Reliability Centered Approaches for Digital Musical Interface Design

Albert-Ngabo Niyonsenga

Music Technology Area
Schulich School of Music
McGill University
Montreal, Canada

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Abstract

This thesis explores the challenges of designing reliable and robust digital musical instruments (DMIs) for long-term use. Techniques and frameworks from other fields of engineering, such as systems and reliability engineering, are examined for their suitability in a Music Technology context. The concept of Practice Interruption Rate is discussed as a way to analyse DMI reliability and availability. A systems engineering framework was used to design the T-Stick 5GW, the fifth generation of the T-Stick, a gestural controller designed in the mid-2000s at the Input Devices and Music Interaction Laboratory. The T-Stick 5GW is evaluated against a series of technical metrics, showing that it successfully meets seven out of the ten criteria put forward. Finally, design improvements are discussed, and potential applications to other projects are summarised.

Résumé

Cette thèse explore les défis de la conception d'instruments de musique numériques (DMI) fiables et robustes pour une utilisation à long terme. Les techniques et les cadres d'autres domaines de l'ingénierie, tels que l'ingénierie des systèmes et de la fiabilité, sont examinés pour déterminer leur adéquation dans un contexte de technologie musicale. Le concept de taux d'interruption de la pratique est discuté comme moyen d'analyser la fiabilité et la disponibilité du DMI. Un cadre d'ingénierie système a été utilisé pour concevoir le T-Stick 5GW, la cinquième génération du T-Stick, un contrôleur gestuel conçu au milieu des années 2000 au laboratoire Input Devices and Music Interaction. Le T-Stick 5GW est évalué par rapport à une série de mesures techniques, montrant qu'il répond avec succès à sept des dix critères proposés. Enfin, des améliorations de conception sont discutées et des applications potentielles à d'autres projets sont résumées.

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List of Acronyms

DMI	Digital Music Instrument
RAM	Reliability, Availability and Maintainability
IDMIL	Input Devices and Musical Interaction Lab
MTTF	Mean time to failure
MTBF	Mean time between failure
MTTR	Mean time to replace/repair
DR	Dispatch Reliability
DIR	Dispatch Interruption Rate
PIR	Practice/Performance Interruption Rate
PMR	Practice/Performance Ratio
MRC	Mean Repair Cost
IMU	Inertial Measurement Unit
FSR	Force Sensitive Resistor
PCB	Printed Circuited Board

Chapter 1

Introduction

Digital Musical Instruments (DMIs) are interfaces that convert the gestures and actions of a musician into control signals that can be used for music synthesis. These devices are typically designed using a wide array of technologies, such as microcontrollers, sensors and actuators, which have been used in many applications. Several such interfaces have been presented at international conferences, most notably the International Computer Music Conference and, more recently, the International Conference on New Interfaces for Musical Expression (NIME), and on venues such as the Computer Music Journal. DMIs have been used in performances by a variety of artists and musicians in the last several decades.

DMIs expand the musical possibilities of traditional acoustic musical instruments thanks to the separation between their control surfaces and sound-generating units. In other words, a gesture made by a musician does not necessarily imply one unequivocal sound. Similar gestures can cause widely different effects, or perhaps no effect at all. Furthermore, DMIs can be played in ways that are not possible with acoustic musical instruments. For instance, sequences of notes or sounds can be pre-recorded and played back without the need to articulate each note produced by the instrument. The musician can perform in a similar way to a conductor, where the task of generating notes is left to someone else, in this case, the computer when playing random notes (Chadabe, 1975). Or perhaps as a space conductor, placing and moving pre-recorded sounds and sequences in a three-dimensional sound space.

Several issues are limiting the long-term usage of DMIs. A large number of DMIs are presented at the NIME conference every year, but only a few of them remain in use due to issues such as inadequate musical notation and non-existing repertoire (Mamedes et al., 2014). Even if an instrument has an existing repertoire, accessing the instrument, the software, and the mappings used is difficult. Most are not available at a typical music store. An important point in our case is that many, if not most, DMIs remain laboratory prototypes that never transition to stable and responsive instruments.

Reliability and robustness are important features of DMI design. To ensure long-term use in a performance context, DMIs have to be built to endure multiple performances without failure. Buxton (Buxton, 1997) notes that "artist spec" is a high standard to reach. Meideros and Wanderley (Medeiros & Wanderley, 2014) note that a balance between art and engineering is required to achieve reproducible, robust and reliable instruments. DMIs designed in research laboratories can suffer from reliability, robustness, and manufacturing issues. A prototype instrument with reliability issues may be tolerated, though a stable instrument would be expected to perform well under various performance conditions.

Although trained technicians may mitigate the issue of instrument failures, Berweck (Berweck, 2012) argues that from a performer's perspective, several common electronic failures are akin to having to abort a performance. Therefore, as DMI designers, we face the difficult task of designing reproducible instruments with low failure rates.

Several approaches to the design and evaluation of DMIs have been used to various levels of success (Ford & Nash, 2020; Possik et al., 2021). However, the lack of proper engineering solutions has been noted in (Wanderley & Depalle, 2004) and (J. Malloch & Wanderley, 2017). A greater focus on engineering approaches can lead to instruments that are robust and usable in the long run.

In this thesis, I propose a systems engineering framework for the design and evaluation of gestural controllers, using the design and development of the fifth generation of the T-Stick, the

T-Stick 5GW, as a case study. The T-Stick is a musical interface designed in the mid-2000s (J. W. Malloch & Wanderley, 2007) by Joe Malloch in collaboration with D. Andrew Stewart and Marcelo Wanderley.

Chapter 2 will cover reliability analysis and availability modelling and introduce Practice Interruption Rate as a measure for DMI reliability. Chapter 3 will cover the design history of the T-Stick. Chapter 4 will introduce the approach for the design of the T-Stick 5GW. Chapter 5 will explain the choices made for the T-Stick 5GW. Chapter 6 will cover how the T-Stick 5GW was evaluated. Finally, chapter 7 presents the general conclusions of this thesis and directions for future work.

Chapter 2

The T-Stick

The T-Stick is a musical interface introduced in the mid-2000s (J. W. Malloch & Wanderley, 2007). For more than 17 years, the interface has existed in a state of perpetual upgrades, downgrades, and sidegrades. During this time, design goals shifted in accordance with existing research projects the T-Stick is a part of, from solo and group compositions to dance pieces and interactive installations. After initial developments by Malloch, resulting in a few instruments, a second period focused on pedagogical goals, with several graduate students building their interfaces as coursework. This brought the total number of interfaces built to more than 20 units. The increase in the number of T-Sticks came with the downside of reliability, as they were not manufactured for extensive musical performance practice.

Overall, the T-Stick has gone through four major revisions, each with its own set of features and design goals, in many cases influenced by component obsolescence or hardware innovations. Over the years, the T-Stick has gotten easier to build, is better documented, and is now wireless rather than wired through a USB port. This trend has sometimes been accompanied by modifications of the original design, e.g., the touch sensor density and speed have decreased since the second iteration of the T-Sticks. Similarly, the piezo sensor used in the original Tenor (120 cm total length) and Soprano (60 cm) versions was removed from recent designs because of the relatively recent focus on the smaller Sopranino (30 cm) T-Sticks. Table 2.1 shows all the current T-Stick variants.

Table 2.1 Current T-Stick variants. Table adapted from(Nieva, 2018)

Generation	Model	Variations	Platform
1G	Alto Tenor	None	Atmega8
2G	Soprano Tenor Sopranino	2G 2GX 2GG 2G-IMU 2GW	Arduino Arduino Arduino Arduino ESP8266
3G	Soprano	None	Arduino
4G	Sopranino Soprano	4GW-2018 4GW-2021	ESP32

The T-Stick can be divided into three subsystems: communication, power, and sensor. The communication system handles the T-Stick's connections with external devices and sends and receives signals. The power system delivers power to the rest of the subsystems and charges and discharges batteries. The sensor system handles the user's input and basic signal processing. The raw and processed signals are sent to the control system for interpretation.

The T-Stick has been used for many performances since its inception in 2006. Dr. Andrew Stewart was an early performer of the T-Stick. Andrew Stewart describes T-Stick playing techniques into two categories: "malleable" and "intractable" (Stewart, 2010). Malleable techniques are repeatable and reproduce the same sound, while intractable techniques give you more timbral nuance. Malleable techniques include fingering and jabbing. Intractable techniques feature techniques such as twisting and rubbing. Common T-Stick gestures include: twisting, brushing, jabbing, rotating, tapping and fingering.

2.1 Original T-Stick Project: A Family of Instruments

The T-Stick was conceived as a new family of DMIs to explore the problem of robustness in DMI design and learn how to perform DMIs. These T-Sticks were wired instruments using a USB serial port to communicate with a computer. The first two generations of T-Sticks (1G and 2G) were designed as part of the Digital Orchestra Project (J. W. Malloch & Wanderley, 2007). As a family of instruments, the T-Stick has multiple variants. The original T-Stick prototype was a tenor T-Stick (120 cm); there are also Alto (90 cm), Soprano (60 cm) and later on Sopranino (30 cm) T-Sticks.

Fig. 2.1 Soprano T-Stick picture from Joseph Malloch's Blog. It shows T-Stick and the MaxMSP patch, which performs gesture acquisition, mapping, and sound synthesis. URL: https://josephmalloch.wordpress.com/portfolio/tstick. Accessed 18 Oct. 2021

The original tenor T-Stick used an Atmega8 microcontroller for sensor processing and communication, a home-made paper sensor (designed by by Rodolphe Koehly (Koehly et al., 2006)) for pressure sensing, a 3-axis accelerometer (STMicro LIS3L02AS4) for acceleration data, a piezoelectric sensor for detecting percussive elements and twists, and a custom touch board based on the Quantum QProx QT161-DG IC and copper tapes for capacitive touch sensing.

