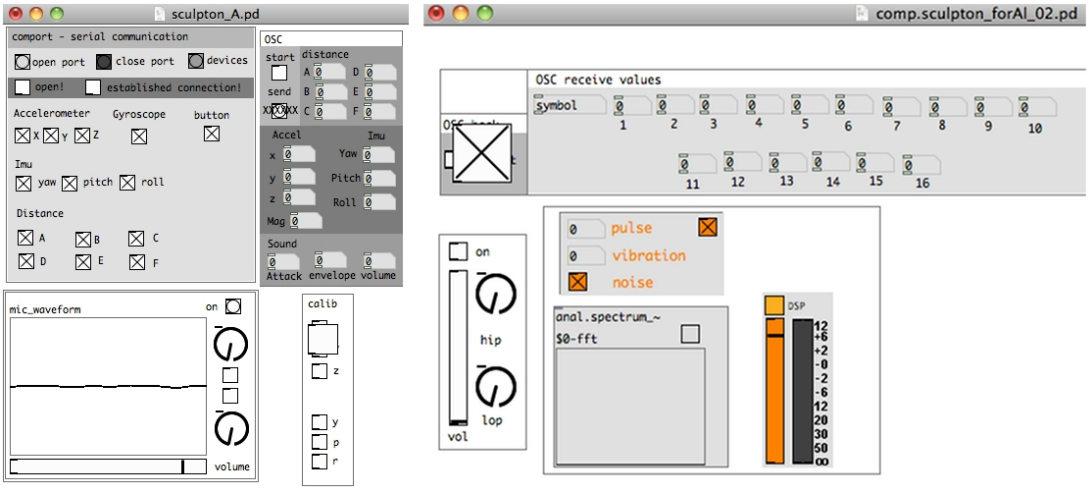


Figure 5.35: *Two screenshots of the SculpTon software.*

5.4.1 The sound model

The relation between voice, speech, gestures and artifacts have long roots. Sir Isaac Newton once he observed that he could hear vowel-like sounds while pouring beer into a glass. In the last centuries considerable cognitive research has proven that humans are highly skilled at identifying vowels and categorizing timbre according to vowel matching. Speech synthesis evolved in three main areas such as *articulatory synthesis*, *formant synthesis* and *concatenative synthesis*.

- *Articulatory synthesis*: this technique tries to model the human vocal organs as perfectly as possible, so it is potentially the most satisfying method to produce high-quality synthetic speech. On the other hand, it is also one of the most difficult methods to implement and the computational load is also considerably higher than with other common methods [Kröger 1992] [Rahim et al. 1993]. Thus, it has received less attention than other synthesis methods and has not yet achieved the same level of success. Articulatory synthesis typically involves models of the human articulators and vocal cords. The articulators are usually modeled with a set of area functions between glottis and mouth. The first articulatory model was based on a table of vocal tract area functions from larynx to lips for each phonetic segment [Klatt 1987]. Advantages of articulatory synthesis are that the vocal tract models allow accurate modeling of transients due to abrupt area changes, whereas formant synthesis models only spectral behavior [O'Saughnessy 1987]. Composer Eduardo R. Miranda used articulatory speech synthesis as an interesting source for "*strange human voice synthesis*" [Miranda 2005].

- *Concatenative synthesis*: connecting prerecorded natural utterances is probably the easiest way to produce intelligible and natural sounding synthetic speech. However, concatenative synthesizers are usually limited to one speaker and one voice and usually require more memory capacity than other methods. One of the most important aspects in concatenative synthesis is to find correct unit length. The selection is usually a trade-off between longer and shorter units. With longer units high naturalness, less concatenation points and good control of coarticulation are achieved, but the amount of

required units and memory is increased. With shorter units, less memory is needed, but the sample collecting and labeling procedures become more difficult and complex. In present systems units used are usually words, syllables, demisyllables, phonemes, diphones, and sometimes even triphones. Word is perhaps the most natural unit for written text and some messaging systems with very limited vocabulary. Concatenation of words is relative easy to perform and coarticulation effects within a word are captured in the stored units. However, there is a great difference with words spoken in isolation and in continuos sentence which makes the continuous speech to sound very unnatural [Allen et al. 1987]. Because there are hundreds of thousands of different words and proper names in each language, word is not a suitable unit for any kind of unrestricted TTS system.

The method used in SculpTon for creating vocal-like sounds uses *subtractive synthesis* based on formant filters. In this method a set between three and five filters whose center frequency, bandwidth, and gain correspond to typical vowel formant values are used to filter a pulse train (pitched vowels).

Formant synthesis has been studied and applied already in different areas [Klatt 1987] [Kleiman-Weiner and Berger 2006], and it seems one of the most convenient and affordable sound model of the human voice especially for real-time approaches. Probably this is also the most widely used synthesis method during last decades. We can recognize two main types of formant synthesis, *parallel* and *cascade* but, as noticed by [Klatt 1980], for a better performance some kind of combination of these is usually required. Formant synthesis also provides infinite number of sounds which makes it more flexible than for example concatenation methods. At least three formants are generally required to produce intelligible speech and up to five formants to produce high quality speech. Each formant is usually modeled with a two-pole resonator which enables both the formant frequency (pole-pair frequency) and its bandwidth to be specified [Donovan 1996].

A parallel formant synthesizer (Fig. 5.36) consists of resonators connected in parallel. Sometimes extra resonators for nasals are used. The excitation signal is applied to all formants simultaneously and their outputs are summed. Adjacent outputs of formant resonators must be summed in opposite phase to avoid unwanted zeros or anti-resonances in the frequency response [O'Saughnessy 1987]. The parallel structure enables controlling of bandwidth and gain for each

formant individually and thus needs also more control information.

The parallel structure has been found to be better for nasals, fricatives, and stop-consonants, but some vowels can not be modeled with parallel formant synthesizer as well as with the cascade one.

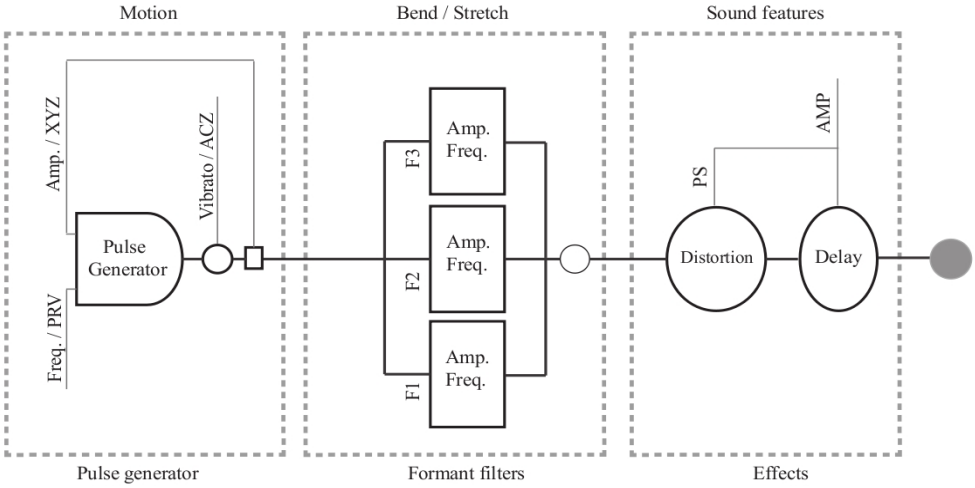


Figure 5.36: *A simplified representation of the formant synthesizer and how it's parameter are mapped to input gestures.*

5.4.2 Translating gestures into sound

Through this project I tried to explore an approach for relating complex gestures, such as deformation, to a digital model of the human voice, which is physically characterized by some sorts of deformations of the vocal tract, use of energy and effort for producing speech. I decide to combine different features extracted from the sensor array through an explicit mapping. The following strategy is also illustrated in Fig. 5.36.

