STRESS:
A TACTILE DISPLAY USING LATERAL SKIN STRETCH

Jérôme Pasquero
Department of Electrical and Computer Engineering
McGill University, Montreal

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ABSTRACT

This thesis describes a new tactile display device (Stimulator of Tactile Receptors by Skin Stretch or STReSS) exploiting lateral skin stretch of the fingertip to create tactile sensations. The device consists of an array of one hundred piezoelectric bending actuators applying local strain patterns on the user's fingertip. It was found that manufacturing the piezoelectric material in a comb shape facilitates the device's fabrication process, allows for a spatial resolution of one actuator per mm^2, and guarantees high structural strength for the display. Simple but creative electronics drive the system at a 700 Hz refresh rate and keep the device compact and portable. The tactile display's manufacturing process and the controlling electronics are described. Finally, some tactile sensations experienced with the display are reported informally.

RÉSUMÉ

Cette thèse présente le STReSS (« Stimulator for Tactile Receptors by Skin Stretch »), un nouvel afficheur tactile qui stimule la peau du bout du doigt par étirement latéral. L'afficheur consiste en une matrice de cent actionneurs piézoélectriques qui, en se courbant, appliquent un modèle de contraintes locales sur le bout du doigt. Le matériau piézoélectrique est usiné en forme de peigne afin de faciliter le procédé de fabrication, pour obtenir une resolution spatiale d'un actionneur par mm^2. Ceci assure aussi une bonne solidité structurelle de l'appareil. Afin d'être aussi compact et portable que possible, l'afficheur tactile est controlé par un système électronique très simple qui rafraîchit les actionneurs à 700 Hz. Ce système électronique, ainsi que le procédé de fabriquation de l'afficheur tactile, sont décrits en détails. Pour finir, quelques sensations tactiles ressenties avec l'appareil sont brièvement rapportées.

AKNOWLEDGEMENTS

This thesis covers a little bit of everything that I've learned and done during my master's studies at the McGill Haptic lab. It goes without saying that most of the credit goes to my supervisor, Professor Vincent Hayward for his unconditional support. The countless hours spent in his company in front of the black board discussing ideas and coming up with new design solutions is probably the strongest memory that I will keep from my master's studies.

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GLOSSARY OF ACRONYMS

ASIC: Application Specific Integrated Circuit

DAC: Digital to Analog Converter

DOF: Degree of Freedom

FIFO: First In First Out

FPGA: Field Programmable Gate Array

FTD: Fingertip Tactile Display

GUI: Graphical User Interface

JND: Just Noticeable Difference

MFC: Microsoft Foundation Classes

OS: Operating System

PC: Personal Computer

PGM: Portable Gray Map

PLD: Programmable Logic Device

PWM: Pulse Width Modulation

RA: Rapidly Adapting

SA: Slowly Adapting

SMA: Shape Memory Alloy

STReSS: Stimulator of Tactile Receptors by Skin Stretch

TD: Tactile Display

USB: Universal Serial Bus

CHAPTER 1: INTRODUCTION

"Touch each object you want to touch as if tomorrow
your tactile sense would fail"
Helen Keller

This chapter gives an outline of what is covered in this thesis and quickly introduces the haptics world.

1.1 THESIS OUTLINE

This thesis describes a new type of tactile display (TD) named "Stimulator of Tactile Receptors by Skin Stretch" (STReSS) for use with the fingertip. A condensed version of the information contained in this document was published in (Pasquero & Hayward, 2003)[1].

Chapter 1 consists of a quick introduction to show the importance of the sense of touch in our daily interactions. This and the fact that technology has greatly improved in the last few decades leads to the realization that commercial haptics devices might start to be useful to the general public.

Chapter 2 reviews basic findings about skin and describes different methods for creating tactile information. From this knowledge, guidelines to design a comprehensive fingertip tactile display (FTD) are suggested. Subsequently, an extensive review of the state-of-the-art FTDs is carried out. Finally, the motivations for the implementation of the STReSS device are explained and the design requirements are stated.

Chapter 3 describes the STReSS specifications in detail. It is meant to be a reference guide for anyone who wants to replicate the device. The STReSS's characteristics are stated.

[1] In fact, section 4.2 that reports on preliminary results with tactile stimuli is identical in the paper.

Chapter 4 reports basic tactile stimuli tried on the STReSS and describes the resulting perceived sensations. Only informal observations are made

Chapter 5 concludes the thesis by suggesting possible future improvements to the design. It stresses out the importance of carrying further research and experiments on lateral skin stretch, following the interesting results obtained with the simple tactile stimuli described in chapter 4.

1.2 TOUCH AND COMPUTERS

At the end of the 19^{th} century, Helen Keller was nineteen months old when she was struck with an illness that left her deaf and blind. Surmounting her handicaps, she would still manage to become an inspirational writer, living a full and successful life. Helen Keller's only link with the outside world however, was through the sense of touch...

Touch is often believed to be less important than vision and hearing. One explanation follows from the fact that the sense of touch is less attended to than the senses of vision and hearing are. Yet, without even noticing or be conscious of it, humans continually explore the neighboring world by touching it, in order to maintain a constant awareness of where they are and of what surrounds them.

The sense of touch is ever present in our daily interactions, even with computers. Whether it is to use a keyboard, a mouse or any other manual peripheral, it is necessary for a user to use touch. However, human-computer communication is unidirectional. Computers return information to a user visually and, in some cases, through sound, but very seldom through touch. The advances in technology in the last few years, however, now permit the development of new bi-directional haptics computer peripherals.

Haptic devices can be classified into two distinct categories: Net force devices and tactile distributed devices. Haptics relates to kinesthesia and touch. Kinesthesia refers to the sensations of motion and force arising in muscles and joints when the body is interacting with the outside world. Touch relates to sensations mediated by the skin such as contact indentation, vibration, temperature and stick/slip. The work presented in this thesis is a step toward the creation of a practical distributed tactile display that can be included in a computer peripheral.

CHAPTER 2: TACTILE DISPLAYS

"At the touch of love, everyone becomes a poet."
Plato

This chapter gives an overview of what needs to be known when designing and implementing a tactile display. It describes the basic properties of touch, covers the different means of coding tactile information, provides design guidelines, and goes through a review of state-of-the-art technologies used in tactile displays. Finally, it states the motivations and requirements for the STReSS device.

2.1 SKIN PROPERTIES AT THE FINGERTIP

Designing a tactile display requires a basic understanding of the skin tactile function. Skin is the largest organ in the body in terms of surface area. It is the body's only external sensor that is not localized. The skin surface of an average sized adult (1.8 m^2) is 1000 times that of a retina. Tactile information from the outside world arising from contact with objects is sensed and encoded by the skin mechanoreceptors before being sent to the brain by neural impulses.

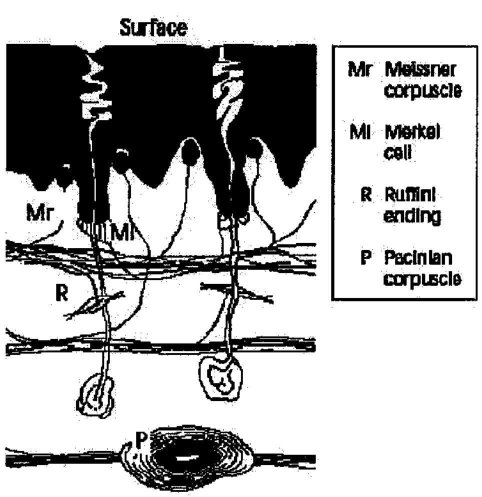

Figure 1: Mechanoreceptors of the skin at the fingertip[2]

[2] Courtesy [Asamura et al., 1998]

Four types of mechanoreceptors are found in glabrous skin (refer to Figure 1): Meissner corpuscles, Merkel cells, Ruffini endings and Pacinian corpuscles. A complete description of these mechanoreceptors is beyond the scope of this thesis (for a detailed description see (Johannson, 1976)). However, an understanding of their specificity in response to different stimuli is useful to build a meaningful tactile display.

Table 1: Summary of mechanoreceptor properties

Mechanoreceptor	Type	Most important stimulus	Type of response	Principal functions
Meissner corpuscle	RA I	Low frequency vibration (Tapping)	Transient	Detect low frequency motion and discriminate spatial localization
Pacininan corpuscle	RA II	High frequency vibration (Buzzing)	Transient	Detect high frequency motion and detect traveling of mechanical vibrations
Merkel disk	SA I	Perpendicular indentation (Pressure)	Sustained	Distinguish pressure magnitude and rates of change in pressure.
Ruffini ending	SA II	Tangential displacement (Friction and stretch)	Sustained	Perceive skin stretch and discriminate spatial localization

Mechanoreceptors may be categorized according to two characteristics: their adaptation rate to a stimulus (Rapidly Adapting [SA] vs. Slowly Adapting [RA]) and the size of their receptive area (type I for a small well defined receptive field vs. type II for a large receptive area with poorly defined boundaries). It is also possible to classify the mechanoreceptors by the stimulus to which they respond the most. It is usually presumed (but there is no proof of it) that:

- SA I units (Merkel disks) respond most to perpendicular skin indentation,
- SA II units (Ruffini endings) react most to lateral stretch,
- RA I units (Meissner corpuscles) are most sensitive to vibrations at low frequencies (5-50 Hz) and
- RA II units (Pacinian corpuscles) respond most to mechanical vibrations at high frequencies (50-1000 Hz).

A summary of the mechanoreceptors is shown in Table 1.

Skin's highest sensitivity occurs at the fingertip where the spatial resolution is around 1 mm. This resolution corresponds roughly to the spacing between peripheral mechanoreceptors (Philips & Johnson, 1981). Vibrations are perceptible up to 1 kHz with a peak response at 250 Hz (Verillo et al., 1969). The two-point discrimination threshold at the fingertip ranges from 1 mm to 2 mm. A persistent temperature over 48° Celsius or under 3° Celsius results in pain (Caldwell et al., 1996). When scanning a texture, contact force ranges from 0.3 N to 4.5 N and the scanning speed goes from 1 cm/sec to 25 cm/sec with an average of 2 cm/sec (Caldwell et al., 1999).

2.2 TACTILE INFORMATION

Tactile information created by devices includes both, the simulation of natural tactile percepts found in the real-world (e.g. the texture of a fabric) and the development of tactile stimuli used as a communication mean for human-computer interactions such as the haptics icons described in (MacLean & Enriquez, 2003) - e.g. the buzzing of a ringing beeper. Achieving the former involves having a clear knowledge of skin-surface interactions and means to extract the significant tactile variables from existing objects. Unfortunately there does not exist any comprehensive and practical model that describes from first principles what happens to the fingertip skin when scanning a texture. The latter, though, can readily be studied and experimented with. Moreover, natural tactile sensations tend to be complex, while efficient artificial stimuli can be very simple. Here, an analogy with audio information can be made. Modeling and synthesizing sounds is still an open challenge, while simple artificial sounds with no real-life correspondence have already been proven to be useful in human-computer interactions (e.g. audio beeps on a PC indicating that new mail has been received or that an illegal operation has been carried out). This shows the need to define primitive tactile stimuli. For example, in (van Erp, 2002), van Erp discusses tactile information coding for vibro-tactile displays. On a broader scope, tactile information can be coded with four tactile primitives:

- **Intensities:** For instance, by using the Just Noticeable Difference (JND), distinct actuator intensities (e.g. pressure for an electromechanical TD, temperature for a heat

TD, amplitude for a vibration TD), can be defined, just as it is the case with pixel values in digitized images.

- **Frequencies:** A range of frequencies up to a few kHz, the maximum frequency discriminated by humans, can be used to code information tactilely.

- **Spatial patterns:** Relative or absolute dispositions of the actuators can convey significant information. Computer Braille uses this principle to display arrangements of six or eight raised dots to represent symbols and characters (256 characters in the Unicode standard).

- **Temporal patterns:** Tactile patterns changing through time can display information the same way a movie displays movement. Temporal patterns are also characterized by the stimulus duration and the number of repetitions between delays.

Complex tactile signals, based on superpositions and combinations of the above coding primitives can lead to rich and useful tactile information. For instance, Rovan and Hayward have experimented with providing tactile sounds (i.e. audio sounds converted to tactile vibrations through a vibrotactile transducer) to musicians performing on open-air controllers (Rovan & Hayward, 2000). They found that varying audio style parameters such as the frequency, waveform and amplitude of the signal and relating these stimuli to certain gestural events (e.g. hitting on a virtual drum) provides the performer with useful tactile feedback.

2.3 REQUIREMENTS FOR A PRACTICAL FINGERTIP TACTILE DISPLAY

2.3.1 Unknown Factors

The slow development of fingertip tactile displays and their inexistence on the consumer market is greatly due to their poor usability. This can partly be explained by the numerous unknown factors that characterize the sense of touch. For instance, designing an optimal tactile display would require a precise knowledge of the skin's **biomechanics**.

Skin has the property of being tough and deformable at the same time (Vincent, 1991). This duality and the fact that mechanical skin properties vary from one individual to the other make it hard to define requirements for an optimal tactile display. Likewise, the skin's **neuroanatomy**, (i.e. the various roles, distribution and nature of the skin's mechanoreceptors) is still open for debate (Paré et al., 2002, 2003). Furthermore, **cognitive factors** such as learning, training and prior knowledge of the sensations experienced certainly influence touch perception. Finally, **psychological and behavioral factors** probably also play an important role in conscious touch perception. Previously published experiments on the behavioral response to skin stimulation have been carried out (e.g. skin stretch with a single contractor (Biggs & Srinivasan, 2002)). However there does not appear to be any published study reporting the behavioral response to a tactile stimulus formed of an organized time-varying strain field. This is probably due to the unavailability of a practical tactile display capable of creating such a stimulus. There is a clear need for a practical display to study skin's biomechanical, neuroanatomical and behavioral properties. Unfortunately, building such an efficient tactile display requires knowledge of these factors, and hence we are caught in a vicious circle…

2.3.2 Design Guidelines

Because of the unknown factors stated in the previous section, the conception of the STReSS prototypes reported in this thesis is highly empirical and iterative. Nevertheless, basic guidelines should still be followed. Considerations to take into account when designing and implementing a practical fingertip tactile display include:

Diversity of displayed stimuli. Most stimuli applied to the skin, such as tapping the skin with a small probe, consist of a superposition of multiple components: vibration components that stimulate RA units, normal indentation components that stimulate SA I units and lateral stretch components that stimulate SA II units. A practical device should be able to stimulate all four types of mechanoreceptors in order to display a variety of tactile sensations. Likewise, different modes of conveying tactile information, (see section 2.2), should ideally be supported by the tactile display so as to maximize the number of possible displayed sensations.