The T-Stick used wired communication via a serial to USB adapter. The T-Stick 2G used the Arduino platform, most using boards such as the Arduino Mini 04 or the Arduino Pro Mini. Several variants were built as shown in table 2.1. These variants had different sensors, such as the

T-Stick 2G-IMU which had a digital IMU rather than an analog or digital accelerometer, and the T-Stick 2GX which included an additional, proximity, breath and light sensor. The T-Stick 3G was the first wireless T-Stick featuring Bluetooth connectivity. See table 2.2 for which sensors are in different T-Stick variants.

Table 2.2 Sensors in different T-Stick variants. Table adapted from(Nieva, 2018)

	Sopranino		**Soprano**			**Tenor**
	2G	2GW/4GW	2G	2GX	2G-IMU	2G
Touch sensing channels	16	16	48	48	48	96
Accelerometer (digital)	-	-	1	-	-	1
Accelerometer (analog)	1	-	-	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	-	-

2.2 Wireless T-Sticks: Transitioning to WiFi

Since around 2017, with the increase of interest in the use of T-Sticks in different performance situations, e.g., (Fukuda et al., 2021), a drive for standardization and reliability has been initiated so that the interface can be reliably used in sustained musical performance practice.

2.2.1 T-Stick 2GW: WiFi Sopranino

When designing the T-Stick 2GW, Nieva decided to keep the gestural language of the previous T-Sticks (Nieva, 2018). The T-Stick 2GW used an ESP8266 SoC for WiFi processing and sensor processing. He transitioned to WiFi for better wireless capabilities than Zigbee or Bluetooth. The touch sensor and motion sensor from the 2G-IMU T-Sticks were utilized in early 2GW designs. A commercial FSR provides pressure sensing, and the piezoelectric sensor was removed to simplify the electronics. Several design decisions were made to improve the maintainability and reproducibility of the instrument. These included giving a visual indicator of the instrument's status, including documentation for how to build the instrument and a schematic for the electronics.

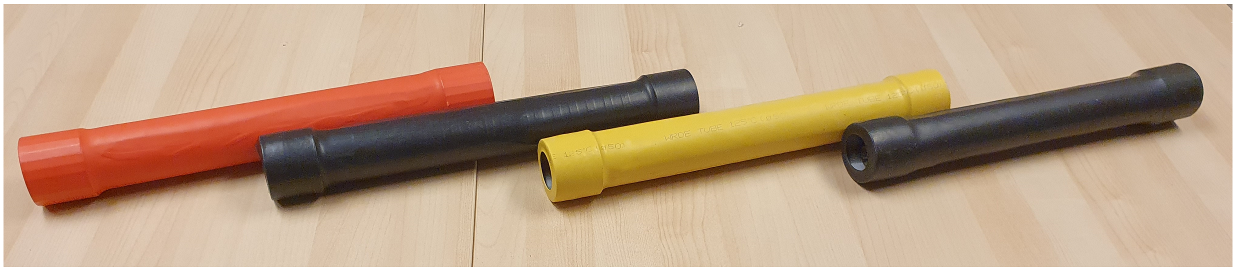

Fig. 2.2 Four Sopranino T-Sticks

The T-Stick 2GW iterated on the split-pipe design of the earlier 2G T-Sticks. The ABS pipe was cut along its long side, the parts were assembled in the pipe, and then the pipe was closed again. 3D-printed endcaps, which held the MCU board and the battery, were also used.

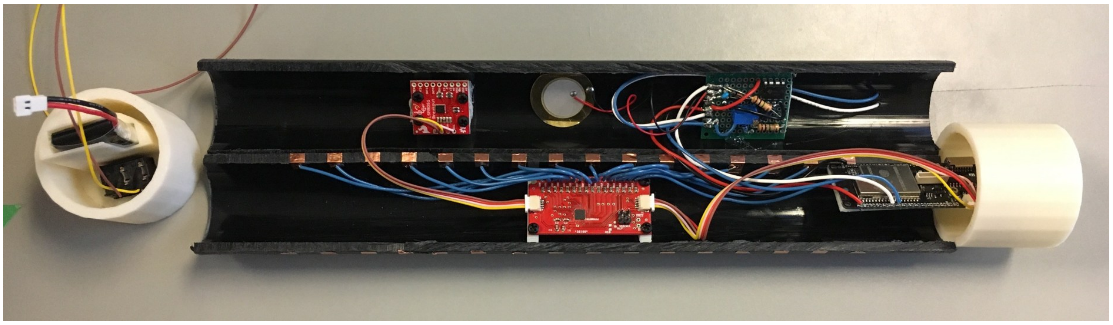

Fig. 2.3 Inside a Sopranino T-Stick, picture from Github. URL: https://github.com/IDMIL/T-Stick/blob/master/Docs/T-Stick_2GW_building_instructions.md. Accessed 18 Oct. 2021

This design makes it easy to access all the components without significant disassembly. That same ease of access also helps with the building process, reducing errors caused by trying to fit a lot of components and wires in a small space. However, this meant that the heat shrink that covered the T-Stick and the endcaps were all critical structural components. Therefore, it was not easy to thoroughly test that all the components were working properly inside the tube before the final application of the heat shrink. Also, splitting the pipes length-wise is time-consuming, increasing the total build time.

2.2.2 T-Stick 4GW: Transition to ESP32

The T-Stick 4GW is a direct successor to the T-Stick 2GW. These T-Sticks used the ESP32 SoC from Espressif[1], a successor to the ESP8266. Featuring two 240MHz Xtensa Lv6 cores, this MCU was significantly more powerful than the ESP8266. The first generation of 4GW T-Sticks used a manufacturing process similar to that of 2GW T-Sticks.

The second generation of the T-Stick 4GW switched the LolinD32 development board for the TinyPico development board. In addition, the touch sensor was changed from Cypress's CY8C20180 sensor[2] to the Trill development board from Bela[3], which uses Cypress's PSoC 1 MCU for capacitive sensing. This T-Stick uses an internal skeleton to avoid cutting the ABS pipe in half (shown in figure 2.4).

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[1] https://www.espressif.com/en/products/socs/esp32

[2] https://www.infineon.com/cms/en/product/microcontroller/sensing-controller/capsense-controllers/

[3] https://shop.bela.io/collections/trill/products/trill-craft

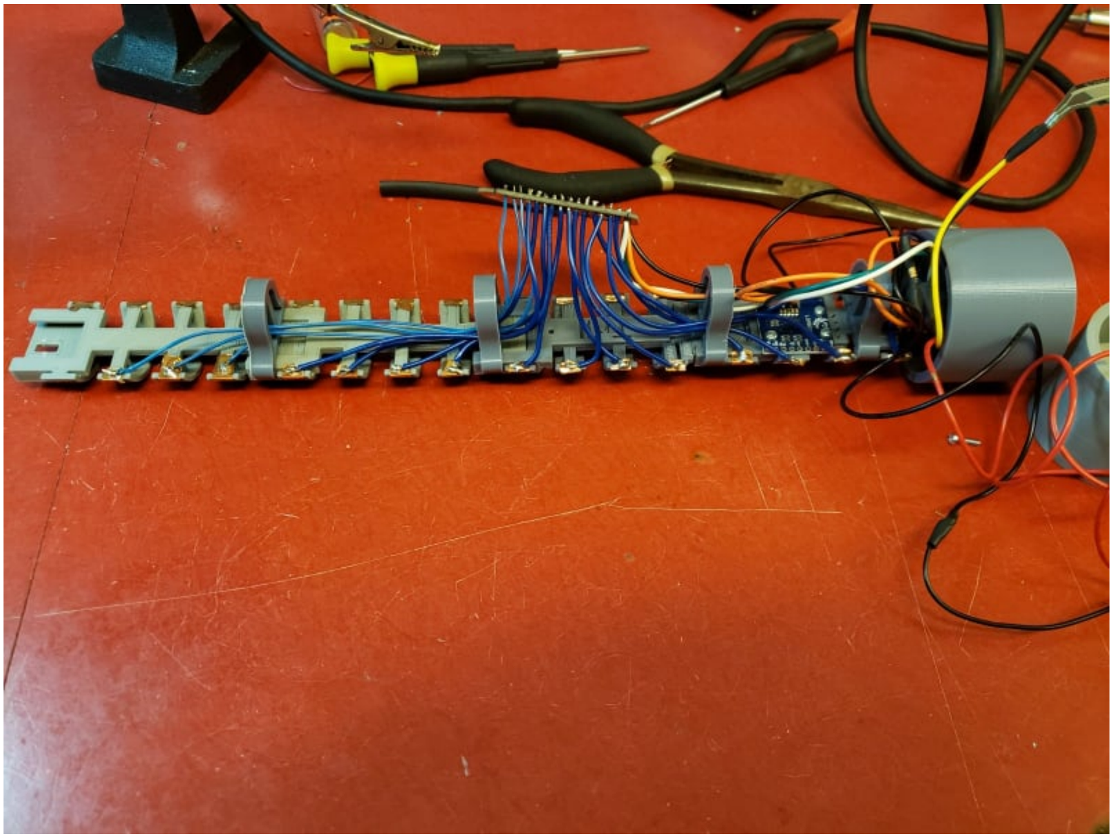

Fig. 2.4 Inside a Sopranino T-Stick 4GW, picture from Github. URL: https://github.com/IDMIL/T-Stick/blob/main/Docs/T-Stick_2GW_building_instructions(trill).md. Accessed 09 Apr. 2024

The T-Stick 4GW-2021 had a closed pipe design. A 3d printed internal skeleton was used for the components. The skeleton was then slid into the pipe, removing the need to slice it. The new design had significant improvements from a manufacturing standpoint. It standardised board placement and connections, lowered the chances of components moving within the pipe and provided a means of testing the components before applying heat shrink. However, it was less maintainable. Accessing components without cutting wires or accidentally breaking other interconnections ranged from difficult to impossible.

