Maintenance Strategies and Design Recommendations on Input Devices for Musical Expression

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List of Acronyms

DMI	Digital Music Instrument
IDMIL	Input Devices and Music Interaction Laboratory
CIRMMT	Centre for Interdisciplinary Research in Music Media and Technology
LDR	Light-Dependent Resistor
NIME	New Interfaces for Musical Expression
ICMC	International Computer Music Conference
OSC	Open Sound Control
DOP	Digital Orchestra Project
DOT	Digital Orchestra Toolbox
IMU	Intertial Measurement Unit
UDP	User Datagram Protocol

Abstract

Various challenges must be overcome when designing and building input devices for musical expression such as digital musical instruments (DMIs), electronic wearables for performance, among others. Amid the technical ones are the rapid unpredictable advancement of technology, changes in supporting personnel, and a lack of technical documentation. These challenges, if not adequately addressed, in many cases lead to abandonment of such devices and endeavors. This thesis presents three case studies that aim to provide maintenance strategies and design recommendations for the creation of more robust, long-lasting interfaces. The first case study illustrates the challenge of maintaining several models of the DMI called the *T-Stick* in the hopes of extending their useful lifetime. The T-Sticks were originally conceived in 2006 and 20 copies have been built in the past 12 years. Although all of the instruments preserve the original DMI design concept, their evolution has distinguished them through variations in choice of microcontrollers, sensors, and size. For this case study, we worked with eight copies of the T-Sticks to overcome issues related to the aging and obsolescence of components, changes in external software, inconsistencies in firmware across versions, a lack of documentation, and, in general, the problem of technical maintenance. In the second case study, we redesigned the electronics of a ninth T-Stick, the WiFi Sopranino. For this process we used the lessons learned from the first case study, while keeping its original DMI design concept. This work, in turn, informed the third case study, where we sought to design and build a new interface for musical expression to augment cello performance by installing a visual affordance on the instrument. In short, this thesis aims to connect the concepts of technical maintenance and electronic redesign and design to provide a systematic approach to the maintenance of these type of devices. We articulate design recommendations such as maintainability, reusability, and self-containment as useful in the design of input devices for musical expression.

Resumé

Différents défis sont à surmonter lors de la conception et la construction d'interfaces pour l'expression musicale telles que les instruments de musique numériques (IMNs), les technologies portables pour la performance, entre autres. Les principaux enjeux techniques sont le développement rapide et imprévisible de la technologie, les changements dans le personnel de soutien et le manque de documentation technique. Ces défis, s'ils ne sont pas traités de manière adéquate, conduisent, dans de nombreux cas, à l'abandon de tels dispositifs. Cette thèse présente trois études de cas qui visent à fournir des recommandations relatives à l'entretien et à la conception pour la création d'interfaces plus robustes et durables. La première étude de cas illustre le défi d'entretenir différents modèles d'un IMN appelé le *T-Stick* dans l'espoir de prolonger leur durée de vie. Les T-Sticks ont été originalement conçus en 2006 et 20 exemplaires ont été construits au cours des 12 dernières années. Bien que tous les instruments préservent le concept original d'IMN, leur évolution les a distingués par des variations spécifiques dans le choix des microcontrôleurs, des capteurs, ainsi que de leur taille. Pour cette étude de cas, nous avons travaillé avec huit exemplaires de T-Sticks afin de résoudre les problèmes liés à l'obsolescence des composants électroniques, aux changements de logiciels externes, aux incohérences entre les versions de microprogrammes, au manque de documentation et, de manière générale, au problème de maintenance technique. Dans la deuxième étude de cas, nous avons reconceptualisé l'électronique d'un neuvième T-Stick, le WiFi Sopranino, tout en conservant son concept d'IMN original et en se basant sur les résultats tirés de la première étude de cas. Ce travail a mené à la troisième étude de cas, pour laquelle nous avons conçu une nouvelle interface pour l'expression musicale afin d'accroître les possibilités gestuelles et visuelles liées à la performance du violoncelle. Cette thèse vise à relier les concepts de maintenance technique et de conception électronique afin de fournir une approche systématique pour l'entretient de dispositifs. Nous proposons des recommandations telles que la maintenabilité, la re-usabilité et l'auto-confinement comme des outils pour la conception d'interfaces pour l'expression musicale.

Acknowledgments

Infinite thanks to Marcelo M. Wanderley. The most important question he asked was: “Is this what you really wanna do?” I can now say yes, this is what I wanted to do.

Many thanks to all the great people at the IDMIL and CIRMMT.

Thanks to my friends all over the world who contributed to this “*trippy que me sube*”.

Thanks to Pocotierno for rockin’ the house.

To my mom, for putting me in this world. Without you, I wouldn’t be what I am. And the rest of my family of course, each member one of a kind!

Chapter 1

Introduction

Expert musicians rely on highly-developed cognitive and motor abilities while interacting with acoustic musical instruments. Their expertise is typically developed through extensive practice with very reliable and responsive devices. Arguably, performers interacting with digital musical instruments (DMIs) may likewise require stable and responsive devices in order to develop similar levels of musicianship.

Unfortunately, DMIs and other input devices for musical expression become rapidly obsolete due to the unpredictably fast evolution of computer and electronic technologies [3]. Even when they are not yet completely outdated, many times non-functioning instruments and interfaces must be repaired. As could be the case of a 200-year-old acoustic instrument that breaks and needs to be repaired with materials that are currently available, the fact that the aforementioned input devices rely on electronics, could make the same issue more complex to approach. For this reason, the choice of replacement parts (when needed), maintenance materials, and software updates must be compatible with the original design, while nevertheless complying with what is currently available in the market. This process may even require electronics to be redesigned when off-the-shelf parts are no longer available.

It would not be advisable to change a DMI every time a new technology becomes available. We would rather study the impact of today's technology and how we could accommodate it to keep the instrument functional in order to support already developed playing expertise, repertoire, and compositions. Making a DMI work 10 times faster than before does not necessarily make a better DMI. We should comply with the original instrument design so that musicians can reuse developed expertise. Of course, this development can inform and provide feedback to morph future generations of the same instrument class or family. Therefore, it is essential to find the best option available while not being seduced by the marketing promise of ever novel, more performative technologies. It is preferable, especially in a research environment, to provide continuity rather than re-engineer a device or "re-invent" a musical instrument or interface.

In practice, several questions arise. First, how can existing devices be maintained while allowing for long-term performance practice? For example, what are the main challenges in keeping hardware and software tools in working order? Second, which current technologies are compatible with their original designs? Finally, drawing on the lessons learned in hardware and software maintenance, how can one design novel instruments targeted to be more robust and less limited by technological obsolescence?

1.1 Thesis Overview

This thesis is divided into six chapters. Chapter 1 outlines its goals and contributions. Chapter 2 frames this thesis into a historical context and connects related fields such as engineering maintenance to DMI building and the problem of instrument longevity. Chapter 3 provides detailed information on the strategies used for the maintenance work performed on eight DMIs from the T-Stick family of instruments. Chapter 4 centers on the electronic redesign of a ninth T-Stick - the WiFi Sopranino. Chapter 5 uses the lessons learned from chapters 3 and 4 as design recommendations to build a new interface for musical expression - an electronic system to visually augment the acoustic cello. Finally, Chapter 6 presents the main conclusions, summarizes the contributions of this thesis and proposes future work on the subject.

1.2 Contributions

This thesis contributes to current literature by outlining strategies for electronic maintenance of input devices for musical expression. The methodology evaluates and compares the advancements of older and newer digital electronics to provide continuity and balance among already existing instruments, newer versions, and the rapid evolution of technology. We present a systematic approach to maintenance that can be extrapolated to similar musical devices.

As a consequence of this work, we will articulate design recommendations that could be applied to any interface that is based on microcontroller boards, use open-source tools, and commercially-available sensors. The fulfillment of these objectives will allow for more mature methods for the design of long-lasting devices.

Chapter 2

Background

2.1 Introduction

New input devices for musical expression have been proposed for over four decades [40]. There is a growing community of researchers and artists designing, building, and using these devices to explore new sonic and visual possibilities. Their proliferation has also sparked an interest in their design, evolution, and longevity [32]. Conferences, such as the International Computer Music Conference (ICMC), the International Conference on New Interfaces for Musical Expression (NIME), among others (SMC[1], CMMR[2]), highlight the widespread interest in multidisciplinary topics like DMI design, sensor data acquisition and communication, software development, mapping, sound synthesis, and applications of machine learning to develop smarter[3] instruments, not to mention music performance, composition, and pedagogy. Fortunately, still the common denominator among these fields is the gestural input device that together with the mapping strategies and sound synthesis engine form the digital musical instrument. Since DMI design relies on engineering, the risk of devices malfunctioning due to technological obsolescence and non-industrialized manufacturing is present, especially in an area so closely related to digital electronics and a do-it-yourself (DIY)

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[1] Sound and Music Computing Conference.

[2] International Symposium on Computer Music Multidisciplinary Research.

[3] Smart in the sense that the instrument interacts with the performer using any kind of automatic gesture recognition and it is capable of autonomous decision making.

community. Therefore, concepts such maintenance and maintainability should be adopted in this field.

2.2 Technical Maintenance and Music Technology

2.2.1 Historical Context

It is well-known that acoustic musical instruments need constant maintenance (preventive and corrective). There are many procedures that ought to be performed on a periodic basis, including cleaning, tuning, replacing parts or maybe even completely overhauling the instrument.

The necessity for maintenance (and even the redesign) of electronic modules (hardware and software) in a digital musical interface was raised early on. One of the first examples is the case of the Bell Labs digital synthesizer (Alles Machine) [36], which is still functioning at the Oberlin Conservatory. Donated by Max Matthews in the year 1980, it posed an interesting and challenging engineering problem applied to the arts. Nelson and Talbert state:

> “The task has been difficult, time consuming, and often deeply frustrating... However, the opportunities brought about by the presence of the Alles Machine on our campus has fostered a strong working knowledge on such systems. It has enriched the TIMARA Program in ways not yet measurable and given us the means to comprehend and perhaps, participate in future developments in computer music synthesis”.

In the DMI community, Michel Waisvisz’s *The Hands*[4] is a classic example of instrument stability in DMI evolution. It was used in performance for the first time in 1984 and persisted for almost 25 years. Yet, little was publicly known about the details of the design, maintenance, and Waisvisz’s several revisions of the instrument until Torre *et al.* revisited his work [41]. In [20] Waisvisz stated that he planned on stopping development of the DMI in the second version to focus on performance (1990). This did not happen until the third version in 2000 [42], but still shows how he relied on instrument stability to refine his performance. *The Hands* design inspired

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[4] `http://www.crackle.org/TheHands.htm`

other instruments with lower entry-fee such as the MIDI conductor [20] and most likely, many other hand-based gestural controllers.

Similarly, sustainable instrument redesign of earlier instruments, like the Stylophone (a 1970's portable electronic musical instrument) redesigned into the Fingerphone [13] have been proposed to motivate the acquisition of musical skills and experience.

These examples speak to the technical challenges and engineering work that need to be part of the building and maintenance of these types of devices to ultimately further music exploration and generation.

2.2.2 Terminology

The literature regarding technological maintenance is vast [10]. In the modern context, the discipline of maintainability can be traced to the World War II and the early 1950s. For example, a study reported that during maneuvers electronic equipment was operative only 30% of the time [35]. Accordingly, a maintenance program was initiated to overcome this problem.

At the outset of this thesis, it is important to define key expressions. In the context of input devices for musical expression, we have extracted and combined several basic concepts that will be useful for understanding our work and would like to define them beforehand. These definitions are not exhaustive but are targeted to the music technology field.

- **Maintenance**: the measures taken to keep equipment in operable condition or repair it to operable condition.
- **Maintainability**: the measures taken during design and development to minimize maintenance time.
- **Corrective maintenance**: procedures performed when a piece of equipment malfunctions in order to restore it to operable condition.
- **Preventive maintenance**: tests, measurements and adjustments to prevent equipment malfunctioning. Usually a periodic task.

- **Predictive maintenance**: set of techniques to predict when a maintenance should be performed.
- **DMI design**: the technical and artistic process of conceptualizing a new digital musical instrument. This includes hardware design, mapping of idiomatic gestures and sound synthesis engine choice.
- **DMI re-design**: changes to create a related or new DMI based on an already existing instrument.
- **Electronic design**: in the context of devices for musical expression, electronic design is the choice of electronic parts based on the sensing and data communication requirements and their interconnection to meet those requirements.
- **Electronic re-design**: measures taken to update or renovate parts to keep an instrument functional but respecting the original DMI design.
- **Refurbish**: restoration of equipment to like-new working condition.
- **Reusability**: especially in software engineering, the use of already developed assets for newer devices.
- **Update**: to address certain issues to account for usability feedback.
- **Upgrade**: to replace with a newer product that usually performs more efficiently.

2.2.3 Longevity and Stability in Input Devices for Musical Expression

When coupled together, trends in the exploration of digital technology and the design of new devices has reached a semi-mature stage that has given rise to a number of questions about the usability, community building aspects, and stability of such devices. Surveys and questionnaires targeted to DMI designers [34], as well as an analysis of 40 years of related literature including performer interviews [40], reveal that instrument stability, reliability, and compatibility are major concerns. This analysis proposes that research should focus on key areas such as functionality, technology, compatibility, build quality, among others. One study is cleverly titled “Old” is the new “New” [14] and suggests that longevity of use depends on stabilizing the interface and innovating the implementation to maintain the required stability of performance for players.

Principles for the design and redesign of instruments have been suggested, tipping the balance towards an artistic approach rather than an engineering one [6]. While the trends towards artistic approaches have been important in many projects and reports on new interfaces for musical expression, this could explain the lack of robustness in current designs [30]. In [7], it is stated that DMI design is practice-based research. This practice could be either the actual design of the instrument or the musical performance. We argue that for the latter to exist, good instrument design is essential. Good instrument design means framing it among good engineering practice, projected maintainability, and robustness of the device, always balancing the artistic outcome with the engineering approach. It correlates with the description in [7] of “The Pragmatic Account” as a description of NIME design. Bongers [5] argues: “The need for a well designed interface ... is bigger than ever”. We subscribe to this idea now even more on account of the widespread accessibility to learning and building tools.

Ferguson and Wanderley have stated that one effective measure for the evaluation of a DMI is its ability to reproduce a performance of a particular piece [12]. Mamedes *et al.* affirm that the problem of DMI longevity is the lack of an instrumental technique, musical notation suitable for DMIs, and the non-existance of repertoire [28]. We would like to add a lower layer to the problem: technical functionality should be guaranteed *over time* if any of the former issues are to be addressed.

In professional artistic applications of new media works, it has proven useful to follow a methodology for the design of hardware devices [18]. Functionality and reusability are mentioned as poles that encompass the design process. This means that newer designs should be informed from previous attempts of similar designs.

As a final example we would like to mention that there is much interest in the preservation of electroacoustic works that involve live electronics [45, 1]. The preservation and recreation of works involving electronics require functional equipment and choosing the most appropriate currently available technology. In the case of ensemble music involving the use of DMIs, re-performing pieces composed for these instruments face greater problems since the DMI is an integral part of the ensemble of instruments. How can a piece composed for an ensemble that requires a DMI be preserved if the instrument does not work or does not exist anymore?

Chapter 3

The T-Stick: Maintaining a 12-year-old Digital Musical Instrument

3.1 Introduction

In this chapter we focus on the maintenance procedures performed on a DMI. These procedures have three main components: 1) hardware maintenance, 2) software updates, and 3) technical documentation [37]. This case study targets the T-Stick, a unique family of instruments more than 12 years old. The T-Stick [26] is a DMI conceived by Joseph Malloch and D. Andrew Stewart at the Input Devices and Music Interaction Laboratory (IDMIL) at McGill University. It has been in development since 2006, and using this DMI for this research is very interesting because it has a relatively long history (for technology artifacts), multiple versions, several expert performers, and an associated repertoire [39]. More than 20 copies were built unintended for commercial use. Nevertheless, it has been adopted by expert performers and composers as part of their musical practice including D. Andrew Stewart[1] (Soprano user) and Fernando Rocha[2] (Tenor user). It has appeared in dozens of public appearances in countries such as Canada, USA, Brazil,

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[1] See `https://blogs.ulethbridge.ca/andrewstewart/tstick/`.

[2] See `http://www.fernandorocha.info/pt/publicacoes.html`

Italy, Norway, and Portugal.[3]

3.2 The T-Stick: From Controller to Instrument and Back to Controller

The origins of the T-Stick date back to the McGill Digital Orchestra Project (DOP) [38, 12]. The T-Stick is a family of instruments, as it was originally conceived in different sizes and weights to allow for a variety that resembles a family of wind instruments. The models include: Sopranino, Soprano, Alto, Tenor, and Bass. The lengths are 0.35m, 0.6m, 0.8m, 1.2m, and 1.8m respectively. There are differences in electronic design decisions such as microcontroller and sensor models, but they maintain the same concept over the idiomatic gestures used to perform with the instrument. A subset of the instruments available at the IDMIL are shown in figure 3.1.

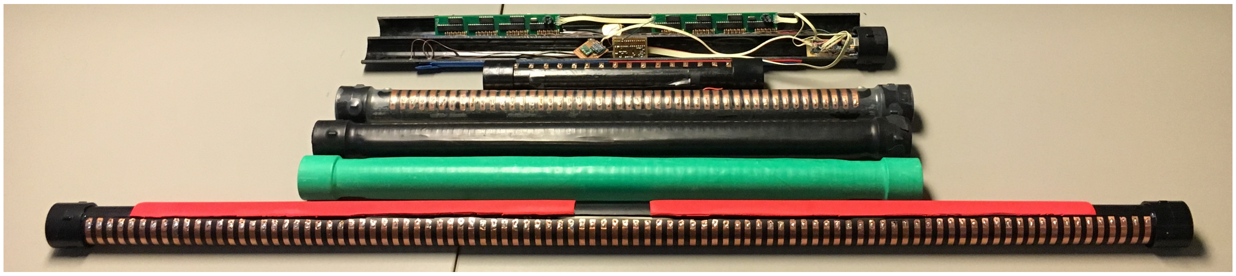

Figure 3.1 6 out of the 9 T-Sticks currently operational at the IDMIL, McGill University. Top to bottom: Soprano 2G-IMU (open), Sopranino, Sopranos (2GX, 2G, 2G), Tenor.