First of all, I calculate a vector from the pitch and roll values (PRV) coming from the integrated motion sensor. This vector was directly mapped to the frequency of the pulse generator. Its amplitude is modulated by another vector derived from the magnitude of the acceleration on the three axis (XYZ). Therefore, when the interface is in a resting position -with no energy applied- no sound is produced, but when some strong movements are detected the frequency is increasing

or decreasing, according to the of the direction of the rotation and modulated by the amount. Other features from the motion sensor, such as the vertical acceleration (ACZ) are extracted and, after a proper scaling, mapped to the vibrato. Then, the sound is passed through a series of three resonant bandpass filters in parallel. If the source signal is produced by the motion of the artifact, the vowels are literally 'sculpted' through a direct manipulation of the interface. According to what I said in Section n. 4.2, bending and stretching gestures are thus detected through a threshold applied on every single data coming from each joint of the sensing structure. Then, a vector was derived from the two gesture, and these vectors are combined in other two vectors, two by two. From six sensors now we obtain three control values (F1, F2, F3) for the formant filters. Since I introduce also a microphone, I implement also some features extraction for this source. At this stage of the development I have not yet introduced the use of the acoustic sound as such, but we are considering to using it as an additional sound layer. When the hands of the performer are moving moving on the surface no relevant sound is captured, but if the user starts to manipulate the object, we can recognize significant variation in amplitude. The sound captured from the microphone is very weak, and additional amplification is required. Extraction of useful data can therefore be achieved with an amplitude analysis and tracking. Having said this, the most meaningful values extracted are the amplitude (AMP), and the peak which is characterizing the staring point of manipulative gestures (PS). Those features are then mapped to the control parameters of two sound effects, such as a distortion and a delay. Although, this configuration has given some positive results during performance and tests, the main limitations are its complexity and the rigidity. I believe that a better exploration of different methodologies, such as the use of machine learning algorithms can efficiently improve the expressivity of the system and a better exploration of the relations between motor skills, manipulative gestures and the sound synthesis.

6. Live tests, performances and audience feedback



Figure 5.37: *Ars Electronica Festival 2013, Linz (AT).*

In Chapter 2, I underline how and why the only possible test and evaluation of musical interfaces is in live performance; and SculpTon, as a musical interface, makes no exceptions.
As a new interface designed and played only by its creator, the evaluation of SculpTon must be conducted by considering different aspects, such as:

- the limitations of the interface;
- how much space is available for improvisation, and the development of a specific musical idiom;
- the relation with the user in terms of gestures and sounds.

Different feedbacks and comments from the audience will be presented together with some personal reflections on the live presentations, and the experience of playing SculpTon.

6.1 Public tests

The first public presentation of SculpTon took place during the "Use at your own risk"[61] exhibition at the Ars Electronica Festival 2013 [Leopoldseder 2013] in Linz (Austria). In this context I decide to combine an hands on demonstration for visitors and spectators who wish to try the interface, a video documentation of the project and eight short live performances. The showcase and the live performances took place at the foyer of the Brucknerhaus (Fig. 5.37).
More than a premiere of a performance, this first demonstration was a crucial test of the entire project. Those little demonstrations I gave two times per day were gathering more people and attracting the interest of the audience on trying the interface.
A second demonstration of SculpTon was made during the "Use at your Own Risk" exhibition at Victoria Art Center (Bucharest, RO) together with a short performance a the National Museum of Contemporary Art – MNAC (Fig.5.38)[62].



Figure 5.38: *Live at MNAC, Bucharest (RO).*

In both occasions a public hands on demonstration took place. I offer to the audience the possibility of experiencing the interface directly. Usually the visitors were mostly driven by curiosity, and at the first time they were not able to understand what this project was: for them was not clear if SculpTon is an artwork, a device, a musical instrument or a weird prototype.
In this context I collect not so many feedbacks in terms of critics or suggestions. For the audience was mainly an enjoinment and a curios experience.
After these events I had the opportunity to play with SculpTon in other two venues. One was on the 23 of April 2014 during "Noise Cocktail Night" at Dokapi Cafe (Linz, AT). The second one

61 http://www.aec.at/totalrecall/en/exhibitions/
62 http://www.interface.ufg.ac.at/blog/bucharest_exhibition/

was on the 6th of June 2014 during my residency at IAMAS – Institute for Advanced Media Arts and Science in Ogaki (Japan), as a lecture and as a live performance on the Club Train (Fig. 5.40).

6.2 Presenting SculpTon

The aim of these performances was the exploration of the possibilities of SculpTon through a framework for free improvisation.

According to drummer John Stevens "*improvisation is the basis of learning to play a musical instrument*" [Bailey 1992]. In the case of SculpTon these performances should be viewed in this way, for both performer and the audience.

As a new instrument without a specific repertoire, and characterized with a peculiar sonic, visual, and physical characteristics, the main problem of presenting SculpTon was to find a sort of compromise between a live presentation and a musical performance.

From the audience point of view they have confront with a new instrument, without any references, so this can result a quite challenging activity.



Fig. 5.39: *Live at IAMASONIC / Club Train, Gifu (JP).*

6.2.1 Improvisation

The improvisations done with SculpTon were 'solo improvisations'. In this case the performer was confronting himself only with the interface and its sound. Solo improvisation, is a particular and problematic area in musical improvisation.

In his fundamental book about improvisation, Derek Bailey devotes an entire chapter to this topic. Several famous improvisors (specially in what is known as free jazz) such as Anthony Braxton, Steve Lacy, George Lewis, Evan Parker, Derek Bailey have been exploring this challenging question of improvising only with their own instruments, without other collaborators.

As I said before, solo improvisation is a common practice between players with acoustic/amplified instruments and with musical interfaces. In both cases "*the music is literally constructed from the instrument*" [Bailey 1992], but if for musicians who are working with 'traditional' instruments this is a very challenging aspects, for the ones how are using new musical interfaces this seems to be a normal kind of play.

For the reasons I expressed before, usually a guitarist or a saxophonist needs to develop new techniques and language by, for instance, augmenting the instrument or by limiting it. For musicians using new interfaces, most of the time, the 'instrument' is shaped around their musical ideas. As an interactive system, the performer is confronting himself with a system. Learning and exploring in which way the system is reacting to gestures became sometimes the fundamental challenge for performers that are using NIME instruments.



Fig. 5.40: *SculpTon live at MNAC, Bucharest (RO).*

This was the case of the live improvisations with SculpTon. I entitled these series "Study for SculpTon".