2.3 Reliability and Robustness

The wireless T-Sticks are not robust against network interference, the manufacturing process is too complex, and there is room for improvement in the instrument's maintainability.

The ESP32 and ESP8266 are both WiFi 4 2.4GHz devices. The 2.4GHz frequency band is congested and, therefore, susceptible to interference from other devices using that frequency range. Therefore, environmental factors outside of a performer's control can significantly impact the reliability of the T-Stick 2GW and 4GW.

Although significant strides have been made to simplify the build process, it is still too difficult for those without substantial soldering and electronics experience. As students built many second and fourth-generation T-Sticks, reliability issues due to poor build quality are becoming more prevalent. Issues such as cold solder joints, short circuits and open circuits are common (Niyonsenga & Wanderley, 2023).

The maintainability of the T-Stick was improved in the T-Stick 2GW, and its improvements were carried on to the T-Stick 4GW-2018/2021 versions. However, there are still points for improvement regarding maintainability. When the T-Stick fails, it is unclear what exactly failed. The visual indicator on the T-Stick only indicates whether it succeeded in connecting to WiFi and if it is charging, if any sensors aren't working or there is an intermittent error, it is not logged, or communicated to the user wirelessly.

2.4 State of the T-Stick

Over the past 17 years, the T-Stick has undergone many design changes and evolution based on new technologies and requirements. The first generation T-Sticks were wired instruments which used piezoelectric sensors, a custom touch solution and an analog accelerometer to create a rich and expressive interface. As the T-Stick developed, the microcontroller, platform and sensors have changed due to the obsolescence of older components, and changing design requirements. The T-Stick 4GW uses a different communication protocol, sensors and signal namespace from the original T-Stick. Although, there are still ongoing robustness and maintainability issues with some T-Stick designs the instrument's remains in use after 17 years.

Chapter 3

Reliability and Availability

Reliability and robustness are often stated as goals for digital musical instrument design (Jordà et al., 2007; Martin, 2017; Schofield et al., 2014). In this chapter, I will discuss the concepts of reliability and availability from a reliability engineering perspective and how they can be applied to DMI design and propose new metrics Practice Interruption Rate (PIR) and Practice/Maintenance Ratio for analyzing the reliability of DMIs.

3.1 Reliability and Availability

Reliability is the measure of the ability of a device to do a function under specific conditions over time (Lienig & Bruemmer, 2017). From this definition, I can break down reliability into three separate elements: 1) function, 2) environment, and 3) time. First, there is the component's *function*. By function, I mean, the role/action the component fulfills in the system. This can be supplying power, acting as a structural component, or acquiring sensor data. When discussing reliability, it is essential to acknowledge what function each component is doing and what a failure looks like for this component. For example, a linear drop-out regulator fails when it cannot provide a stable power output. The second element is *environment* the component operates in. This includes but is not limited to the ambient temperature and typical mechanical stresses such as impacts, vibrations, and shakes. If the instrument needs to operate outdoors, humidity might also be a factor. It also includes factors such as whether the instrument is used continuously or intermittently. The third and final element is *time.* For most complex systems, I assume that failures are random (Lienig & Bruemmer, 2017), meaning that the failure rate is constant over time. However, that may not be the case for a specific instrument or the individual components of an instrument.

Reliability can be expressed as a function $R(t)$ representing the probability that the device is still functioning after time t. Given multiple devices, t becomes the total operating time of all devices. Assuming a constant failure rate λ, this can be expressed as an exponential function.

$$R(t) = e^{-\lambda t} \tag{3.1}$$

I can look at the expected value of Equation 3.1 to find the *mean time until failure* (MTTF). This is equal to the reciprocal of the failure rate λ.

$$MTTF = \frac{1}{\lambda} \tag{3.2}$$

The MTTF is not the average time until half of the devices fail. In fact, for an exponential function, the MTTF as computed in Equation 3.2 is the point where one can expect that 63% of the devices would have failed. One can see this by plugging the MTTF back into Equation 3.1.

$$\begin{aligned} R(MTTF) &= e^{-\lambda \times (\frac{1}{\lambda})} \\ &= e^{-1} \\ &\approx 0.37 \end{aligned}$$

3.2 Reliability Handbooks and Analytical Tools

Information about the reliability of particular components can be problematic to find for various reasons. Suppliers may not make the information public, existing information might be irrelevant to one's use case, or the component is too recent, and no data exists. Several popular reliability handbooks have been used to estimate the reliability of electronics using past data from similar components. Handbooks such as the MIL-HDBK-217F handbook (Department of Defense, 1991) were popular due to covering a wide array of parts. However, these handbooks come with several drawbacks.

Since the 1990s, several scientists and engineers have outlined the weaknesses of these reliability handbooks (Jais et al., 2013). They are not updated frequently, leading to bias against newer components, and the existing data is based on small datasets. Cushing et al. (Cushing et al., 1993) note that "This approach, based on fear of the unknown, rather than on science-based analysis, discourages change and cost-effective reliability enhancement." FIDES (Charpenel et al., 2003) is an analytical reliability tool that uses the product's mission profile and environmental conditions to estimate the product's reliability.

3.2.1 Availability Modelling

Niyonsenga and Wanderley presented a basic example of availability modelling involving calculating the average uptime (Availability) using the reliability and maintainability of individual components (Niyonsenga & Wanderley, 2023). However, one can consider more advanced models more applicable to our scenario. Availability modelling uses information such as the reliability characteristics of the components and maintenance schedules to model the availability of the device (INCOSE, 2015). This can be done with the simplistic model by just taking the average uptime and dividing that by the sum of the average uptime and average downtime, but that is not a good enough model for instruments (Niyonsenga & Wanderley, 2023). Consider that an instrument is rarely meant to be used 24/7. I am not concerned with the average availability but with measuring the availability of the instrument when the artist wants to use it. Downtime outside of performances or practice is not relevant.

I draw from the commonly used availability metric in the aerospace industry *Dispatch Reliability*(DR) to build an availability model. Dispatch reliability is measured as the probability that a flight will leave on time with minimal delay. The specifics of the length of the delay may vary from airline to airline. I can also consider the *Dispatch Interruption Rate* (DIR) $1 - DR$. It is the probability that a flight will be interrupted. DIR Models incorporate the maintenance time of components, regular maintenance intervals, available stock of replacement components, and the cost of the components and the maintenance to build a model of how the DIR will be impacted. This is also paired with a measurement of the *Direct Maintenance Costs* (DMC), which are the costs per flight hour of maintenance. This takes into account the expense of more reliable designs that have additional redundancies. For example, if an airplane has a failure that can be fixed before the next flight, then the DIR has not been increased, but the DMC would still be impacted. These two figures help companies maximise their Dispatch Reliability while minimising their costs.

There are similarities to instruments that can be drawn from this approach. Instruments can be "dispatched" for performances. There is only a certain amount of time a performance can be delayed before it is either cancelled or other plans must be considered, and an instrument that has been maintained before a performance in such a way that it didn't impact the performance would not count towards the interruption rate of the instrument. However, there are a couple of significant differences. Airplanes are dispatched on a regular schedule, compared to instruments which do not have that same amount of stability. Furthermore, DIR modelling is done for airplane companies which control multiple aspects of the airplane's life directly compared to instruments where the manufacturer has no direct control over the maintenance actions of a musician. However, despite these limitations, I believe DIR modelling can be applied to musical instruments. Consider that professional musicians already regularly maintain their acoustic instruments. Guitar players will not wait until right before a performance before replacing strings; brass players will keep slides and valves well lubricated, and woodwind players will have extra reeds in case a reed fails.

Furthermore, people generally undertake regular maintenance actions for their electronics, most notably charging them regularly and cleaning them if they get too dirty. I can assume that an interested musician committed to performance will take the time to do maintenance as long as it is within their abilities.

3.3 Metrics for DMI Availability

I propose two metrics for DMI availability that are more relevant to DMIs than standard metrics such as MTTF and availability: *Practice Interruption Rate* (PIR) and *Practice Maintenance Ratio* (PMR).

Practice Interruption Rate is the average failure rate for performances/practices involving a DMI. In other words, if one plans to use a DMI for a performance/practice session, what is the likelihood that it will work for this session?

Practice/Maintenance Ratio is the ratio between the expected amount of performance/practice hours and the expected maintenance time of the instrument. It is effectively the MTTF divided by the MTTR, with a few caveats.

PIR for the T-Stick can be computed as follows. One divides the mean time to failure of a T-Stick (MTTF$_p$) by the performance time (t_p) to get the *mean performances between failure* (MPBF).

$$MPBF = \frac{MTTF_p}{t_p} \tag{3.3}$$

One can then compute the PIR by taking the reciprocal of the MPBF.

$$PIR = \frac{1}{MPBF} \tag{3.4}$$

Computing the Practice/Maintenance Ratio (PMR) is a matter of taking the MTTF$_p$ of the T-Stick and dividing that by the average mean time to repair (MTTR$_p$). To compute average maintenance time, one considers the mean time to repair (MTTR$_c$) of each component and the failure rate of each component (λ_c). One can then take a weighted average of all the repairs by considering each component's contribution to the total failure rate of the T-Stick (λ_{tstick}).