The T-Stick provides integral sensing and mapping that is intended to provide a logical and discoverable response to the player's actions. New users should be able to produce sound from the DMI, but not necessarily *musical* sound. *Low entry fee* [44] was not prioritized; the instrument requires training and practice to reach a significant level of virtuosity [23]. The T-Stick was designed to have a robust physical interface usually made of ABS plumbing pipe with a diameter of 5cm (several subsequent models use transparent PVC or bamboo for their body material). Some of them were built with vibrotactile feedback and others with Bluetooth radios and batteries [24].

Historically, there are three generations of T-Sticks. They are labeled as 1G, 2G, and 3G

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[3] See `https://josephmalloch.wordpress.com/portfolio/tstick/`, for a partial list of performances.

respectively. See table 3.1 for a classification. Over the world, there is one Soprano 2G-IMU in Halifax, Canada, one Soprano 2GG[4] in Lethbridge, Canada, and a Tenor 2GG in Brazil. T-Sticks have been shared with research groups in Denmark and Australia.

Table 3.1 T-Stick family of instruments classification.

Generation	Models	Variations	Platform
1G	Alto Tenor	None	Based on the ATmega16
2G	Soprano Tenor Sopranino	2G 2GX 2GG 2G-IMU 2GW	Arduino Arduino Arduino Arduino ESP8266
3G	Soprano	None	Arduino

The first and second generations of the controller were developed during the duration of the DOP. Defined mappings and sound synthesis engines also completed the DMI paradigm to give birth a fully functional DMI [26, 39]. Subsequently, other performers with other mapping approaches and concepts developed additional DMIs. As the instrument matured, newcomers to the field built more copies as part of courses on Input Devices for Musical Expression at the Master and PhD level at McGill University (See figure 3.2). For the final project, students were tasked with building their own version of a T-Stick. This, with the help of the original designer[5], allowed for numerous copies of the instrument to be available for use in demonstrations and performances. T-Sticks have also been used for teaching mapping strategies in graduate seminars of Gestural Control of Sound Synthesis. This has led to further use of the instrument by new performers.

The T-Stick has been used in performance and composition workshops multiple times. One of the first performances was on April 10th, 2006 by Xenia Pestova as can be seen in figure 3.3 along with the credits for composer, perfomer and music technologists[6].

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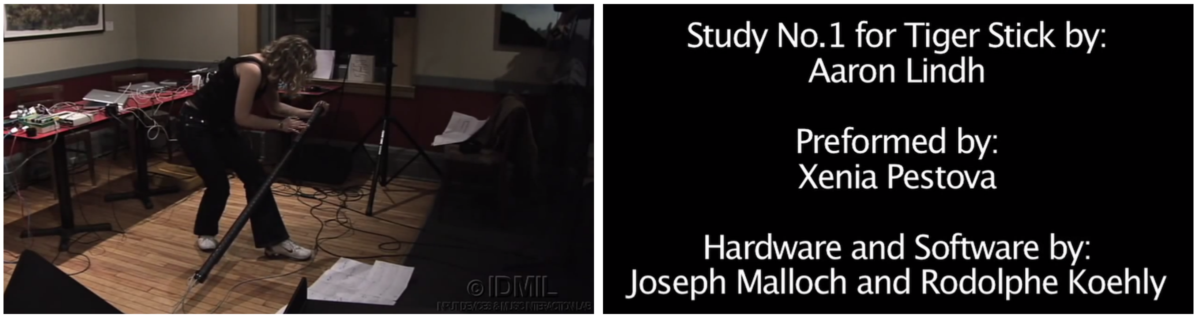
[4] The extra G in the model is due to the use of a gyroscope in addition to an accelerometer

[5] `https://josephmalloch.wordpress.com/mumt619/`

[6] `https://youtu.be/Lss5H242OdE?t=3m37s`

Figure 3.2 Students from DMI seminar at McGill University where several T-Sticks were developed as part of the final project. Photo by Joseph Malloch.



(a) Xenia Pestova playing the T-Stick in April 2006. (b) Video credits for the Study No. 1 for T-Stick.

Figure 3.3 One of the very first concerts showcasing the T-Stick, called the Tiger Stick at the time.

Performer and instrumentalist D. Andrew Stewart is one of the most important T-Stick players and has adopted the Soprano as part of his artistic practice traveling around the world presenting works like *Still Life*[7], premiered at the International Conference on New Interfaces for Musical Expression 2013 in Daejeon, South Korea. Part of this artistic practice involves developing subsequent mappings for specific compositions and creating idiomatic gestures that collectively form the playing techniques of this instrument as can be seen in figure 3.4. He has also held composition workshops that can be found in `https://tcw2010.wordpress.com/`. Another performer playing the T-Stick and DMIs in general is Fernando Rocha. As a percussionist he has adopted the Tenor T-Stick transferring his refined technique to the T-Stick[8]. The T-Stick has also been used in collaboration with dancers and in ensembles with traditional acoustic instruments. It is reasonable to say that the T-Stick has definitely shaped the artistic practice of people that have adopted the instrument as their DMI. For more information on the history of the T-Stick visit `https://josephmalloch.wordpress.com/tag/t-stick/`.

During these 12-years, the building process (either hardware or firmware) had to be modified to match advancements in microelectronics riding the wave of technological obsolescence, or to fulfill a different DMI design criteria. This posed a problem of interoperability and maintainability for future users due to changes in operating systems (specifically OS X), software compatibility used along for mapping and sound synthesis (*libmapper*[9] [25], Max/MSP[10]), hardware aging, and a lack of accurate documentation.

For this thesis we worked with a total of nine instruments that belong to the second generation of T-Sticks. The models are: the Sopranino, Soprano and Tenor. All of them are operational and currently available for use at the IDMIL.

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[7] `https://youtu.be/T-pZ0Xj378o`

[8] `https://vimeo.com/1620495`

[9] `http://libmapper.github.io/`

[10] See `https://cycling74.com/`.

Figure 3.4 D. Andrew Stewart performing with the Soprano 2GG. Photo by Vanessa Yaremchuck.

The T-Stick Gestural Language

The original instrument design of the T-Stick provided three layers of data processing to be able to perform interesting and meaningful many-to-many rather than one-to-one mappings of gestures to the sound synthesis engine. Table 3.2 contains a summary of the gestural acquisition characteristics and the sensors used to achieve them in the T-Sticks reported on in this thesis.

Gestures such as brushing, tapping, pressing, jabbing, among others, are efficiently recognized by the instrument driver patches. The revision and maintenance of this software is explained in detail in the subsection Software Maintenance.

For this thesis, the spatial orientation of the T-Stick[11] has been defined as follows: The X axis runs along the length of the tube with origin at the USB cable end. The Z axis points upwards towards the capacitive sensing keys. Finally, the Y axis follows the right hand rule for coordinate systems. See figure 3.5.

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[11] The original T-Stick firmware is flexible enough to allow for rotation of coordinates if needed by the user.

Table 3.2 The T-Stick gestural acquisition characteristics and their correspondent sensors.

Type	Model	Touch	Motion	Shock	Pressure	Air Press	Light	Distance
`Sopranino`	2G	16 `Cu` strips	Accelerometer (digital)	Piezo	Paper	x	x	x
	2GW	16 `Cu` strips	IMU	x	FSR	x	x	x
`Soprano`	2G	48 `Cu` strips	Accelerometer (analog & digital)	Piezo	Paper	x	x	x
	2GX	48 `Cu` strips	Accelerometer (digital)	Piezo	Paper	yes	LDR	IR
	2G-IMU	48 `Cu` strips	IMU	Piezo	Paper	x	x	x
`Tenor`	2G	96 `Cu` strips	Accelerometer (analog)	Piezo	2 FSR	x	x	x

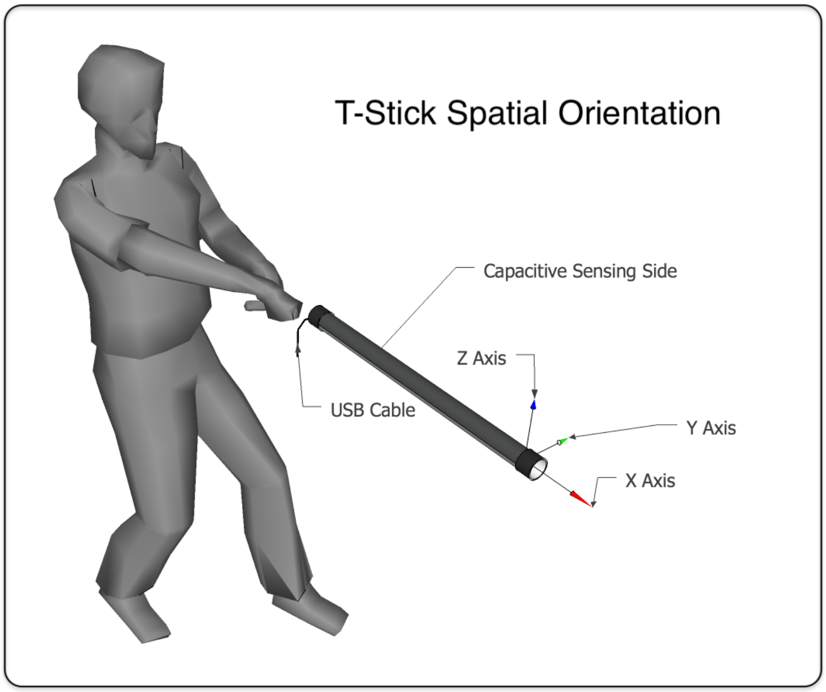
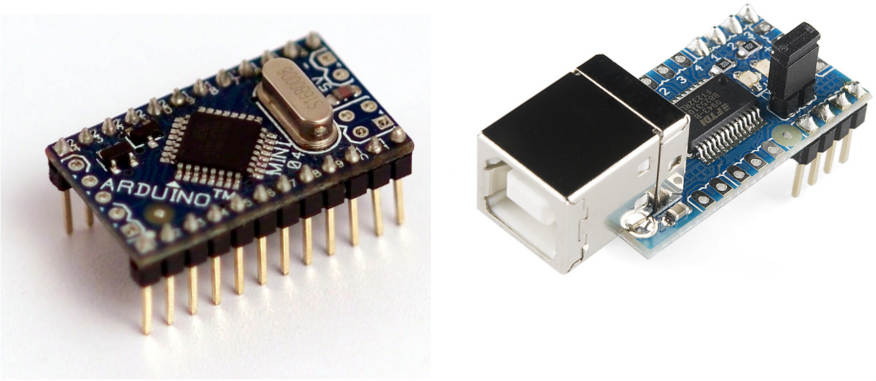


Figure 3.5 Spatial Orientation of the T-Sticks

The T-Stick Electronics Specifications

Most existing T-Sticks at IDMIL are based on the 2G design because some of them were built as part of a class project for a graduate seminar at McGill University and laid down a semi-mature proven-to-be-functional design. All of them (except the Sopraninos) use the Arduino[12] Mini 04 board (discontinued - See figure 3.6a). This board is based on the ATMEL ATmega168 microcontroller running at 16MHz - 5V. A serial to USB adapter (officially named Arduino mini USB adapter) based on the FT232RL chip from FTDI[13] is attached to this microcontroller board. This allows for communication between the instrument and the host computer at 115200 baud. An important characteristic is that this USB adapter uses a USB 2.0 type B jack. This defines the type of USB cable to use with these model of instruments and after 12 years of existence it could potentially pose a problem of maintainability. See figure 3.6b.



(a) Arduino mini 04 used in the Sopranos and the Tenor T-Sticks.

(b) Arduino mini USB adapter used in the Sopranos and the Tenor T-Sticks.

Figure 3.6 Microcontroller board and USB adapter for the Soprano and Tenor T-Sticks.

The Sopranos 2G T-Sticks have 4 types of sensing capabilities: a 3-axis analog accelerometer

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[12] See `https://www.arduino.cc/`

[13] See `http://www.ftdichip.com/`

based on the LIS3L02AS4 mems intertial sensor: ±2g/±6g or a 3-axis digital accelerometer based on the LIS302DL mems motion sensor: ±2g/±8g, copper strips around one side of the body for capacitive sensing, a piezoelectric sensor and a commercially produced force sensitive resistor (FSR) or a paper-based force sensor fabricated at the IDMIL [19]. The firmware loaded onto the Arduino mini 04 allows the configuration patch to write on the EEPROM, where information about the configuration of the instrument can be changed or retrieved. Capacitive sensing is performed via custom designed boards at the IDMIL by Joseph Malloch based on the Quantum QProx QT161-DG QTouch integrated circuit (IC). Each of these ICs can handle 6 capacitive sensors. Each board uses 4 of these ICs.

The Soprano 2GX was built by Marcelo M. Wanderley and Joe Thibodeau and has additional sensing capabilities such as proximity, breath, and light via an infra-red diode, an air pressure sensor and a photoresistor, respectively.

Table 3.3 Summary of sensors used in the T-Sticks evaluated in this project.

	Sopranino		Soprano			Tenor
	2G	2GW	2G	2GX	2G-IMU	2G
Capacitive strips	16	16	48	48	48	96
Accelerometer (analog)	-	-	1	-	-	1
Accelerometer (digital)	1	-	1[a]	1	-	-
IMU	-	1	-	-	1	-
Piezoelectric	1	-	1	1	1	1
FSR	-	1	-	-	-	2
Paper force sensor	1	-	1	1	1	-
IR	-	-	-	1	-	-
Air pressure sensor	-	-	-	1	-	-
Photoresistor	-	-	-	1	-	-

[a] The Soprano 2G-024 has a digital accelerometer. See next sections.

The Soprano 2G-IMU has a digital IMU instead of an accelerometer for motion detection. The Tenor 2G, built by Marlon Schumacher and Vanessa Yaremchuk, is twice as long as the Soprano and has one additional FSR for pressure sensing.

The Sopraninos are half the length of the Sopranos and the sensing capabilities resemble those of the Soprano 2G versions, except the 2GW that does not implement a piezoelectric sensor (details on the Sopranino 2GW and electronic redesign are given in Chapter 4). Moreover, due to the time of instrument design of the Sopraninos, the 2G uses a different microcontroller board: the Arduino Pro Mini and a different serial to USB adapter still based on the FT232RL chip but now with a different layout. See the subsection on the Sopranino 2G-172 in this chapter for more details. The summary of sensors used in each model are listed in table 3.3.

3.3 Maintenance Procedure

Part of the work performed in this thesis is grounded in the concepts of corrective and preventive maintenance. Once we decided on the importance of revisiting the operational status of the T-Sticks, a systematic approach was developed and is depicted in the flowchart in Figure 3.7. The first step was a visual inspection of the instruments to separate them in groups. Next, the pertinent literature was reviewed. Specifically, the Master's and PhD thesis written by the designer Dr. Joseph Malloch [23, 24]. This revision informed all the instrument models developed to date. It also revealed that there existed Max/MSP **configuration patches** to set parameters of the hardware and data communication in the device, and **instrument driver patches** to process the sensor data, perform the first two layers of mapping, and expose the signals and their Open Sound Control (OSC) addressing scheme into *libmapper*.

While the instruments were physically available at the laboratory, the configuration patches and driver software was still lacking. There was a demo working version of a Soprano T-Stick in one of the computers at the laboratory that pointed us to the contents of the DOP [12] archive, where much of the work on software was developed [38]. This was a comprehensive archive of the DOP and among the software located there, configuration patches and instrument driver patches were found for the different models of T-Sticks.

Additionally, there were many firmware Arduino sketches, probably sequential versions that evolved in parallel as well as the instrument did. These sketches presented different ways of

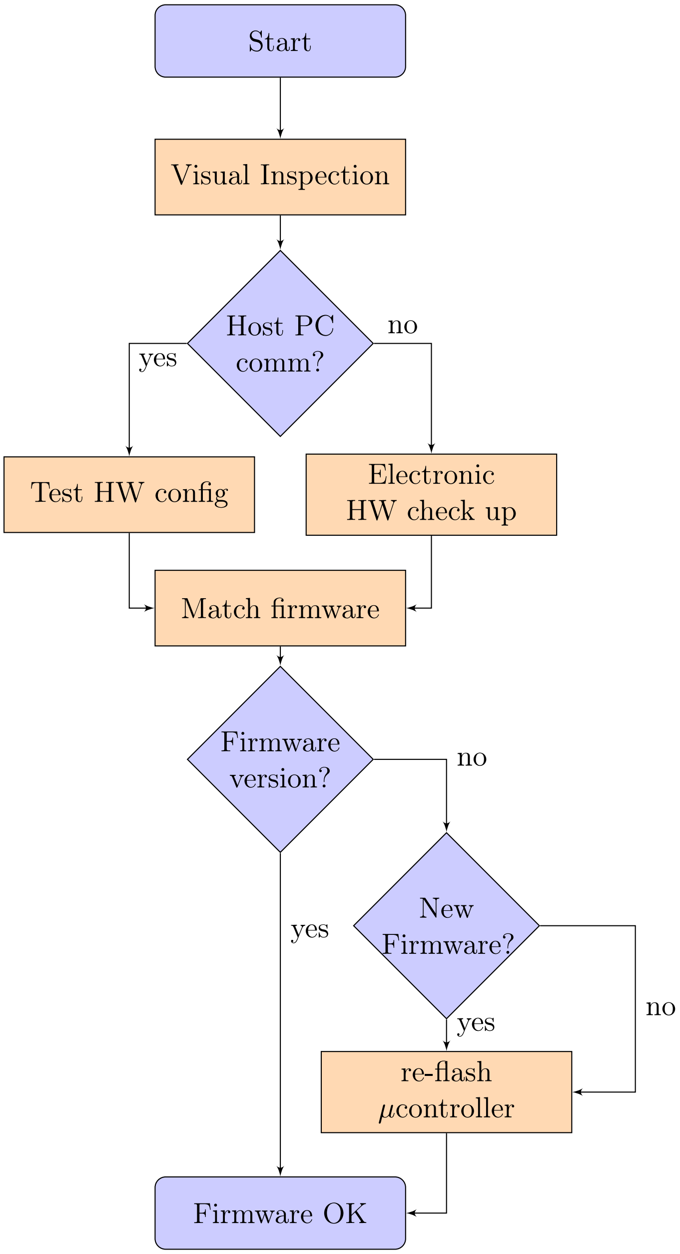

Figure 3.7 Flow diagram showing the maintenance process performed on the T-Sticks.

handling serial data communication. There was firmware that polls the instrument for data, another firmware that sends priority data at fixed time intervals, and another firmware that allowed for in depth configuration with the possibility of storing important information of the T-Stick on the EEPROM. Most configuration patches implemented commands to write information on the EEPROM, we therefore started under the assumption that the T-Sticks had the firmware with the EEPROM writing option and we planned our tests from there.