Actuators spatial resolution. It is generally accepted that the spatial resolution of the actuators should be approximately 1 actuator/mm^2 to get a continuous tactile sensation at the fingertip.

Display Area. Ideally, the FTD should be formed of a large surface area populated by a matrix of miniature actuators in order to create a "programmable surface". However, this is a practical challenge given the smallness of needed details. A possible solution is to have a small movable tactile window – say of 1 cm^2 - in constant contact with the fingertip while it is scanning the surface (e.g. a FTD mounted on a computer mouse).

Stimulus intensity. The device should be capable to display a number of distinct signal intensities in order to fully take advantage of the skin's subtlety and to transmit as much relevant information as possible. The JND method could be used to find the optimal number of intensity levels.

High temporal resolution. The FTD should be able to operate at different controllable frequencies ranging from 0 Hz to 1 kHz. Three sets of frequencies are of particular importance:

1. Frequencies below 20 Hz are mostly responsible for small-scale shape perception (Lamotte, 1987).
2. Maximum sensitivity occurs at frequencies around 250 Hz.
3. Frequencies around the limit of perceptible vibrations (around 1 kHz) are rich in tactile information and are usually believed to be responsible for the perception of micro-textures.

Power consumption and safety. A tactile device is a computer peripheral in direct interaction with the user. For obvious safety reasons, the device should comply with the International Safety Standard for Information Technology Equipment IEC 6095[3]. This

[3] UL 1950/CSA C22.2 950

issue is still a challenge today because the state-of-the-art actuators require a significant amount of power and the user's fingers are in direct contact with the tactile actuators.

Maintenance. Skin secretions such as oil and sweat are highly corrosive. With prolonged exposure, these secretions can severely damage a device. Moreover, small-scale actuators used in tactile displays tend to be fragile and delicate. A practical tactile display should be impervious to dirt and skin secretion. It should also be easily maintainable and reparable.

Texture/Shape. Ideally, FTDs should display small-scale shape and texture. Both are needed to provide a comprehensive representation of the surface under investigation. However, currently available actuators cannot provide large strain and force required for shape representation, as well as a large bandwidth and finesse required for texture representation, at the same time. A solution might be to combine a net force display with a distributed display.

Device cost. Tactile devices available on the market are very uncommon and expensive. Among the very rare are Braille displays such as the Satellite Braille display from Alva Corporation. Other devices, such as the Optacon from Telesensory have ceased to be manufactured. Their high cost can be explained in part by the complexity of the technology required to build high-performance tactile actuators. As a consequence, the evolution of such devices is very slow. Ideally, the price of a consumer FTD should only be a small fraction of the cost of the system that controls it, usually a personal computer.

Refresh rate. The sense of touch has a fairly high temporal resolution (between audition and vision). Moreover, it is highly adaptive. In other words, a prolonged stimulation, such as the wear of clothes on the skin, quickly fades away or modifies the perception of the stimulus. Therefore a dynamic FTD should be able to switch between different tactile signals at a high refresh rate.

Real-time issues. Operations involving tactile feedback, such as the exploration of a virtual texture using a tactile display mounted on a mouse, need to be carried out in real-time.

Usability. The ideal device should be comfortable and painless. Moreover, it should be small and flexible, meaning that for instance, it could be added to a glove. It should also produce minimal audible noise.

Active/Passive touch. Humans' tactile interactions with the real world consist of both active explorations (e.g. scanning a surface with a finger to determine its texture) and passive interactions (e.g. the feel of clothes on the skin). Active touch usually conveys more information than passive touch because the operation is guided (i.e. the subject employs heuristics to accelerate the identification process). Consequently, the optimal FTD should support active touch. However, stroking a textured surface with a finger or having the textured surface rub against the finger result in the same tactile sensation. Therefore, as long as the user is given the modality to explore, passive touch devices can also be useful.

Applications. The applications and advantages of most of the today's current tactile devices are not clearly known by the general public. This contributes to the general skepticism among potential users towards the usefulness and value of such devices. A good FTD must be more than a fun gadget. It must demonstrate that it can either:

- Substitute for another deficient or overloaded sense.
- Enhance sensation by adding tactile feedback.
- Convey meaningful information.
- Increase performance in doing a task.
- Make a task more comfortable or more enjoyable.

2.4 STATE-OF-THE-ART TACTILE DISPLAYS

Building an efficient tactile display requires high-performance actuators. The challenge lies in the need for miniature actuators that can produce high forces over a large bandwidth. In appendix A, Table 5 shows an extensive review of state-of-the-art tactile displays and the mechanism of their respective actuators.

2.4.1 Electrostatic Tactile Displays

Electrostatic tactile displays consist of a dielectric sandwiched between the plates of a capacitor (Beebe et al., 1995), where the fingertip is used as one of the capacitor's plates. Applying a voltage across the capacitor creates an attraction between the skin's surface and a smooth surface. While sliding a finger over the display, the subject experiences a sensation of friction. Unfortunately, electrostatic actuators require high operating voltages and can be sensitive to skin's humidity. Furthermore, the fabrication process of the dielectric layer is complex. In some cases such as (Jungman & Schlaak, 2002), industrial expertise has not yet been developed and the required dielectric is not even available on the market.

2.4.2 Rheological Tactile Displays

Rheological tactile displays use a liquid that changes to a near-solid state when exposed to an electric or magnetic field. This type of display however is not very practical. The user, for example, might need to wear latex gloves to avoid direct contact with the fluid (Bicchi et al., 2002). Problems, such as liquid accumulation, can also arise. Finally, it is very difficult to get a good spatial resolution of the actuators because the solenoids, used to create the local fields, are cumbersome.

2.4.3 Electromechanical Tactile Displays

The most effective class of tactile displays is probably the one that employs electromechanical actuators. The majority of these devices convey tactile sensations by indenting the skin normally. The principle is to move miniature skin contactors up and down in order to create a tactile sensation. Three main types of electromechanical actuators have been exploited:

1. *Electromagnetic* actuators consist of devices such as solenoids and servomotors. They exhibit large force and displacement but they are often too big to conform to the optimal spatial resolution for actuators of 1 actuator/mm. In addition, they can be limited to a small bandwidth.

2. *Shape Memory Alloys* (SMA) contract when heated (the Joule effect). They are usually used with pulleys or levers to control the vertical position of the skin contactors. SMAs provide miniature actuators and they are capable of exhibiting high force and strain, especially when mechanically amplified. On the other hand, they suffer from large power dissipation, a small bandwidth and an undesired hysteretic behavior.

3. *Piezoelectric* actuators necessitate high operating voltages. The forces and displacements that they exhibit are also often not comparable to motor and SMA actuators. They can be operated however, over a large bandwidth (the entire sensitive bandwidth – 0 to 1000 Hz). Ongoing research promises steady improvement of their capabilities. Every year, piezoelectric materials increase in performance.

2.4.4 Air Jet Tactile Displays

Air jet tactile displays are interesting. Air jets compress the skin locally without any mechanical contact with the actuators. The resulting sensation (similar to "a bug creeping under the skin") can be intriguing and difficult to reproduce with the other types of tactile displays (Asamura et al., 1998). Air jet TDs require compressed air and small valves. They can only be driven at low frequencies and are bulky.

2.4.5 Thermal Tactile Displays

Thermal tactile displays make use of heating and cooling elements (Peltier cells). However, they do not convey any shape or texture information, but thermal characteristics.

2.4.6 Pneumatic Tactile Displays

Pneumatic tactile displays control the air pressure in valves to drive skin contact pins. They can exhibit large forces and displacements. They can also be operated over a large bandwidth. Moreover, certain pneumatic tactile displays (Caldwell et al., 1999) are capable of more than one mode of interaction (e.g. shear and normal indentation). Unfortunately, pneumatic tactile displays are not practical because they require complex control systems.

2.4.7 Electrocutaneous Tactile Displays

Electrocutaneous tactile displays pass electric pulses to the skin. They are easy to make and are adaptable to a multitude of devices such as tactile gloves. On the other hand, adaptation to the electric stimulus occurs very rapidly. Moreover, electrocutaneous TDs can eventually cause pain.

2.4.8 Other Tactile Displays

Other actuator technologies useful for tactile displays include MEMS and a multitude of polymers. In fact, any new type of material having some actuation properties and that can be easily miniaturized is worth considering when designing a tactile display. The future may show that more than one type of actuator technology might be necessary to build a complete and practical TD.

2.5 MOTIVATIONS AND REQUIREMENTS FOR THE STReSS DEVICE

A quick look at the tactile displays from appendix A reveals that most FTD use normal indentation of the skin as a mean to display tactile information. It has been shown, however, that lateral stretch of the skin can transmit the sensation of a feature moving under the fingertip (for a convincing demo, see (Hayward & Cruz-Hernàndez, 2000)).

Hayward and Cruz-Hernàndez built a first prototype capable of stretching the skin locally. The tactile display consists of a matrix of 112 contactors mounted on a membrane held by a sub-layer of 64 piezoelectric actuators. By expanding and contracting, the actuators deform the membrane and the contactors move laterally. The device showed promising possibilities. Typical sensations felt were described as buzzing and pulses. However, the lateral movement of the skin contactors was insufficient to reproduce meaningful sensations, such as a moving feature. The STReSS display presented in this thesis is an improved structure. The design requirements are:

- A small, portable and low-cost device, practical enough to be mounted on a computer mouse,
- controllable from a standard personal computer without the need for extra hardware,
- with low power consumption,
- formed of a high resolution matrix of tactile actuators of 1 actuator/mm,
- capable of exhibiting significant movement and force in the order of tens of microns,
- and operating over a large bandwidth up to close to 1 kHz.

Of course, the general guidelines defined in section 2.3.2 were also followed.

2.6 TACTILE DISPLAY APPLICATIONS

In the last few decades, computer graphics and vision have been the primary focus in the field of human-computer interactions. Applications to tactile devices, however, have only started to emerge in the last 10 years.

Applications for tactile displays can be found in:

- the entertainment industry – e.g. tactile paddles for game consoles,
- the automotive industry - e.g. tactile devices mounted on the steering wheel of a car which return information on the current speed of the vehicle,
- the medical field - e.g. virtual surgery training for doctors as well as minimally invasive surgery,
- rehabilitation - e.g. recovery of tactile sensations by burn victims,
- sensory substitution systems - e.g. Braille displays for the blinds,
- the research world - e.g. studies on roles of mechanoreceptors, development of texture renders,
- e-commerce - e.g. remote sensing of a material via the internet,
- engineering design - e.g. computer aided design ,
- virtual reality - e.g. enhancement of telepresence.

CHAPTER 3: STRESS DESIGN

"Have a heart that never hardens, a temper that never tires, a touch that never hurts."
Charles Dickens

This chapter consists of a detailed description of the STReSS system. It covers the main components of the system and their properties as well as the manufacturing process of the device. It is mainly meant to be a reference guide for people who wish to replicate the device.

3.1 STRESS SYSTEM DESCRIPTION

The Stimulator for Tactile Receptors by Skin Stretch is a small, low-cost, high-bandwidth and high-resolution tactile display system that uses lateral skin stretch and compression as a means to stimulate the fingertip skin. The STReSS exploits a parallel between vision and touch. A tactile sensation felt on the display is the result of patterns of skin strain varying over time that can be called a tactile movie.

The STReSS system is composed of four main components (refer to Figure 2):

1. Tactile Player software. The Tactile Player is a simple Graphical User Interface (GUI) developed with Microsoft Foundation Classes (MFC). Its primary role is to configure the Constellation™ development board and to manage the communication between the Personal Computer (PC) and the Programmable Logic Device (PLD).

2. PLD development board. As mentioned earlier in section 2.3.2, the production of interesting tactile sensations requires a high refresh rate and precise timing. A Constellation™ development board from Nova Engineering Inc.[4] handles this. The PLD generates 100 simultaneous Pulse Width Modulation (PWM) signals that control the piezoelectric actuators' positions.

[4] Nova engineering, Cincinnati, OH, USA - www.nova-eng.com

3. Amplifier network. The analog voltage signal required to drive the piezoelectric actuators varies between –40 V and 40 V. The digital signal output from the PLD development board is 3.3 V. An amplifier network is used to convert the Constellation™ board 0-3.3 V PWM output voltage to an amplified 0-80 V PWM (40 V reference) signal.

4. Piezoelectric actuators. A matrix of 10 by 10 piezoelectric actuators forms the tactile interface. The piezoelectric material being capacitive, the amplified PWM signal can be low-passed without the need for any extra components to obtain an analog control voltage between –40 V and +40 V.