This stands as an analogy of the practice of the *étude* (french word for *study*) in classical music. The *étude* is an instrumental musical composition, usually short, of considerable difficulty, and designed to provide practice material for perfecting a particular musical skill. This is a practice that became really popular in the 19th Century. The main difference between the studies written for instruments such as piano, guitar or violin is that they are written for a particular idiom. Compositions written for specific instruments are known as idiomatic, because they take into consideration features of the instrument such as basic articulation, and note range. Then the idiom became a reference point for judging the technique, the virtuosity and the expressivity of performer with a specific instrument.

But, as Tanaka [2000] noticed this notion can not be applied to new interfaces, because the lack of history, common shared practice and the reality that each interface is very or slightly different from the other, testify that this idiom has not yet been defined. Tanaka said that "*there is a priori no codified performance vocabulary for a new instrument*" [2000], and this must be created for each new interface.

The main challenge of the first performances with SculpTon was to identify and create a specific performance vocabulary for the interface. Between the presentations at Ars Electronic Festival and the one at MNAC I change the style of improvisation. During this period I was rehearsing a lot with SculpTon, mainly for the purpose of discovering playing techniques, gestures, and

exploring the sound space. Apart from some little and not very noticeable changes in the software, I decide to create a simple playground for improvisation.

As a controller for speech synthesis, I tried to emulate a sort of prosody and rhythmicity of the language by using a loop station pedal (Boss RC-2). This pedal - originally designed for electric guitar or bass - allows the user to record short live samples, loop them and dub other sequences and phrases on the top of the other.

Through this system I became able to create some small improvisations. The live performance consist in different short pieces created in real-time. Usually they starts from some rhythmic ideas, and keep evolving by adding many several sound layers.

By looking at the video documentation of those performances is possible to notice that they are developing in very different ways, and there is no point of references as a key to comprehension.

From this point of view, SculpTon can be included in the big family of musical interfaces defined by Jordà as "*idiosyncratic instruments*" [2006]. This element can be considered both a quality and a limitation.

After the first performances in 2013 was clear that what most appealed some listeners was the particular coupling of sound and gestures, amplified by the unconventional appearance of the interface and the sound produced. Most of the audience feedbacks were highlighting this aspect.

It's important to notice that several researchers have described how the recognition of the relations between gestures and sound, is for the audience an important element for making sense of new interfaces [Ryan 1992].

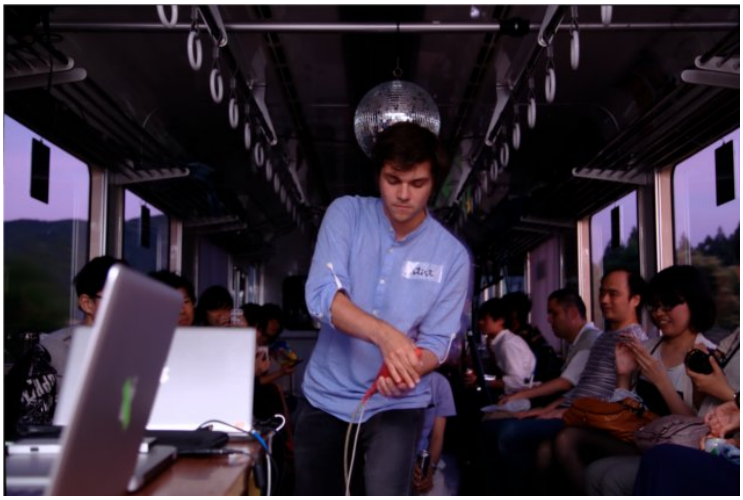


Fig. 5.41: *Live at IAMASONIC / Club Train, Gifu (JP).*

6.2.2 Physicality

Playing SculpTon requires to performer to develop a physical engagement with interface itself. Flute player Jim Denley describe that this happens also with 'traditional' instruments: "*For the improvisor the physicality of producing sound (the hardware) is not separate to the activity to the thoughts and ideas in music (software). In the act of creation there is a constant loop between the hierarchy of factors involved in the process. My lungs, lips, fingers, voice box and their working together with the potentials of sound are dialoguing with other levels which I might call mind and perception*" [Denley 1991].

Then, *physicality* can be consider as a crucial important element in solo improvisation with SculpTon, and it's actually quite crucial. This was highlighted mostly by some audience comments, such as "*you looks like Jimi Hendrix*" (MNAC, Bucharest). One interesting comment was articulated in this way: "*SculpTon reminds me of a musical version of eXistenZ, organic and alien, and when he performs, it looks like both artist and instrument completely merge into one and simultaneously struggle with each other*" (Dokapi, Linz).

6.2.3 The performer, the music, the interface

By taking into account this particular mix of theatrical and musical aspects can be the way of evaluating the performances with these instruments. There is always a connection between gestural, musical and visual aspects. I think that is not possible to separate them.

Again Bailey points out an interesting element: "*some playing* (…) *has produced some remarkable, even spectacular, performances, usually of a dense, furiously active nature: a panic of loneliness; a manic dialogue with the phantom other; virtuosic distortion of natural bodily functions unequalled since the days of Le Petomaine*" [Bailey 1992].

There is also a risk in this approach, such as the one highlighted by Gavin Bryars: "*in any improvising position the person creating the music is identified with the music. The two things are seen to be synonymous. The creator is there making the music and is identified with the music and the music*

with the person" [Bailey 1992].

This physical, corporeal unity of the performer and the music can be seen as a possible problem. Some members of the audience noticed that, as a solo instrument, SculpTon is quite one dimensional, both sonically and visually (Ars Electronica Festival, Linz).

This suggested me some future improvements in the sound synthesis, as well as in the visual feedback. Using the interface with other instruments can also a possible option that I'm are taking into consideration.



Fig. 5.42: *Live at MNAC, Bucharest (RO).*

6.2.4 Public response

As I said before sometimes (for instance at Ars Electronica Festival and Victoria Art Center) the device was also offered to the public for an hands-on experience and evaluation.

Most of the first questions of the audience were: "This a device ? A music instrument ? What is about ?", and especially "in which way have to use and /or playing with it?".

One of the main reason is mainly due to the physical appearance of the interface in the visual and haptic aspect. At a first look the interface appears fragile, and gestures such as squeezing, stretching are not viewed as suitable for music making.

Usually I'm starting to show some little gestures, for example the one used for producing a short

or a long sound, how can stop it and which modifications can be performed. After this brief demonstration people started very quickly to make sense of the interface and understand its idiom.

At first, many people were concerned with questions such as "I'm not going to break it ?"

During this hands-on session I had the possibility also of proving the reliability and efficiency of the whole system.

Apart from some little breaks on the latex surface, the entire structure and all of the components remain stable and no problem was encountered. For instance, approximately 100 people tried the SculpTon interface during the four days of the Ars Electronica Festival, so the entire artifact was exposed to a lot physical stress.

A discussion with the audience highlight that technology is always associated with ideas such as 'efficiency', 'stability', 'reliability' that are manifested with qualities such as hardness.

In the case of SculpTon another elements has been introduced. The interface is not only a new device but also a new compound / computational material. The audience have to make sense also of a new material that is not a real one (for instance clay, sponge, fabric) but with totally unique tactile and physical qualities. Most of the comments where "*it's strange*", "*particular*", "*weird*", "*horrible*", "*I like it…but I'm afraid of touching it*".