As stated at the beginning of the chapter, there were three main procedures performed: 1) hardware revision and maintenance that included identifying the firmware, 2) software revision to update configuration and instrument driver patches, and 3) documentation including specification sheets, drawings and general information about each instrument.

3.3.1 Overview of State and Identification of Instruments

At the beginning of this work, the T-Sticks were in different functioning states. As we gathered them, we performed the first process of the maintenance work, which was the visual inspection. This informed us that we should divide them in three groups as follows:

- Group 1: 5 instruments assembled and wrapped in heat-shrink tube. 4 were Sopranos and the other one the Tenor.
- Group 2: 2 Sopranos that were bare open (no heat-shrink tube, exposed electronics, broken or disconnected parts).
- Group 3: 2 Sopraninos. One was disassembled with complete electronics to be implemented and the second one only had the capacitive sensing chips soldered to the sensing strips on the PVC structure.

Once grouped, we needed to identify each of the instruments by probing communication between the DMI and its respective configuration patch in the host computer. Three Sopranos and the Tenor in group 1 had physical labels with their serial numbers. Connecting them to the computer with the configuration patch confirmed their serial numbers as well as their firmware revisions. The extra Soprano (2GX), was probed with its correspondent configuration patch, and while not being labeled due to the position of the sensors on the instrument, it provided their serial number and firmware revision stored in the EEPROM.

Table 3.4 identifies the instruments with their serial numbers. Throughout this thesis we will refer to the instruments by name, model and serial number. For example, the first instrument in the table will be referred as Soprano 2G-010. These serial numbers were assigned depending on the order or construction of the instrument during initial stages of design and graduate seminars hosted at McGill University. At the time they were built, batches of several instruments were produced so it made sense to number them in an ascending order as is the case of instruments in group 1. DMIs in groups 2 and 3 were given new serial numbers since there was no other information available for them.

Table 3.4 Group 1 of T-Sticks

Instrument Model	Serial Number	Firmware Revision
Soprano 2G	Serial 010	1730
Soprano 2G	Serial 012	1730
Soprano 2G	Serial 024	1793
Soprano 2GX	Serial 015	1793
Tenor 2G	Serial 014	1742

The instruments in the second group, even if they were bare open, were probed with a working configuration patch to test if communication with the computer was possible. While the microcontroller showed up as present in the serial port, there was no response from valid firmware. These instruments were assigned new serial numbers since no other information was available. Similarly, in group 3, the only Sopranino that had a microcontroller was known to have never been finished and we probed its microcontroller to determine if it was operational. The second Sopranino only had the capacitive sensing structure and electronics and was left for the next step of this research, which is documented in detail in Chapter 4.

Table 3.5 identifies the instruments that were bare open. Now as the construction and im-

Table 3.5 Group 2 of T-Sticks

Instrument Model	Serial Number
Soprano 2G	Serial 171
Soprano 2G-IMU	Serial 173

plementation of the T-Sticks was part of a maintenance research project, the serial number was defined as the year of refurbishment/construction and the order in which the instrument went through the process. In this case, the Soprano 2G-171 was the first instrument refurbished in 2017 and the Soprano 2G-IMU-173 was the third.

Table 3.6 Group 3 of T-Sticks

Instrument Model	Serial Number
Sopranino 2G	Serial 172
Sopranino 2GW	Serial 181

Table 3.6 presents group 3. In this case the Sopranino 2G was the second instrument to be implemented in 2017 and the Sopranino 2GW was first built in year 2018. To finish this section we summarize the main procedures performed on each instrument in Table 3.7. We provide specific details on the hardware maintenance performed on each instrument in the next section.

3.3.2 Hardware Maintenance

Starting with the hardware, we focused on the electronic maintenance and data communication to the configuration patch. Since the most common instrument was the Soprano we started with that instrument model. One important original DMI design decision was to implement a very basic LED feedback indicator on the instrument. When connected to the USB port of a computer the T-Stick should go into stand-by mode with the LED blinking every 1 second. The configuration/driver patch would send a heartbeat/keep-alive signal every 1.5 seconds to the instrument to enable data communication. In the event that the Max patch is closed or crashes the instrument would go automatically into stand-by mode waiting to receive the heartbeat again. This proved to be critical to match the firmware flashed on the microcontroller later on.

Table 3.7 Summary of maintenance work performed on each T-Stick.

Instrument Model	Hardware	Software
Soprano 2G-010	Operative	Firmware match Update driver
Soprano 2G-012	Operative	Firmware match Update driver
Soprano 2G-024	Operative	Firmware match Update driver
Soprano 2GX-015	Operative	Firmware match Update driver
Tenor 2G-014	Open Fix electronics	Firmware match Update driver
Soprano 2G-171	Refurbish - Reflash Firmware Fix electronics	Firmware update Update driver
Soprano 2G-IMU-173	Refurbish - Redesign electronics Fix electronics	Firmware upgrade Update driver
Sopranino 2G-172	Implement - Redesign electronics Fix electronics	Write firmware Write driver

As the flowchart in figure 3.7 shows, probing instruments gives rise to two possibilities. First, if there is communication we would go onto testing the hardware configuration, the correct functioning of the sensors in the DMI, and identifying the firmware. Otherwise, the instrument would undergo electronic check up. Once the instrument was repaired (if needed), we matched the Arduino firmware sketches found in the DOP archive with the sensing characteristics of the DMI. Group 1 firmware was correctly identified, while for groups 2 and 3 we had to either update or rewrite firmware according to their hardware specifications. Next, we provide detailed information pertinent to each instrument.

The Sopranos 2G-010, 2G-012, and 2G-024

These three instruments present the same general characteristics. They are all wrapped in black heat-shrink tube and fully operational with the exception that they do not respond to the heartbeat. This indicates that the firmware version installed precedes a more stable version. Nevertheless, all the sensor data is delivered successfully to the host computer. Based on the serial numbering and informal discussions with the original designer, these belong to a group that was developed as part of a graduate seminar on input devices for musical expression.

While these Sopranos were undergoing hardware maintenance, we also noticed that the accelerometers inside the 2G-010 and 2G-012 were soldered to pins 5, 6, and 7 of the Arduino board and the piezoelectric and FSR sensors to pins 4 and 3 respectively. This seems to be the layout of the first designs because later in time, the analog accelerometers were wired to pins 0, 1, and 2 (See section on the Soprano 2G-171). This means pins 4 and 5 were freed up to use the I2C bus for digital accelerometers since those are the pins assigned by default in this Arduino board as is the case of the 2G-024.

A decision was made to keep the hardware of these instruments as is since their status allow for acceptable operation. They would go onto the software maintenance phase.

The Tenor 2G-014

This instrument was found in finished condition wrapped in black heat-shrink tube. After a visual inspection some rattling of components was noticed but nonetheless, it was first evaluated with the configuration patch located in the DOP IDMIL archives. The connection to the host computer and data enabling of the instrument showed data coming only from the accelerometer and the capacitive sensors. Therefore, the decision was made to open the instrument (See figure 3.8). The heat-shrink tube was cut giving us access to the full electronics of the instrument. The piezoelectric sensor and the FSR connections were broken. New soldering points were applied and this procedure enabled full communication with the configuration patch.

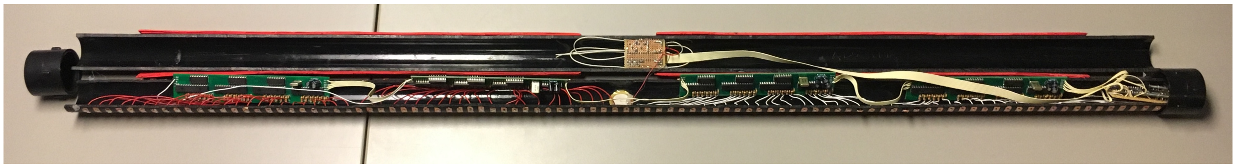

Figure 3.8 T-Stick Tenor model opened to be repaired.

The IDMIL archive listed two possible firmware sketches for the Tenor: 2G and 2GG. This instrument works as described by the 2GG patch with the option for enabling a gyroscope set to false (no gyroscope was found inside). The decision to open the instrument also gave us the opportunity to document the wiring of the instrument and the components used in its construction. All this is reported in the documentation for this instrument.

After the repairs were performed, the Tenor soldering points were secured with silicon glue to prevent movement and break up of the wires. The boards were better secured with foam padding so that they would not vibrate when the instrument was used in performance. Finally, the Tenor was wrapped again with black heat-shrink tube.

The Soprano 2GX-015

The Soprano 2GX went through visual inspection and one problem that we noticed was that the paper FSR was not padded with foam as the other instruments are. This padding allows for some compliance when pressing the T-Stick and also prevents the heat-shrink tube from compressing the FSR to its maximum value. The configuration patch confirmed that the paper FSR is fully pressed by the heat-shrink tube and sends its maximum value. All the other sensors are in working condition. Even if the pressure sensing capability is not functional, the instrument performs in an acceptable way and unless the pressure sensing capability is crucial for a performance it should be left as is.

Figure 3.9 shows the difference of this instrument from the other Sopranos. It has 3 extra sensors for light intensity, air pressure, and distance measurement at the opposite end of the USB connector end-cup.

The Soprano 2G-171

This T-Stick is part of group 2. Circuits were exposed and some electronics with soldering points broken. It was refurbished and its circuit diagram documented. This instrument has exactly the same hardware as Sopranos 2G in group 1 so the decision was made to keep it as close to the original DMI design as possible. Once the electronics were fixed it was connected to the computer

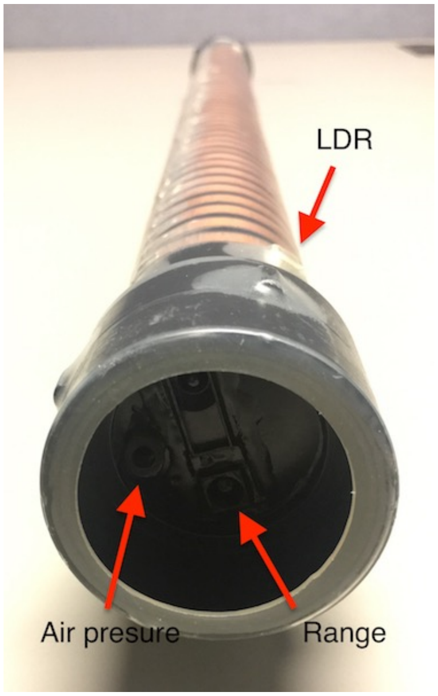

Figure 3.9 Soprano 2GX-015 showing the extra sensors in this model.

and probed with Max/MSP to find out if data communication was possible. This instrument did not respond to the basic patch used to probe de instruments, however we could verify that the microcontroller was in correct functioning state. Therefore, the decision to re-flash new firmware was taken. At the time of design and building (as is also the case of instruments in group 1), the reset pin of the microcontroller was hard-wired to PULL-UP state in order to avoid random or accidental resets of the board. In this case we had to momentarily enable the reset pin to be able to re-flash the microcontroller. The final form of the device can be seen in figure 3.10.

Figure 3.10 The Soprano 2G-171 fully assembled after repairing and firmware re-flash.

While there were a number of firmware sketches available, the work already done with the DMIs in group 1 informed us on which of the sketches was appropriate for this refurbished DMI. In order to re-flash the microcontroller, the sketch was updated to work with the latest version of the Arduino IDE. The original firmware was written in the IDE version 00xx, which is no longer supported by the developers. All the updated or new firmware works with the IDE version 1.8.3. As mentioned in a previous section, the wiring of this T-Stick had the accelerometer in different pins but functionaly, the T-Stick performs as the older instruments. This is important since the instrument driver patches are the same for each instrument model. This is a good example of modifiying the electronics to keep the same functionality, working against electronics obsolescence.

The Soprano 2G-IMU-173

This instrument was also found bare open but the difference is that it had the usual analog accelerometer and an analog gyroscope that was re-purposed from an old Wii MotionPlus controller. There is a set of instruments with model name 2GG that were part of the experimentation with an accelerometer and a gyroscope (none of them are part of this thesis). This led us to infer that this T-Stick was used to explore the possibility of using such a system to be able to sense absolute motion with respect to earth. The accelerometer and the gyroscope were partially disconnected. The microcontroller together with the serial to USB converter would appear in the host computer but no data was transferred. The decision was made to replace the motion sensing components for an alternate piece of electronics that could perform the same function while being compatible with the original electronics. While analog accelerometers and gyroscopes are still available in the market, they are rapidly becoming obsolete, therefore an upgrade was reasonable and feasible for this instrument. IDMIL had been working with a breakout board based on the LSM9DS0 digital IMU and in-house development already existed, therefore the choice was made to work with this device. The firmware had to be upgraded to allow for data transfer via I2C. Figure 3.11 shows, highlighted in a red oval, the IMU replacing the old analog motion sensors. For this, we also had to include a bi-directional logic level converter since the newer IMU works at 3.3V while the

Arduino supplies 5V.

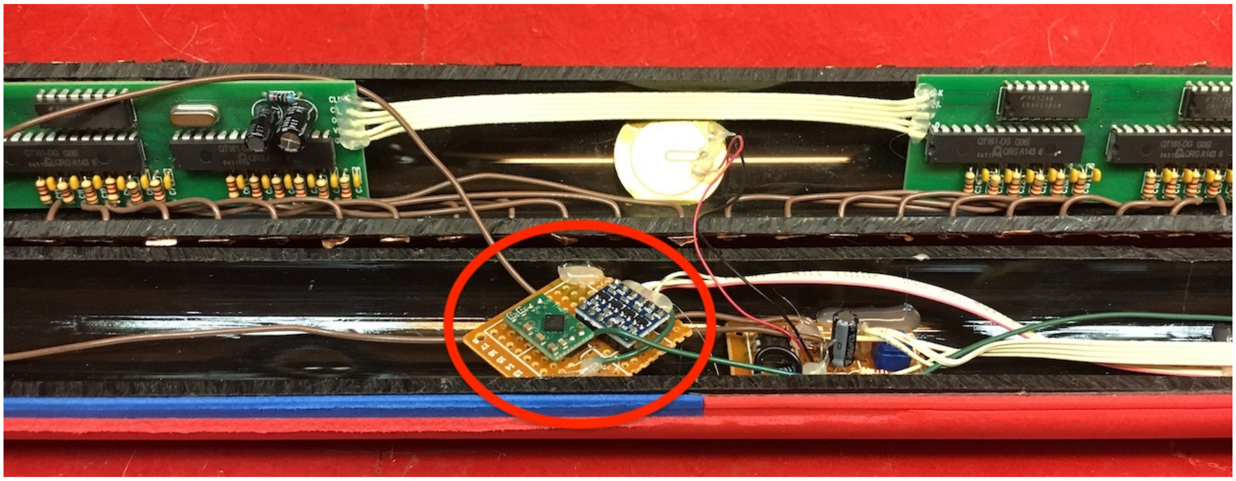

Figure 3.11 Soprano 2G-IMU-173 with new IMU (in red oval) adapted to work with original Touch24 boards and Arduino Mini 04.

Moreover, since there was now additional sensor data from the magnetometer and the gyroscope, the configuration patch and instrument driver were modified to handle these values. This IMU provides a 16-bit integer value that needs to be scaled accordingly so that the instrument driver patch can still extract idiomatic gestures of the Soprano and allow for newer ones that can be implemented now that the instrument utilizes an IMU.

Once the instrument was tested and the firmware was optimized and upgraded, it was wrapped with red heat-shrink tube. The next stage was to condition its instrument driver patch.

The Sopranino 2G-172

The smallest member of the family, belonging to the third group, is the Sopranino T-Stick shown in figure 3.12b. Several were started as part of another graduate seminar covering DMI design, but none completed to a performable condition. Part of our objective is to create a functional version of the Sopranino which is presented below. Although it maintains the same instrument concept, it is smaller in size and due to its more recent development it uses a different microcontroller board: the Arduino Pro Mini (see figure 3.12a), which is based on the ATMEL ATmega368P microcontroller running at 8MHz - 3.3V.


(a) Arduino Pro Mini and serial to USB adapter.

(b) The Sopranino 2G fully assembled before being wrapped with heat-shrink tube.

Figure 3.12 Sopranino 2G-172 microcontroller unit and final assemblage.

According to our terminology, the Sopranino is a **DMI redesign** based on the T-Stick family of instruments, which also involves an **electronic redesign**. It is important to point out that this electronic redesign decision (circa 2010), created an interesting technological compatibility problem since we found that there was no reliable data communication at 115200 baud. This issue was solved in this thesis in order to have a functional instrument.