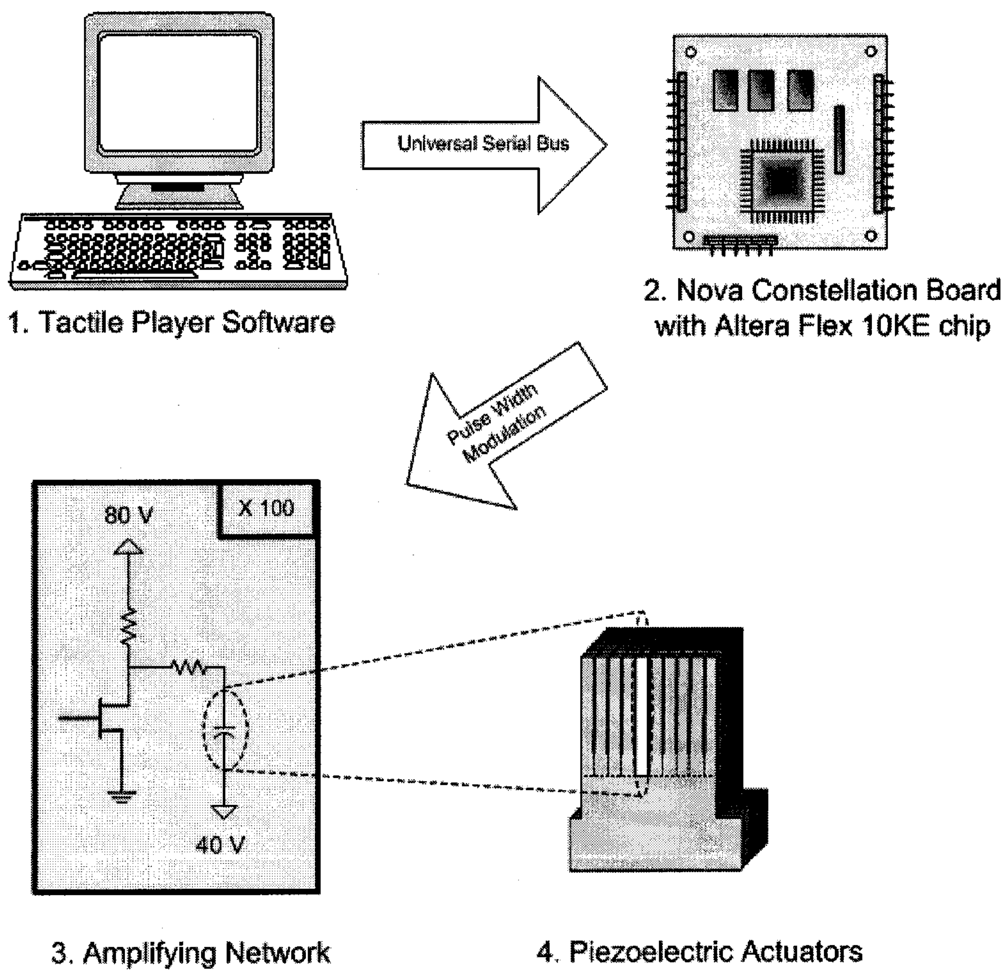

Figure 2: Four main components of the STReSS system

3.2 TACTILE PLAYER

This GUI application handles the communication between a PC running Microsoft Windows® and the tactile display. Its primary task is to send a stream of tactile images, specifying a time-varying 2D pattern of actuators' positions - or tactile movie - to the PLD via the Universal Serial Bus (USB). The GUI turned out to be a basic tool to create and edit tactile movies. It also offers functions to play, pause or stop tactile movies on the STReSS. Furthermore, the Tactile Player constantly graphically indicates the displacement of each actuator on the STReSS for monitoring and debugging. Refer to appendix B for a more complete description of the Tactile Player's features.

3.3 PROGRAMMABLE LOGIC DEVICE

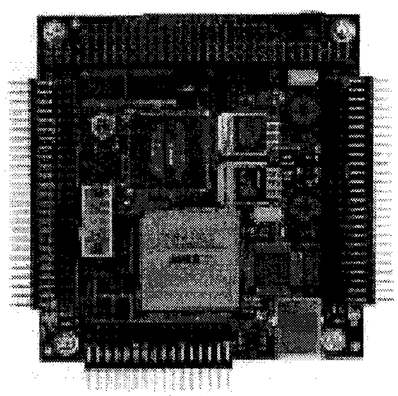

Figure 3: Constellation™ 10KE Programmable Logic Device[5]

A Constellation™ development board from Nova Eng.® is used as the middleware interface between the PC and STReSS device. This system offers several advantages:

- firmware reconfiguration without hardware changes,
- tactile image processing done on the FPGA itself,
- simple USB communication between the PC host and the peripheral,
- no need for digital to analog conversion hardware,
- device much more portable,

[5] Courtesy, Nova engineering – www.nova-eng.com

- "quasi real-time" operation possible by compensating for the poor reliability of Microsoft Windows® under real-time operations,
- parallel refresh of the 100 actuators' positions at a high controllable rate (up to 700 Hz).

A summary of the Constellation™'s main features is given in Table 2.

Table 2: Main specifications for the Constellation™ 10K50E development board[6]

CONSTELLATION™ 10K50E	
Size	PC/104 form factor (3.6" x 3.8" x 0.6"),
User I/O pins	132
Altera device	Flex EPF 10K50E *
Configuration option	Direct configuration via USB
Logic Compatibility	CMOS and TTL compatible I/O
Operating Voltage	5 V supply, 3.3 V I/O
Operating Frequency	40 MHz On-Board oscillator
USB Interface software	Win98, WinME, Win 2000

* 50,000 typical gates and 40,960 bits of RAM

The configuration firmware programmed on the FPGA consists of three modules (refer to Figure 4):

1. The **interface module** catches the data from the USB and passes it to the FIFO unit. The data consists of the actuator's positions - also called taxels - where each position is encoded with a single byte. Data is sent from the PC in frames of ten tactile images, where one image is made of 100 taxel values.

2. The **FIFO module** is a dual-clock buffer. It accepts the input stream from the computer and outputs it to the PWM module at a fixed rate of 700 tactile images per second. This strategy overcomes the poor reliability of Microsoft Windows® under real-time requirements. The Windows® operating system (OS) sends data to the FPGA whenever it can. The FIFO then rectifies the timing discrepancies by outputting data at a fixed frequency. A handshaking protocol attempts to keep the FIFO always half-full. As a result, a small lag from the OS sending data will not

[6] For the complete specifications refer to www.nova-eng.com/downloads/con_specs.pdf

affect the overall behavior of the system. In order to minimize data losses, the size of the FIFO (40 frames) is chosen to avoid data overflows and data underflows. In the rare instances where such events occur – for instance, when the PC host is under heavy computational load – the Tactile Player GUI informs the user that a FIFO underflow (or overflow) has occurred and waits until the system gets back to a stable state.

3. The **PWM module** consists of 100 PWM generators, one for each actuator. Every PWM generator outputs a pulse width modulation voltage that controls - once amplified - a single piezoelectric actuator. The period of the PWM signals is around 6.4 μs. Since piezoelectric material is capacitive, the amplified control signals are low-passed by the actuators. This results in DC control voltages across the actuators varying from –40 V to 40 V. The DC control voltages are updated at 700 Hz.

At the time of writing, the Constellation™ board does not carry out any tactile image processing. However, the use of an intermediate FPGA mounted on a development board allows for the integration of on-board tactile image processing algorithms in future versions of the STReSS. Moreover, once a satisfying and stable design is reached, an Application Specific Integrated Circuit (ASIC) chip at much lower cost and smaller size can replace the Constellation™ board.

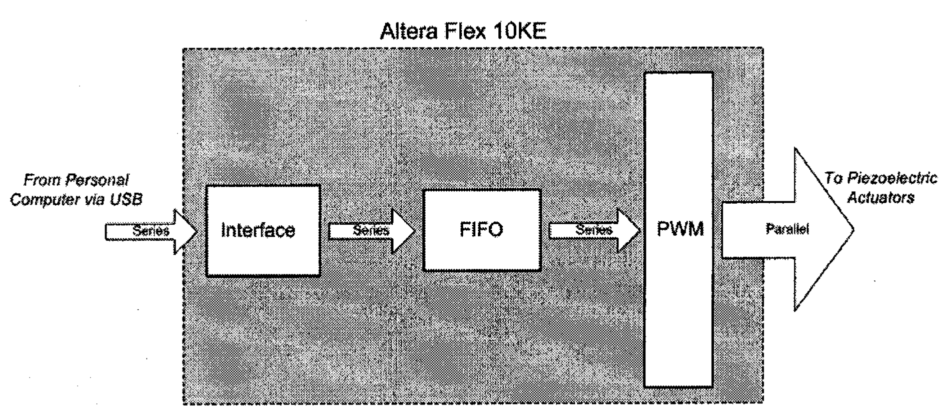

Figure 4: Internal modules of the PLD firmware (implemented in VHDL)

3.4 AMPLIFIER PRINTED CIRCUIT BOARD

Each PWM signal (3.3 V) supplied by the Constellation™ board needs to be amplified to control the position of the respective piezoelectric actuator. Since there are 100 actuators, an amplifier circuit is required to concurrently carry out 100 amplification operations. The challenge was to design an efficient amplifier element with the smallest possible number of electronic components. In order to make the STReSS as compact as possible, the amplifier network PCB is mounted on the PLD board directly. As a result, the entire amplifier network had to fit on a PCB roughly the same size as the Constellation™ board (9.15 cm x 9.65 cm x 1.52 cm).

Filtering the amplified PWM signal is another design requirement for the amplifier PCB. A piezoelectric actuator's displacement is directly proportional to the applied DC voltage across its electrodes. Given that piezoceramic actuators are capacitive, they can be used directly to filter the amplified PWM signal and convert it to a DC voltage, minimizing the number of electronic components required.

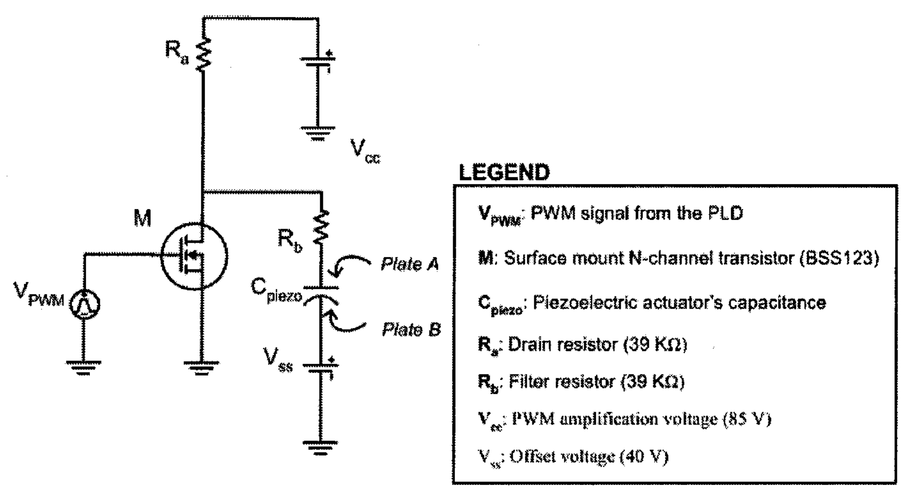

Figure 5: Amplifier element

A simple one-transistor/two-resistors circuit (refer to Figure 5) was found to be an optimal design meeting the above requirements. A first-order RC arrangement, made of a single resistor and of the piezoelectric actuator itself, turned out to be sufficient to properly filter the amplified PWM signal. The surface mount BSS123 transistor from

Fairchild® and resistor values of 40 KΩ were found to be a compromise between power dissipation, rise time and size. An offset voltage (V_{ss}) polarizes one armature of the piezoelectric material (plate B) so that bipolar voltages can be created across the actuators.

Spice™ simulations were run to predict the performance of a piezoelectric actuator when driven by a PWM signal with a 1.42 ms period in order to generate cycles at 700 Hz.[7] The piezoelectric actuator's electric behavior was modeled by a 2.5 nF capacitance. Figure 6 shows the capacitor's voltage responses (at plate A) to PWM signals with duty cycles varying between 1.6% and 100%. Points to consider include:

- **Ripples.** The PWM signal filtering introduces small ripples (clearly shown in Figure 6 (a)). However, the ripples never exceed ±2 V. In addition, their frequency, in the order of hundreds of kHz, is higher than the piezoelectric actuators' mechanical bandwidth.

- **Time Constant.** The time constant is around 0.2 ms, which corresponds to 14% of the 1.42 ms period.

- **Induced Voltage.** The voltage at plate A of the capacitor is not exactly proportional to the PWM duty cycle. This non-linearity comes from the fact that the transistor's slew rate limits the switching speed required for high duty cycles. Nevertheless, voltages between 0 V and 80 V can be set at plate A, with a decreasing resolution as we get closer to 80 V. This behavior can be corrected by calibration.

- **Power Dissipation.** As mentioned in section 2.3.2, the issue of power dissipation must also be considered. The maximum dissipated power, which occurs when all 100 transistors are turned on - in other words, when the voltage across all the actuators is

[7] Tests carried out with the system showed that a PC running Windows 2000 could transfer data via USB to the Constellation™ board at a maximum rate of 700 tactile images/sec. At a faster rate, the system cannot follow and a FIFO underflow occurs.

set to –40 V - is 18.5 W. This value was judged to be acceptable since it is an impossible extreme condition.