For the MTTR$_c$ of each component, I will assume a worst-case scenario where no spares are available. Therefore, I will add the time to acquire new components as part of the mean time to repair.

$$MTTR_p = \sum_{c=0}^{n} \frac{\lambda_c}{\lambda_{tstick}} (MTTR_c) \tag{3.5}$$

To compute the Practice/Maintenance Ratio (PMR), one divides the MTTF$_p$ by the mean time to repair (MTTR$_p$).

$$PMR = \frac{MTTF_p}{MTTR_p} \tag{3.6}$$

Note that as this is a ratio of mean time to failure is *performance-hours / failure* and the mean time to repair is *maintenance-hours / failure*, the Practice/Maintenance ratio unit is *the number of performance hours per hour of maintenance.*

3.4 Relationship to Artist Spec

Buxton's idea of the "artist spec" is often used to highlight the high-performance standards of tools for artists (Buxton, 1997). “Artist spec” is a catch-all term for the high-performance demands that artists expect from their tools. It is hard to achieve not just because of the strict technical specifications but also because if one is not an accomplished artist, it is difficult to understand these requirements, and they may differ from artist to artist. Similarly, artists are inherently creative and do not necessarily follow instructions to use tools.

In this section, I will discuss how "artist spec" has been interpreted in DMI design and how reliability and availability metrics can be used as a proxy for it.

Medeiros and Wanderley discuss “artist spec” as justification as to why the use of robust engineering methodologies are needed in DMI design (Medeiros & Wanderley, 2014). They argue that although some designers may say that DMI design is more art than science, to reach the levels of reliability and robustness needed, more thorough engineering is needed. When “artist spec” is stated as a requirement, it is measured qualitatively like by the creators of the Cinejack (Schofield et al., 2014). They tested their system in live performance environments to ensure that it met “artist spec”. These approaches are good for finding bugs and failures that may not present themselves in a laboratory environment but, this approach cannot test how well the system may perform in the long term. “Artist spec” can also be interpreted in terms of long-term support, such as maintenance and support. Tremblay et al. say that for their tool to meet “artist spec” it needs to be sustainable beyond their project (Tremblay et al., 2021). Analytical methods for quantifying “artist spec” such as those presented by Niyonsenga and Wanderley (Niyonsenga & Wanderley, 2023) can also be used but are limited by a lack of supplier data for the reliability of individual components and inappropriate metrics for DMI reliability and availability.

Some of Cook’s principles for designing DMIs (Cook, 2001) are a reflection of the need for reliable instruments. Specifically, principles 8 and 9 regarding that “*Batteries, Die*” and “*Wires are not that bad (compared to wireless)*” directly address reliability and robustness issues. Mitchell et al. and Wang et al. both address many key metrics for evaluating the reliability of WiFi in a music technology context such as scalability (ie: how many devices can be on the network), latency, throughput, and packet loss (Mitchell et al., 2014; Wang et al., 2020).

For DMI design, the terms reliability and robustness are used interchangeably to represent the general idea that instruments should not break when used in performances. Sullivan and Wanderley (Sullivan & Wanderley, 2018) define *stability* and reliability in the following ways:

> By stability, We refer to the proper and robust operation of all aspects of an instrument - it should be playable in a dependable state without unreasonable risk of failure. Reliability extends the concept of stability over time. An instrument should remain stable, dependable, and in good working order throughout long-term use. It should also

> be designed to withstand the rigours and wear and tear of normal operation throughout the intended life cycle of the instrument. We include topics of maintainability and repairability here as well.

"Reliability and stability," as defined by Sullivan and Wanderley, merge several aspects of reliability, robustness and availability. The authors define stability similarly to how a reliability engineer might define reliability or robustness. Their definition of "reliability" is much closer to the concept of availability. They fold the concepts of maintainability and repairability into the definition of "reliability," making its scope wider than failure rates.

From a reliability and robustness perspective, I believe that the Practice Interruption Rate and the Practice/Maintenance Ratio of an instrument serve as a good metric for evaluating whether a DMI meets "artist spec." Unlike reliability and robustness, PIR takes maintenance and repairability into account, giving a more comprehensive view of the instrument's stability. It focuses not on the failure rate per hour, which is not likely to be tracked by a performer, but on the failure rate per performance. PMR indicates the amount of performance hours an artist should expect per hour of maintenance, which indicates the amount of maintenance workload an instrument will require.

3.5 DMI Design and Reliability

Practice Interruption Rate and Practice/Maintenance Ratio can serve as metrics to evaluate the "artist spec". As discussed in this chapter reliability and robustness are important aspects of DMI design and are measured both qualitatively by using the instrument in performances and quantitatively by testing different aspects of the instrument such as their communication method. Reliability analysis and availability modelling techniques from reliability engineering can be used in a DMI context to provide an analytical tool for estimating the performance of your instrument. PIR and PMR take into account, the reliability, maintainability and repairability of the instrument, acting as a comprehensive proxy for "artist spec".

Chapter 4

Design Approach

The design approach I undertook for this thesis was inspired by Systems Engineering Design approaches. This chapter will describe the main system engineering design activities and then will apply these activities to my design process with the T-Stick.

4.1 Systems Engineering Design Activities

Systems engineering activities can occur at all life cycle stages of a system. This encompasses concept, development, production, utilization, support and retirement. In this chapter, I'll focus on the first two stages: concept and development. The concept stage is where the need for a new system of interest may originate either from research or new enabling technologies. The development stage is where this system gets further defined, and stakeholder requirements are developed. Systems Engineering approaches can be broadly split into two categories: sequential and iterative. Sequential approaches follow a more formally defined framework that manages the system's entire life cycle. They tend to be less resistant to change and are typically used by organizations to tackle large, complex systems (INCOSE, 2015). The Vee-model is an example of such a framework.

The Vee-model is a sequential systems engineering process that involves a specified set of plans. These plans involve understanding stakeholder requirements and developing more detailed model specifications and verification plans as you go down the V. Once the system has been prototyped/implemented, you go back up the V and verify each level, from the lower-level system components to the upper-level system components.

Incremental and Iterative Models are another approach to systems engineering. These models are used when the requirements are less clear and for smaller, less complex systems. They better account for systems where experimentation is needed to develop a better product. Examples of these processes include the Spiral Model for systems. Generally, these models go through the following steps:

- Stakeholder and Requirements Analysis
- Functional Analysis and Functional Allocation
- Concept Generation
- System Architecture
- Validation and Evaluation

4.1.1 Stakeholder Requirements Analysis

Stakeholder and Requirements Analysis further define the stakeholder and their requirements. These requirements may change and evolve as more is learned about the system throughout each iteration. These user requirements are essential, and ensuring that design decisions can be traced back to these requirements helps ensure that the solution will satisfy the stakeholder.

4.1.2 Functional Analysis and System Architecture

Functional analysis considers these requirements and what the system must do to achieve them. These functions may also be allocated to subsystems. Once these two stages are complete, concepts are generated, and system architectures are developed for each concept.

4.1.3 Verification and Validation

The verification and validation phase ensures that the product meets all of the technical requirements, relevant regulations, and stakeholder requirements. The following verification methods for requirements (SEBoK, 2021) were used.

Table 4.1 Verification Methods

	Verification Method (IADT)
Inspection	Visual inspection of the device
Analysis	Simulation, mathematical models and data analysis
Demonstration	Demonstrate the functionality for the user
Test	More rigorous form of demonstration to show performance

In an iterative approach, this process can occur several times. With each iteration, the requirements become more refined, and the solutions become more specific and detailed.

4.2 Initial Requirements and Goals

In October 2022, the former and current members of IDMIL met for a hybrid meeting to discuss the T-Stick. This involved discussing what we wanted from a new design, interesting ideas to explore and ongoing issues or bugs that need to be resolved.

The items discussed in this meeting are included in the list below:

1. Fast touch sensing
2. Higher resolution touch sensing
3. vibrotactile feedback
4. Robustness
5. Easily assembled
6. Better battery life estimation
7. better power consumption mitigation in firmware

8. audio rate tap/brush excitation
9. Onboard sound synthesis (even primitive would work for a quick test)
10. More polished appearance
11. “Framming” gestures embedded in firmware
12. Calibration functionality
13. Better sensor management (T-stick should be able to identify non-responsive sensors and stop pinging them)

These items were split into four categories: 1) Better sensor resolution and speed, 2) improved reliability/robustness, 3) improved maintainability, and 4) additional features that would be interesting to try out or add to the T-Stick. When making requirements, I will focus on items that fit the first three categories. Although some of the ideas are interesting and worth exploring, the primary goals of this project are to improve reliability and maintainability, hardware documentation, and sensor resolution and speed.

4.2.1 T-Stick Design Guidelines

As ongoing design continued, a set of design guidelines were slowly being developed. Written in collaboration with my colleague Travis West, these guidelines were written to improve the replicability of the T-Stick. The guidelines are split into four sections.

- Section 1: Identity Characteristics
- Section 2: Hardware Standards
- Section 3: Sensor Measurements
- Section 4: Signal Namespace

Section 1: Identity Characteristics This section outlines what makes a T-Stick a T-Stick, focusing on the physical characteristics of a T-Stick. It introduces vocabulary for the T-Stick and outlines some standard features of the T-Stick.

Section 2: Hardware Standards This section outlines common hardware standards for the T-Stick.

Section 3: Sensor Measurements This section outlines common sensor properties across T-Sticks.

Section 4: Signal Namespace This section outlines recommendations for the namespace of the T-Stick.

The design guidelines are not overly specific about the specific types of sensors or exactly how the namespace should be outlined. Instead, they should be thought of as a document that future T-Stick designers can look over and use to design a T-Stick-like instrument. A full copy of the design guidelines can be found in the appendix B.

4.3 Technical and User Requirements

From the items presented in Section 4.2 I derived a set of user requirements listed in table 4.2. These requirements are the main goals of this initial design work on the 5th generation of T-Sticks.

Table 4.2 User requirements

ID	**User Requirements**
U1	Redesign the T-Stick to be easier to construct and maintain
U2	Improve the reliability and robustness of the T-Stick
U3	Improve battery and power management system
U4	Improve sensor management system
U5	Improve quality of existing signals
U6	Improve feedback to end-user

These user requirements reflect the goals and motivations carried over from the 1G-3G T-Sticks designed by Malloch and the 4G T-Sticks designed by Nieva and Meneses. The T-Stick 5GW is, in effect, an attempt to merge the focus on reliability and robustness from the original T-Stick project with the accessibility and reproducibility that was the focus of the 4G T-Sticks.