Most of the second generation T-Sticks use the Arduino Mini 04, except the Sopranino 2G-172, that uses the Arduino Pro Mini which was commercialized as an 'upgrade' to small footprint development boards at the time. The Mini 04 uses the ATmega168[14] and the Pro Mini the ATmega368P[15]. While electronic advancement was moving from 5V towards 3.3V, manufacturers stated that they put a slower resonator on the Pro Mini to guarantee safe operation of the ATmega[16]. Looking at the specification sheets for both microcontrollers in figure 3.13, we notice performance differences when using different clocks in the chips. Highlighted in a red square in figure 3.13a, at 16MHz and 115200 baud, we have an error of -3.5% which was acceptable for the instruments with the Mini 04. On the other hand, for the Pro Mini in figure 3.13b working at

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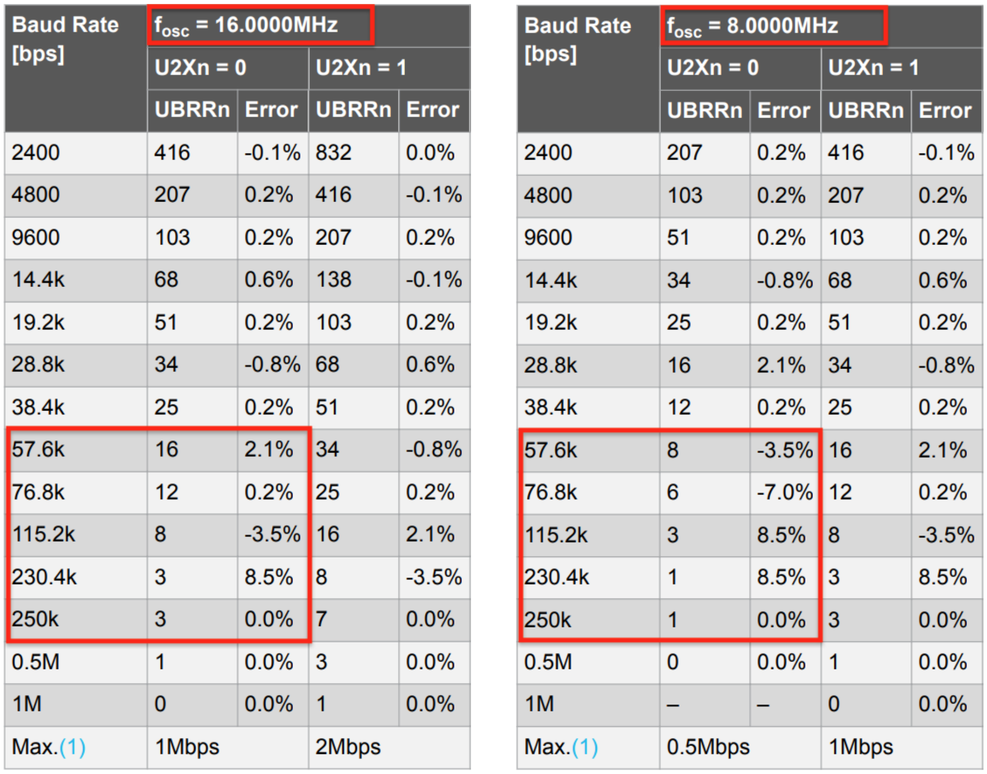
[14] `http://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-2545-8-bit-AVR-Microcontroller-ATmega48-88-168_Datasheet.pdf`

[15] `http://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-42735-8-bit-AVR-Microcontroller-ATmega328-328P_Datasheet.pdf`

[16] `https://learn.sparkfun.com/tutorials/using-the-arduino-pro-mini-33v`



Baud Rate [bps]	f_{osc} = 16.0000MHz			
	U2Xn = 0		U2Xn = 1	
	UBRRn	Error	UBRRn	Error
2400	416	-0.1%	832	0.0%
4800	207	0.2%	416	-0.1%
9600	103	0.2%	207	0.2%
14.4k	68	0.6%	138	-0.1%
19.2k	51	0.2%	103	0.2%
28.8k	34	-0.8%	68	0.6%
38.4k	25	0.2%	51	0.2%
57.6k	16	2.1%	34	-0.8%
76.8k	12	0.2%	25	0.2%
115.2k	8	-3.5%	16	2.1%
230.4k	3	8.5%	8	-3.5%
250k	3	0.0%	7	0.0%
0.5M	1	0.0%	3	0.0%
1M	0	0.0%	1	0.0%
Max.(1)	1Mbps		2Mbps	

(a) Baud rates for the ATmega168 working at 16MHz.

Baud Rate [bps]	f_{osc} = 8.0000MHz			
	U2Xn = 0		U2Xn = 1	
	UBRRn	Error	UBRRn	Error
2400	207	0.2%	416	-0.1%
4800	103	0.2%	207	0.2%
9600	51	0.2%	103	0.2%
14.4k	34	-0.8%	68	0.6%
19.2k	25	0.2%	51	0.2%
28.8k	16	2.1%	34	-0.8%
38.4k	12	0.2%	25	0.2%
57.6k	8	-3.5%	16	2.1%
76.8k	6	-7.0%	12	0.2%
115.2k	3	8.5%	8	-3.5%
230.4k	1	8.5%	3	8.5%
250k	1	0.0%	3	0.0%
0.5M	0	0.0%	1	0.0%
1M	–	–	0	0.0%
Max.(1)	0.5Mbps		1Mbps	

(b) Baud rates for the ATmega368P working at 8MHz.

Figure 3.13 Charts comparing baud rates in the Arduino microcontrollers used in the already existing T-Sticks. Taken from the manufacturer's specification sheets.

8MHz and 115200 baud the error increases to 8.5%. This was a problem when trying to establish communication between the configuration and instrument driver patches and the DMI. This is a compatibility problem since Max/MSP uses native OSX serial drivers which only allow for fixed baud rates. The termios.h header file from Apple Computer, Inc. specifies the following as the highest baud rates: 57600, 76800, 115200, and 230400.

Figure 3.13b shows high percentage error for the last three baud rates mentioned above. This was confirmed by probing the T-Stick at different baud rates using an open-source serial port terminal application (CoolTerm[17]) for the baud rates highlighted in red. There was correct data communication for 57600 and 500000 baud but it failed for all the others. The 8.5% error was also

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[17] `http://freeware.the-meiers.org/`

confirmed establishing communication at 125000 (which is 115200×1.085) which worked without problems. Since Max/MSP in OSX only allows the values accepted by the driver, this instrument is set to work at 57600 baud rate without a major compromise in its performance.

The sensing capabilities of the Sopranino are based on the characteristics of the Soprano 2G. When the components were gathered, there was no motion sensor available so a choice based on current market availability was made. This DMI uses the ADXL-345 digital accelerometer, which communicates with the microcontroller via I2C and is a very popular open-source option. In addition, this accelerometer provides a more stable signal than the older analog ones used in previous instruments. The capacitive controller chips are 2 Cypress Capsense CY8C20180. Each of these chips can handle up to 8 capacitive sensor strips. These instruments were designed around 2010 and these chips were state-of-the-art at the moment. They need a microcontroller that supports I2C clock stretching, which was a parameter to take into account when accommodating the existing firmware to a newer microcontroller. The Sopranino uses 16 copper strips for touch sensing. The firmware is adapted to allow I2C communication to the Capsense chips and the digital accelerometer. For force sensing, it uses a paper force sensor and, as with the Soprano, it implements shock sensing with a piezoelectric sensor.

The Sopranino's body is made of ABS plumbing pipe as the other family members. It communicates with the host computer via a USB-to-serial adapter (FTDI Basic Breakout 3.3/5V manufactured by DFRobot) attached to the Arduino board. It is important to note that this DMI uses a USB 2.0 Mini Type B jack, which requires a different type of connecting cable to the computer. This allows for the instrument to use serial based communication and appear as another serial device in the driver patch. Once the implementation was finished, it was wrapped with black heat-shrink tube and passed to the instrument driver conditioning stage.

3.3.3 Software Maintenance

The T-Stick configuration and instrument driver software are based on Max/MSP. Each of these rely on the Open Sound Control protocol to route signals among Max patches, *libmapper*, and the sound synthesis engine of choice. The original patches had dependencies on external Max objects. For example, they would use the Jamoma[18] set of externals to perform OSC routing. They were also using old *libmapper* Max bindings and json instrument definition files to expose the DMI on the network. Instrument driver patches made partial use of the Digital Orchestra Toolbox [27], which is a set of externals developed at the time of the DOP now included as toolbox for Max/MSP. For links to all the software related to the T-Stick please consult the Appendix at the end of this thesis.

Configuration Patches

The Max patch for configuration allows us to monitor the serial data coming from the T-Stick. It also allows for data to be sent to the T-Stick if data throughput needs to be changed or updated information needs to be written on the EEPROM. It also creates OSC addressing to relay this data into a higher level patch, as is the case of the instrument driver software that will be treated in the next section. Configuration patches also provide calibration options for the pressure and piezoelectric sensors and a mask for the capacitive strips in case they need to be muted.

In our work we have updated and optimized these configuration patches to work with their correspondent instrument. The patches for group 1 were in a functional state and they needed minor changes to standardize the OSC addressing scheme. Configuration patches for groups 2 and 3 had to be implemented from scratch but keeping the original patches as a model. Figure 3.14 shows the configuration patch for the Sopranino 2G-172. Although it resembles the one from the Sopranos it had to be modified to handle the digital accelerometer data in a way that subsequent instrument driver patches would not need to be modified in that respect and the idiomatic gestures could be preserved. The same approach was taken for the capacitive sensor information since the Capsense CY8C20180 chips return sensor data by reading specific registers from the chip instead of bit banging, which is the case of the QT161-DG chips on previous circuit boards.

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[18] `http://www.jamoma.org/`

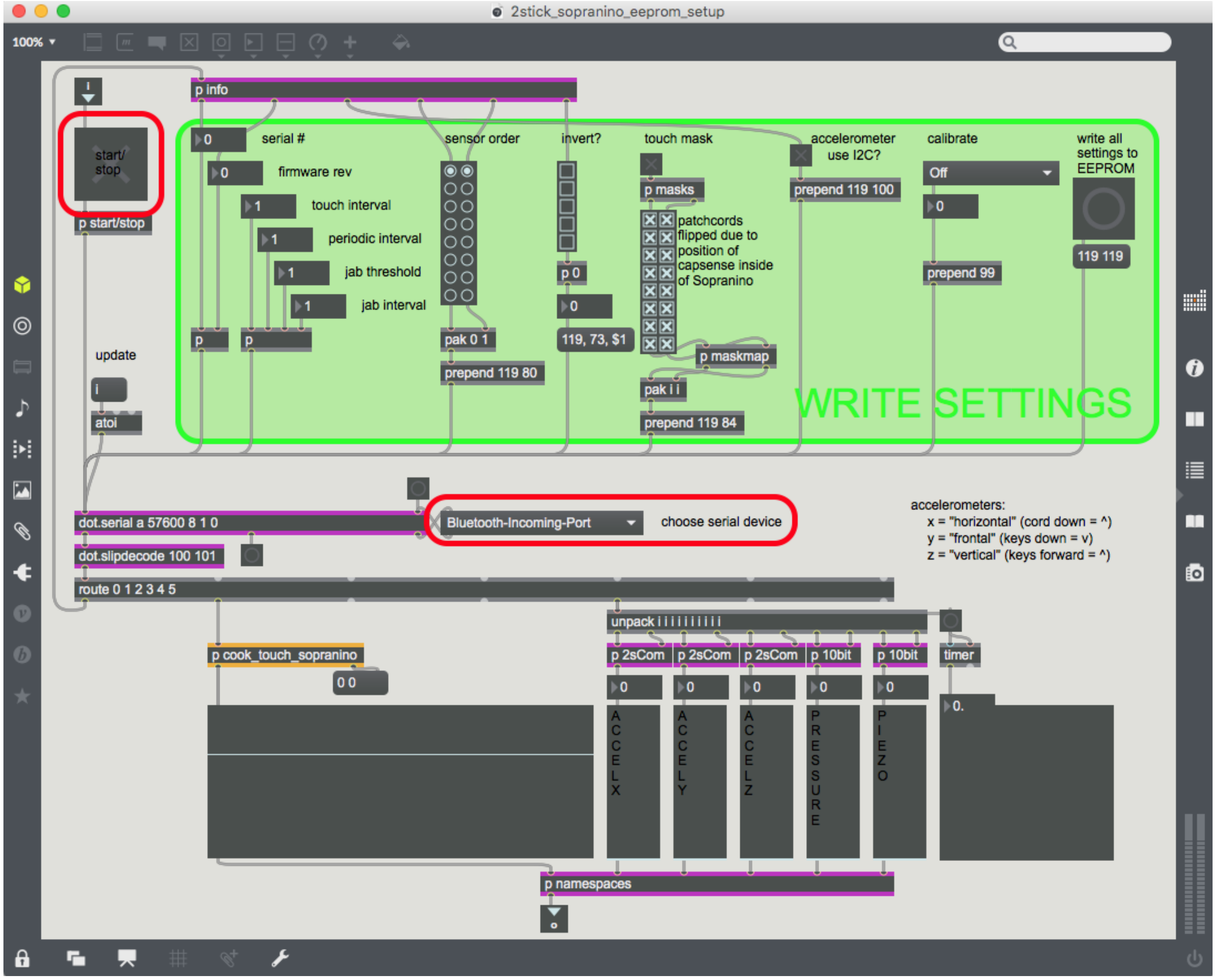

Figure 3.14 Configuration patch for the Sopranino 2G-172.

Instrument Driver Patches

Once the DMI is configured and calibrated it is ready for performance. For this purpose, there is an instrument driver patch that is in charge of collecting the serial data, 'cooking' the raw data as a first mapping layer, and subsequently performing a gesture extraction process that will expose numerical data in an OSC namespace for each instrument. As mentioned at the beginning of this section, the original patches had dependencies on third party externals and old versions of the Max bindings for *libmapper*. All these were updated to work only with the in-house developed

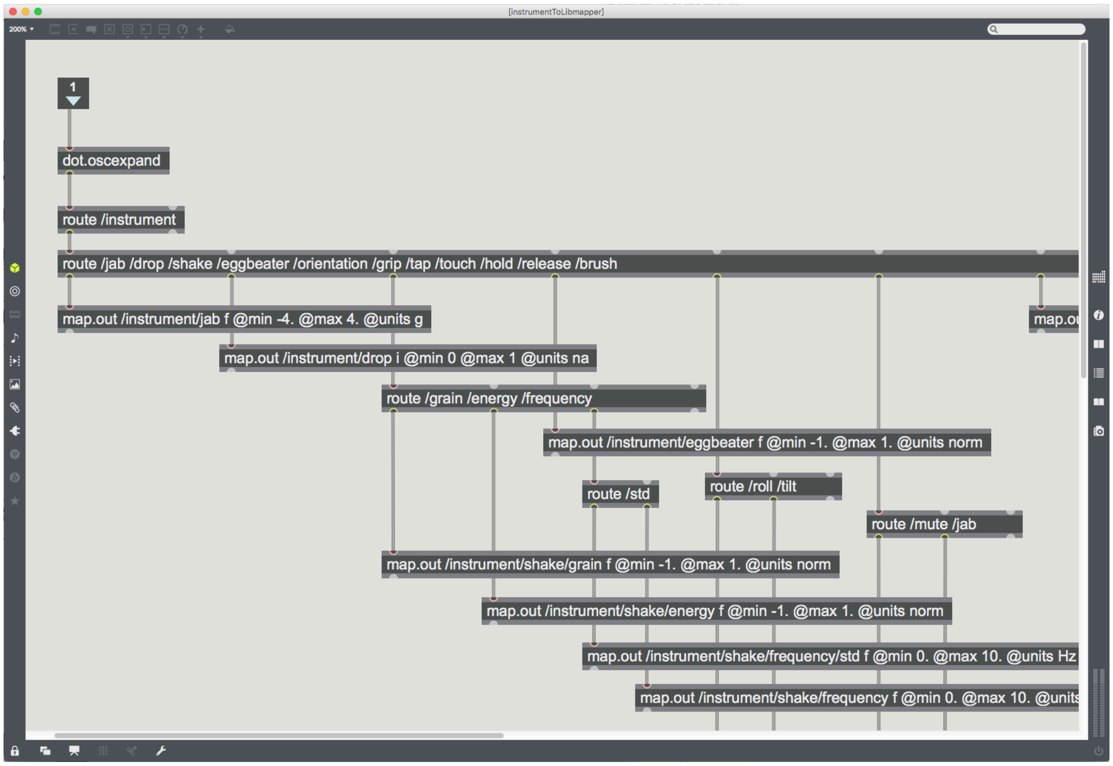

Figure 3.15 Instrument definition subpatch to expose signals into *libmapper*.

digital orchestra toolbox and the newest *libmapper* bindings. These new bindings do not allow for a json instrument definition file anymore (probably not to rely on additional external files for implementation of *libmapper* based patches) so the instrument definition outputs for *libmapper* had to be embedded in the driver patch. As for the configuration patches, DMIs in groups 2 and 3 required instrument patches to be implemented for their own characteristics. Figure 3.15 shows the instrument definition subpatch for the Soprano 2G-171. This will correctly expose the gesture extraction signals into *libmapper*.

3.3.4 Documentation

During this maintenance process we had the opportunity to work with functional and bare open instruments. We also had to open others. Probing the functional instruments allowed us to reverse-engineer their electronic design, while opening others gave us direct access to the circuitry,

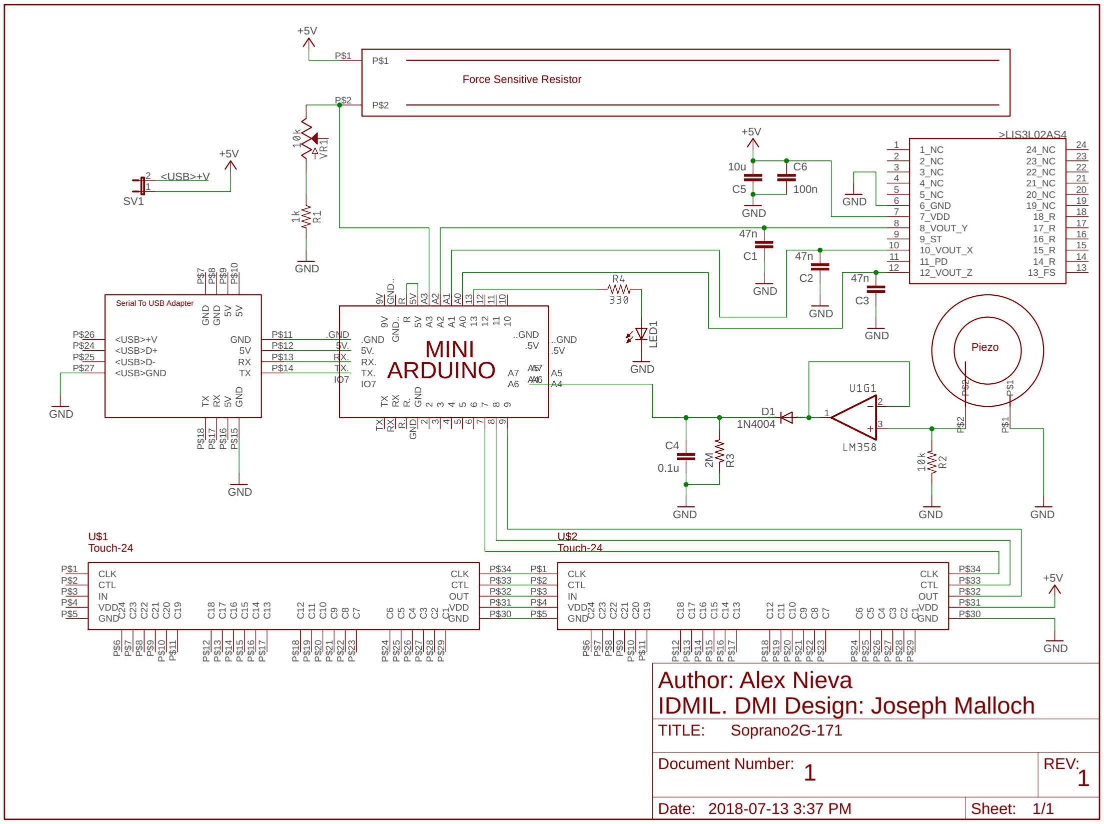

Figure 3.16 Schematics for the Soprano 2G-171

therefore allowing us to annotate the schematics and components used in all T-Sticks. For example the basic configuration of a Soprano 2G is depicted in the schematic presented in figure 3.16. All this information also allowed us to create a Specification Sheet for each of the instruments.