For some people the interface was kind of scary, or they feel not so comfortable to try. Most of them were actually afraid of breaking something, for some others the texture of the object was not very appealing.

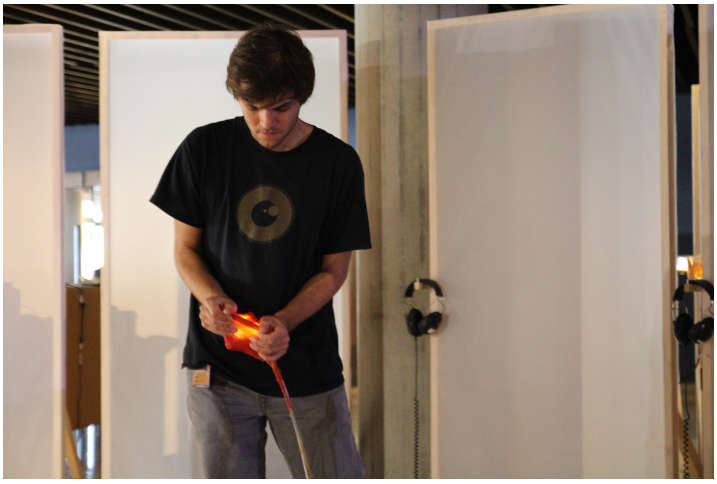


Fig. 5.44: *Live at Ars Electronica Festival, Linz (AT).*

6.2.5 Gesture to speech

For the audience the main idiom of SculpTon seems to be the coupling between manipulative gestures, a malleable electronic device and an artificial speech-like sound.

During different evaluation sessions (such as at Ars Electronica and MNAC) a common comment was "*seems that you are torturing someone!*".

This gave me the possibility of considering another particular aspect of SculpTon that goes probably beyond the idea of music expression or sound control and production.

It's a link between pain and enjoyment, which emerges from the relation between manipulative gestures and the production of an artificial voice. The interface is invested of different meanings and was describing it with terms used for addressing feelings normally associated with living beings, and not with musical instruments: pain, joy, anxiety.

In some of his writings and interviews Michael Waiszvisz was referring very often to puppetry [Wanderley and Battier 2000] [Norman et al. 1998], as an example of physical and mental engagement between a performer and an interface in live performance. He introduced also the idea of *animistic interfaces*[63], which unfortunately was not exposed in details.

During my live improvisations with SculpTon I started to think very seriously about this

63 http://www.chi2005.org/program/prog_closing.html

possible relation between musical interfaces and puppetry, but some more investigations on this topic must be taken.

One of the main reactions of the public is enjoyment, that was expressed mainly through laughing. In a private conversation, the composer and professor Masahiro Miwa has defined SculpTon as a "*comic interface*".

This element of comedy in the performance is especially reinforced by the way how SculpTon is being played. This is a relatively small interface, held in the hands that requires a lot of hands and corporeal movements in order to be played.

7. The possible impact of Malleable Interfaces for Musical Expression

Usually musical interfaces are designed for a unique user; this is also the story of acoustic, classical and folk instruments. But as we already saw the framework of TUIs introduced the possibility of collaborative and sharable interfaces. Already some examples of malleable tangible interfaces [Piper et al. 2002] [Watanabe et al. 2007] [Reed 2009] have showed that those kind of interfaces are suitable for collaboration and they are promoting it very well.

I believe that this is an important step to take into account for future developments and works. Some musical TUIs such as the ReacTable [Jordà et al. 2004] represents a very interesting examples of a shared interface for group playing.

The next step in the context of Malleable Tangible Interfaces for musical expression is also the design of new materials suitable for this. Introducing malleability as a fundamental material quality opened a more organic, expressive and explorative interactions. During the presentation of the first prototype at the TEI Conference some attendances said "*this is really what we called tangible interfaces!* (…) *you can really touch and manipulate it*" (private conversation with the author).

Maybe malleable tangible interfaces can be considered the main aspiration, or also a stereotypical idea of TUIs. Especially during my presentation of SculpTon at TEI Conference I heard many researchers and designers said that they have been thinking for many years about making a malleable interface for musical expression (private conversations).

In conclusion, SculpTon is not an ultimate interface that solves the problem of expressivity in tangible musical interfaces. It's more a project that opened different possibilities of new directions and it still posing a lot of research questions.

Project documentation

This project was initiated within the "Tangible Interfaces" class (Summer Semester 2012) of Prof. Martin Kaltenbrunner at the Interface Culture at the Kunstuniversität Linz.
The first prototype was documented through some internal reports and presented at the end of the class.
The second prototype was then presented at the TEI Conference 2013 in Barcelona. This version of SculpTon was presented at the "Work in progress" section [Boem 2013], together with a poster and a demonstration at the FabLab Barcelona. The paper was published in the digital and online proceedings of the conference[64].
The final version was presented in September 2014 at the Joint ICMC + SMC (International Computer Music Conference + Sound and Music Computing Conference)[65] in Athens. The paper was presented in the special session "Dematerializing - Rematerializing: Tangibility in Computer Music" with an oral speech. The paper was then published and included in the official proceedings of the conference [Boem 2014] .
Besides these academic publications, the project was fully documented and be publicly available in a dedicated website[66], and in the personal web page of the author[67].

64 http://www.tei-conf.org/13/wip
65 http://www.icmc14-smc14.net/
66 http://sculpton.tumblr.com/
67 http://www.albertoboem.com/index.php/project/sculpton/



Fig. 5.43: *Live at MNAC, Bucharest (RO).*

Performances, demonstrations, presentations

Push.Conference, Munich (DE), 10 - 11.10.2014

ICMC + SMC Conference, Athens (GR), 14 - 20.09.2014

IAMASONIC / Club Train, Gifu (JP), 12.06.2014

IAMAS – Institute of Advanced Media Arts and Science, Ogaki (JP), 7.04.2014

"Noise Cocktail Night", Dokapi, Linz (AT), 22.04.2014

MNAC - National Museum of Contemporary Art, Bucharest (RO), 7.03.2014[68]

"Use At Your Own Risk", Victoria Art Centre, Bucharest (RO), 6 - 26.03.2014[69]

68 https://vimeo.com/88884450

69 http://www.interface.ufg.ac.at/blog/bucharest_exhibition/

"Tag der offenen Tür", Kunstuniversität Linz, Linz (AT), 22.11.2013

ARS ELECTRONICA FESTIVAL 2013, Linz (AT), 5 - 09.09.2013[70]

TEI Conference 2013, Barcelona (SP) 10 – 13.02.2013

Media and press

IAMAS News (JP), 14.06.2014 (Concert review)[71]

Digi24, Bucharest (RO), 17.03.2014 (TV show, interview)[72]

Radio Romania Cultural, Bucharest (RO), 6.03.2014 (Radio show, interview)[73]

Dimineata Crossover, Radio Romania Cultural, Bucharest (RO), 5.03.2014 (Radio show, interview)[74]

D'Ars Magazine (IT), 20.09.2013, (Review)[75]

Artribune (IT), 19.09.2013, (Festival report)[76]

DORF.TV, Linz (AT), 9.09.2013, (Tv show, interview)[77]