From the user requirements, I extracted a set of technical requirements. The technical requirements can be verified with the methods from table 4.1. They are grouped by the major subsystems of the T-Stick and by topics that apply more broadly to the whole design.

4.3.1 Communication System Requirements

Communication System of the T-Stick is the set of hardware and software components that handle the controlling and regulating configuring of the instrument, communicating with the instrument, communication between subsystems. The communication requirements, including sub-requirements, are shown in table 4.3.

Table 4.3 All Communication System Requirements

ID	Requirements	Verification Method (IADT)
1.1	Continuous signals will have a wireless signal rate of at least 100Hz and no slower than 50Hz.	Test/Analysis
1.2	Wireless Signal Latency will be below 10ms.	Test/Analysis
1.3	Wireless Signal Jitter will be below 5ms.	Test/Analysis
1.4	The packet loss will not be above 2.5% under good networking conditions.	Test
1.5	The communication system will send any errors experienced by other subsystems to the user.	Demonstration
1.5.1	The communication system will send errors experienced by the sensor system to the user.	Demonstration
1.5.2	The communication system will send errors experienced by the power system to the user, excluding errors that cause a complete power delivery failure.	Demonstration
1.5.3	The communication system will send errors experienced by the control and communication system to the user.	Demonstration

Requirements 1.1 - 1.4 specify the technical performance of the communication system. All of these requirements specify the worst acceptable performance. The specific metrics ensure that the

5G T-Stick has the same or better performance to the previous generation of T-Sticks. Designs that significantly exceed this performance are viewed more favourably. Requirement 1.5 and its sub-requirements outline the communication system's functions to meet the user requirements (U6).

4.3.2 Power System Requirements

The power system of the T-Stick delivers power to all components of the T-Stick and measures the remaining power when the T-Stick is on battery power. Hardware components include regulators and fuel gauges, and software components include battery life estimation algorithms. Table 4.4 lists all the Power System requirements.

Table 4.4 All Power System Requirements

ID	**Requirements**	**Verification Method (IADT)**
2.1	The device will be powered by both batteries and USB.	Demonstration
2.2	The power system will provide continuous power to the T-Stick for at least 4 hours on a single charge.	Test
2.3	The power system will be able to measure the battery's state of charge with an average error of less than 10%.	Analysis

Requirement 2.1 is a constraint coming from the 4GW T-Sticks. All T-Sticks must be able to operate with a battery and USB power. Requirements 2.2 and 2.3 are performance requirements. Like the performance requirements of the communication system, these requirements specify the minimum acceptable performance. A four-hour minimum battery life is the minimum required for a T-Stick to do an entirely battery-powered performance. An error of up to 10% is acceptable for state-of-charge estimations as an artist is expected to have their T-Stick fully charged before a performance, and the high minimum expected battery life will compensate for poor state-of-charge estimation. These requirements are based on the user requirement U3 for improving the power management system.

4.3.3 Sensor System Requirements

The Sensor System manages the initialisation, communication, and analysis of sensors in the T-Stick. This includes all the sensors except those related to power management and the software components communicating with the sensors and processing their data. Table 4.5 lists all the sensor requirements.

Table 4.5 All Sensor System Requirements

ID	**Requirements**	**Verification Method (IADT)**
3.1	The sensor system should have a polling rate of at least 1000Hz for continuous signals.	Test
3.2	The sensor system will have an average error of less than 1%.	Analysis/Test
3.3	The sensor system will be able to detect when sensors are not communicating.	Demonstration
3.4	The sensor system will be able to identify sensors that are not communicating.	Demonstration
3.5	The sensor system will continue operating regardless of the states of the sensors	Test
3.6	The sensor system will have a calibration mode, enabling artists to calibrate the sensors manually.	Demonstration/Test
3.7	The sensor system will be able to measure or approximate the following properties listed in Section 3 of the T-Stick Design Guidelines.	Demonstration

Requirements 3.1 and 3.2 refer to the performance specifications for the sensor system. A low average error is needed for the artist to trust the sensor system's signals and address user requirement U5. Requirements 3.4 - 3.6 relate to user requirements U4 and U6, relating to improving sensor management and feedback to the end user. Requirement 3.7 exists to ensure continuity with previous T-Sticks, particularly the T-Stick 4GW.

4.3.4 Reliability and Availability Requirements

As the name suggests, this section contains all requirements related to reliability and availability. These requirements address user requirement U2 to improve the reliability and robustness of the instrument. This includes a PIR and PMR target for the T-Stick. The robustness requirements ensure the T-Stick can handle elevated levels of shaking and jabbing for short periods without permanent failures. Table 4.6 shows all the Reliability and Availability Requirements.

Table 4.6 All Reliability and Availability Requirements

ID	**Requirements**	**Verification Method (IADT)**
4.1	The T-Stick will have a Practice/Performance Interruption Rate (PIR) of 1%.	Analysis
4.2	The T-Stick will have a Playing/Maintenance Ratio (PMR) of at least 1 Performance/maintenance hours.	Analysis
4.3	The T-Stick will be robust to jabs.	Test
4.4	The T-Stick will be robust to shakes.	Test

4.3.5 Manufacturability Requirements

The manufacturability Requirements are all the requirements related to T-Stick manufacturing, including constraints on the Bill of Materials (BOM), required documentation, and time to assemble the T-Stick. Table 4.7 shows all the Manufacturability Requirements. These requirements are inspired by user requirement U1 about redesigning the T-Stick to be easier to maintain and build.

Requirement 5.1 refers to Sections 1 and 2 of the T-Stick Design guidelines. These sections outline the physical constraints of the T-Stick and the hardware standards. I specify this to ensure better interoperability with current and future T-Stick designs.

4.4 Summary of Requirements

The technical requirements presented in this chapter are the basis for future evaluation of the T-Stick 5GW. User requirements were derived from discussing with artist and previous designers of the T-Stick. From these user requirements, a set of technical requirements were derived. Sections 1 - 3 of the requirements cover the performance standards and constraints for the communication, power and sensor systems of the T-Stick. Sections 4 and 5 cover the reliability and manufacturing requirements and constraints for the T-Stick. These requirements will be used to evaluate the success of the T-Stick 5GW against the goals of the project.

Table 4.7 All Manufacturability Requirements

ID	Requirements	Verification Method (IADT)
5.1	The T-Stick will follow the design guidelines and requirements outlined in sections 1 and 2 of the T-Stick Design Guidelines.	Demonstration
5.2	The physical design documentation will include a bill of materials.	Demonstration
5.2.1	The bill of materials will have fewer than 64 individual parts, including fly wires, screws, nuts, and heat shrink.	Demonstration
5.2.2	The bill of materials will have fewer than 40 distinct types of parts.	Demonstration
5.3	The physical design documentation will include a schematic.	Demonstration
5.4	The physical design documentation will include assembly instructions.	Demonstration
5.5	The mean time to assemble one T-Stick, not counting the time to gather parts and materials, will be less than 5 hours.	Test
5.6	The final assembly and repair of the T-Stick will be possible using only a soldering iron, wire stripper/cutter, heat gun, saw, and hex key.	Demonstration
5.7	The T-Stick will use commonly available parts and materials.	Demonstration

Chapter 5

Designing a new T-Stick

In the past two chapters, I have discussed reliability analysis, availability modelling, and the design requirements for evaluating the performance of new and current T-Stick prototypes. In this chapter, I will go through the design of the T-Stick 5GW. This will include initial prototypes, critical design decisions, and the final design chosen for testing and production.

5.1 Functional Analysis

As shown in figure 5.1, the T-Stick has a relatively straightforward functional flow block diagram.

The sensors must be initialised, and then regularly polled for raw sensor data. Any sensor errors must be processed and then converted to error messages for the user. This function is not fully developed in the fourth generation of T-Sticks but still exists, as most errors are at least printed to the serial monitor. The power system of the T-Stick handles charging the instrument, providing power to all components and changing the power state between active operation and deep sleep. The control and communication system outputs signals via OSC or libmapper and interprets user inputs/signals, such as using the serial monitor to reboot the T-Stick.

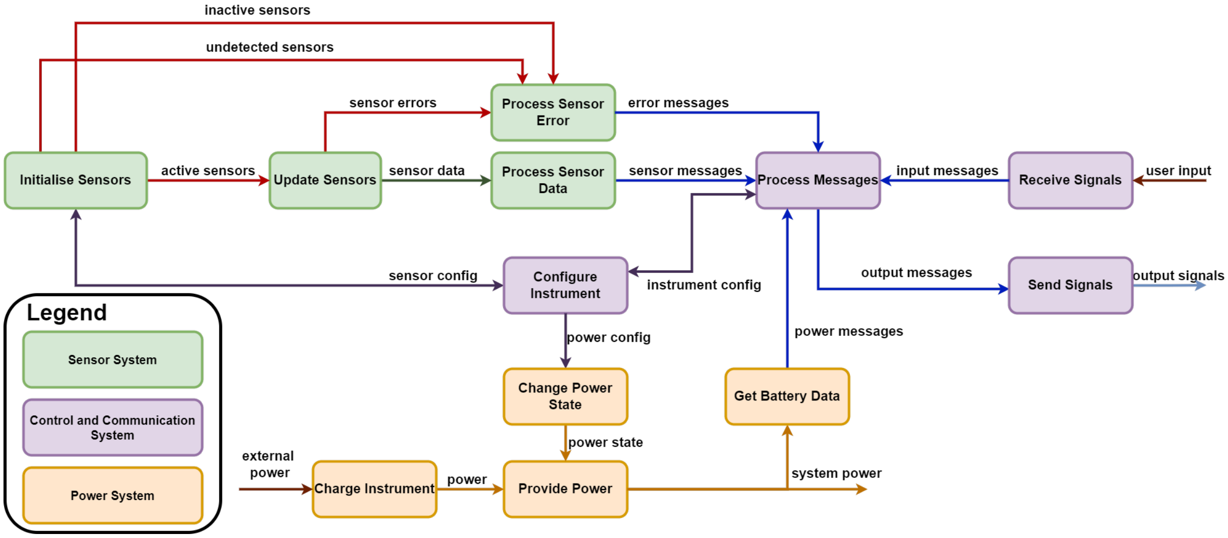

Fig. 5.1 Functional Flow Block Diagram of the T-Stick, Legend on the bottom left shows which functions are in which system