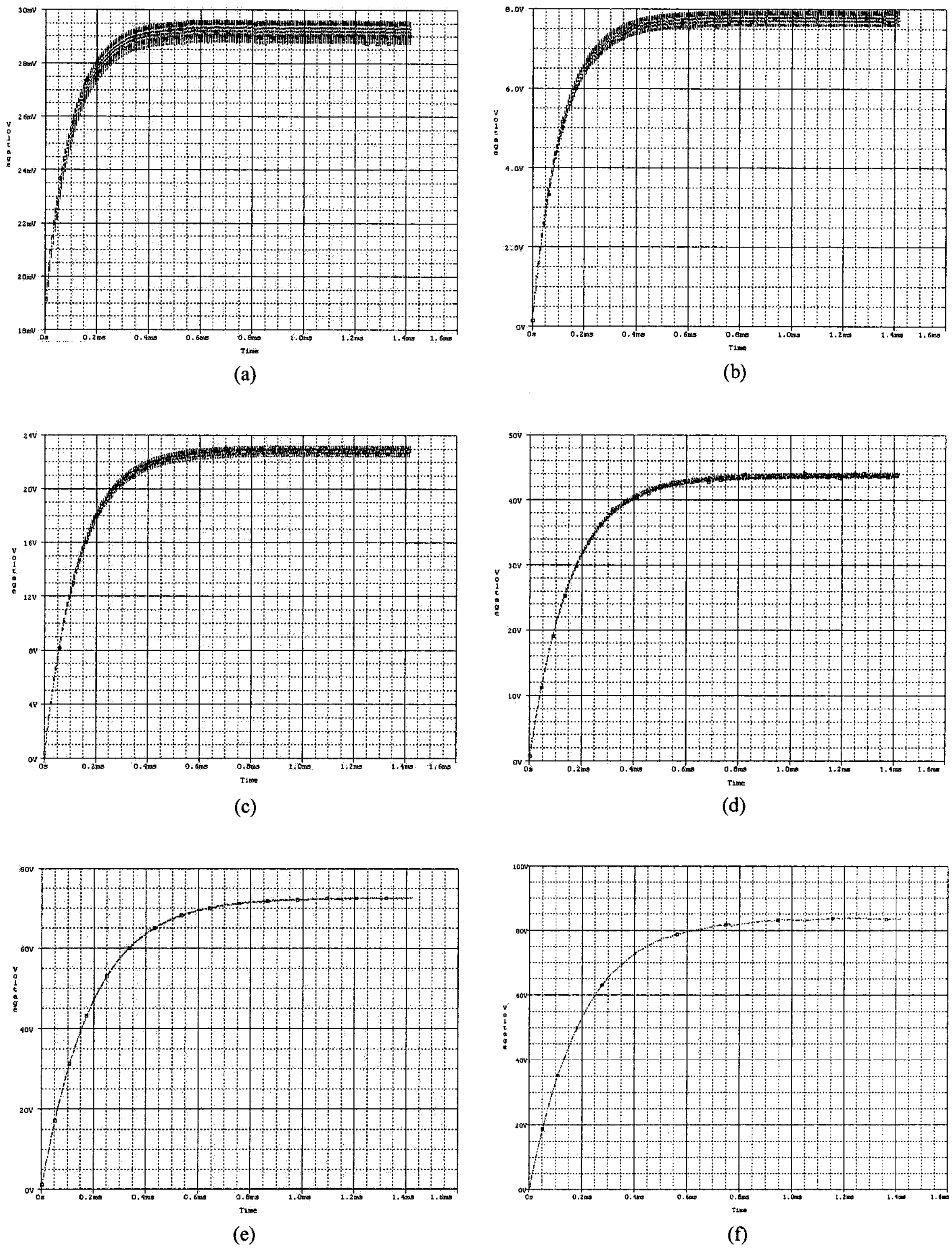

Figure 6: Capacitor's voltage responses to amplified PWM signals with duty cycle of (a) 1.6%, (b) 25%, (c) 50%, (d) 75% , (e) 99.5% and (f) 100%

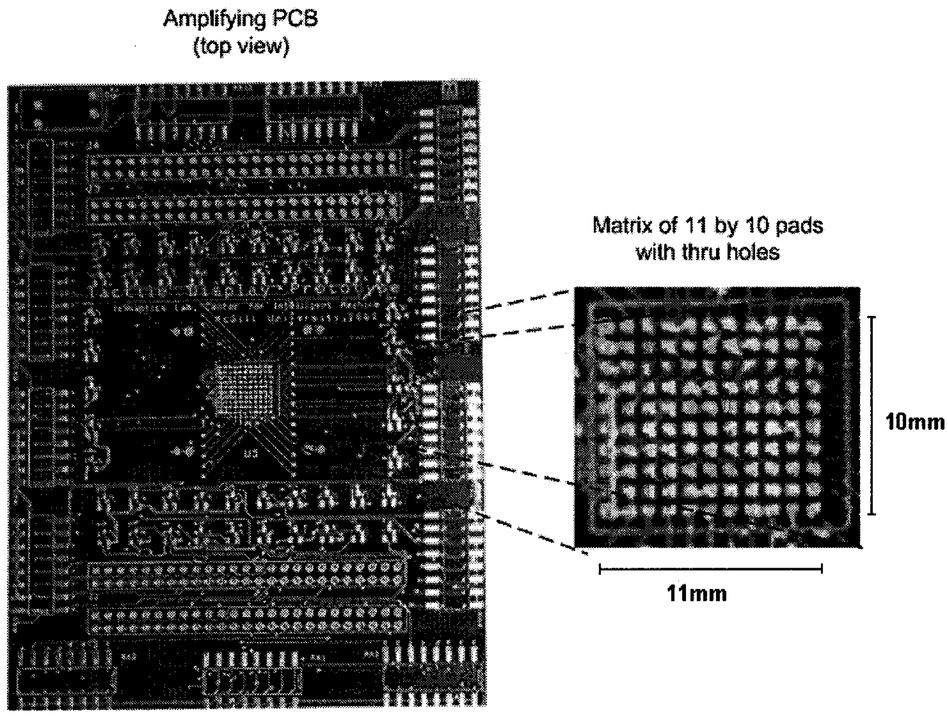

Figure 7: Amplifier PCB next to the magnified matrix of 11 by 10 pads with thru holes. The thru holes are used to thread copper wires that electrically connect the actuators to the board. From the left, the 11th column is used to access the center electrode and is set at a fixed 40 V potential.[8]

The amplifier PCB was designed and routed with OrCAD® Capture and OrCAD® Layout. The resulting board is shown in Figure 7.

3.5 PIEZOELECTRIC ACTUATORS

This section covers the piezoelectric actuator properties needed to design a tactile display.

3.5.1 Piezoelectricity

The piezoelectricity[9] effect was discovered by Pierre and Jacques Currie at the end of the 19th century (1880). Piezoelectricity refers to both, the conversion of mechanical energy to electric energy in dielectric crystals subjected to mechanical strain as well as the conversion of electrical energy to mechanical energy in such crystals subjected to an

[8] Credits for the layout and routing of the PCB go to Qi Wang.
[9] The term piezoelectricity comes from the Greek word *piezo* for pressure and electricity.

applied voltage[10]. Consequently, piezoelectric materials can be used both as generators (sensors) and as motors (actuators).

Piezoelectric properties are obtained by poling a crystalline material such as the natural crystal Quartz and the synthetic ceramic Lead Ziconate Titanates (PZT). The process of poling refers to the exposure of the dielectric crystal to a high electric field in order to force the material's randomly oriented dipoles into permanent alignment. Afterwards, a lower electric field applied in the opposite direction exerts a stress on the polled molecules resulting in the deformation of the piezoelectric material.

3.5.2 Advantages of Piezoelectric Actuators

Piezoelectric materials provide actuators that are most suited to make tactile displays. They are easily controllable, inexpensive and widely available on the market[11]. They allow for a display with high spatial resolution. They can also operate over a wide frequency range without dissipating large amounts of power.

On the other hand, piezoelectric actuators are limited in force and displacement when compared with other types of miniature actuators such as SMAs. In cases where more displacement is needed, piezoelectric actuators can be mechanically amplified. Extensive research and development is being carried out and piezoelectric actuator properties should continue to improve steadily in the foreseeable future.

3.5.3 Piezoelectric Actuator Arrangements

Piezoelectric actuators come in different arrangements:

1. A *unimorph* element consists of a single piezoelectric piece (refer to Figure 8). Applying a voltage across the piezoelectric element expands the entire structure. Unimorph elements are often used as sensors.

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[10] From the online dictionary www.atomica.com

[11] Piezo systems: www.piezo.com, Morgan Electro Ceramics: www.morgan-electroceramics.com, Piezomechanik: www.piezomechanik.com, PI ceramic: www.piceramic.de

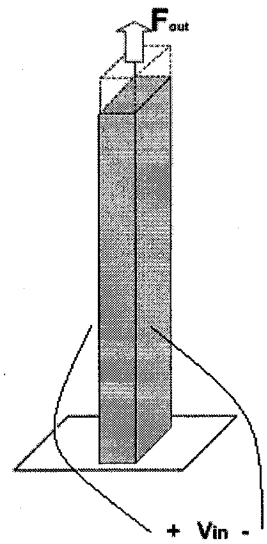

Figure 8[12]: Uniform piezoelectric extender bonded to a substrate (d_{31} mode)

2. A *bimorph* actuator consists of two piezoelectric layers bonded together face to face. The actuator arcs when one layer expands while the other one contracts (refer to Figure 9). The transducer provides two modes of configuration, X-poled and Y-poled. The mode of configuration refers to the direction of the polarization vectors (see Figure 10). In an X-poled bimorph, the polarization vectors of both layers face each other and only two wires are needed to polarize the actuator. On the other hand, Y-poled configuration requires three wires: two wires for the outside electrodes and one for the center shim. The main advantage of parallel operation is that it requires half of the driving voltage used for series operation. Bimorph elements provide more displacement than unimorph actuators due to their intrinsic, yet very inefficient, mechanical amplification

[12] Figure 8 to Figure 12 are adapted from Piezo Systems inc. - www.piezo.com

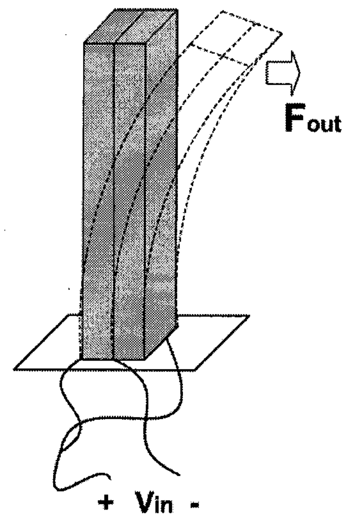

Figure 9: Bimorph piezoelectric bender configured for parallel operation (d_{31} mode)

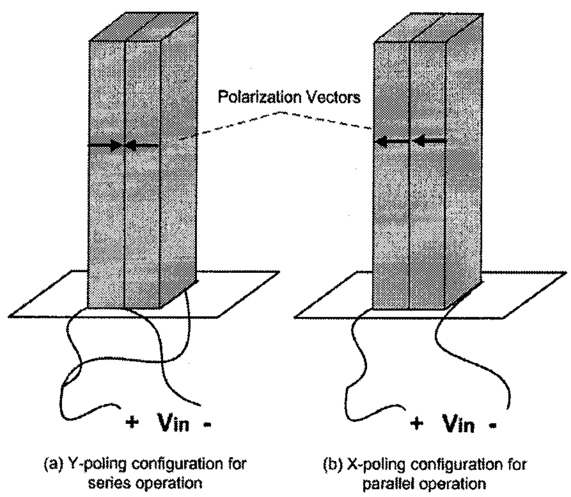

Figure 10: Polling configurations

3. A *stack* actuator is composed of a large number of piezoelectric layers on top of each other (refer to Figure 11). The extension of each piezoelectric layer adds to the total extension of the actuator. They are suitable for applications requiring large force and motion over a wide area.

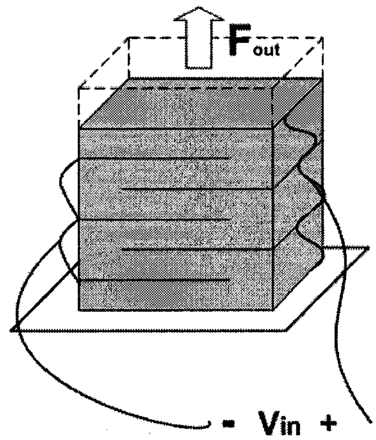

Figure 11: Stacked piezoelectric extender (d_{33} mode)

The STReSS system uses bimorphs. Lateral force against the fingertip skin is obtained directly from the bending motion of the bimorphs. Bimorph actuators provide enough force and displacement so that mechanically amplified contactors are not required. This greatly simplifies the design and allows for a high spatial resolution of the actuators.

3.5.4 The Comb Shape[13]

The STReSS display uses bimorphs type T215-H4CL-303Y from Piezo Systems Inc. This piezoelectric material consists of a Y-poled bender for parallel operation. When purchased from the manufacturer, the actuator comes in 12.7 x 31.8 x 0.38 mm sheets. Figure 12 shows its internal structure. It is composed of five layers of four different materials (piezoceramic, nickel, a composite reinforcement and an adhesive). Once charged, the outside nickel electrodes and the middle composite shim generate electric fields across the piezoceramic layers and lateral displacement is induced. An adhesive bonds the piezoceramic layers to the composite center shim.

Manufacturing 100 independent piezoelectric mini-actuators, so that they can be assembled on a 1 cm^2 PCB surface is challenging. All actuators must be identical in shape and be electrically accessible. Moreover, the tactile display structure, composed of

[13] All manufacturing pieces, materials and products used for the manufacturing of a piezoelectric comb are listed in detail in Appendix E for documentation purposes.

all hundred actuators, must be sturdily fixed to the PCB. It was found that manufacturing the piezoelectric material in a comb shape leads to a solid and efficient structural configuration. Moreover, the manufacturing and the assembling processes are greatly simplified when compared to the method of cutting and assembling each actuator one by one (as in (Hayward & Cruz-Hernàndez, 2000)).

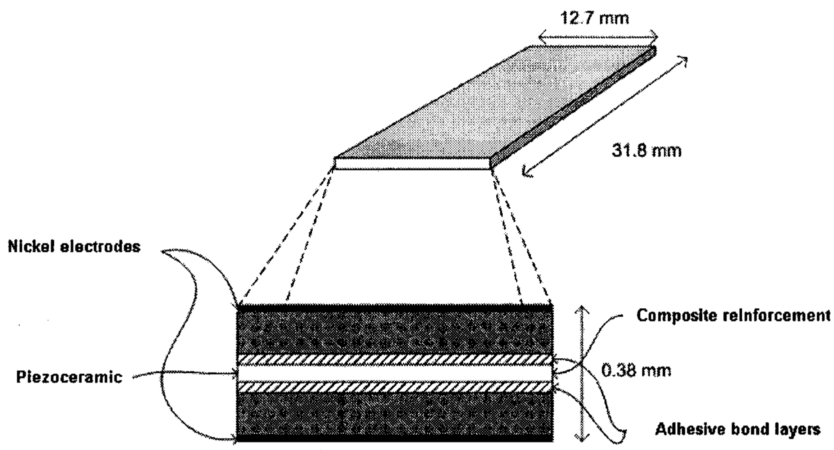

Figure 12: Piezoelectric sheet layers

Figure 13 shows the comb structure and its dimensions. A piezoelectric comb consists of ten tooth-like actuators sharing the same base. Each tooth-like actuator is electrically isolated from its neighbors by selectively removing the outside electrode on both sides. Small copper wires (diameter 0.15 mm) are employed on both sides as connection links between the amplifier PCB and the actuators (Figure 14). The copper wires are soldered to the piezoelectric material. A second solder underneath the comb takes care of the connection between the two wires - one on each side - of a same tooth-like actuator. The amplifier PCB has thru holes in its matrix of pads through which the copper wires are threaded. These small holes allow for an easy and final soldering of the copper wires to the PCB.

All tooth-like actuators share a common ground, the composite center shim. The center shim must also be accessed electrically. Here, no hole is required: conductive paint electrically connects the center shim to one electrode of the comb's right shoulder and a copper wire is used as before, to insure connection with the PCB.