Radio FRO, Linz (AT), 10.09.2013 (Radio show, interview)[78]

Artribune (IT), 3.09.2013,(Mentioned)[79]

70 http://www.aec.at/totalrecall/en/2013/07/29/campus-exhibition-interface-cultures-use-at-your-own-risk/
71 http://www.iamas.ac.jp/9759
72 http://www.digi24.ro/Emisiuni/Digi24/Digicult/Secvente+emisiune/Arta+pe+propriul+risc
73 http://www.radioromaniacultural.ro/use_at_your_own_risk_expozitie_de_arta_interactiva-12336/
74 www.albertoboem.com/files/Dimineatacrossover.mp3
75 http://www.darsmagazine.it/ars-electronica-2013-use-at-your-own-risk/
76 http://www.artribune.com/2013/09/arte-elettronica-report-dal-festival-piu-importante-al-mondo/
77 http://www.dorftv.at/video/7835
78 http://www.fro.at/article.php?id=6644
79 http://www.artribune.com/2013/09/ars-electronica-a-linz-al-via-la-27esima-edizione-e-questanno-il-festival-austriaco-vanta-anche-una-buona-quota-di-artisti-italiani/

Conclusions

The research presented in this dissertation has focused on the description of the theoretical foundations, the design and development of SculpTon. This work is situated inside one of the contemporary direction of Tangible User Interfaces (TUIs), but its also deeply intertwined in the frame of New Interfaces for Musical Expression (NIME).
The aim of a project such as SculpTon is exploring the possibility of merging these two fields of research through the renovated attention on the materiality of the interface, especially when materials are becoming media [Fuchsberger et al. 2013]. One of the main characteristics of this project was to explore the potentials and highlight the limitations of malleability in tangible interaction, for reach a sculptural approach not only as a physical action, but also as a musical gesture.
During this last chapter some conclusions will be drawn by analyzing the limitations in design and usage of SculpTon and some future implementations will be discussed.
Then, some open research questions will be formulated, by imagining some possible scenarios that goes beyond SculpTon but they are starting from it, and finding in it their foundations.

1. Limitations

Apart from some limitations already mentioned in the previous chapter, it's important to highlight and discuss in details the possible improvements some open issues.

1.1 Sonic and visual limitations

As already mentioned in Chapter 5, one of the first criticism moved to SculpTon was resulting either visually and sonically results to be unidimensional.

Firstly, the the object, thanks to an internal light system, is visible either half-darkness situations. This create a simple effect, that is highlighting the object among the performer and the environment. At the moment the visual feedback is only limited to inform the user about the state of activity or inactivity of the object. More work must be conducted to elaborate better this element.

For the user playing SculpTon means to not rely on any additional display or screens but only to the object itself and its tactile and physical characteristics.

On the contrary, if visually the impact is limited, the unidimensionality of the sound is identified in this way mainly because the level of complexity reached by sound models, softwares, sensors and computation is leading to a vast explorations of sonic spaces and the interaction with multiple agents, sampling, looping and other techniques are common for digital and electronic musicians.

Despite these considerations, the aim of SculpTon was to pursue another goal, that is the possibility of reaching and high level of embodiment, and a meaningful coupling between the interface physical properties and the sound model. This represents a real risk if the performance is perceived as unidimensional that means that the music produced with such interface was not interesting or attracting for some spectators.

One solution can be to adapt SculpTon to another sound model, or at least changing the mapping; but, as Jordà [2005a] noticed, if the mapping between the interface and the sound model change, also the nature itself of the instrument itself is changing.

I tried to overcome this limitations by using an external sampling and looping machine during the live performances for creating more sound levels that can go from rhythmical to melodic. According to some feedbacks received from the audience this seemed to be a good solution.

1.2 Design limitations

One of the initial goal of SculpTon was to create a malleable interface that can be handled by

the user. The artifact was then design and build following this idea, to make a device that every person can use, with limited dimensions and volume, in a reasonable size that can be used with one or two hands.
Another important factor in the decision about the size and the dimension of the interface were the sensors. As I already described in Chapter 5, commercial sensors have limitations in size, and also the ones developed especially for SculpTon have better range of action, but they are also quite limited in size. Due to these factors, it was difficult to imagine a bigger object.
Also, thinking about the gestures that can be applied to the surface, such as stretching, there is an high probability that with a larger surface not every person will able to manage with the lengthening of the of the object.
If those considerations are a result of some empirical studies and many iterations, one of the biggest problem related to a situation such as the of SculpTon is the difficulty of correcting possible mistakes in the internal side of the object. The internal structure and all of the hardware components and connections are placed under the latex hull.
For repair some internal broken wire or adjust a sensors, it is required to cut the latex cover and then replace it with another one. Even if the material itself is not very expensive, it requires some days of hand working for creating a new latex skin. This can represent a possible problem that can generate some negative consequences if the damage appear, for instance, before a live performance.
Interfaces such as SculpTon that are subject to a strong physical stress and continuos manipulations, need to consider carefully this aspect.
One of the major studies and future work will certainly include the research and development of more adequate computationally augmented malleable materials suitable for hand's manipulation.

1.3 Sensors limitations

The third critical element present in SculpTon regards the resolution and the stability of the sensors network. Even if the one present in the actual version of SculpTon are not particularly problematic, some latency and little malfunctions are becoming noticeable after a period of

usage. They present some jittering and sometimes are giving some imprecise measurements. A possible solution to this problem can be a further improvement of the actual sensor modules. Probably only some little adjustments together with a better design, are needed for achieving some more stable and accurate results.

Alongside with those improvements on the hardware side, it's important to consider also some on the software side. Processes such as data scaling and filtering, can be designed in more efficient way.

If hardware and software improvements can refine and develop the potentials of SculpTon, another important work to consider regards the sensor modules and their fabrication. At the actual stage, those sensors are easy to create and assemble, but they are not designed for being freely combined in different forms. This represent one of the main future development concerning the idea of "*sensing through structure*". Different design solutions must be evaluated in order to produce some scalable and independent modules ready for being assembled together. Only in this way it will be possible to prove if the approach adopted in SculpTon can be applied in different contexts for building new malleable interfaces.

Other topologies and relations must be investigated, mostly for experimenting to which interactions they are leading, which one can be the much stronger, and which one the meaningless.

2. Research questions and some notes for the future

The theoretical and practical work developed around SculpTon have opened the doors to many questions and open scenarios.

Besides improving different elements of the interface, some other works should be conducted for exploring different possibilities about malleable media.

In this last section I will try to expose which are the most interesting and fundamental questions that are surpassing the work described in this thesis, and opening up new possible scenarios that must be investigated.

- If malleability is identified as one of the main qualities of the digital world and digital informations, why we relate to it with rigid artifacts and interfaces ?

  If synthesizers should be used like clay [Rosenboom 2014], and live sound processing can be interpreted as sculpting [Tanaka 2001], why we have still to move knobs, sliders, computer mouses and using other rigid devices ?