5.2 Early Prototypes

5.2.1 Prototype 1: DIY Plus

Initial design ideas of the 5th generation of T-Sticks focused on simplifying the design process and removing the need to solder each device individually. To do this, I considered using JST-SH connectors to connect the different sensors to the microcontroller. Furthermore, I planned to leverage Sparkfun's Qwiic Connectors/Adafruit's StEMMA QT connectors. Both companies use the same JST-SH 4-pin cable and pinout for their sensors. These connectors can daisy chain multiple sensors over an I2C bus. The connectors would help achieve the manufacturing requirements by reducing build time. Finally, a fuel gauge such as the MAX17048 was considered to improve the accuracy of the battery life estimation in accordance to the power system requirements (Req. 2.3).

In addition to using cables to connect sensors, the touch array was to be replaced by a flexible PCB connecting to a Trill Flex[1] through its 32-pin FFC 0.5mm pitch connector. This would easily double the touch sensor density from 1 sensor every 2cm to 1 sensor every centimeter while reducing the build time.

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[1] https://shop.bela.io/products/trill-flex

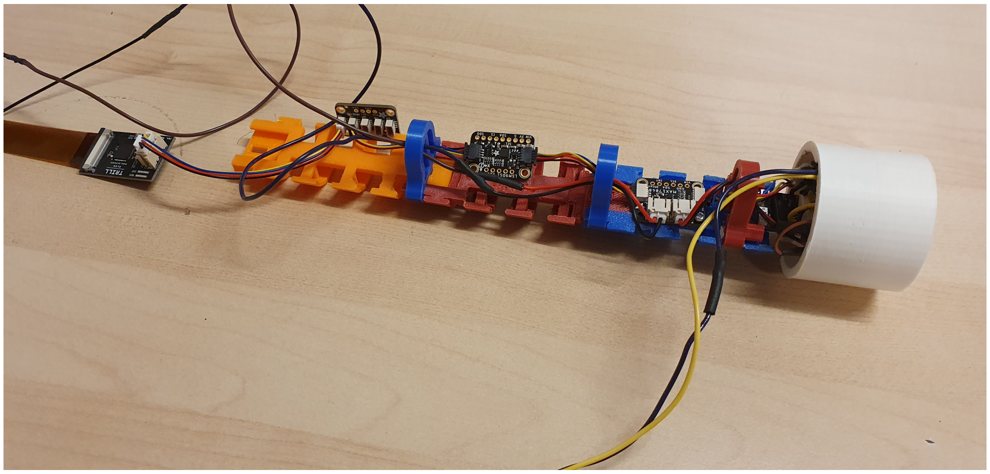

Fig. 5.2 Example of T-Stick DIY Plus Design

These changes would have improved the manufacturing of the T-Stick by lowering the time needed to build it, which would improve its performance for requirement 6.4. Similarly, this assembly would be easier to do even for those without soldering experience, improving reliability requirements 4.3 and 4.4, as the T-Sticks would be more robust to shakes and jabs. Such cables are easier to maintain. If the interior of the T-Stick is assembled so that the cables are easy to access, it wouldn't be unreasonable to assume that a musician could check that the cables are secure before performing. This would reduce the interruption rate for performances and practices due to loose cables.

However, this design also had several drawbacks. It would still require soldering the FSR and button directly to the ESP32. I would also need to find an ESP32 board that has a JST-SH 4-pin header on the board. Nevertheless, this design would still be at risk of either Adafruit or Sparkfun discontinuing or changing their Qwiic and STEMMA QT connectors, either changing the pinout or changing to a different type of connector. In addition, introducing the flexible PCB would increase the production cost of the T-Stick. It is also difficult to expand the design using a flexible PCB for longer T-Sticks, given how the PCB will have to lay in the actual tube.

5.2.2 Prototype 2: Prosumer

As the drawbacks of my initial idea for the T-Stick's hardware design became more apparent, I decided to increase my scope and design a custom ESP32 board. This was done for a couple of reasons, mostly related to manufacturing requirements and robustness requirements.

A custom ESP32 board would have several benefits from a manufacturing perspective. In Chapter 2, I mentioned that the T-Stick has a manufacturing problem that manifests itself in severe reliability issues while in use. A custom ESP32 board can have most of the sensors used in the T-Stick in a single printed circuit board (PCB). This strategy outsources the manufacturing to an external organisation specialised in manufacturing. It reduces the bill of materials for final assembly, though with the drawback of increasing costs and design complexity. The idea would be to have the ESP32 board have all the necessary sensors and connect to additional touch boards for design.

Initially, a "T-Stick Prosumer" board was designed, with headers for a TinyPico board and Trill Craft board, and the IMU and fuel gauge were already added to the board. The IMU was changed from the LSM9DS1 9-DoF IMU used in the current T-Sticks to an ICM20948 IMU. This is done for two reasons. First, the software rewrite for the T-Stick currently only supports the ICM20948, and the company that produces the LSM9DS1 no longer seems to be making new IMUs. The fuel gauge was also updated from the MAX17048 fuel gauge to the MAX17055. This fuel gauge also has a coulomb counter for a more accurate state of charge and capacity estimation. The touch sensor was also redesigned. The connector is now on the long end of the sensor and is in the middle of the flexible PCB. Two small JST-SH connectors are used to connect the button and FSR. The prosumer board and new flexible PCB design are shown in figure 5.3. Extension touch boards for longer T-Sticks were also designed and are shown in figure 5.4.

Five boards were ordered and tested. One of the five boards has a fuel gauge that does not consistently respond to I2C communication due to a faulty I2C circuit for the 1.8V bus.

In addition, LEDs were added for visual indication that the sensors worked, though they draw more current from the battery even while the T-Stick is in sleep mode. This idea improved on

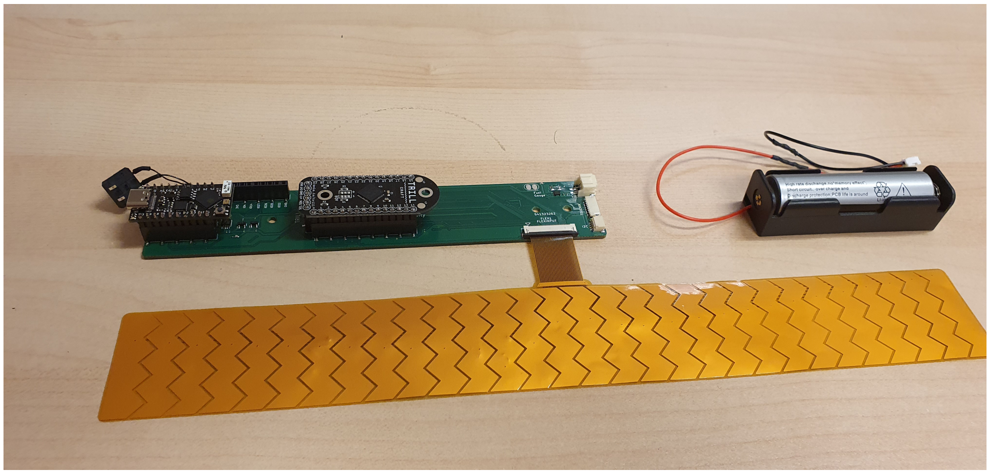

Fig. 5.3 T-Stick Prosumer Board, including TinyPico and Trill Craft Board

the previous notion by simplifying construction further. A single Sopranino T-Stick only needs a single board and 3 additional cables, compared to connecting multiple cables between sensor boards. However, this design significantly increases the design complexity of the T-Stick. The benefit of using development boards is that one does not need to understand what is happening on the board; they just need to understand its inputs and outputs. If the boards need to be replaced, all one needs to do is find a similar board with the same or similar sensor with the same inputs and outputs on the board.

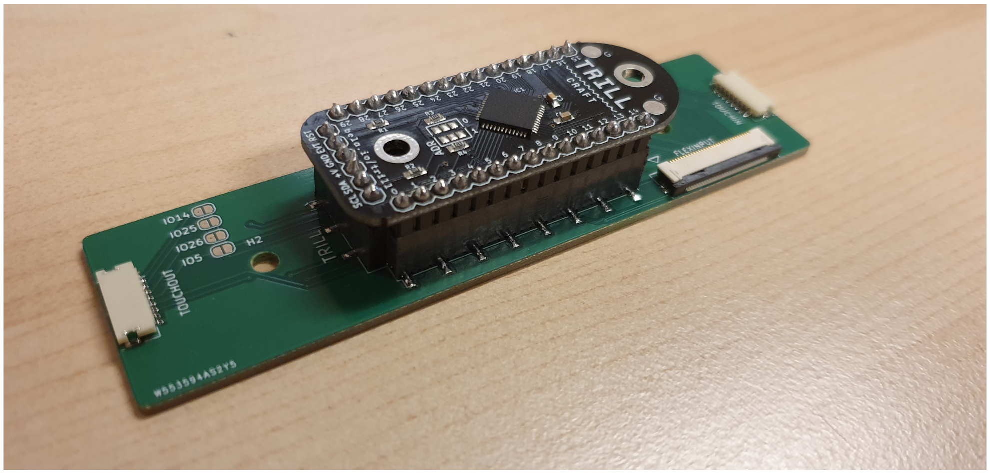

Fig. 5.4 Extension Touch Boards for longer T-Sticks

The prosumer board is complex enough that designing a custom ESP32 board is not significantly more complex. A custom ESP32 board would allow me more control over the power system on the board rather than having to use the TinyPico's power circuitry.