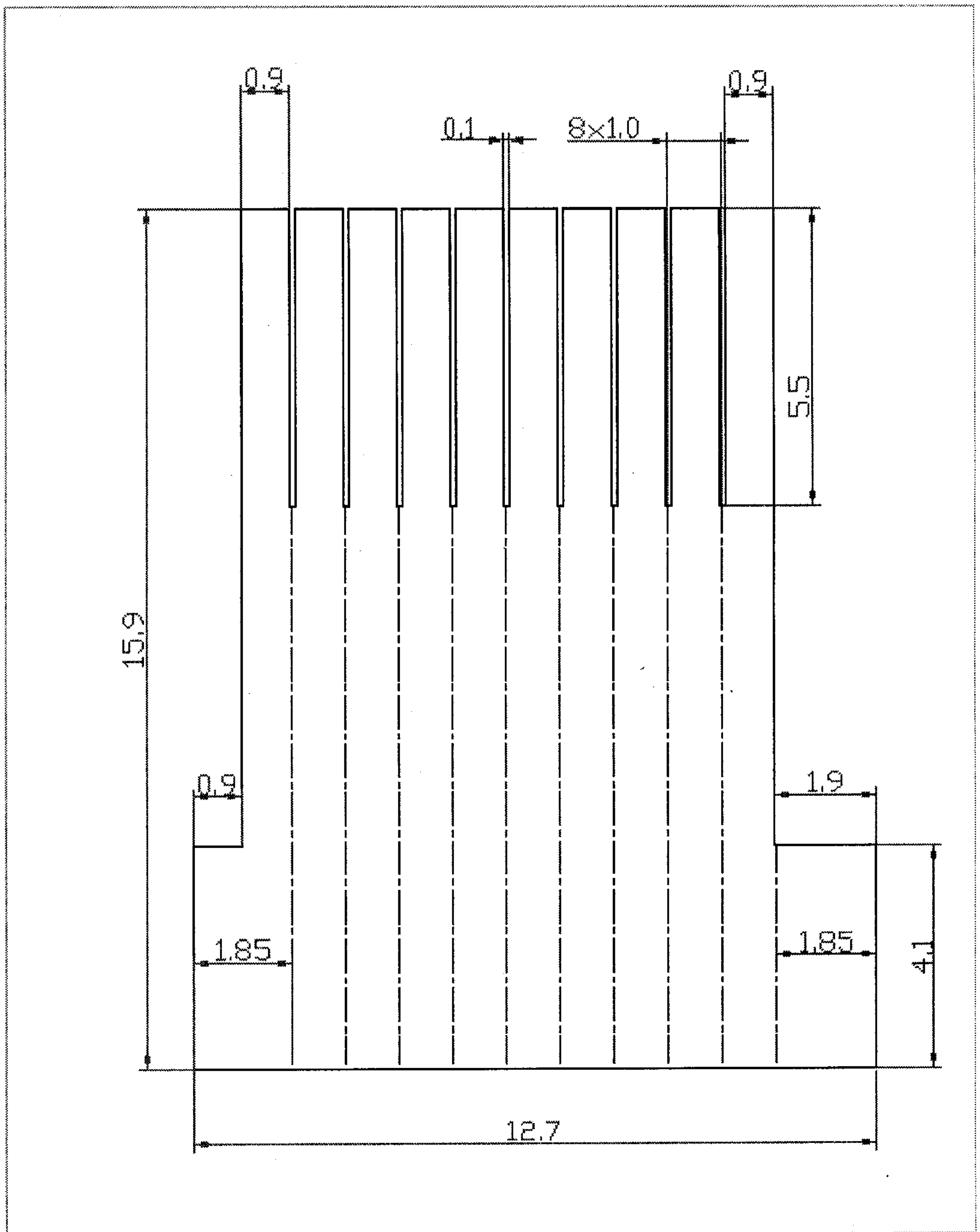

Figure 13: Drawing of the piezoelectric comb[14]

[14] OrCAD plans developed with Qi Wang, from the McGill Haptic Lab.

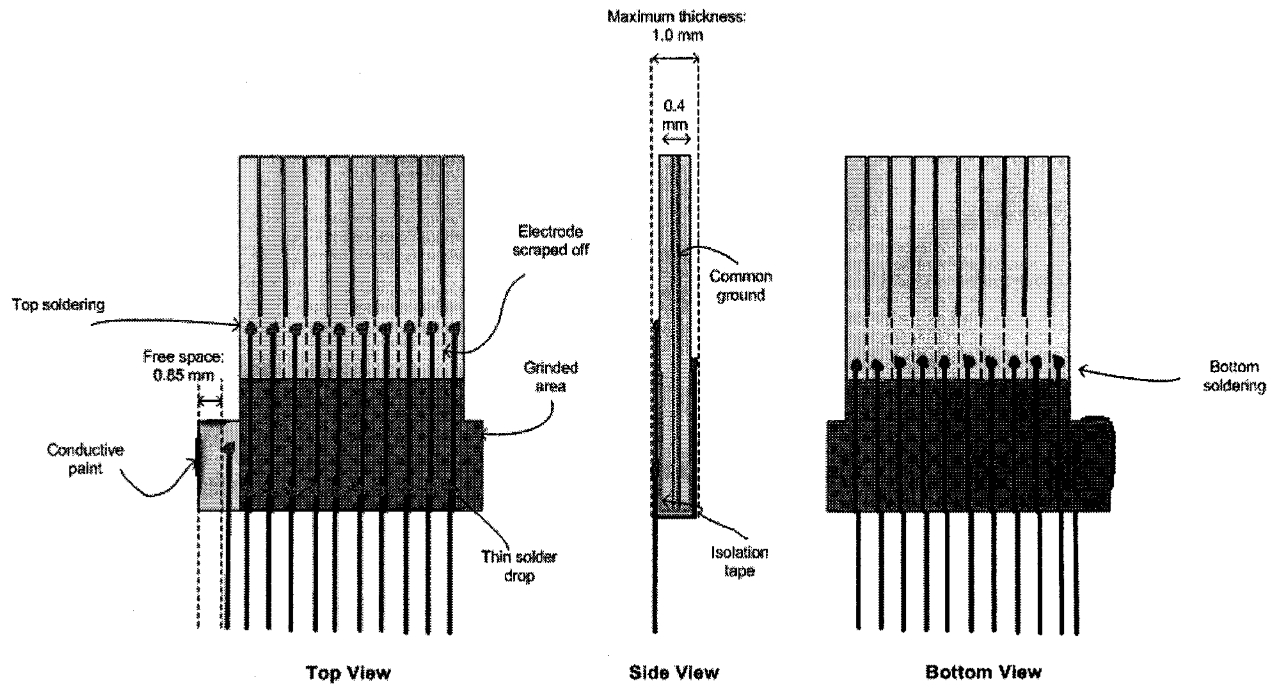

Figure 14: Wiring of the comb shape

The complete manufacturing of a single piezoelectric comb requires a certain expertise that was acquired mainly through trials and errors. The iterative process was not straightforward and was time-consuming, but the result was worth the effort. It led to a manufacturing procedure from which a solid mini-actuator structural arrangement is obtained. There is the possibility that once an optimal comb shape is reached, the manufacturing process be automated with little trouble. Once ten piezoelectric combs are manufactured, it is simple to assemble them on the amplifier PCB to create a 10 x 10 actuator display. Figure 15 shows the mounting process. Delrin™ clamps pushing down on the combs' shoulders and a rubber base are used to guarantee that the display surface is as flat as possible. An uneven surface would introduce tactile noise (i.e. simply by touching the display at rest, an undesired texture would be felt).

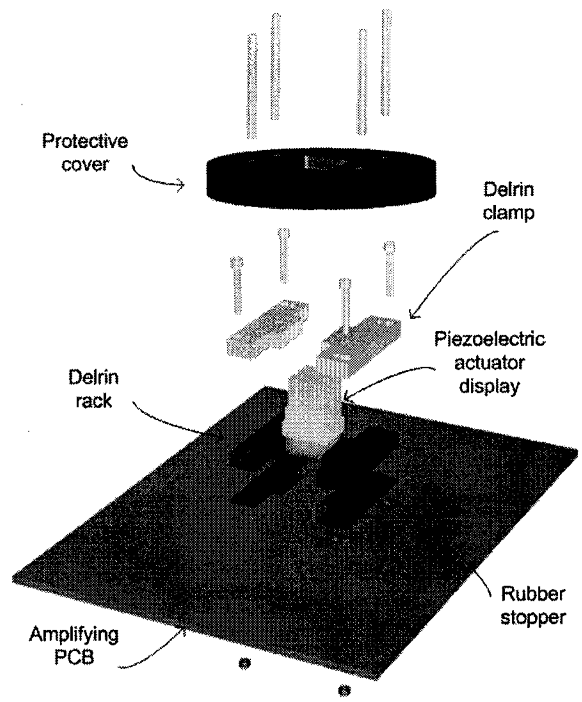

Figure 15: Assembly of the STReSS device to hold the piezoelectric matrix

The resulting structural configuration of the actuators consists of a square matrix of 100 actuators (see Figure 16). The pitches in the x and the y directions are the same, at 1 mm. All the actuators move along the same axis, perpendicularly to the piezoelectric combs. This might look like a significant limitation of the device. However, intuitive experiments with a real comb have demonstrated that at that scale, the direction of the skin deformation has little to do with the stimulus perceived (Hayward & Cruz-Hernàndez, 2000). In addition, more complex configurations can still be obtained by arranging combs in different directions and interlocking them like Lego® blocks. For the moment, the focus is on a simple working prototype.

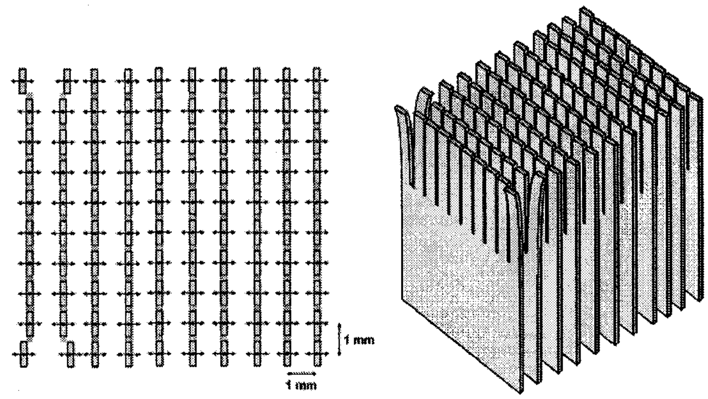

Figure 16: Tactile display structural configuration

3.5.5 Properties of a Free Bimorph

A basic understanding of bimorph properties is sufficient to address the design issues of the STReSS display.

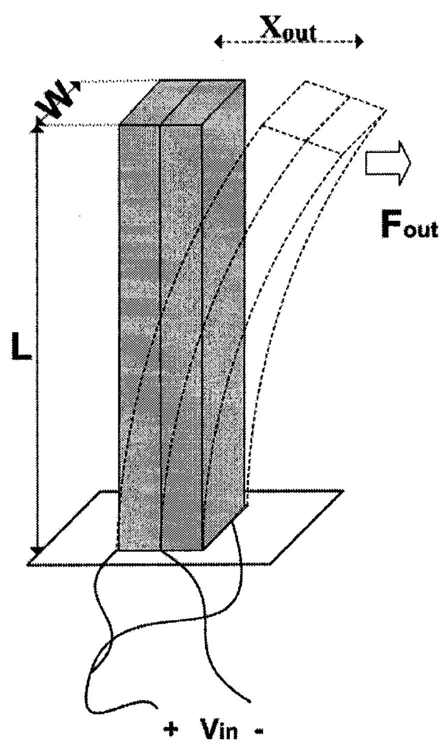

Figure 17: Bending bimorph variables[15]

[15] Adapted from Piezo Systems inc. - www.piezo.com

Table 3: Proportionality relationships of a free bimorph

	Proportional to
Free Deflection X_{out}	L^2
Blocked Force F_{out}	W/L
Resonant Frequency F_o	$1/L^2$
Capacitance C	W x L

Figure 17 illustrates a free piezoelectric bimorph used as a bending motor. The bimorph is fixed at one end to produce a cantilever effect at the other end. Applying a differential voltage V_{in} between the middle electrode and the outside electrodes results in a lateral displacement X_{out} and a force F_{out} at the tip of the bimorph. The bimorph has resonant frequency F_o. From basic cantilever mechanics, these terms have simple relationships with the length and the width of the piezoelectric beam. Likewise, from basic electrical relationships, the total capacitance of the bimorph is directly proportional to its area. The proportionality relationships are summarized in Table 3.

The frequency response of a free piezoelectric actuator is second-order-like. It is possible to model the performance of a free piezoelectric actuator by an equivalent circuit. To model a free actuator around resonance, the Van Dykes RLC equivalent circuit takes into account both, the mechanical resonance of the device and its electrical capacitance. Far from resonance, a basic RC circuit is sufficient to represent the free actuator and therefore, the displacement is directly proportional to the applied voltage.

3.5.6 Bimorph Design

When the piezoelectric actuator is loaded - that is when the user's finger is touching the display - the above relationships do not hold anymore and an unknown impedance Z is introduced to the system (Figure 18). Considering that biomechanical properties of the fingertip skin are still obscure, little can be done to model this. Therefore, the dimensions of the tooth-like actuators were chosen empirically. It was found that loaded tooth-like actuators of length 5.5 mm and of width 0.9 mm exhibit a good compromise between displacement, force and bandwidth; that is they induce sufficient local stress on the user's fingertip to be felt over a large range of frequencies.

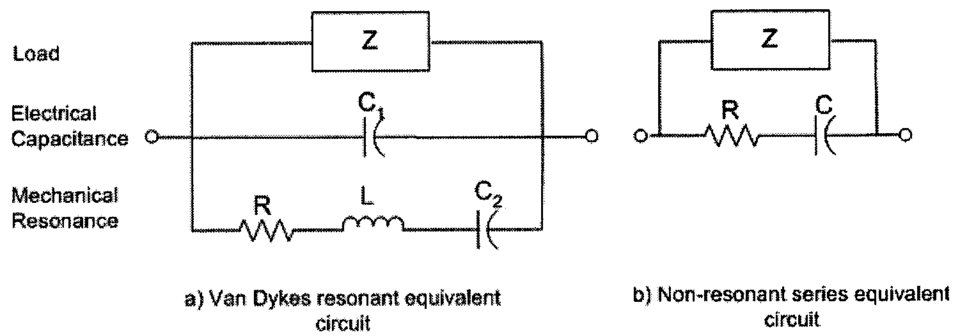

Figure 18: Piezoelectric actuators equivalent circuits

3.5.7 Theoretical Performance of a Free Bimorph

Table 4: Motor performance of the T215-H4-303Y material in its raw shape (piezoelectric sheet) and its manufactured comb shape (piezoelectric tooth actuator).