  Apart from our body, that is flexible and adaptable, we are still relying on rigid devices. As I already mentioned, the difference between rigid and flexible devices are the affordances that they generate, their invitation to an action [Norman 2004]. Affordances can be viewed as a configuration of properties that invite a direct link between perception and action. In his seminal work, Gaver [1991] have been exploring the particular aspect of "*technology affordances*", through his famous example of the handle, he demonstrates that also the sense of touch and sound as are conveying information for affordances not based on the visual cortex [Gaver 1991].

  Tanaka, Altavilla and Spowage [2012] have proposed an experimental study about gestural music affordances, by analyzing which kind of actions are inviting different devices together with different sounds. They highlight that the construction of affordances in gestural musical instruments is a very complex task, because of the particular mix of high technological artifacts and advanced softwares. This is true if we are considering mobile phones, tablets, interactive surfaces. It is also important to underline that the idea of affordances it's also a cultural construct, which makes things even more complex.

  My investigation into malleable media for musical interaction was employing a different approach. Instead of creating an interface, I was thinking on creating a material, characterized by some particular affordances, and combining of visual, tactile, and auditory informations.

  I'm proposing an extended investigations about the materiality and physicality of the interfaces used for music making, and to rethink their design and conception from this point of view.

  In an contemporary situation, characterized by the availability of transducers, speakers, PA systems, adequate sound processing techniques, and machines for performing calculations, we can imagine to stop to worry about the output (the sound) and think

more about the experience of playing an interface.

Recent studies have highlight the importance of studying in which ways people hold and handle different shaped objects [Sheridan and Kortuem 2006]. Those kind of studies can guide us in the design of physical forms for interactive purposes. Variation in size, shape and material of an object affect the ways in which users handle it. Rapid prototyping and digital fabrication techniques can help in this process, or at least they can facilitate it.

One of the possible future investigation should regards the possibility of thinking and designing a musical interface not only as a group of sensors used for capturing specific gestures but, mostly, to which kind of affordances they are offering to us.

Getting engaged with materials, through their physical qualities can led to more expressive musical interfaces ?

In this case, I believe *malleability* can be a starting point that can be extent in many directions.

- The contemporary focus on dynamic materials in the area of Tangible User Interfaces, is focused on Shape Changing interfaces, especially displays. Musical applications are still left behind. Programmable affordances and behavior are two new aspects that started to be explored by artists and interface designers. Researcher Annie Luciani, which together with Claude Cadoz a pioneer in the the of force feedback devices for musical applications [Cadoz et al. 2003], think that this possibility will affect, and probably changing, our perception about technological devices, and the artificial in general [Luciani 2014].

  It's legitimate to imagine that programmable matter will probably affect also the area of musical interaction, can change the idea of musical interfaces, especially by challenging the definition of 'controllers'. With those new materials, the separation between a 'controller' surface and a 'controlled' process can drastically loose its importance.

  Which can be the consequences, in musical interaction, of surfaces that are changing their affordances according not only to the input received, but also to the process that they are going to influence ? Currently, the answer can be: we don't need them, it's about sound, it's not about matter.

For decades electronic and computer musicians have employed genetic algorithms, Neural Networks, audio and visual feedback for simulate (and stimulate) the emergence of a behavior in live musical performances and real-time interactions. But, the interface was never invested by this element, only the musical process. We are still talking about gesture acquisition, gesture recognitions, control parameters. Even if the agenda of TUIs and its emphasis on embodiment and physicality started to be considered as an important topic in the computer music community, seems that this topic started to be addressed only by few researchers in the area of haptic interfaces.

The possibility of programming matter and make it reactive to digital processes is going probably to change also our idea about computation and computers in general, not only of physical artifacts.

It's important for artists working that with computer music to explore and sketch some new scenarios. The community of artists and researchers in the area of NIME are emphasizing the role of engagement and presence as a quality promoted by 'traditional' musical instrument in opposition of new ones.

If we thinking about *dynamic materials* it's possible to imagine that the possibility of having a reactive interface that is changing and adapting its affordances according to different elements (eg. sound characteristics, events, processes, gestures) can promote a sort of collaboration between the interface and the artist, where someone is really invited to react and do something. Similar to acoustic instruments, the possibility is the one of getting engaged with material's properties their behaviors. Michael Waisvisz noticed that even "*a string is a pretty wild thing and it takes a while to come to grips with it; you learn to engage with it. A real player knows that it will never be fully under control, and the art is somewhere in the middle*" [Dykstra-Erickson and Arnowitz 2005] .

Getting engaged with a material rather then with a group of sensors can reinforce, promote and allow more human activity, more enjoyment, and let to more expression. And if the interface will be programmed for generating several affordances, the music composition can evolve also through this aspect, that is the invitation to different physical actions. In this way seems possible to surpass elements such as mapping and gesture recognition. By changing its physical state, the interface open new doors for new gestures, not only for one. There can be more rooms opened for expression. And the process can be reversible.

> Regarding this aspect of *dynamic materials*, Akira Wakita evoked the idea of "*flow*"[80]: I believe that this is a fundamental point.
>
> When the performer is not only absorbed into the sonic flow, but also in a physical one, "*trapped into the haptic groove*" [Waisvisz 2003], the human expression can emerge better and be stronger, together with a major impact.
>
> This is the starting point of a profound and challenging interactive process: a continuos collaboration, a continue negotiation between a person and something else. A relation that can create something, profoundly human, even with and through computation.

Being conscious that we are far from this situation, and some more research and work must be conducted into the area of programmable matter and dynamic materials, it's important if even crucial for artists and performer starting to imagine and prototyping future scenarios.

The community of artists and designers can also contribute to the open access and creative use of those techniques, otherwise only accessible for scientists and corporates research labs.

Like in many other period of the history, music can be a leading and exiting field of experimentation and research for driving technology into something more human, such as expression.