5.2.3 Assembly Prototyping

As a significant portion of the T-Stick 4GW's reliability problems were due to poor assembly, the assembly process for the T-Stick 5GW was also redesigned to be easier to build. For the first iteration of the 5GW assembly, I opted to iterate on the closed pipe design as I believed that the reliability benefits offset the losses to maintainability. Furthermore, I thought it was possible to offset the loss of maintainability with some design changes to the internal skeleton, however it was not possible to offset the loss to maintainability with new internal skeleton designs.

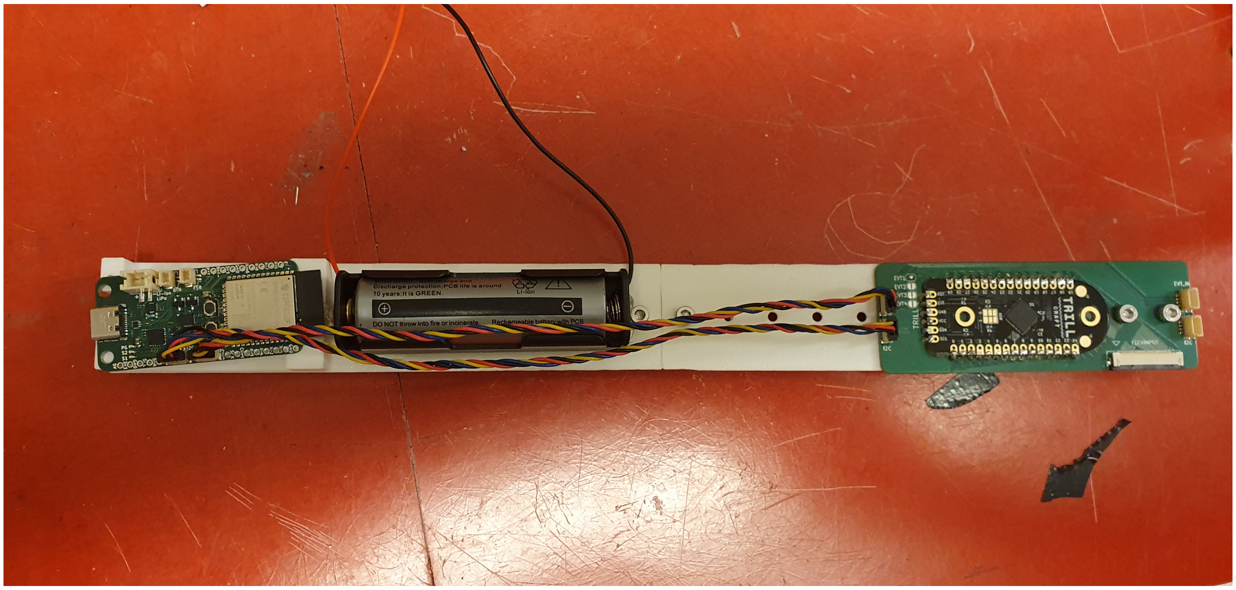

Fig. 5.5 Internal Skeleton for T-Stick 5G prototype

The main innovation of this design, which a colleague, Travis West, primarily designed, was the separation of the internal endcap and the external endcap. The internal endcap would help remove the internal skeleton without removing the heat shrink, reduce waste, and make it possible for an artist to check and fix minor issues on their T-Sticks. However, these benefits did not outweigh the losses to maintainability or significantly improve the reliability of the T-Stick.

5.3 Final Design: T-Stick 5GW

The final design of the T-Stick electronics consists of a custom ESP32 board using the ESP32-S3 WROOM 2 Module, a touch board with a pinout for the Trill Craft board, and two JST-SH 4-pin connectors to daisy-chain multiple touch boards together.

This design is an improvement over the previous T-Stick as the custom PCB for the ESP32 board is a much more reliable component than the prior solution of using individual fly wires to connect components and the alternative idea of using Qwiic cables to connect components. Additionally, having a custom solution gives us more control over the individual components, reducing our reliance on other suppliers to develop boards that suit our needs.

5.3.1 Hardware Architecture

Figure 5.6 shows the hardware architecture for the new T-Stick design. Most of the power system functions, such as providing power, charging the instrument, and changing the power state, are handled by the Microchip Technologies' MCP73871[2]. This integrated circuit (IC) handles charging the LiPO/Li-ion battery and changing between the USB power and battery power depending on the input voltage. In addition, two regulators, the NCP167AMX330/180TBG[3] series, are used to step down the system power to 3.3V and 1.8V respectively. Maxim Integrated's MAX17055[4] is used as a fuel gauge.

Either the Trill Craft board[5] or a custom touch board such as IDMIL's EnchantiTouch[6] is used for processing the touch data from the touch sensor. Both boards use the PSoC devices from Infineon Technologies, with the Trill Craft board using a PSoC 1 device[7] and the EnchantiTouch

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[2] https://www.microchip.com/en-us/product/mcp73871

[3] https://www.onsemi.com/products/power-management/linear-regulators-ldo/NCP167

[4] https://www.analog.com/en/products/max17055.html

[5] https://shop.bela.io/products/trill-craft

[6] https://github.com/IDMIL/EnchantiTouch

[7] https://www.infineon.com/cms/en/product/microcontroller/legacy-microcontroller/legacy-8-bit-16-bit-microcontroller/psoc-1/

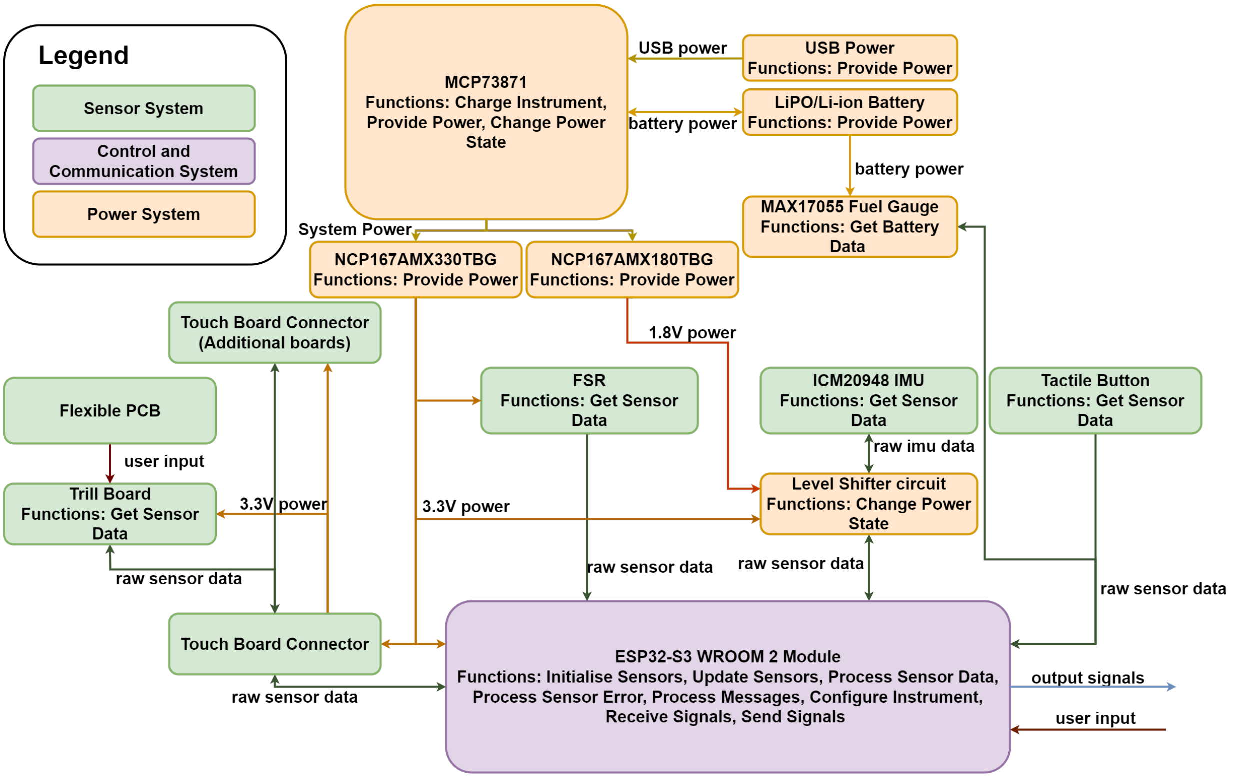

Fig. 5.6 Hardware Architecture Diagram for the T-Stick 5GW, Legend on the top left shows which components are in which system.

being a PSoC 4100S Max device[8]. The Trill Craft and EnchantiTouch use a 32-pin FFC connector to connect to the touch sensor. The touch sensor has been redesigned to use a single flexible PCB with 30 touch sensors. The IMU was changed to an ICM20948 9-DoF IMU[9], which receives the 1.8V power from one of the regulators. Three MOSFETs convert the 1.8V logic from the ICM20948 to 3.3V to communicate with the ESP32-S3.