	Piezoelectric Sheet[1]	Piezoelectric Tooth Actuator[2]
Length [mm]	31.8	5.5
Width [mm]	12.7	0.9
Thickness [mm]	0.38	0.38
Weight [g]	0.9	0.01
Rated Voltage [V]	±40	±40
Capacitance [nF]	148	**1.8**
Resonant Frequency [Hz]	280	**5972**
Free Deflection [μm]	±360	**±17**
Blocked Force [N]	0.18	**0.06**

[1] Values taken from the manufacturer's Performance Selection Comparison Chart on www.piezo.com. Based on a 25.4 mm bending length.

[2] Computed from basic proportionality relationships of free bimorphs.

While the motor performance of the free tooth-like actuators do not reflect their mechanical behavior when loaded, measuring the free displacement of the actuators can be used to determine whether the device works as expected. Table 4 displays the manufacturer's performance chart of a piezoelectric sheet next to the theoretical values of a single tooth-like actuator computed directly from the proportionality relationships found in Table 3. Note that theory predicts a free deflection of ±17 μm and a capacitance of 1.8 nF.

3.6 STRESS CHARACTERISTICS

A top view of the first resulting piezoelectric display is shown in Figure 19. Most tooth-like actuators exhibited the expected behavior when charged. However, because of technical problems during the manufacturing and assembling, a few actuators (10%) were inoperable. Moreover, some actuators showed signs of cross-talk (15%), meaning that driving one actuator partially drove a neighboring one. Fortunately, most actuators were still functional, allowing for interesting time-varying strain patterns to be displayed. In future improved versions of the STReSS device, it is likely that a 100% yield will be obtained.

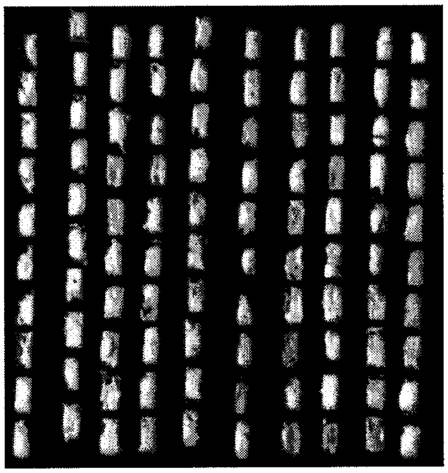

Figure 19: Top view of the piezoelectric display.

The measurement of the maximum free displacement of a tooth-like actuator was done by driving the actuators in a check board pattern: half of the actuators were set to their maximum left displacement while the others were set to their maximum right displacement. A high-resolution camera was used to image the display in this state and in the inverted state. Figure 20 shows how the binarized difference of the two images obtained can be used to approximate the maximum free deflection. By counting the number of difference pixels (i.e. black pixels) and relating this value to a known dimension such as the piezoelectric actuator's thickness, it is possible to estimate the maximum free deflection. Note that image calibration and sub-pixel analysis were not implemented because they are unlikely to provide useful information at this stage. It is estimated that the maximum deflection is around ±25 μm. Besides the fairly poor measurements caused by the lack of image calibration, other factors can also explain the discrepancies between the theoretical (±17 μm) and measured (±25 μm) displacements. Possible explanations include the fact that:

- A slightly higher maximum voltage (±43V) than the manufacturer's suggested ±40 V is applied to the piezoelectric actuators,
- The tooth-like actuators are slightly longer than 5.5 mm,
- The manufacturer's specifications are probably conservative.

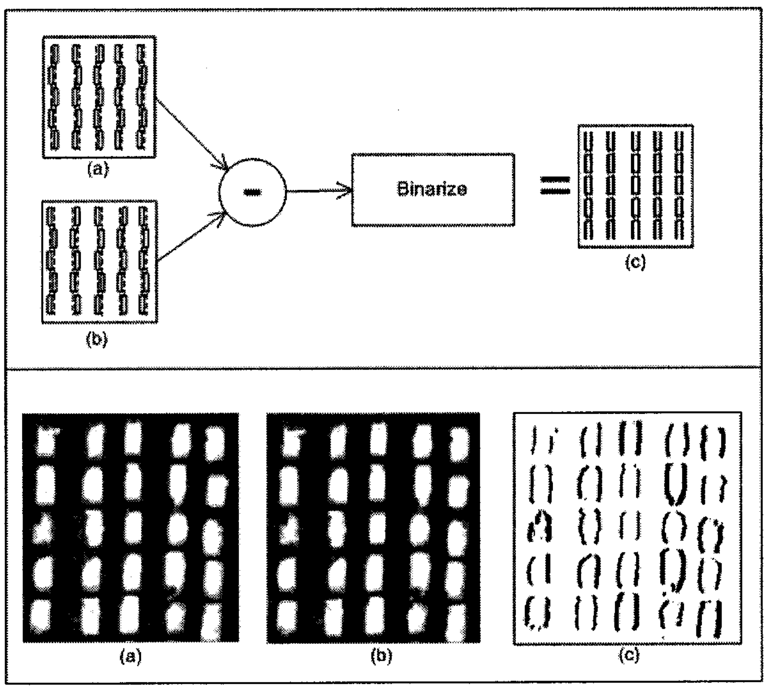

Figure 20: Free deflection measurement technique and resulting images carried on the top right quadrant of the display

The measured relationship between the voltage applied to an actuator and the controlled duty cycle sent to the amplification network is not linear as the theory would predict (see Figure 21). The non-linearity is mainly due to the fast speed (156 kHz) and high voltage (86V) of operation. At this rate, the transistor switching characteristics are important. Figure 21 shows that the applied voltage resolution is better for high duty cycles than it is for duty cycles closer to 0%. Zero crossing occurs at a duty cycle of 28.2%. The tactile software takes care of the necessary voltage rectification. Note that this could also be carried out by the FPGA firmware itself. The resulting calibrated resolution is 5V, implying a deflection resolution of about 1.5 μm[16]. In other words, an actuator's deflection can be chosen from a set of 17 different linear values. Note that this resolution is defined by the 5 V voltage gap that exists between a duty cycle of 0% (where the transistor is always turned off and therefore does not require any switching) and a duty cycle of only a few percents (where the transistor switches at 156 kHz). Of course, by clipping the full dynamic range, a much better resolution of around 0.5 V can be obtained, but the device is not used at its optimal potential. One last characteristic worth mentioning is that the measured piezoelectric actuator's capacitance is around 2.3 nF on average. Individual capacitances vary from 1.8 nF to 3.0 nF because of fabrication problems.

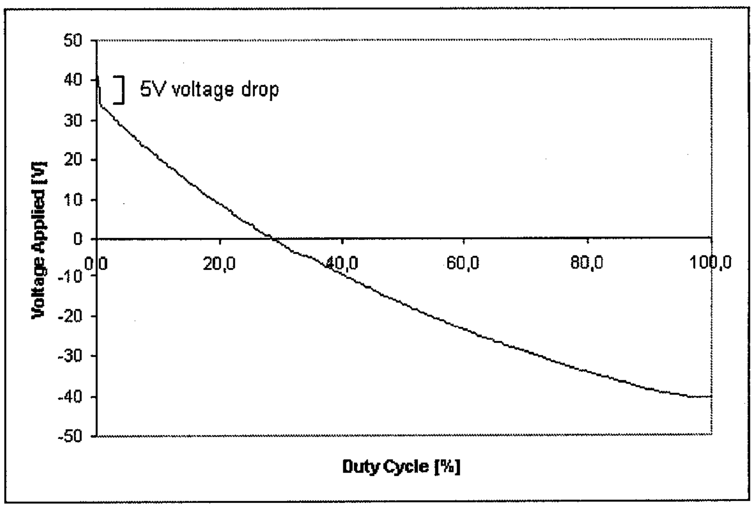

Figure 21: Measured voltage applied to a piezoelectric actuator in function of the PWM duty cycle generated

[16] The free deflection of a piezoelectric actuator is proportional to the voltage applied across its electrode. Therefore, relating the applied voltage to the duty cycle comes back to relating the free deflection to the duty cycle.

CHAPTER 4: TACTILE STIMULI GENERATION

"If you want me to believe in God, you must make me touch him"
Denis Diderot

This chapter reports on preliminary tactile stimuli tried on the STReSS. Informal observations are made concerning the resulting sensations perceived. Note that the early stage of the research does not permit strong conclusions to be drawn.

4.1 TACTILE MOVIES

The generation of the tactile movies displayed by the STReSS is not straightforward. Simulating real-life texture on the STReSS would require a precise model of the local deformation of the fingertip skin during surface exploration[17]. To the author's knowledge, there does not exist yet a systematic method to create these movies from first principles.

Another solution consists of directly measuring the local skin deformations. In (Levesque, Hayward, 2003), an apparatus and a method are described to track the fingertip pores when a finger slides over a simple transparent surface such as a bump or a hole. The method was extended by dividing the fingertip into a matrix of 10 x 10 equal regions in order to analyze the local deformation of each region. In theory, this should allow for a direct mapping between the local deformations measured by their system and the strain patterns displayed on the STReSS. Some patterns seem to emerge in particular situations (e.g. well-defined and interacting stretch and compressed regions occasionally appear when the finger slides over a bump). During preliminary experiments, the measured lateral strain was directly replayed on the first STReSS prototype but no significant tactile sensation was perceived. It is clear that only tactile noise was felt. At the time of writing, the measured data hadn't been re-processed and tried on the

[17] At this point, the definition of a tactile movie format becomes necessary. A format similar to the Portable Gray Map (PGM) image standard is used to encode the tactile movies. The .tac format is described in details in appendix F

improved second version of the STReSS tactile display. Instead, artificial patterns were designed empirically.

4.2 PRELIMINARY RESULTS[18]

One pattern that was tried was such that a pair of adjacent actuators was activated to cause successive stretch and compression of an enclosed patch of skin. This was achieved by driving the actuators in phase opposition as illustrated in Figure 22, where the variables $d_{i,j}$ represent actuator displacements indexed by rows and columns. A progressive wave was created by time-overlapping strain changes in successive neighboring patches, as shown in Figure 22. The waveform (smoothly represented by 60 samples of period of 1.4 ms) was traveling from row 0 to row 9 at a speed of about 2.5 cm/s (a typical tactile scanning speed). This particular pattern has the property that the rate of change of strain is roughly constant within a small space-time neighborhood. Informally, for most subjects, the conscious experience could be described as that caused by one (sometimes two) small raised dot(s) sliding under the fingertip.

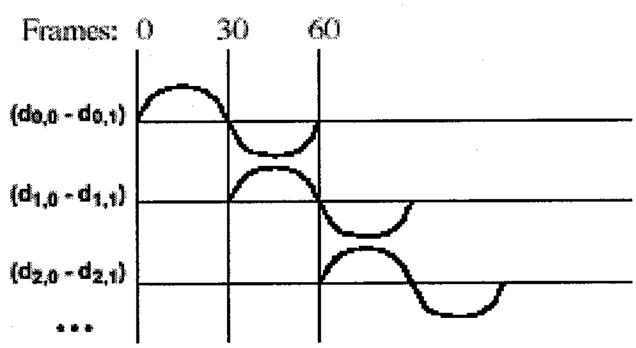

Figure 22: Progressive wave activation for pairs of actuators, indicating the gap size variations through time and space

Another pattern that was tried was created by replicating the above sequence for each 5 pairs of actuators on the same row. Thus, at any given instant in time, if one patch was stretching, its row neighbors were compressing at the same rate (and vice-versa). As above, the pattern was made to travel column-wise at 2.5 cm/s. In this case, the experience was that of a uniform horizontal edge scanning the finger vertically.

[18] This section is identical to section 6 that was published in [Pasquero & Hayward, 2003].

Moreover, there was no ambiguity whatsoever regarding the direction of the edge movement.

While it would be inappropriate to draw strong conclusions from these informal tests, they do seem to vindicate the notion that that liberties can be taken with millimeter-scale details of time-varying skin deformation in order to create meaningful sensations.

CHAPTER 5: CONCLUSION

"One touch of nature makes the whole world kin"
William Shakespeare

This brief chapter concludes the thesis by identifying the STReSS limitations. Possible developments are suggested for improved prototypes. Finally, the need to continue research on lateral skin stretch is emphasized because of the encouraging preliminary results obtained.

5.1 DEVICE LIMITATIONS AND POSSIBLE IMPROVEMENTS

The STReSS project's goal is to ultimately come up with a practical tactile device that is flexible enough to be used for a multitude of tactile experiments. The device must also be easily replicable so that many copies can be supplied to researchers who are interested in conducting these tactile experiments. While the second STReSS prototype turns out to be a considerable improvement on the first one, there is still a lot of room for progress. Future prototypes should try to address the following issues:

- **Power dissipation**: While the heat generated by the tactile display cannot seriously harm a user, the resistive networks used for the signal amplification still exhibit too much power for the device to be completely comfortable. Moreover, with time, it is probable that the dissipated heat damages the device. Using bigger resistor values and finding a MOSFET with a higher switching speed will probably fix this problem. Another solution is to move to an all-switching design, but this will require some serious microelectronics research.

- **Soldering**: The current piezoelectric comb design requires three soldering operations for each tooth-like actuator (two for the wires on each side and one to connect these two wires). The solders, in addition to being very time consuming, increase the thickness of the combs, making them harder to be stacked together properly (with a desired 1 mm pitch). This explains why the alignment of the piezoelectric combs is not perfect on the display shown in Figure 19. In fact, the obtained pitch in the y-direction is more in the order of 1.2 mm. This is currently being addressed by using conductive tape to connect both sides of a same tooth-like actuator, and therefore reducing the number of required solders to one per actuator – or even eliminating them. It is still too early to report on the success of this new technique.