80 http://xd.sfc.keio.ac.jp/en/features/2012/interview-wakita/

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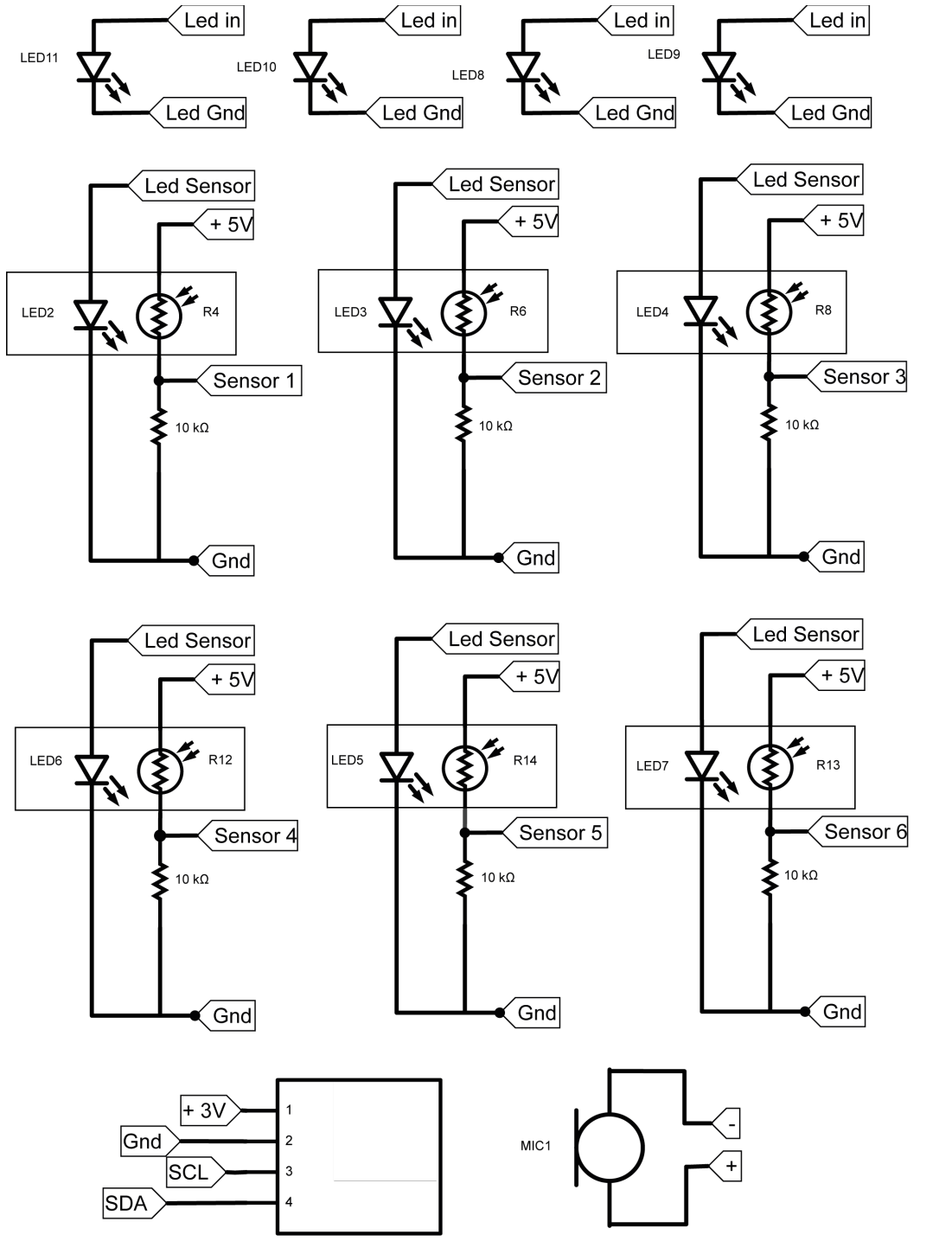
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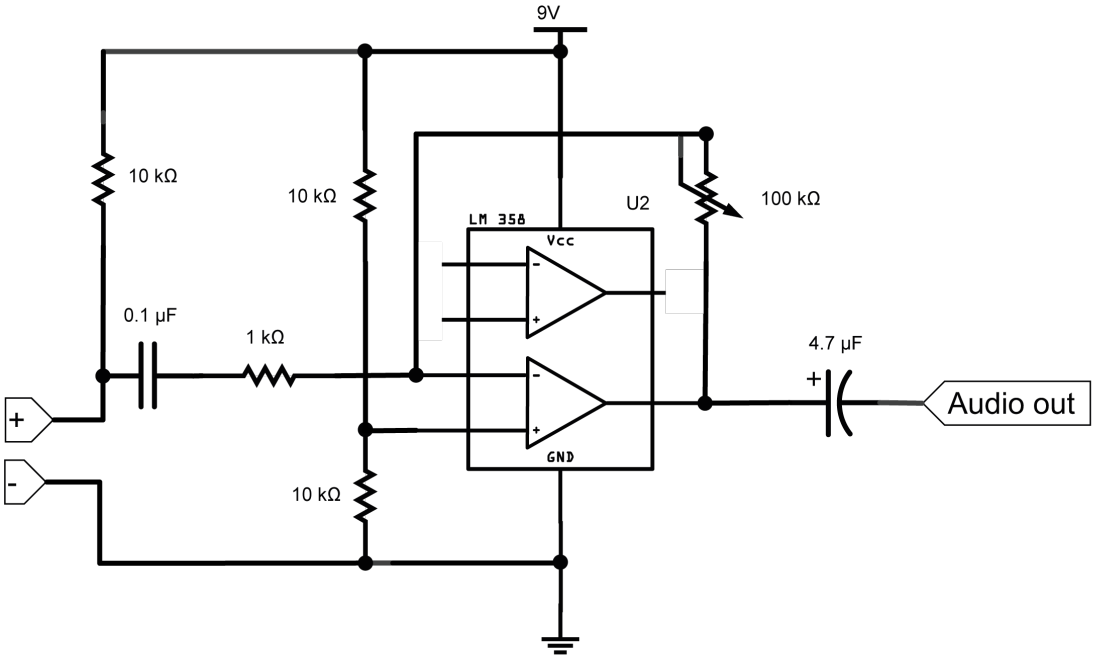
Appendix 1

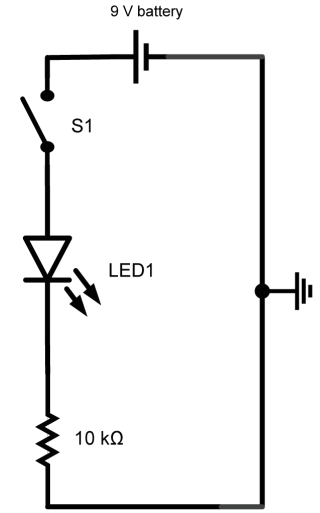
SculpTon : circuit schematics



Schematic for the sensors placed inside the Sculpton controller		
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Filename	SculpTon controller	Rev
Date	17 feb 2014 15:10:04	Sheet 1/3