The current state of collaborative resources in Cloud technology permits us to create a comprehensive repository of the software - firmware and configuration/driver patches - as well as related documents such as schematics and their corresponding files created in Eagle PCB design software[19]. All this documentation can be found in the GitHub repository for the project: `https://github.com/IDMIL/TStick` or in the information provided at the project webpage at

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[19] `https://www.autodesk.com/products/eagle/overview`

`http://www-new.idmil.org/project/the-t-stick/`. A sample of specification sheet can be seen in figure 3.17. For direct links to all the instruments software and additional information see the Appendix at the end of this thesis.

It is important to highlight that the process of maintenance benefits of available documentation. This practice should be encouraged at any design stage. Moreover, with cloud storage services available nowadays, this becomes feasible at any point of an electronic design.

3.4 Lessons Learned from Technical Maintenance

The work performed in these 8 instruments has provided us with very interesting and useful information on how to maintain DMIs. We can summarize our findings listing maintenance strategies and design recommendations derived from the work performed:

3.4.1 Maintenance Strategies

Organized Maintenance Workflow As shown in the flowchart in figure 3.7, preventive and corrective maintenance benefits from an organized workflow, especially when multiple copies of a device exist.

Repair Decisions Fully functional instruments are desirable, but when it comes to exposing the inner circuits and open devices for repair, a planned decision should be made based on the mapping requirements and performance objectives. It is advisable to exhaust troubleshooting options before opening an instrument.

Update, then Upgrade When approaching a broken instrument it is tempting to upgrade the functionalities which could actually change the instrument metaphor. One should be cautious when making the decision on updating or upgrading the instrument as well as updating or upgrading the electronics of the instrument.

T-Stick Soprano 2G

Specifications:

- Touch Sensing: 48 capacitive sensing strips
- Motion Sensing: 3-axis analogue accelerometer
- Pressure Sensing: 1 Force Sensitive Resistor
- Shock Sensing: 1 Piezoelectric sensor
- Connectivity: USB 2.0 Type-B
- Dimensions: 71cm x 5cm (diameter)
- Weight: 0.567 Kg
- Serial Number: 012

Requirements:

- Mac OSX with Max/MSP
- Libmapper externals for Max/MSP
- Sound Synthesizers that work with libmapper: granul8, modal.
- Other sound synthesizers to create ad-hoc mappings.

Figure 3.17 Specification Sheet for the Soprano 2G-012

Electronic Parts Procurement Especially with electronics, off-the-shelf replacement parts are volatile and compatibility should be always checked before implementing or disassembling an instrument.

3.4.2 Design Recommendations

Planned Manufacturing The fact that there were several copies of the T-Stick showed that there was a non-industrial standardized procedure to build the instrument[20]. Being able to open the Tenor, Soprano and having implemented the Sopranino shows similarities in construction, which informs future implementations of the DMI and facilitates its maintainability. When building a large quantity of instruments, serial numbering is important for future identification.

Open-Source Electronics Open-source electronics and code development help in the maintenance process. Platforms such as Arduino and its vibrant community provide tools to troubleshoot and repair non-functioning instruments.

Working version of a DMI Although continuous development is part of a research project, in the case of DMIs and in general, input devices for musical expression, there should always exist a working version of the device. This allows for continuous testing and demonstrations of the instrument.

Documentation Even though working software was found and allowed us to perform this research, the lack of detailed specification sheets or building diagrams posed a challenge in order to have all the instruments working and exchange information among them. This reinforces the necessity of applying the widely accepted engineering concept of technical documentation.

Software Versioning As is the case with documentation, software/firmware versioning is good practice. Current cloud storage options for open-source code provide useful tools for this purpose.

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[20] See `https://josephmalloch.wordpress.com/mumt619/`

Visual Feedback Any electronic design benefits from offering visual indicators/feedback, as is the case of commercial electronics. In this case, even if there was only one visual indicator on the instrument, it proved to be of crucial importance during the maintenance process.

3.5 Conclusions

This chapter has informed several maintenance strategies and design recommendations based on connecting the engineering concepts of maintenance and maintainability to already existing digital musical instruments. These instruments, while not completely obsolete, faced many technical artifacts that prevented them from being used in research and music performances.

These maintenance and design recommendations will be applied in chapter 4 to streamline the electronic redesign of an already existing DMI such as the Sopranino T-Stick.

Chapter 4

Electronic Redesign Case Study: The WiFi Sopranino T-Stick

4.1 Goals

In this chapter we focus on the electronic redesign of one of the Sopranino T-Sticks. The work presented in Chapter 3 encompassed the maintenance of finished or already designed instruments in different functional states. During our research, we found an instrument with the basic capacitive sensing implemented but all the other electronics missing. This gave us the opportunity to apply the lessons learned in Chapter 3 to find a more streamlined approach to build a T-Stick with currently available electronics.

4.2 To Upgrade or Not To Upgrade

As their acoustical traditional counterparts, we can argue that digital musical instruments should be available to develop playing techniques, musical works, and to be embraced by amateur and professional musicians. The decision on upgrading or 'enhancing' an instrument should be carefully thought specially in a rather old device such as the T-Stick. Expert performers may not suddenly want the instrument to respond in different ways that may not allow them to reproduce their work or apply their already developed playing techniques. In chapter 3 we recommended that upgrading the DMI should be carefully thought through, therefore, that was one of the first decisions to be made at the beginning of this case study.

For this new Sopranino, we made the decision to keep the gestural language the same with the electronic components upgraded. This posed an interesting question on how to adapt current technological development to a 12-year-old design. The capability of microcontrollers nowadays gives us more headroom to implement more data processing on-board. Therefore, in the case of the second Sopranino, we decided to keep the sensor data acquisition as it was performed with the original Arduino Mini and Pro Mini boards and use that available headroom to implement higher level functionalities that would not interfere with the gestural affordances the instrument already has, but facilitate its usability.

One of the most important changes for this instrument is its WiFi capability. Although there were previous T-Stick designs that were implemented using Bluetooth (2 instruments, one of them the Soprano in figure 4.1), it was less troublesome at the time to use a USB based connection as reported in [24]. Bluetooth requires a quasi direct line of sight from the device to the host computer. Even if it was a class 1 device which technically provides up to 100 meters of operating range, in reality, it has been proven to be closer to 20 or 30 meters. Nevertheless, there is much interest in the use of wireless systems for DMI design and for interactive music/dance installations. Several technologies, such as Bluetooth or Zigbee, have been used in new interfaces and creative applications, but now they are being displaced by the ubiquitous WiFi [33]. Technological advancements in wireless data communication are opening doors for artists and non-skilled programmers to have access to wireless transmitters to be incorporated in their artistic practice [2].

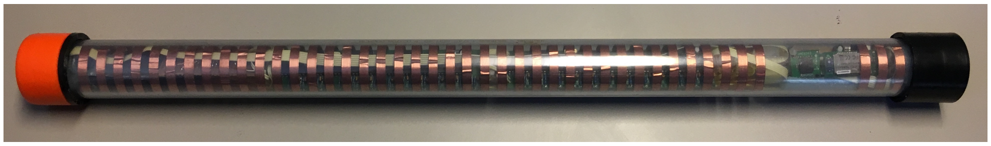
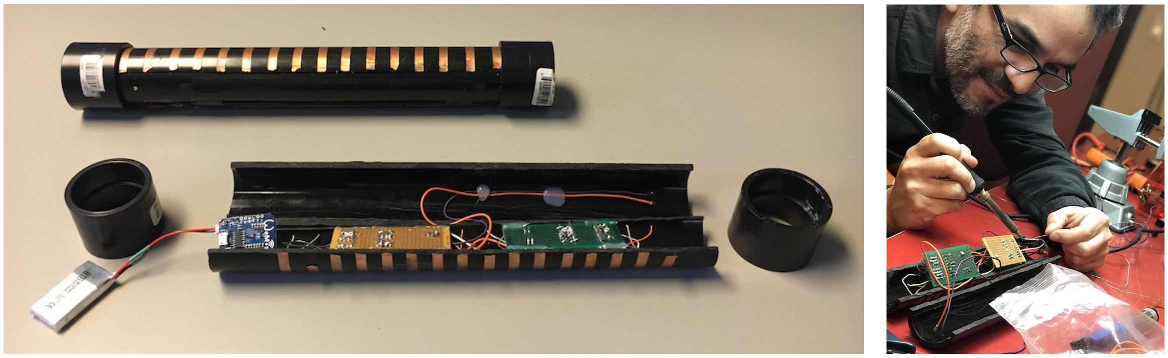


Figure 4.1 Soprano 3G Bluetooth. Serial Number 009. Not part of this maintenance work.

For this instrument we decided to use the open-source microcontroler board named Wemos D1 manufactured by Wemos Microelectronics and based on the ESP8266 System on a Chip (SoC) by Espressif Systems Ltd. (See figures 4.3a and 4.5a). This chip has a 32-bit processor and WiFi capability. As is the case of the Arduino, the community built around this SoC is growing since 2015 because of its availability and low price. Developers also provide support for the ESP8266 chip to work in the Arduino environment. This way, we can write and re-purpose firmware written for the Arduino boards into this microcontroller. This SoC would allow us to have a wireless device (much like a smartphone). This would not change the way the gestures are performed but would free up the movement of the performer since the device does not have to be wired to a computer (unless the battery is charging).

The motion capture capability was again implemented using the same breakout board used for the Soprano 2G-IMU-173 because of its already available implementations at the IDMIL. The pressure sensing is possible due to a commercial FSR. Since the ESP8266 has only one analog sensing pin, we made the decision to discard the piezoelectric sensor. It could have been possible to multiplex both analog inputs but this would have required more electronics on board. For this particular instrument, space was scarce, but this could be a possibility for future electronic designs. Although this is a DMI design decision, when evaluating its importance, and after informally analyzing performances with the Soprano and Tenor models by expert performers such as D. Andrew Stewart and Fernando Rocha, the piezoelectric sensor was only used when the T-Stick was mapped to percussive sounds specifically on the Tenor (because of the compliance of the larger tube, making it possible to twist it, bend it, and hit it). If the shock sensing capability is needed, this effect can be replicated by programming the accelerometer data to respond to shock excitation since the IMU used can sense up to 16G of acceleration. Bending or twisting the Sopranino is very difficult due to the short length of the tube.

Finally, one of the prototyping boards holding the Capsense chips (the same ones used in the Sopranino 2G-172) had to be completely re-soldered and re-wired due to the aging of the soldering points and broken connections. This work is shown in Figure 4.2b.



(a) Top: Sopranino 2G-172, Bottom: Sopranino 2GW-181 under construction. Notice the different boards. The brown perfboard holds the original electronics while the green one is the reconstructed one.

(b) Soldering the new electronics to work with the older parts.

Figure 4.2 Building and repairing electronics in the Sopranino 2GW-181.

Since this Sopranino has the same gesture extraction capabilities as the Sopranino 2G-172, Soprano 2G-IMU-173, includes higher level functionalities such as WiFi, and was built in the winter of 2018 we decided to name it Sopranino 2GW-181. The fact that the Soprano 2G-IMU-173 and the Sopranino 2GW-181 use the same motion sensor reinforced the idea of reusability by using existing assets already developed for all the T-Stick models.

4.3 Higher Level Functionalities

4.3.1 Manufacturing

The size of the Sopranino does not allow for much electronics to be packaged inside of the PVC pipe. The Sopranos had more space to twist cables, use longer circuit boards, etc. Therefore, in the Sopranino 2GW-181 we decided to maximize the space by using the end-cups as circuit and battery holders. Instead of using the original PVC end-cups, 3D printed[1] ones were designed to hold the battery and an ON-OFF switch on one side and to hold the microcontroller, a battery shield, the indicator LED and expose the USB jacks at the other end. These designs were conceptualized so that they could be easily attached to the instrument (and replaced when necessary), and that the battery and circuits rest in a modular piece free of additional vibrations apart from the ones that

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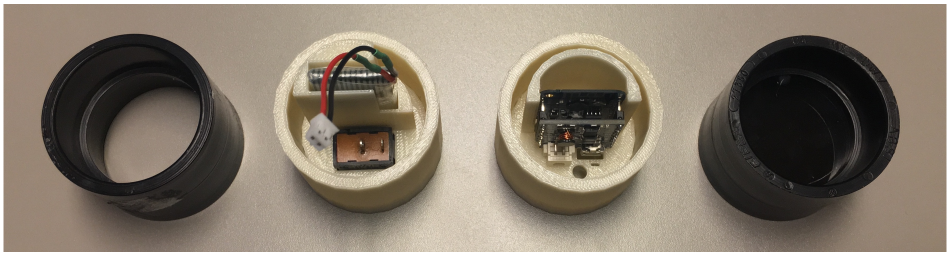
[1] 3D printing facilities provided by CIRMMT - McGill University.

belong to the performance.



(a) Old end cups (black) used for previous versions of the T-Stick versus 3D printed end cups (white) designed to hold the microcontroller board, battery, and ON-OFF switch.

(b) End cups mounted on the Sopranino 2GW-181 with electronics built-in.

Figure 4.3 Sopranino 2GW-181 manufactured parts.

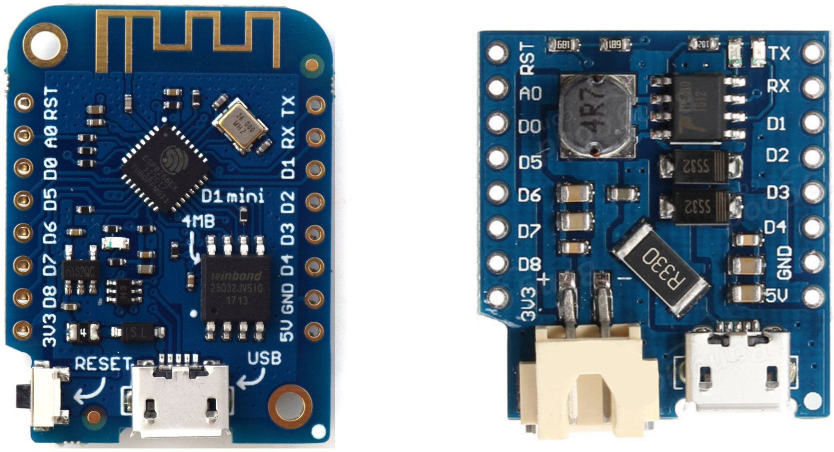
Figure 4.3 shows the manufactured pieces for the electronic redesign of the Sopranino 2GW-181. Figure 4.3a shows the actual 3D printed pieces compared to the old end cups used in previous versions of the T-Stick. Figure 4.3b shows the end cups mounted on the instrument before wrapping with heat-shrink tube. See Figure 4.4.

4.3.2 Power Management

Most designs of T-Sticks draw power from the USB connection to the computer (the two Bluetooth based T-Sticks used a AA battery pack inside of the instrument). While this was preferred and recommended [6] while wireless technologies evolved, in year 2018 the stability and potential of wireless data communication has proven to be able to co-exist with cabled based devices. This of course changes the requirements regarding power supply. As with consumer electronics (hand-held devices such as cellphones or laptops) the preferred way to provide energy is with the use of batteries. The Sopranino 2GW-181 is operated with a battery installed on one of the 3D printed

Figure 4.4 Finishing the construction of the Sopranino 2GW-181 by wrapping it with transparent heat-shrink tube.

end cups respecting the form factor of the original instrument. It uses a Li-Po battery capable of providing 600mAh at 3.7V. The Wemos D1 microcontroller was also chosen because of the available shields that provide great complement to electronic design. The battery shield has the same form factor as the microcontroller board therefore providing easier mounting compared to older designs.



(a) Wemos-D1 - ESP8266 SoC. (b) Battery Shield for Wemos D1.

Figure 4.5 Microcontroller board and Battery Shield used in the electronics redesign of Sopranino 2GW-181.

The maximum current consumption of the Wemos D1 is when transmitting wireless data. This is 170mA according to the manufacturer[2]. In our tests, the nominal current of the ESP8266 is around 80mA. The Capsense maximum operation current is 2.5mA according to the specification sheet[3]. The IMU LSM9DS0 specification sheet report a typical current consumption of 350μA for the accelerometer and magnetometer together, and 6.1 mA for the gyroscope. Apart from the opamps and usb-to-serial adapter we are looking at around 100mA of nominal consumption of the instrument under normal operation. The 600mAh battery is enough to keep the instrument running for a minimum of 4 hours, which was tested during development and demonstrations at the NIME 2018 conference.

4.3.3 Data Handling and Distribution

As mentioned before, the choice of microcontroller was greatly influenced by the wireless capabilities of the ESP8266 SoC. For the Sopranino 2GW-181 we have developed a comprehensive network setup firmware that allows to operate in an already existing Local Area Network (LAN) or as a standalone instrument. The network based operation allows the Sopranino to connect to an access point or router that has Internet access and join the LAN where the host computer is. The standalone option sets the Sopranino as an access point where the computer running the driver software can connect and provide the mapping and sound synthesis capabilities. In any of these two scenarios, there is a webserver running that provides a configuration webpage where we can choose the WiFi network or Standalone operation, choose the host computer IP address and Port where the T-Stick will be sending OSC data (See figure 4.6). The procedure for handling the WiFi connection is depicted in the flowchart on figure 4.7.