- **Optimal actuator's length**: Mainly because of the many unknowns regarding touch listed in section 2.3, the optimal length of a tooth-like actuator had to be chosen empirically. Recall that the longer the actuator is, the more it can deflect but the lower the force it provides. Therefore, a tradeoff must be found. The current implemented STReSS prototypes have already given us insight on what this optimal length might be. It appears that the force displayed is more important than the maximum displacement. We are constantly monitoring the progress in piezoelectric technology for the best-suited actuators for the STReSS. The objective is to develop a STReSS actuator capable of achieving a distributed skin strain of about 10%.

- **Bandwidth**: The current STReSS display is refreshed at 700 Hz, which is under the desired rate of several kHz. This restriction is mainly due to the limited maximum data USB transfer rate supported by the Constellation™ development board under Microsoft Windows®. It is probably possible to increase the device's bandwidth by either reconfiguring the firmware and decreasing the taxel's resolution or simply by using an ASIC chip instead of the development board. For the time being, the refresh frequency is not a major consideration and will probably be improved easily.

- **Size**: While the device is already compact enough to be roughly mounted on a computer mouse, its size can still be reduced to improve its usability and portability. On the long term, this could imply getting rid of the FPGA development board and replacing it with an embedded system in order to create an industrialized device.

- **Display configuration**: It has already been mentioned in this thesis that, intuitively, a single axis of stress does not seem to greatly influence the possible meaningful tactile stimuli that can be displayed by the device. However, in order to develop a device that is as flexible as possible, it might be interesting to develop more complex configurations in the future. This involves the design of piezoelectric combs that interlock one in another.

- **Firmware development**: While this is not the case at the present, there is nothing that stops the FPGA from optimizing the data transfer. Also, PWM should be replaced by sigma-delta switching. Some form of tactile image processing should also be done. Moreover, the use of firmware makes it possible to create a self-contained system that does not need to be hooked up to a PC. The firmware development is left entirely to the user for the desired application.

5.2 FUTURE WORK AND CONCLUSION

A practical fingertip tactile display was designed and implemented to provide subjects with interesting skin stimulation patterns via lateral skin stretch. Ten piezoelectric bimorphs were cut to form piezoelectric combs, each consisting of ten independent tooth-like actuators. Stacking the combs together and mounting the resulting structural configuration on a PCB created a solid miniature tactile array of 100 bending actuators. The tactile array was hooked to an FPGA development board, permitting a high refresh rate computer control of the device.

Simple time-varying distributed strain patterns were displayed on the device and preliminary observations were made concerning the perceived sensations. It is still too early to draw conclusions from these informal observations. However, the inspiring results and the distinct capabilities of the device create strong motivation for future behavioral, biomechanical and neuroanatomical experiments and their analysis. Future work also involves the development of a model of skin deformation under lateral stress based on first principles. The STReSS tactile display is still under constant redesign so that improved copies can be built and sent to interested parties.

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APPENDIX A

Tactile Displays

Table 5: Survey of state-of-the-art tactile display technologies

TD Type	Actuator	Actuator Mechanism	Number of Actuators	Interaction	Interesting Properties	Drawbacks	Ref.
Electrostatic	*Capacitor with Polyimide (PI) insulator*	Capacitor formed of the conducting fluids in the fingertip acting as a plate and external electrodes acting as the other plate. A voltage induced across the capacitor creates attraction between the skin surface and the external electrode surface.	49	Friction	Reproduction of shear forces at the surface of the skin. Active touch device (sliding of finger).	High voltage (200-600V). Complex fabrication process of the PI layer. Fixed operating freq. (100 Hz). Sensitive to humidity of skin.	(Beebe et al., 1995)
	Capacitor with polymeric elastic dielectric	Stimulator tip mounted on a stack of capacitors with polymeric elastic dielectrics. When a control voltage is applied across the capacitors, the dielectric material contracts and the position of the stimulator tip is set.	No prototype implemented	Normal indentation	Low cost, lightweight and flexible material. Potential for high strain (up to a few mm).	High operating voltage (100-1000V). Little current knowledge of the material properties and manufacturing process.	(Jungman, Schlaak, 2002)
Rheological fluid	*Electrorheological (ER) fluid*	ER fluid cell resisting the motion of the fingertip. The ER fluid changes from a liquid state to a solid state when exposed to an electric field. Altering the ER fluid's state induces horizontal and vertical reactive forces during finger scanning.	25	Resistance to finger motion	Low energy consumption. Simple mechanical design. Active touch.	Problems, such as liquid accumulation, related to the use of an ER fluid. Tradeoff between the resolution of the array and the force of the response (due to the hazard of having high control voltages close to each other).	(Taylor et al., 1996)

TD Type	Actuator	Actuator Mechanism	Number of Actuators	Interaction	Interesting Properties	Drawbacks	Ref.
	Magnetorheological (MR) fluid	MR fluid placed in a Plexiglas box surrounded by solenoids. Inducing a current in a solenoid creates a magnetic field that changes the fluid to a near-solid in the vicinity of the solenoid.	16	Shape Softness	Active exploration from the user. Both a kinesthetic device and a tactile device.	Low actuator spatial resolution. Need to wear latex glove. Large power dissipation (overheating).	(Bicchi et al., 2002)
Electromechanical	*Piezoelectric*	Bending bimorph carrying an L-shaped wire acting as the skin contactor.	100	Normal indentation	Large working bandwidth (20-400 Hz). Interesting controllable amplitude for a piezoelectric device (0-50um).	High control voltage (85 V). Complexity of manufacturing.	(Summers, Chanter, 2002)
		Mechanically amplified piezoelectric actuator driving a vibratory pin.	50	Vibration	Controllable actuator amplitude (5-57μm). Simple circuitry.	Fixed operating frequency (250 Hz). Limited to simple sensations of vibration.	(Ikei, 1997)
		Vertical movement of a contactor induced by a pair of piezoelectric levers.	48 (~4000 virtual)	Normal indentation	Vertical movement of up to 0.7mm. The device is mounted on a sliding apparatus. This permits the exploration of a large surface area without the need for an extensive number of actuators.	Small spatial resolution (~1 actuator/8mm^2). High control voltage (200 V) coming out of a power supply card. Low bandwidth (20 Hz).	(Maucher et al., 2001)

TD Type	Actuator	Actuator Mechanism	Number of Actuators	Interaction	Interesting Properties	Drawbacks	Ref.
		Skin contactors glued on a membrane that is deformed by a matrix of piezoelectric actuators.	64 (112 cont.)	Lateral stretch	High spatial resolution of contactors. Portability of device (e.g. can be put on a computer mouse). New mode of interaction (lateral stretch).	Small actuator displacement and force. High control voltage (±200V). Indirect control of the positions of the contactors.	(Hayward, Cruz-Hernàndez, 2000)
	Motor	RC servomotor slightly rotating a lever arm on which a skin contactor is fixed. The small rotation of the lever arm results in a vertical motion of the contactor. A sheet of rubber covers all the contactors to create a spatial low pass filter.	36	Normal indentation	High vertical displacement (up to 2 mm). Poor actuators spatial resolution (2 mm) compensated by a rubber sheet acting as a spatial low-pass filter. A mouse is attached to the display to permit active exploration.	Complex control system. Fairly big and cumbersome device. Low bandwidth (~25 Hz).	(Wagner et al., 2002)
		The rotation of a step motor is transformed into vertical movement of a skin contactor by using a lead-screw mechanism.	4096	Normal indentation	High contactor force. Large contactor displacement (up to a few mm). Considerable surface area (200 mm x 170 mm) and large number of actuators.	Very slow refresh rate (~15 s). Limited to display shape (i.e. no texture) because of high contactor spatial resolution (3 mm). Complex and expensive control system.	(Shinohara et al., 1998)
		Two fixed coils and a moving magnet suspended by two helical springs act as a motor controlling the displacement of a long stainless steel probe.	400	Normal indentation	High contact force (up to a few Newtons). Large displacement of the actuators (up to 2.5 mm). Good actuator resolution.	Very large control system. Very complex and expensive device.	(Pawluk et al., 1998)

TD Type	Actuator	Actuator Mechanism	Number of Actuators	Interaction	Interesting Properties	Drawbacks	Ref.
	Shape Memory Alloys (SMA)	An SMA wire pulls a lever that lifts a skin contactor. The contactor indents the fingertip skin.	24	Normal indentation	High vertical extension of the contactors. Large contact force.	Hysteretic behavior of the SMA material. Low control bandwidth (~10 Hz) Large power dissipation.	(Kontarinis et al., 1995)
		Vertical pin fixed to the middle of a SMA wire like an arrow is mounted on the wire of a bow. Controlling the length of the SMA wire with an electric current moves the pin up and down. A latex rubber membrane acting as a seal is laid on top of the pins.	Line of 10	Normal indentation	Interesting bandwidth for a SMA device (30 Hz). Low strain of the SMA material amplified by an ingenious mechanical arrangement.	Hysteretic properties of the SMA material. Complex cooling system. Uses a line of skin contactors instead of a matrix distribution. As a consequence the edges of the line are felt.	(Wellman et al., 1997)
		SMA NiTi wire attached to a sprung pin in contact with the skin. An electric current induced in the SMA, makes it contract and pulls the pin down.	64	Normal indentation	Fairly large controllable strains of the SMA wires (up to 5% - 5 mm).	Low operating frequency (1-3 Hz). Large heat generation.	(Taylor et al., 1997)
Air jet	*Piston*	Air jet produced by controlling the pressure through a tube with a piston.	1	Air jet	Stimulation of superficial receptors creating a sensation ("bug creeping under the skin") not reproducible with other TDs. No direct mechanical contact with the skin.	Impossibility to get a high-resolution array due to the size of the jet actuators.	(Asamura et al., 1998)
Thermal	*Peltier element*	Electric current controlling the temperature at the skin/element interface.	1	Heat	Very simple. Capable of simulating real sensations of the quality of materials under passive touch.	Only one single actuator. Incapable of presenting dynamic information such as pressure or strain.	(Ino et al., 1997)

TD Type	Actuator	Actuator Mechanism	Number of Actuators	Interaction	Interesting Properties	Drawbacks	Ref.
Pneumatic	*Pneumatic valve*	Array of pressurized silicone tubing. By changing the pressure in the chambers, the displacement of vertical contactors in the tubes is controlled.	25	Normal indentation	Constant contact with the finger. No leakage and no pin friction. Controllable pin displacement (up to 0.7 mm). Highly portable.	Very low bandwidth (5 Hz). Low spatial resolution (actuators are 2.5 mm apart). Undesired operating vibration resulting from the PWM control signal.	(Moy et al., 2000)
		Pneumatic inflow controlling the pressure and vibration of stainless steel pins. Pneumatic muscle generating lateral forces to simulate friction.	16	Normal indentation Vibration Shear	Compact and integrated package capable of three different types of stimulations. High normal force (~2N) High normal displacement (~3.5 mm) Large vibratory bandwidth (20-300 Hz)	Complex system Few contact pins with fairly high spacing separation (~1.75 mm).	(Caldwell et al., 1999)
Electrocutaneous	*Electrode*	Active electrode becomes electrically connected to ground through the fingertip when the user touches it. The current passing through the finger creates a tactile sensation of vibration and pressure.	49	Electric current	Simple method. Possibility of high tactile resolution. Flexibility (e.g. can be put in a glove).	Can cause pain. Adaptation to the stimulus occurs very quickly.	(Kaczmarek et al., 1997)
Other	*Ionic Conducting Polymer gel Film (ICPF)*	ICPF cilium-shaped actuator submerged in water. Applying an electric field between the surfaces of the actuator makes it bend.	10	Vibration (at high freq.) Shear (at low freq.) Brushing	The softness of the ICPF material allows for very delicate touching. Low driving voltage (under 1.5V). Fairly high frequency operation (up to more than 100 Hz).	ICPF actuators require to be submerged in water in order to bend. Low actuator resolution.	(Konyo et al., 2000)

APPENDIX B

Tactile Player 1.0

Tactile Player 1.0 is the first version of the application that handles the communication between the PC and the Constellation™ development board. In other words, it displays the tactile movies on the tactile display. It is also responsible for the configuration of the FPGA. The GUI is divided into three modules that are shown and described in Figure 23. Tactile Player 1.0 is an MFC application developed under Microsoft Visual Studio 6.0®.

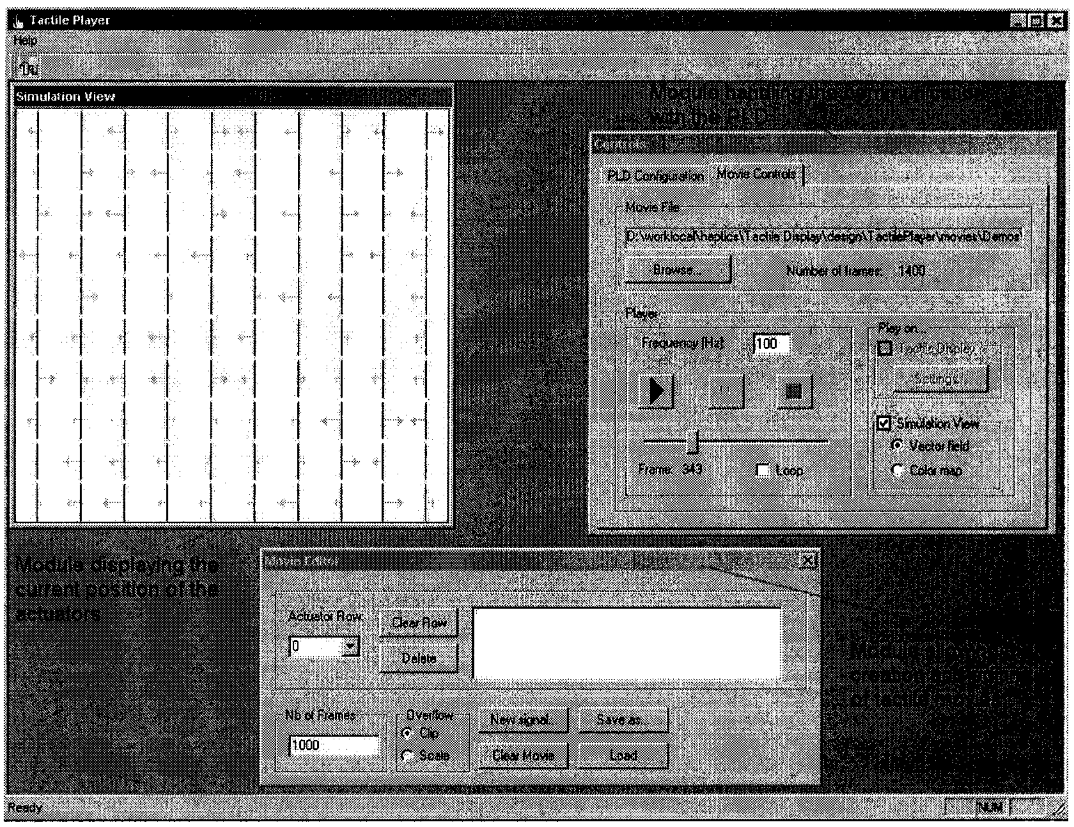

Figure 23: Snapshot of Tactile Player 1.0

APPENDIX C

Constellation™ Board Firmware

Figure 24 illustrates the architecture of the firmware uploaded on the Constellation™ board. The firmware is responsible for catching the data sent by the PC host and outputting the correspondant PWM signals. It was developed under the Altera Max Plus II® environment.