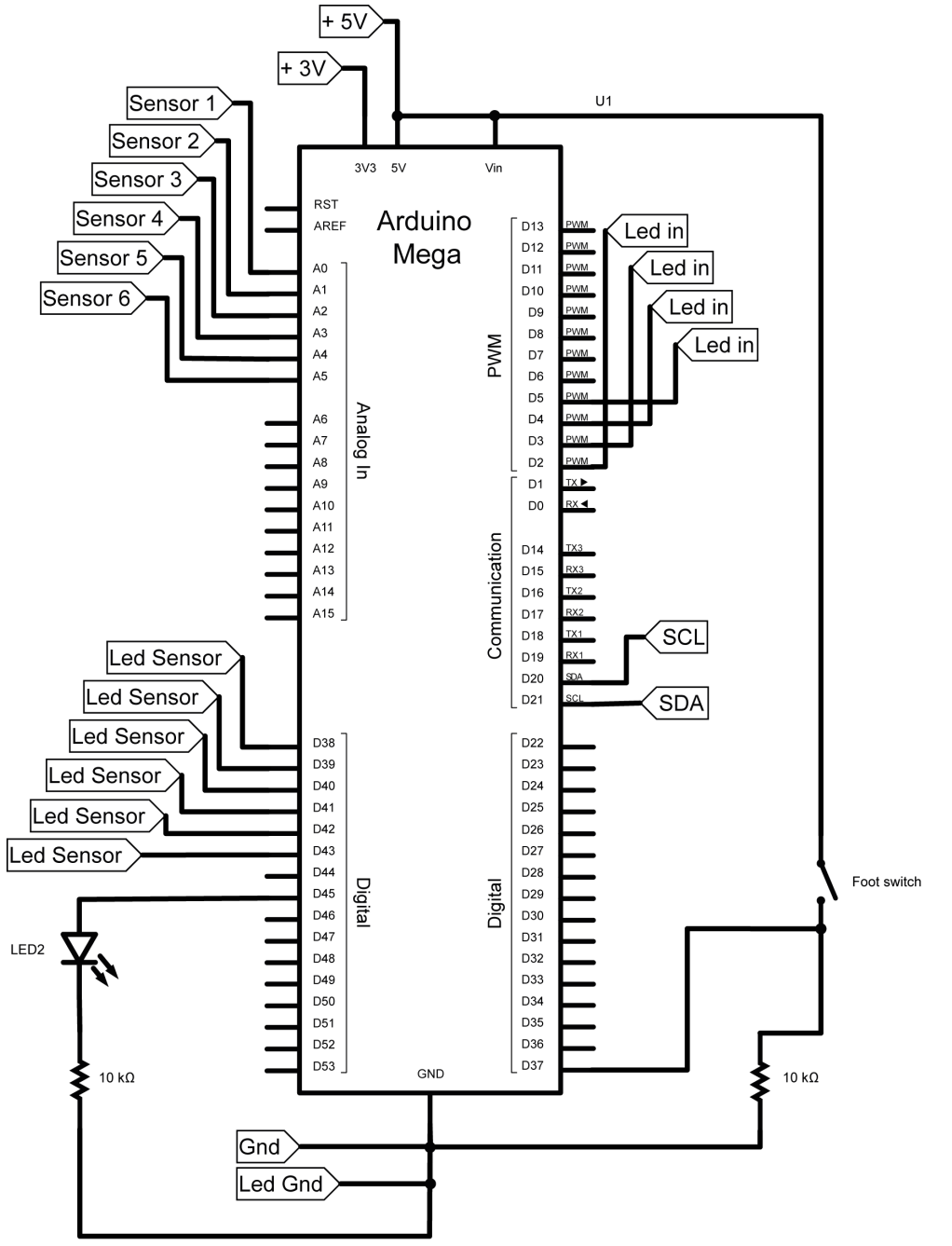
Made with Fritzing.org





Audio amplifier for electret microphone		
Project	SculpTon	
Filename	Amplifier	Rev
Date	17 feb 2014 18:11:33	Sheet 2/3

Made with Fritzing.org



Schematic of the : Arduino shield, and the stompbox		
Project	SculpTon	
Filename	SculpTon - Arduino shield	Rev
Date	17 feb 2014 16:10:14	Sheet 3/3

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Appendix 2
DVD – Additional materials

1. SculpTon circuit schematics;

2. SculpTon Arduino Mega shield layout;

3. SculpTon code for Arduino (plus external libraries);

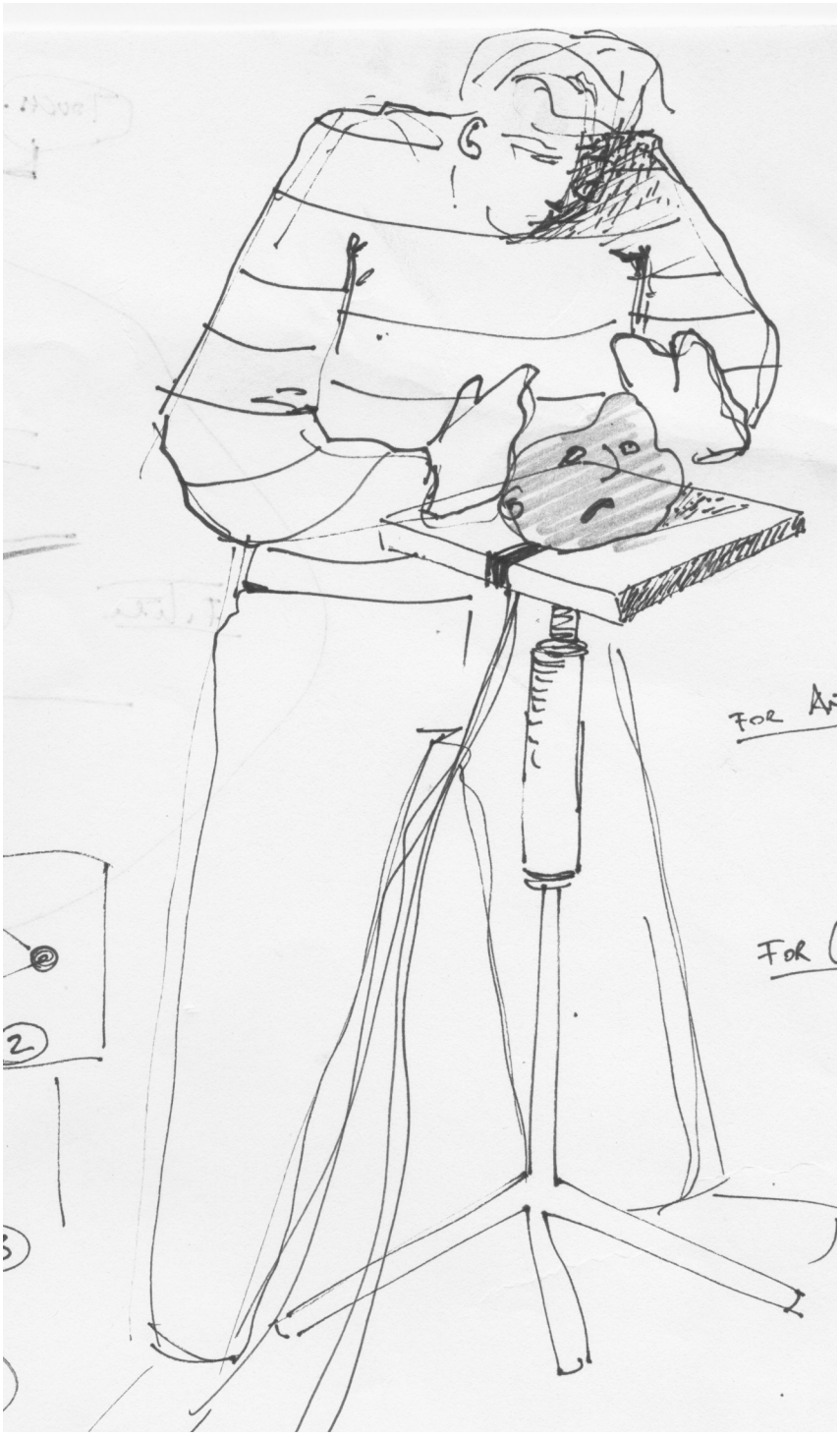
4. SculpTon software for Pd-Extended (plus additional externals);

5. A text file that contains all of the informations for understand the hardware and the software, and the complete instructions for using them;

6. Publications :

   BOEM, A. 2013. SculpTon: a malleable tangible object for musical expression. In *Proceedings of the 2013 International Conference on Tangible Embedded and Embodied Interactions* (TEI'13), New York, NY: ACM.

   BOEM, A. 2014. SculpTon: A Malleable Tangible Interface for Sound Sculpting. In Proceedings of the Joint ICMC +SMC, San Francisco, CA: ICMA, pp. 737-743.



Concept, Alberto Boem (Linz, June 2013).



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