The firmware developed for the Sopranino 2GW-181 can handle OSC data encryption to send sensor data via UDP to a computer on the same network as the DMI. There are libraries already developed in the Arduino environment that target this specific SoC. This is important since most of the configuration patches and instrument drivers already implement OSC addressing to process

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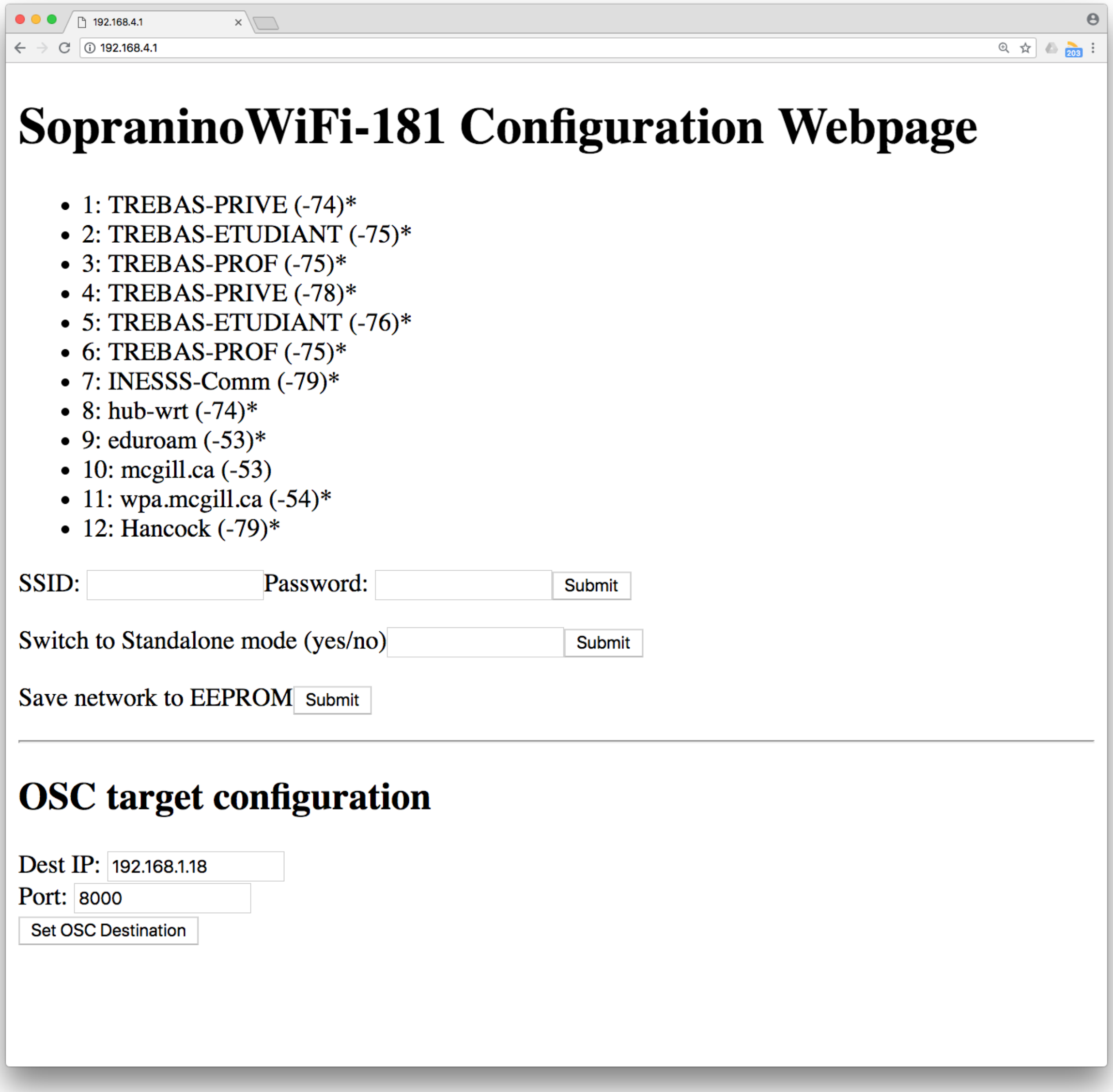
[2] `https://bbs.espressif.com/viewtopic.php?t=133`

[3] `http://www.cypress.com/file/134026/download`



SopraninoWiFi-181 Configuration Webpage

- 1: TREBAS-PRIVE (-74)*
- 2: TREBAS-ETUDIANT (-75)*
- 3: TREBAS-PROF (-75)*
- 4: TREBAS-PRIVE (-78)*
- 5: TREBAS-ETUDIANT (-76)*
- 6: TREBAS-PROF (-75)*
- 7: INESSS-Comm (-79)*
- 8: hub-wrt (-74)*
- 9: eduroam (-53)*
- 10: mcgill.ca (-53)
- 11: wpa.mcgill.ca (-54)*
- 12: Hancock (-79)*

SSID: Password: Submit

Switch to Standalone mode (yes/no) Submit

Save network to EEPROM Submit

OSC target configuration

Dest IP: 192.168.1.18
Port: 8000
Set OSC Destination

Figure 4.6 Configuration webpage for the Sopranino 2GW-181. This is running on the microcontroller operating in the T-Stick.

the T-Stick data. New configuration patches were developed for this Sopranino and the Instrument driver patches were upgraded to also process the data generated by the instrument. The complete OSC namespace is presented in table 4.1.

Table 4.1 Sopranino 2GW-181 OSC namespace.

Send	Variable type
`/information`	(2) unsigned int
`/rawcapsense`	(2) int
`/rawgyro`	(3) float
`/rawaccel`	(3) float
`/rawmag`	(3) float
`/rawpressure`	(1) unsigned int
Receive	**Variable type / Description**
`/status`	(4) int
`/status 115`	Heartbeat every 1.5 sec
`/status 120`	Stop
`/status 119 105 i i`	Write info: Serial Number, Firmware Rev.
`/status 119 84 i i`	Touch Mask
`/status 99 i`	Calibration of FSR
`/status 119 119`	Write Settings EEPROM
`/status 119 114`	Read Settings EEPROM

4.4 Application of Recommendations from Technical Maintenance

In Chapter 3 we listed a set of recommendations based on our work maintaining a set of eight T-Sticks. We learned that **planned manufacturing** and **open-electronics** help in DMI design and construction. We also decided not to upgrade the DMI but to **upgrade the electronics**. This helped us to build the new Sopranino hardware in a span of 3 days. This is our first **working version** with higher level functionalities and we plan to stop development for this instrument when this thesis work concludes. More versions are planned for the future. The electronic redesign not only includes **visual indicator/feedback** of the instrument state, but also for the battery charge. As recommended, **documentation** has been performed for this instrument. See the electronics schematic in figure 4.8 and the specification sheet in figure 4.9. Additional links to the online documentation can be found in the Appendix at the end of this thesis.

Even if much of the electronics was new to the DMI, we decided to **repair** part of the already existing capacitive sensing electronics to prevent future malfunctioning. **Electronic parts procurement** was carefully thought trying to avoid compatibility issues since the capacitive sensing chips were approximately eight years old while the microcontroller used is two years old at the most.

4.5 Lessons Learned from Electronic Redesign

In this last section we list lessons we learned while building the Sopranino 2GW-172.

Rapid Prototyping The advancement of technology gives us rapid prototyping tools that ought to be used in designing DMIs. This allows for more robust instruments.

Modularity Instruments should be able to be opened and repaired in modular sections. This prevents damaging parts while opening the instruments.

Self-containment With the advancement of electronics and more powerful microcontrollers and microcomputers, it is possible now to embed most of the functionalities in the instrument. While this is still not the case of the T-Stick, it can be applied to newer designs. For example, sensor signal processing for mapping purposes that is being performed in Max/MSP can be performed on board and expose the OSC name space directly on a patch that handles only the *libmapper* connectivity.

4.6 Conclusions

This chapter shows how we applied previously gained knowledge to leverage the electronic redesign and maintenance of a DMI. This provides continuity in the research involving DMI design and construction. It is not advisable to start every design from scratch or to completely redesign an instrument because of malfunctioning especially when looking at the problem from a practice-based research approach.

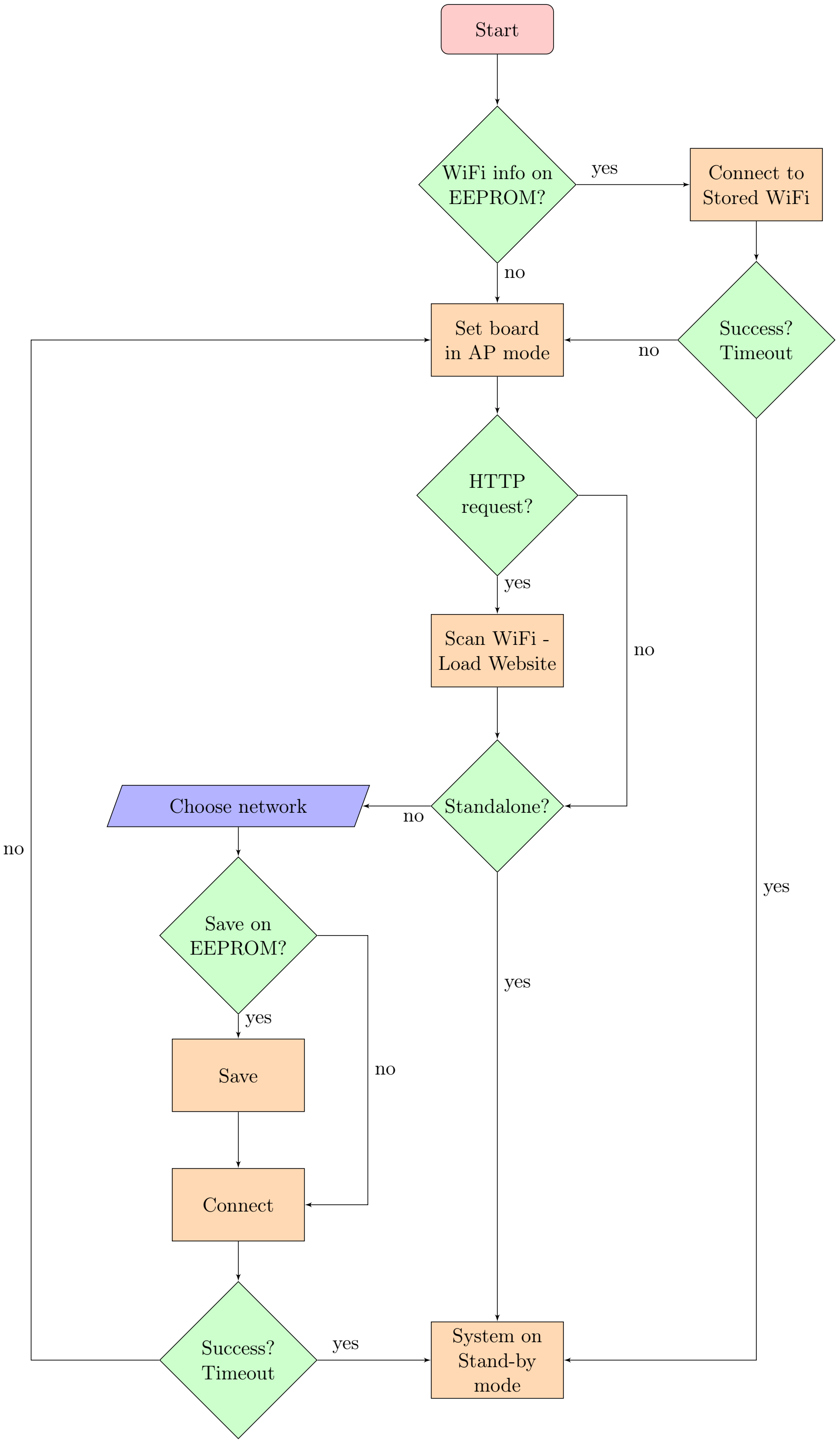


Figure 4.7 Flowchart showing the process to setup the WiFi connection on the Sopranino 2GW-181.

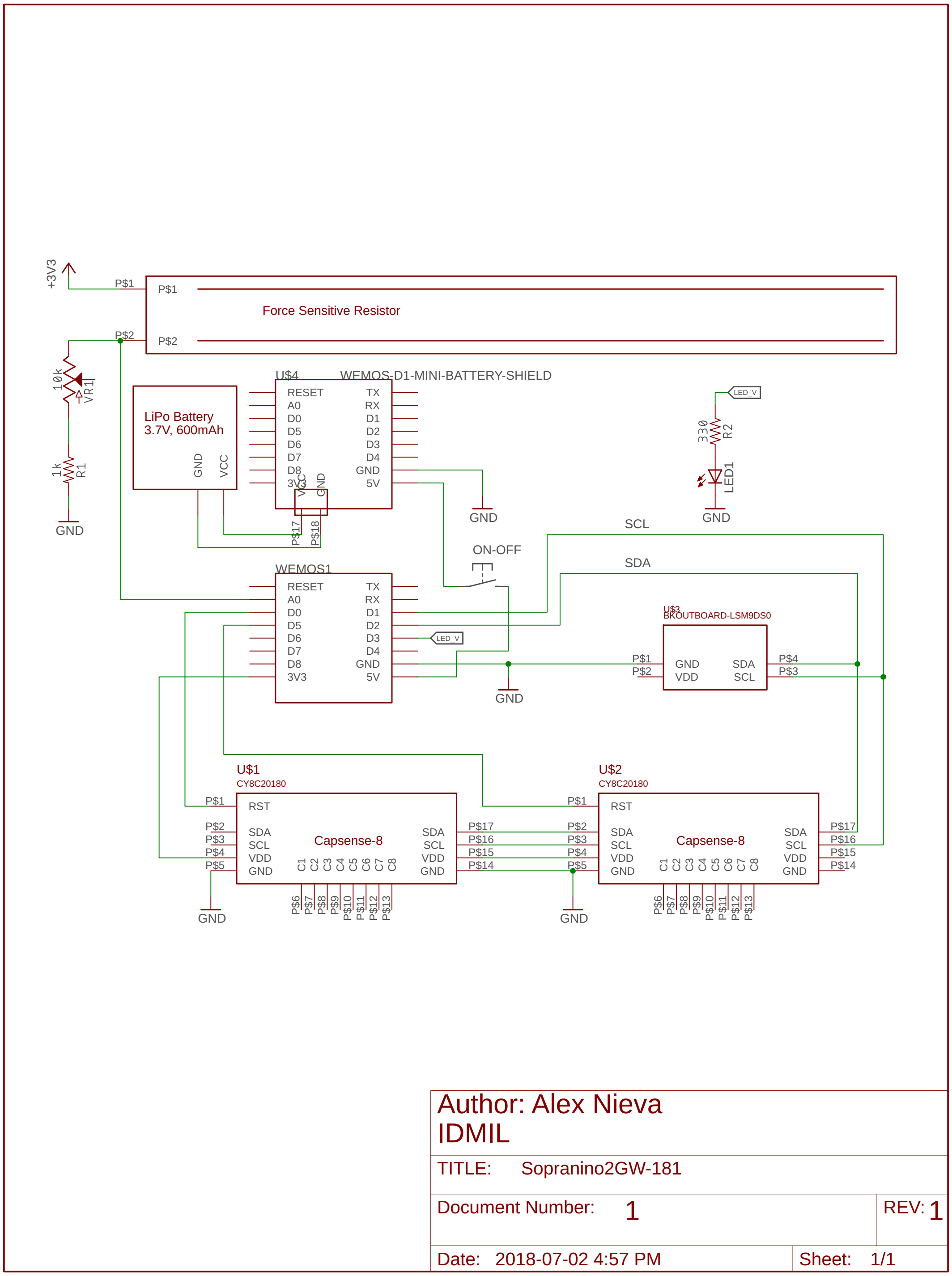
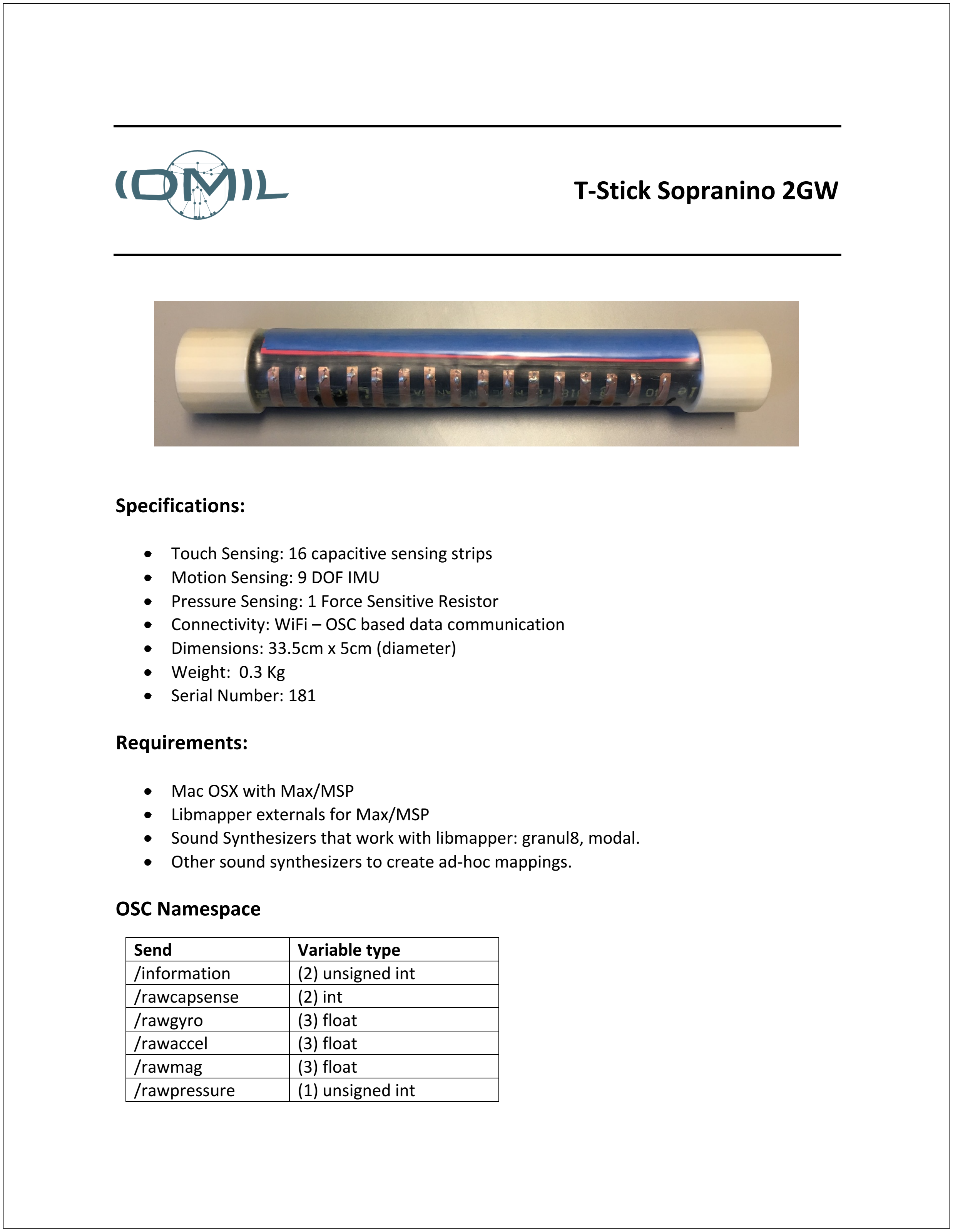


Figure 4.8 Schematics for the Sopranino 2GW-181



T-Stick Sopranino 2GW

Specifications:

- Touch Sensing: 16 capacitive sensing strips
- Motion Sensing: 9 DOF IMU
- Pressure Sensing: 1 Force Sensitive Resistor
- Connectivity: WiFi – OSC based data communication
- Dimensions: 33.5cm x 5cm (diameter)
- Weight: 0.3 Kg
- Serial Number: 181

Requirements:

- Mac OSX with Max/MSP
- Libmapper externals for Max/MSP
- Sound Synthesizers that work with libmapper: granul8, modal.
- Other sound synthesizers to create ad-hoc mappings.