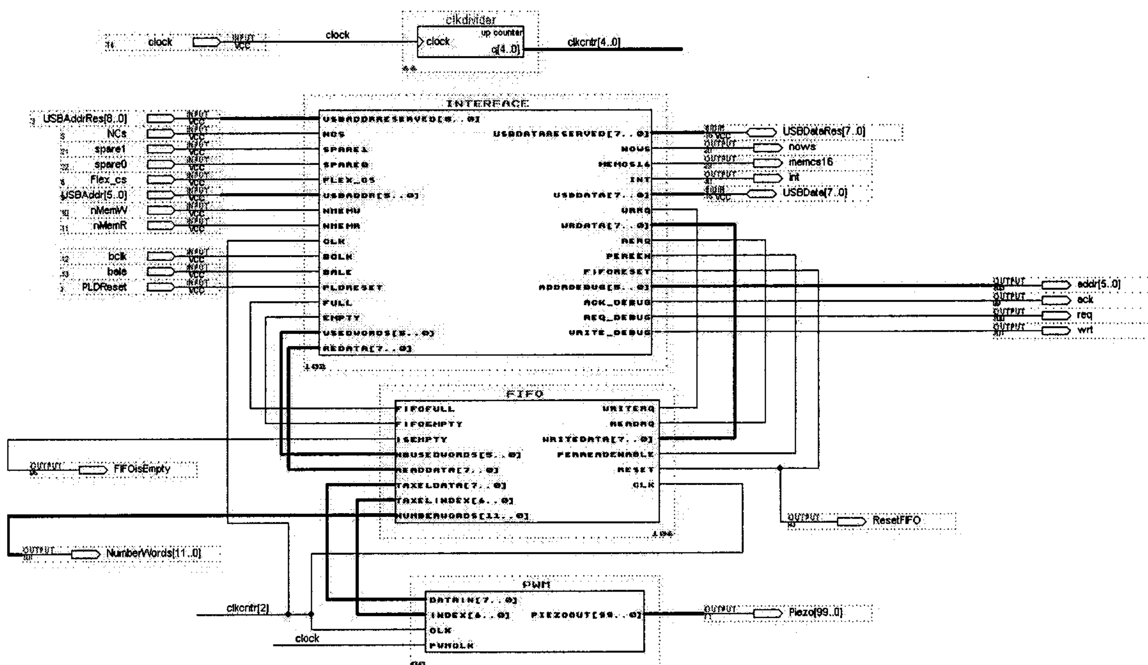

Figure 24: Overall VHDL architecture of the Constellation™ board firmware

APPENDIX D

Manufacturing Tips

The piezoelectric comb described in section 3.5.4 is in fact the result of the third attempt at building a working piece. It is the piezoelectric comb used for the latest version of the STReSS device. The following appendix describes the two previous attempts. It is thought important by the author to report and document these partial failures so that others trying to replicate the STReSS tactile display will not repeat the same mistakes.

The overall shape of the piezoelectric comb hasn't much evolved since its first version and has always been very similar to the one depicted in Figure 13. In fact, the only contour change that has been made resides in the lowering of one of the right shoulder to form a single and uniform right shoulder. All the other transformations concern the independent electrical access of each tooth-like actuator.

The comb 1.0

For the first version of the comb design (see Figure 25), the electrical contact between the two sides of a same tooth-like actuator was made by conductive paint applied at the base of the comb. The process involved the application of a first insulating layer of enamel paint to avoid shorting the outside electrodes with the center shim. Then, the application of a conductive paint (on top of the insulating paint) would electrically connect both sides of the same electrode. Unfortunately, this delicate procedure turned out to be highly unreliable. It was difficult to paint 10 conductive channels (i.e. 10 independent conductive traces) on the same comb with a 1mm-pitch. Extra manufacturing operations at the base of the comb were necessary to avoid shorting between adjacent tooth-like actuators. Moreover, with time, the conductive paint tended to eat into the insulating paint and undesired shorts were still found to occur between the outside electrodes and the middle composite shim. Another small source of problem came from the fact that the wires in charge of connecting the actuators to the PCB were glued (using conductive glue) to the piezoelectric material, a time-consuming process with unpredictable results. Nevertheless, a first STReSS prototype was built using this method. As expected, this prototype had only about 50% of its tooth-like actuators functioning.

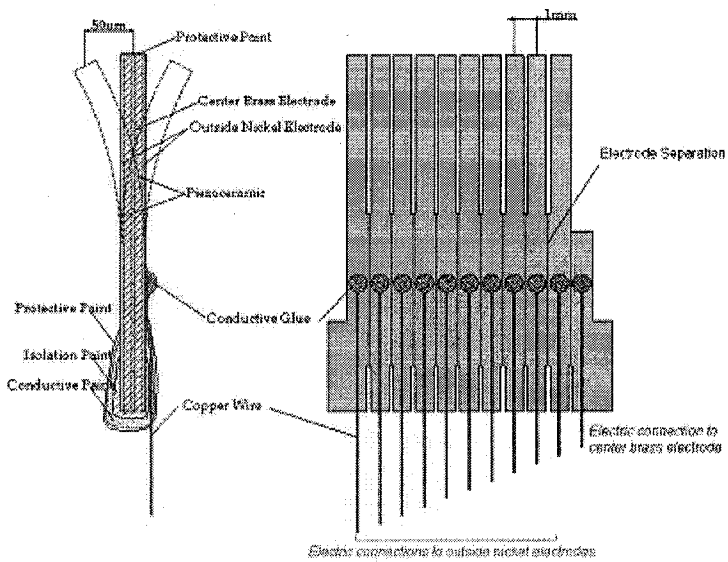

Figure 25: The "conductive paint" comb design (version 1.0)

The comb 2.0

The second version of the comb design (refer to Figure 26) avoided using conductive paint to connect both sides of a tooth-like actuator, by using small thru-holes to pass the wires[19] from one side to the other. While this seemed like an excellent idea at first, no simple method was found to reliably drill a small hole (diameter 0.2 mm) through the piezoelectric material. While coming out of the material, the drill would shatter the outside electrode, making it unusable. A lot of effort and time was put into finding a solution to this problem, including:

- using a micro high speed carbide mill bit instead of a drill bit,
- sandwiching the piezoelectric sheet between other materials,
- using wax at the back of the piezoelectric sheet to avoid the shattering,

[19] This time the wires needed to be insulated to avoid a short between the middle electrode and the outside electrodes in the thru-holes.

- drilling the holes by laser cutting .

Unfortunately, no satisfying solution was found and the thru-hole approach was dropped.

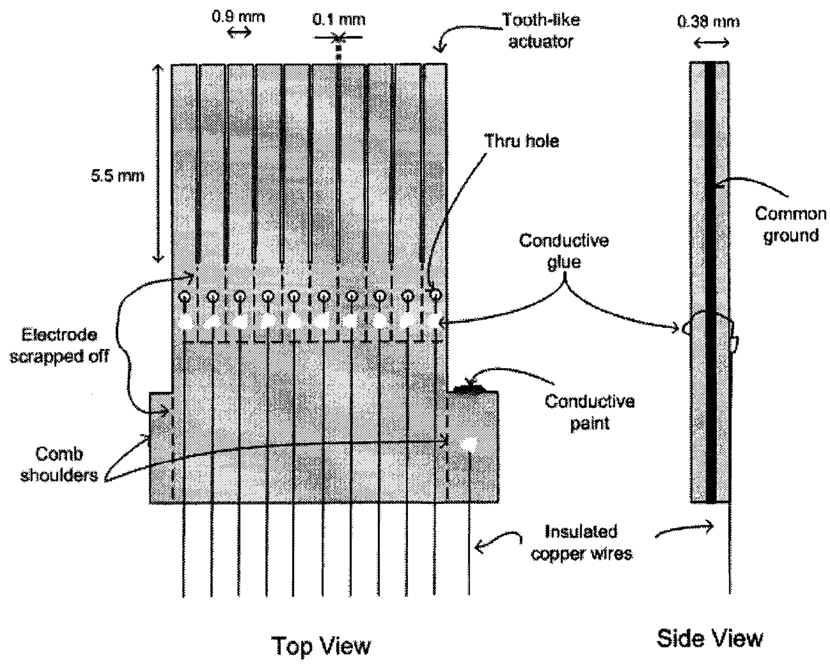

Figure 26: The "thru-hole" comb design (version 2.0)

APPENDIX E

Materials, Pieces, Tools and Companies

Conductive paint: Loctite® (www.loctite.com) Quick Grid™ found in rear window defogger repair kits - product #15067.

Conductive epoxy: CircuitWorks conductive epoxy from Chemtronics® (www.chemtronics.com) - product #CW2400.

Piezoelectric material: High performance bending motors from Piezo Systems inc. (www.piezo.com) - product #T215-H4CL-303X.

Copper wire: Silver plated copper wire (0.15 mm diameter) from Goodfellow (www.goodfellow.com) - product #CU005350/1.

FPGA development board: Constellation™ development board from Nova Engineering inc. (www.nova-eng.com) - product # L201-050-3.

Manufacturing stencils: The stainless steel stencils used for the manufacturing of the comb shape needed to be extremely precise and therefore were cut with an EDM (Electro Discharge Machining) process performed by Elimetal inc. (www.elimetal.com). The CAD drawings are available on request.

Diamond saws: Diamond saws (0.1 mm thickness and 18 mm diameter) from Brasseler Canada inc. were used to give the piezoelectric material its comb shape – product #911HEF.

Milling machine: The milling machine used for the manufacturing of the piezoelectric combs is manufactured by Servo Products Company (www.servoproductsco.com) - model #7231 709, 60 cyc., 120V, 2.5A, No load R.P.M 20000.

Amplifier PCB: 8-layer PCB developed on OrCAD® and manufactured by Multifor ltd. (www.multifor.com).

Amplifier circuit: The amplifier circuit is composed of:

1. a Fairchild semiconductor™ (www.faircildsemi.com) surface mount MOSFET – product #BSS123 SOT-23,
2. and 39 kΩ network transistors from Bourns® (www.bourns.com) - product #4116R -1-393.

Power supply transformer: A Hammond manufacturing™ (www.hammondmfg.com) center tap 2A transformer is used in the power supply unit to provide both the required 40 V and 80 V potentials – product #167L60.

APPENDIX F

The tac Format

The tac format was formulated by the author to have a simple way to represent tactile movies. A tac file is nothing more than a standard Portable Grey Map image (pgm). However, the information that it contains is interpreted differently. This permits for an easy editing of the tactile movies, either by using a standard image editor supporting the pgm format or simply by changing the taxel values directly in ASCII.

A tac file starts with the pgm magic number P2. It is followed by the number of taxels in a single image, the number of images and the maximum possible taxel magnitude[20]. The rest of the file is raw ASCII taxel values from the top left taxel of the first image to the bottom right taxel of the last image. The taxel values found in a .tac file have no physical meaning. Values over 127 and fewer than 128 indicate actuator displacements to the right and to the left respectively, with maximum displacements at 0 and 255.

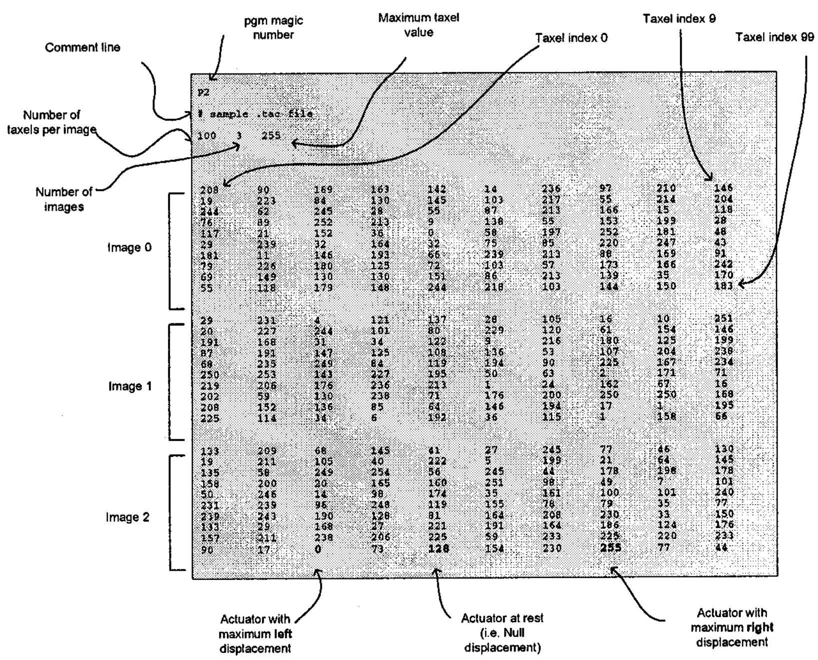

Figure 27: Tactile movie format (.tac)

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[20] In the case of a tactile movie to be played on the STReSS device, the number of taxels will always be 100 and the maximum taxel magnitude will always be 255, corresponding to the maximum right displacement of an actuator.