OSC Namespace

Send	Variable type
/information	(2) unsigned int
/rawcapsense	(2) int
/rawgyro	(3) float
/rawaccel	(3) float
/rawmag	(3) float
/rawpressure	(1) unsigned int

Figure 4.9 Specification Sheet for the Sopranino 2GW-181

Chapter 5

Design Case Study: Multimodal Visual Augmented Cello

5.1 Introduction

One important lesson learned from the T-Stick is its collaborative origins. The design was informed establishing common grounds between a music technologist and a composer/performer. In this chapter we document a similar approach to collaboration between the author of this thesis and professional cellist Juan Sebastián Delgado. The main goal of this project was to develop an electronic system that will allow the performer to explore the interaction of his playing techniques with visuals placed on his instrument for extending the audience perception of the performance.

5.1.1 Background

It has been shown that performing musicians produce ancillary gestures - gestures that do not have a straight link to the generation of sound, but are nevertheless an integral part of musical performance [43]. Moreover, emotions are also conveyed through physical movements which can be interpreted as body language providing additional meaning to the musical experience [8].

There is broad interest in augmenting the expressive capabilities of traditional acoustic instruments by using electronic sensors worn by the performer or mounted on the instrument itself. There is work in augmenting pianos [29], the violin [4] or the guitar [31], to mention just a few. Previous work on augmenting cellos makes use of sensors attached to the body of an electric cello [15], audio-driven effects to complement cello acoustics[21], actuators to map gestures into sound synthesizers [11], or to the cello itself to provide resonant feedback [9].

One important example is Tod Machover's work on hyperinstruments, which gave birth to the Hypercello. It used hand gesture tracking, physical sensing, and acoustic analysis for mapping to sound synthesis engines hosted in desktop computers using an electric cello along with a customized bow [22].

The use of interactive lighting as a complement for interactive installations, digital musical instruments, and augmented traditional acoustical instruments is broad and diverse. This project proposes to augment audience perception through the creation of a visual display that is responsive to performance gesture. Several projects that explore the interaction of digital musical instruments (DMIs) and light have been carried out at the Input Devices and Music Interaction Laboratory (IDMIL) at McGill University and have informed the concept developed in this project [16, 17]. Professional cellist Juan Sebastián Delgado and the author of this thesis teamed up to collaborate in a project that integrates electronics, interactive lighting and cello performance with the aim of exploring the interaction of human-machine cooperation systems.

5.2 Design Criteria

Our new design aligns with the lessons learned from the work with the T-Stick and the recommendations proposed at the end of Chapters 4 and 5. The system had to be self-contained, flexible, portable and expandable. In addition it should provide:

- Reliable wireless data communication
- Robust mechanics
- Easiness of access for maintenance.

- Status indicators and visual feedback.
- Secure electronic mounting
- Defined mapping space
- Defined gestural language

In spite of the many possibilities and approaches to create augmented instruments, in our case one of the design requirements was to preserve the acoustic properties of the cello and take advantage of the refined technical skills of the cellist. Our main goals were: a) to control the interactive lighting (visual display) by mapping the gestural information collected; b) to use the interactive lighting to augment interpretation of the musical text; c) to make performance practice decisions in parallel to designing the lighting/gestural interface; and d) to identify and display meaningful information within performance gestures that are not apparent to the listener. Figure 5.1 shows the system working during our mapping studies and interaction with the performer.

Figure 5.1 Lights mounted on the cello during mapping studies and rehearsals.

5.3 Hardware Design

Among the technical considerations for the design of this system one of the most important was long-term stability. The performer wanted to incorporate the work with electronics and interactive lighting into his practice. It was therefore desirable to avoid early obsolescence [37]. One of the main goals was to develop a self-contained system that would not rely on a laptop computer to work. It would also have to function on rechargeable batteries and allow the performer to move freely in and out of the stage as well as maintain the correct posture while playing the instrument.

After a few iterations on how the system should be implemented, it was decided that the best option was to sense motion of the bowing hand, capture vibrational data from the top of the cello's body and display lights on the border and the bridge of the instrument. Since the system had to be self-contained, three nodes of data collection and processing were defined: one on the cellist's hand and two others on the body of the instrument. Knowing the capacity of microcontroller boards available, it was decided by the author of this thesis that each node in the system would use a WiFi enabled microcontroller board dealing with wireless data communication among the three of them, sensor data acquisition, and mapping of this data to the visual output projected for the system. See Table 5.1.

Table 5.1 Summary of microcontrollers, sensors and lighting output used in the Cello electronic system.

Sensor/Output Microcontroller	Piezo	IMU	Lights
Wemos D1 (Node 1)	x	LSM9DS0	x
The Thing Dev (Node 2)	via ADC	x	8x2 WS2812 LEDs
The Thing Dev (Node 3)	x	x	134 WS2812 LEDs

In order to design a long-lasting human-machine cooperative system the first decision was the choice of microcontroller board. When working with open-source electronics in a non-commercial project, the decisions ought to be made based on community driven use of components. As it is the case of the Arduino board (and variants) or the Raspberry Pi, their ecosystem and the DIY community usage has influenced their longevity and their presence on the market. Currently, building upon our experience as DMI builders, there are a few systems that are affordable and at the same time have a reliable source of information and user base that narrow down the options to choose from.

Therefore, based on our current electronic designs, we decided to work again with the ESP8266-based microcontroller board Wemos D1 on the hand due its form factor, availability, and community based pedagogical resources. In addition, two boards called The Thing Dev (also implementing the aforementioned ESP8266) manufactured by Sparkfun whose size was better fitted to hold shields for the sensors to be put on them, and because of their built-in JST battery connectors.

The next step was the sensor choice. In order to capture motion from the cellist's bowing arm, we decided to sense absolute motion of the hand based on an electronic system board attached to a glove for him to wear on the right hand. This board has an in-house developed shield that supports an IMU sensing device - LSM9DS0 by STMicroelectronics - the same used in the Soprano 2G-IMU-173 (See Fig. 5.2). There were multiple tasks assigned to this board. First it had to create a WiFi Access Point for the other two nodes on the system to connect to. Secondly, it would perform communication via I2C to the IMU chip to sense motion and process ('cook') this data, and finally it would be in charge of receiving input data from the other two boards using OSC-UDP to perform mapping decisions that would be sent back to the client boards that control the LED lights.

Our design tried to balance the technological aspect with its artistic outcome. The decision on interactive light placement was a choice to obtain an organic blend among the cellist, cello, and electronics. By organic blend we mean that the cellist and the cello already seem to be one entity because of the way the cello is held by the performer. The lighting would have to be part of this entity, therefore, we decided to install strips of addressable LEDs based on the WS2812 chip following the physical shape of the instrument. One strip was installed on the cello bridge and another around the lower cello border starting on the instrument corners. Each of these strips is controlled by one Thing Dev, which is able to perform precise clocking for the LEDs since it is capable of direct memory access (DMA) and implements the protocol to use the I2S bus. This

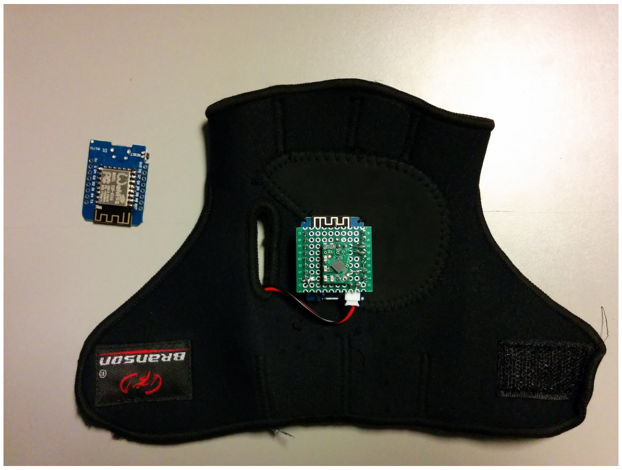


Figure 5.2 Glove with motion sensor and Wemos D1 microcontroller board to capture cellist bowing gestures (Node 1)

avoids problems of latency to communicate with this type of LED chips.

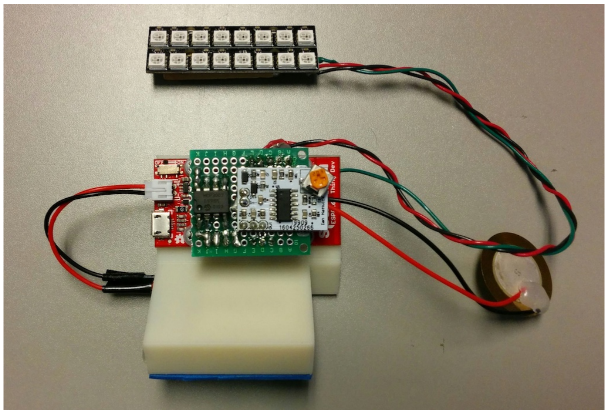


Figure 5.3 Piezoelectric sensor with ADC and lighting for the cello bridge (Node 2).

Together with the LEDs mounted on the cello bridge we also installed a piezoelectric sensor that would pick up the vibration of the top of the instrument so that we could perform real-time audio feature extraction for our mapping objectives. In Fig. 5.3 we can see the piezoelectric sensor with an electronic buffer developed at IDMIL and a 10-bit analog to digital converter (MCP3002 manufactured by Microchip) together with the LED strip. The microcontroller performs three tasks in this circuit: WiFi communication via UDP and OSC, control of the interative lighting, and analog sensor data acquisition.

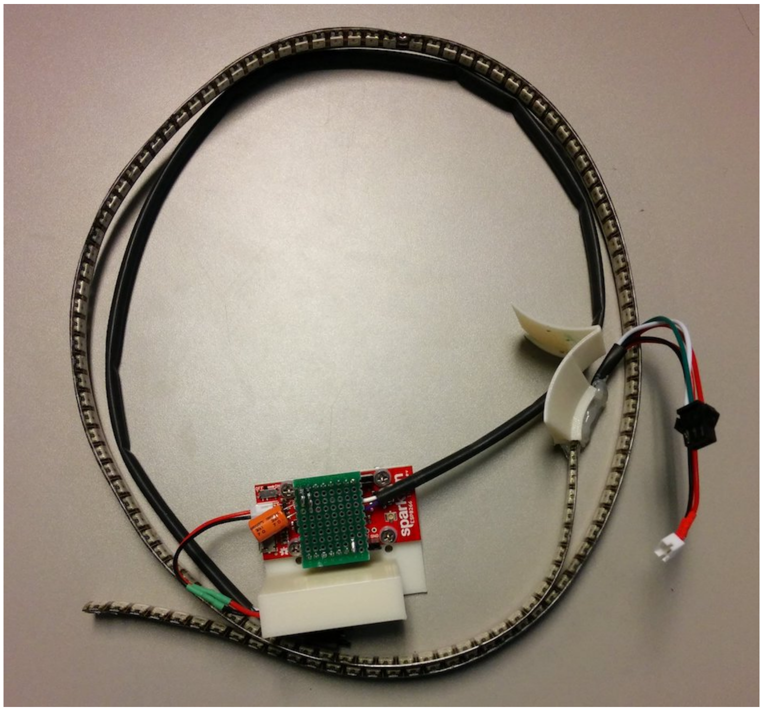


Figure 5.4 Strip with 134 digitally addressable LEDs (Node 3).

In Fig. 5.4 we present the third component of this system. This strip of LEDs is attached to the cello bottom border and the microcontroller has the task of receiving mapping information from the host board on the glove and activate light patterns for the 134 LEDs.

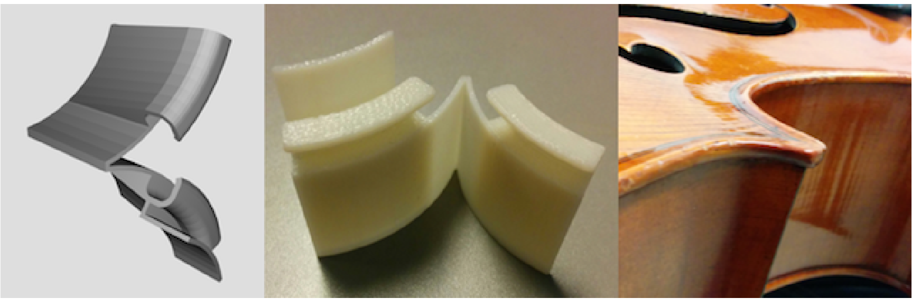


Figure 5.5 3D printed parts for mounting electronics on the cello corners.

5.3.1 Cello Mounting Considerations

One of the main challenges we faced while designing the lighting system was not to interfere with the physical playing of the cello. Given that our research goal was studying and decoding the physical gestures of the musical performance, it was clear that in order to do so, the cellist needed his normal freedom to play and approach the instrument. In addition, care was a must so that we would not damage an ancient and valuable instrument (Charles Bailly, Mirecourt, France, 1936). Only after fulfilling these considerations, we could focus our attention on how to bring our design to life. All these electronics were chosen in order to be mounted and unmounted from the cello in the context of the time constraints a musical show demands.

For this purpose, we heavily relied on the rapid prototyping facilities at CIRMMT, where we developed tailor-made 3D printed pieces to clamp the LED lights on the cello as well as the circuit boards each one requiring a LiPo battery. As can be seen in figures 5.3 and 5.4, the boards were securely placed on parts that can be easily attached to the cello body with adhesive putty for contact microphones without compromising the acoustics or the playability of the instrument. We even had to make custom shaped corner adapters (see figure 5.5) to be able to hang and hold the LED stripe to the border of the cello. This design decision increased the robustness of the system.

5.3.2 Mapping and Visual Output Concept

The mapping of sensor data to the interactive lighting was a central part of the design process since the beginning of the project. The work underwent continuous feedback between the performer and the music technologist. As can be seen in the diagram in figure 5.6, captured sensor data from the cellist arm and the vibration of the top of the cello were ‘cooked’ to obtain different values that would trigger several lighting patterns that were already defined in the firmware of each of the microcontroller boards. Data from the IMU and the piezoelectric sensor was fused to make mapping decisions more interesting. The main lighting pattern would follow the intensity of the RMS value of the audio and the tilt angle of the bowing arm. This information would be displayed in a gaussian shaped light pattern that was possible due to the 134 LEDs that were installed on the cello border. When the intensity of the cello vibrations was low and the motion gesture was subtle the light would concentrate on the center of the strip at the bottom part of the cello. In contrast, when the loudness of the cello was strong and gestures increased in intensity the light would spread out throughout the length of the strip lighting up all the instrument. The system also has four lighting patterns that are triggered depending on specific gestures performed by the cellist.

In addition, the LED strip on the bridge would be activated when certain frequencies as well as pizzicato gestures were present in the cellist performance creating a complementary light visual previously planned based on the piece that was composed for the purpose of this project.

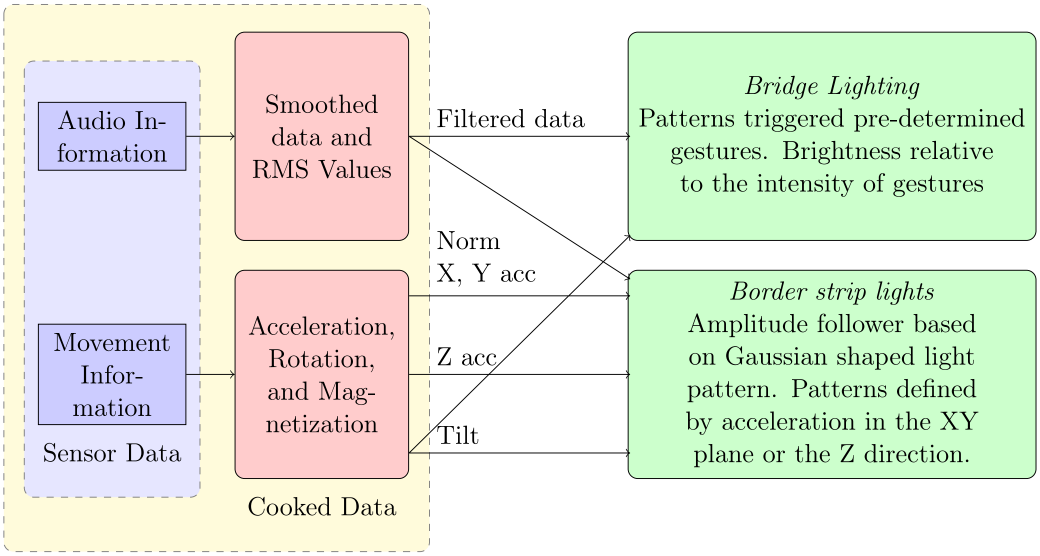


Figure 5.6 Diagram showing the mapping process to take gestural data to a visual affordance.

5.4 Software Design

Firmware was written for the 3 microcontroller boards on the system. Flowchart in figure 5.7 shows the processes happening at the time of performance in each of the boards. Wemos is the board on the glove, The Thing 1 is the board assigned to the bridge and The Thing 2 is the board assigned to the lights installed on the bottom part of the cello. As was the case in the

Sopranino 2GW-181, much of the IMU implementation was based on firmware developed for the T-Sticks, while the lighting patterns and control of the lights was based on custom development and contributions to the DIY community using the ESP8266 and the Arduino platforms.

5.5 Documentation

The electronic design as well as the performance of this project has been documented as it was also done with the T-Stick. The schematic diagram for this self-contained system is shown in figure 5.8.

All the developed software, specification sheet, and additional material that relates to the project can be found in GitHub at `https://github.com/alexnieva/Visual_Augmented_Cello`. Detailed information and links to specific documents and videos can be found in the Appendix at the end of this thesis.

5.6 Performance Objectives

For the purpose of this research, a new work for cello, ensemble and electronics also adapted for solo cello and live electronics was commissioned to composer Luis Naon. *P/'ajaro contra el borde de la noche*, which in English means: Bird against the edge of the night, is an exploratory work in which the cello, representing the bird, is given a wide array of performance gestures. These gestures became a primary reference in which to develop our project.

Part of this work was also to use this system in a real performance. This was achieved on the CIRMMT Student Symposium Concert on May 25, 2017. As planned, the system worked fulfilling most of the design requirements and this also gave us feedback on how to refine and continue the development of the visual output as well as to explore other possibilities to showcase our work[1]. See figure 5.9.

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[1] Performance video at: `https://youtu.be/zd7dEjJuMaY`

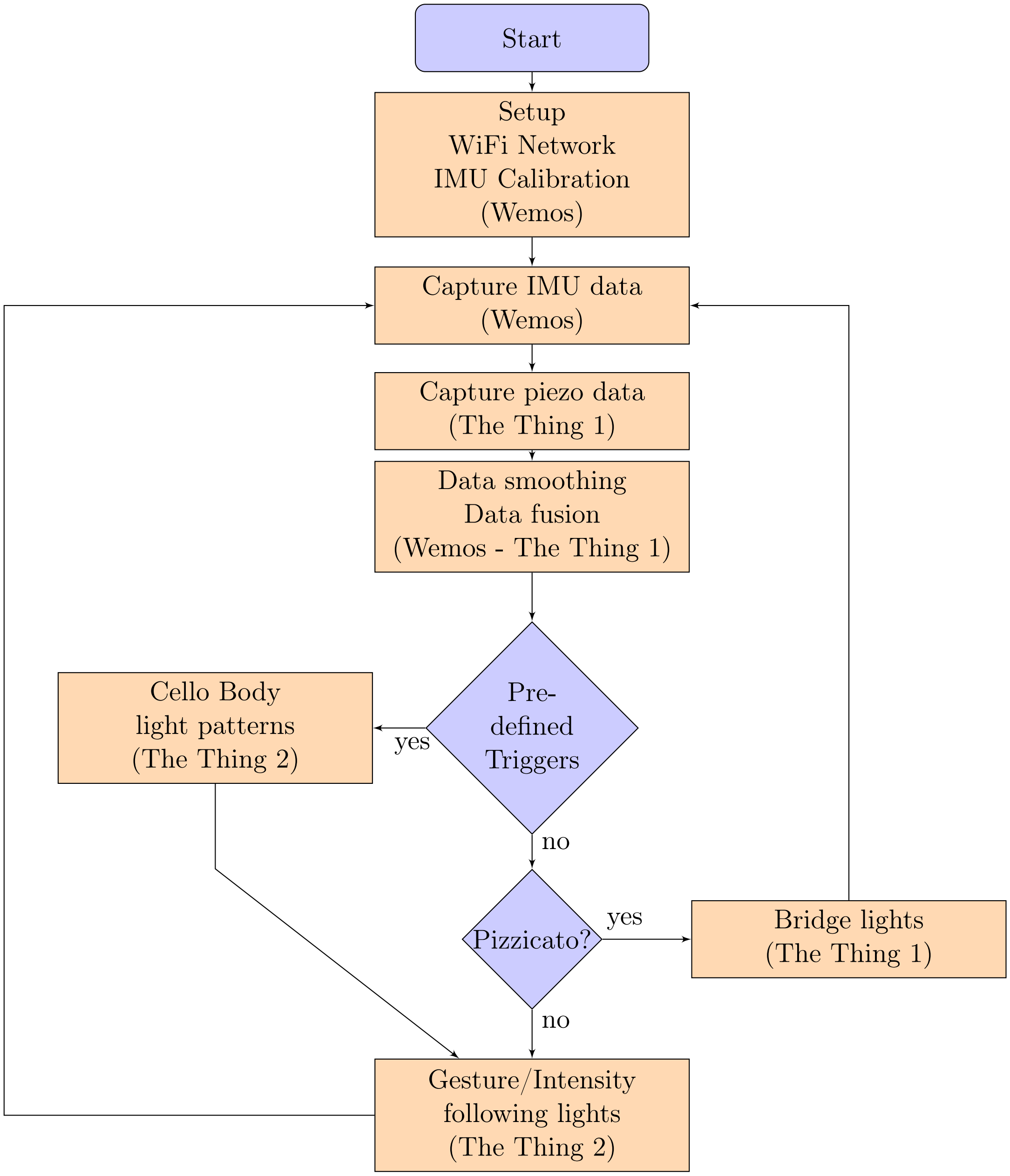

Figure 5.7 Flow diagram showing Cello lighting functional system.

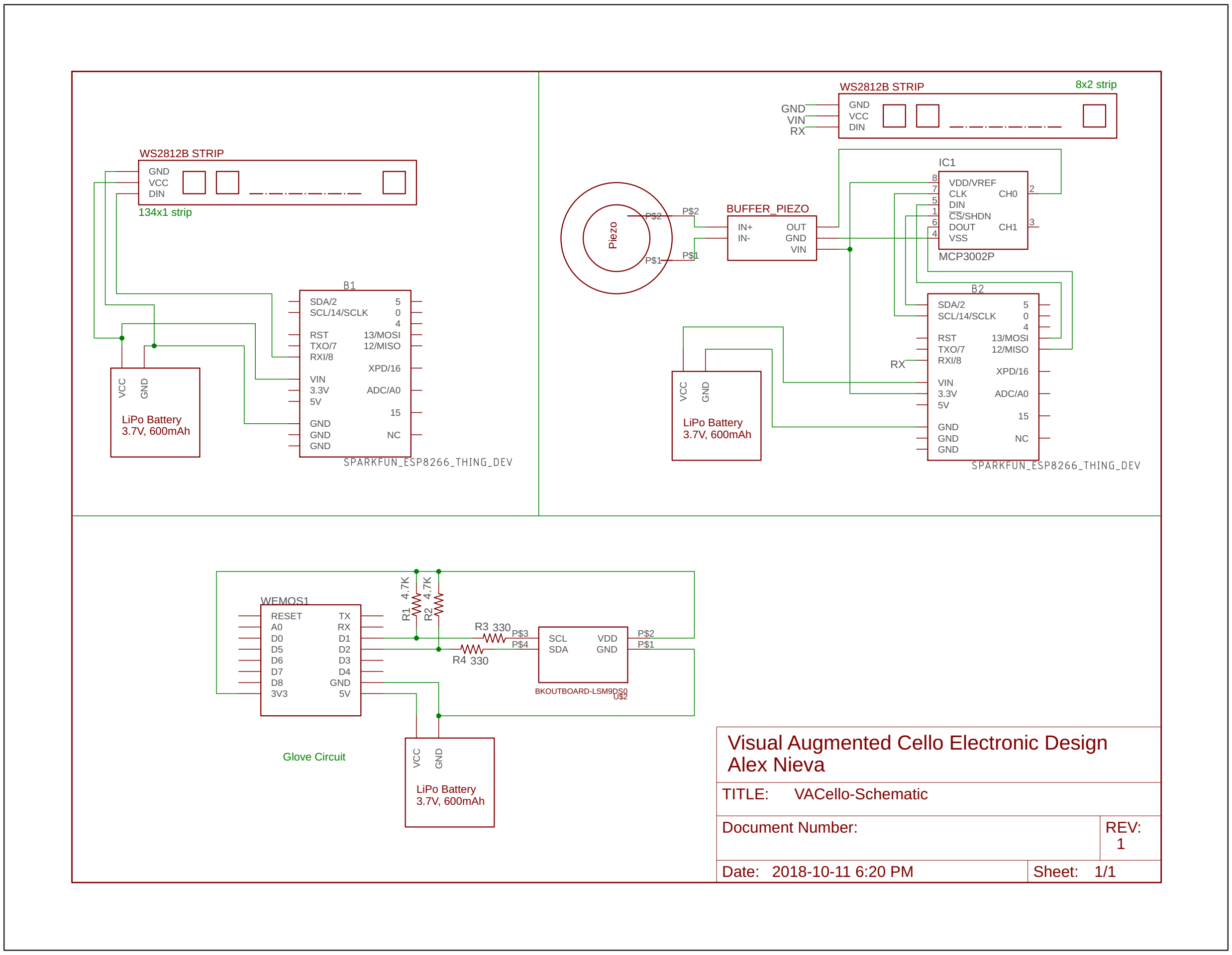

Figure 5.8 Schematic diagram for the Visual Augmented Cello system.

Figure 5.9 Premiere of the Multimodal Visual Augmented Cello in Montreal, May 2017.

5.7 Discussion

We noted that the presence of the lights on the cello provided both a challenge and an additional resource for the musician. It provided a challenge because they required him to expand his performance bandwidth to interact with the system. The lights provide an additional resource because they gave the cellist feedback based on the musical text and the gestures he performed since the lighting output could be correlated to the composer's musical language. He worked on finding an organic way (cellist, cello, and lights as one entity) to give meaning to the musical score by selecting a few important performance gestures (induced by the music or added by the performer) to be mapped and translated into light. This was an essential component in the creative process. Even though the position of the lights targeted the audience, he had to be aware of the lighting output and his ongoing performance to blend the music with the visual output.

From a engineering point of view, the process of conceptualizing, designing, and delivering a working real-time computing system that can interact with a human in the context of musical performance showed us the importance of making the right technical decisions before implementing any sort of manufacturing or purchasing. This efficiently allowed us to manage a limited budget to build the system since this project was funded by an student award[2]. There are many interesting tasks for future work such as optimizing the data rate of communication, creating a web application to allow for different mapping options and changes to the lighting output.

Two of our design criteria were flexibility and expandability. It is straightforward to add an additional board with extra lights or sensors to be part of this WLAN network. It is also possible to connect this network to the Internet to explore data connectivity and distributed interactive performances or remote sensing and analysis of gestural data.

5.8 Conclusions

This project has allowed us to convey specific gestural information into a visual display to complement and communicate expressive musical features based on the musical text and performance. The fact that this is a self-contained system allows for extended use and life span incorporating this type of human-machine collaboration into the musicians practice.

This work shows how an interactive lighting system can provide additional audience interaction that enhances the musical performance. The shapes and positioning of the lights can dramatically change the way the performance is experienced and also change the way the performer manages its cognitive and motor skills to blend with the additional variables to deal with when the electronics are mounted on the cello. This opens up an exploratory channel for the study of human-machine interaction in musical performances specifically for cello performance and could be extrapolated to other string-based instruments.

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[2] This work was funded by the Centre for Interdisciplinary Research in Music Media and Technology by the CIRMMT Student Awards 2016 – 2017.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

This thesis has reported on the technical maintenance, redesign, and design of input devices for musical expression. We have justified the need of maintenance procedures for such devices in the research community and confirmed the importance of incorporating the concept of maintainability in the design process.

We have successfully made available to the community 8 twelve-year-old DMIs (T-Sticks) performing various repairs and updates. This proves that when approaching already designed instruments either functional or not, corrective or preventive maintenance should follow a defined procedure as was done with the T-Stick. If instruments are based on open-source tools, the procedure can be structured following the maintenance strategies presented at the end of chapter 3.

We have redesigned the electronics of an additional Sopranino T-Stick to work with currently available electronics. This reaffirms that in order to provide long-term functionality to an instrument, compatible and stable electronic parts should be favored when refurbishing or redesigning the electronics of an instrument. Upgrading an instrument should be approached respecting original DMI design unless DMI redesign is the objective.

Drawing on the lessons learned in chapters 3 and 4, we have designed a system from scratch to augment the expressive capabilities of a traditional acoustical instrument such as the Cello. The concepts of maintainability, reusability, and self-containment have been taken into account to design a system that works independently of third-party hardware and software manufacturers updates.

We approached these three cases from an engineering point of view, while respecting the overall concept of a musical instrument or input device for musical expression. We argue that such devices should be functionally available for researchers, performers, and composers to explore their artistic possibilities. In order to promote and disseminate the use of new interfaces for digital expression, their design, construction and maintenance should aim for balance, approaching them from an engineering as well as an artistic point of view.

It is important to point out that all the instruments used in this thesis were never meant to be commercial. A degree of flexibility, criteria, and patience should be applied when maintaining DMIs since they probably had never been assumed finished by its original designer. Matching software is a challenge since extracting firmware already flashed onto memory in a microcontroller is a daunting task.

We recognize that there is a somewhat polarized community working with NIMEs and DMIs, analyzing them either with the eye of an artist or the eye of an engineer. We believe that both points of view are valid and they should co-exist to foster this field. Instrument design should be robust and stable to allow performers and composers to use the instrument. If not, the proliferation of short-lived instruments will continue while performances in conferences such as NIME will resemble live electronics from 20 or 30 years ago.

Finally, we have observed that building DMIs as part of a pedagogical endeavor, leverages expertise, promotes the use of these type of interfaces, and streamlines processes that would not be optimized if only one version of the instrument existed.

6.2 Future Work

This work can be extended in many different paths. The most direct one is to embrace technological advancement but respecting the idiomatic gestures established by the designers of this instrument. For this purpose a new generation of T-Sticks with completely renovated electronics and planned manufacturing should be built. The available technical powerhouse allows for more embedded processing inside the DMI. There are several self-contained platforms that can be adapted to work with the T-Stick such as the Prynth[1] or Bela[2]. This would avoid the use of intermediary 3rd party software that as shown in this thesis, poses a problem of software maintenance.

In terms of preventive maintenance, the T-Sticks that were not opened should be scheduled for a revision of components and electronic connections. The Soprano 2GX-015 should be opened to install padding on top of the paper FSR to allow for this sensor to be available again if necessary.

The concept of instruments for research and instruments for performance can be explored by building a T-Stick targeted to the most experienced user of the T-Sticks: D. Andrew Stewart. As a composer and performer, he has developed higher level mappings targeted to specific compositions. With the available technology a T-Stick that performs on-board "cooking" of the data and that exposes the instrument as a MIDI device to the computer should be explored to have what can be called a signature model T-Stick.

Also, a T-Stick that handles different types of communication protocols can be envisioned now. OSC, MIDI over bluetooth, WiFi and MQTT[3] can co-exist to open up other mapping possibilities for researchers. The concept of sending data over the Internet should be implemented and tested to study the possibility of having a digital musical instrument as part of the Internet of Things.

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[1] `https://prynth.github.io/`

[2] `http://bela.io/`

[3] Lightweight messaging protocol, designed for constrained devices and low-bandwidth, high-latency or unreliable networks.

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Appendix

Online Documentation

This Appendix provides links to the documentation for the T-Stick and the Visual Augmented Cello. All this information is open-source and is hosted in GitHub.

T-Stick

The file structure convention for the T-Stick is as follows:

`../TStick/tree/master/InstrumentName/Model/SerialNumber/`

Inside each serial number directory you will find the firmware installed in the instrument, Configuration and Driver patches (Max/MSP), schematics of the instrument and their specification sheets. You will also find the Eagle PCB library used to generate the schematics.

- For Sopraninos go to: `https://github.com/IDMIL/TStick/tree/master/Sopranino`
- For Sopranos go to: `https://github.com/IDMIL/TStick/tree/master/Soprano`
- For the Tenor go to: `https://github.com/IDMIL/TStick/tree/master/Tenor`

Relevant links to information regarding the T-Stick can be found in the following links:

- Project webpage: `http://www-new.idmil.org/project/the-t-stick/`
- Joseph Malloch (Designer): `https://josephmalloch.wordpress.com/portfolio/tstick/`

- D. Andrew Stewart (Composer/Instrumentalist): `https://blogs.ulethbridge.ca/andrewstewart/tstick/`
- T-Stick composition workshop: `https://tcw2010.wordpress.com/`

Sample video links:

- One of the first T-Stick (Tiger Stick) performances: `https://youtu.be/Lss5H242OdE?t=217`
- Original project description: `https://youtu.be/BudSGA511pg`
- *Catching Air and the Superman* (excerpt) by D. Andrew Stewart: `https://vimeo.com/77112292`
- *Sill Life* by D. Andrew Stewart: `https://youtu.be/T-pZ0Xj378o`
- T-Stick Sopranino and GuitarAMI + Sound Processing Unit developed at the IDMIL by Edu Meneses: `https://youtu.be/n-r9-c2jAG0`

Visual Augmented Cello

The documentation for the Visual Augmented Cello is hosted in GitHub at: `https://github.com/alexnieva/Visual_Augmented_Cello`. The firmware for the three microcontrollers used in this project as well as the schematics for all the electronics connections are hosted in this repository.

Sample video links:

- Teaser video: `https://youtu.be/zd7dEjJuMaY`
- *Pájaro sobre le borde de la noche* by Luis Naon - Full Concert. Juan Sebastián Delgado (cello): `https://youtu.be/KDjv-pBykD8`