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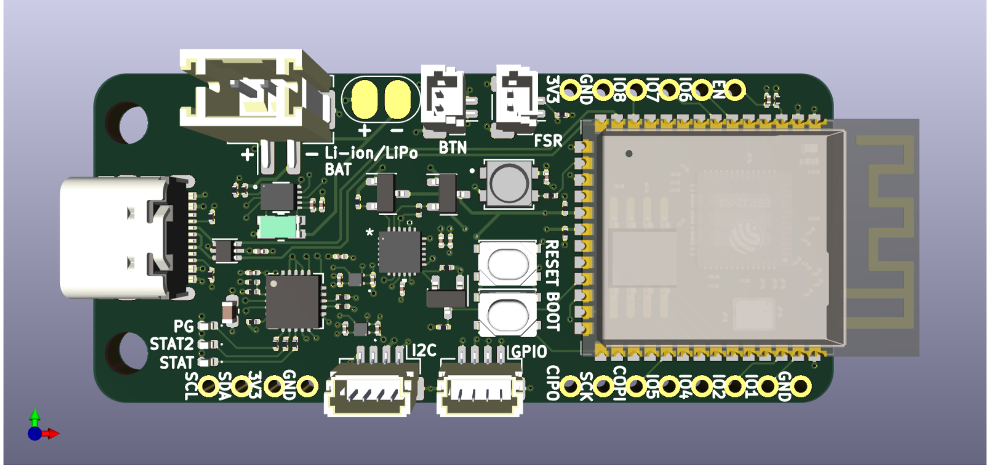
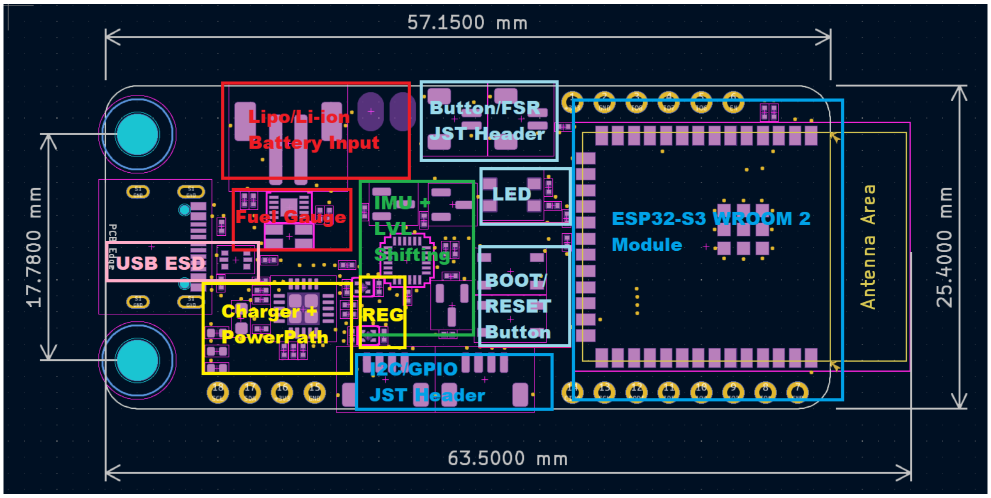
[8] https://www.infineon.com/cms/en/product/microcontroller/32-bit-psoc-arm-cortex-microcontroller/psoc-4-32-bit-arm-cortex-m0-mcu/psoc-4100/psoc-4100s-max/

[9] This is because the LSM9DS1 is no longer actively supported by STMicroelectronics.



(a) 3D rendering of the ESP32-S3 board.



(b) PCB layout, comments highlight important components.

Fig. 5.7 PCB Layout of the ESP32-S3 board, figure 5.7b highlights important components and regions on the board.

The main microcontroller was changed from the ESP32 Series to the ESP32-S3 WROOM 2 Module[10]. This integrates the PSRAM, antenna, and flash necessary for the ESP32-S3 to function. According to the manufacturer, this module will be supported until 2032 as opposed to the original slate of ESP32, whose support ends in 2028[11]. In addition, using a module over a bare ESP32-S3 chip reduces the complexity of the PCB design. No changes to the tactile button and force sensing

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[10] https://www.espressif.com/en/module/esp32-s3-wroom-2-en

[11] https://www.espressif.com/en/products/longevity-commitment

resistor (FSR) are made. The board's layout is shown in figure 5.7b.

The custom board uses 0402 imperial packages for the resistors and capacitors since a smaller size (e.g., the 0201 imperial packages) would make maintenance on the board much more complex despite potentially saving space and making routing traces easier. Furthermore, it allowed us to use components with voltage and power ratings higher than what they would experience on the board[12]. This improves the reliability performance of the components compared to using them at their rated power/voltage/current. By using passive components such as resistors and capacitors at a higher power/voltage rating, I am improving the overall reliability of all the passive components and, consequently, of the board.

5.3.2 T-Stick 5GW Assembly

The highly integrated nature of the custom ESP32-S3 board means they are all on a single board rather than having three separate boards for the fuel gauge, IMU, and ESP32-S3. This means that only three components must be mounted in the pipe: the custom ESP32-S3 board, the touch board (either the Trill craft board or the EnchantiTouch board), and the battery. Given the small number of components that need to be mounted, there is no need for a long internal skeleton to hold all the components. Taking inspiration from the T-Stick 2GW design, I instead designed individual 3D-printed parts for the endcaps that can hold the ESP32-S3 board and battery and the middle section that can hold the touch board. These parts are shown in figure 5.8.

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[12] Derating is a technique of using components at a lower power/voltage/current rating than they are designed for (Silverman, 2011).

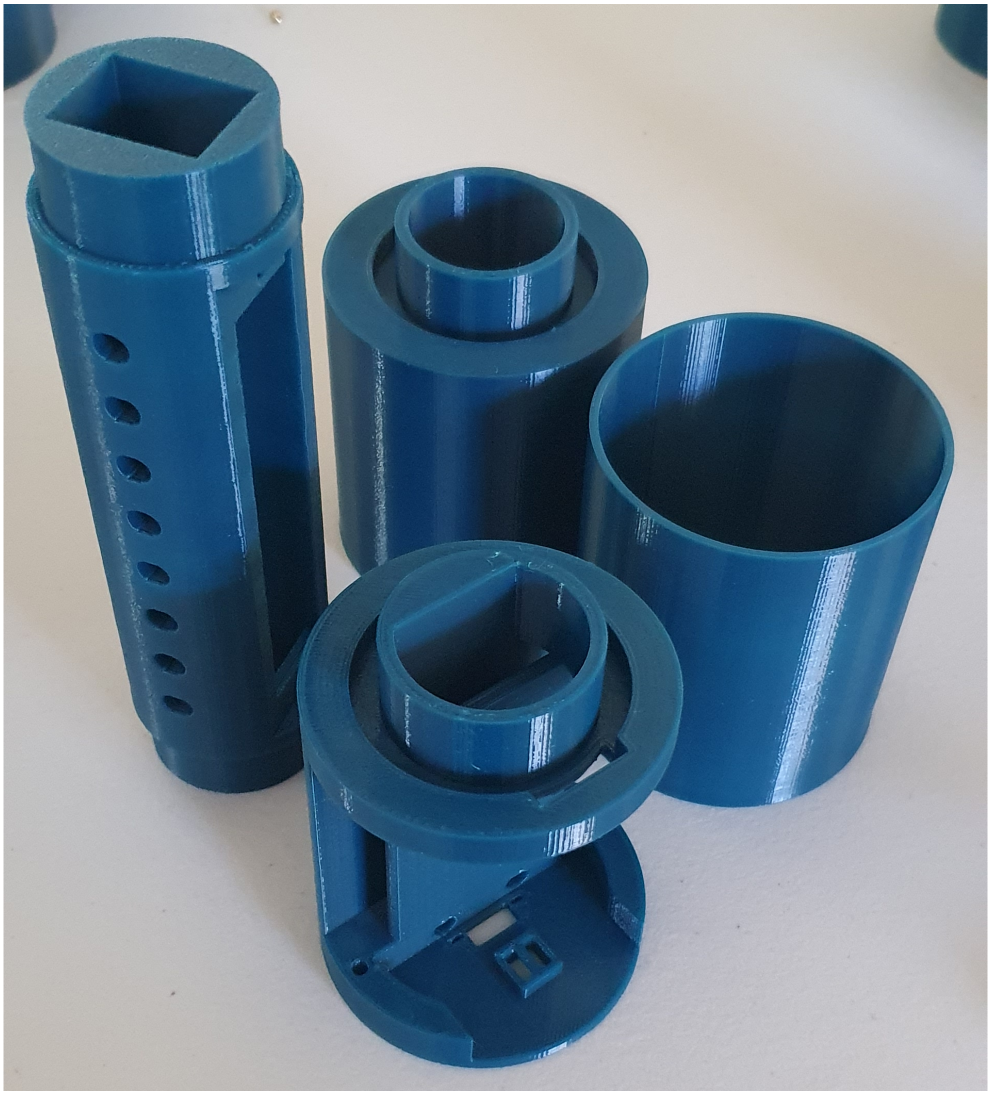

Fig. 5.8 Components for the second version of the assembly, the touch board bed, and ESP32-S3 endcap are shown.

The 3D-printed components were designed with removable doors. The doors can be removed whenever a battery needs replacing, or the boards need maintenance. Threaded inserts are used for all the parts that must be regularly opened and closed. From experience, although the friction between the screws and the 3d printed plastic was often sufficient, it degraded quickly with time. A threaded insert has extended longevity, assuming it is properly inserted.

Fig. 5.9 Partially assembled Soprano T-Stick 5GW, the touch board bed and endcap are glued onto the plastic pipe.

As shown in figure 5.9, the 3D-printed parts for the endcap and the touchboard bed are glued to two plastic pipes. The touch sensor is taped along the bottom of the pipe, and the FSR is taped on the top. This design achieves similar ease of access as the earlier split pipe designs while maintaining the rigidity and sturdiness of the closed pipe design. It introduces some complexity to the assembly procedures as the 3D printed parts are more complex, and the plastic glue and threaded inserts add additional prep time.

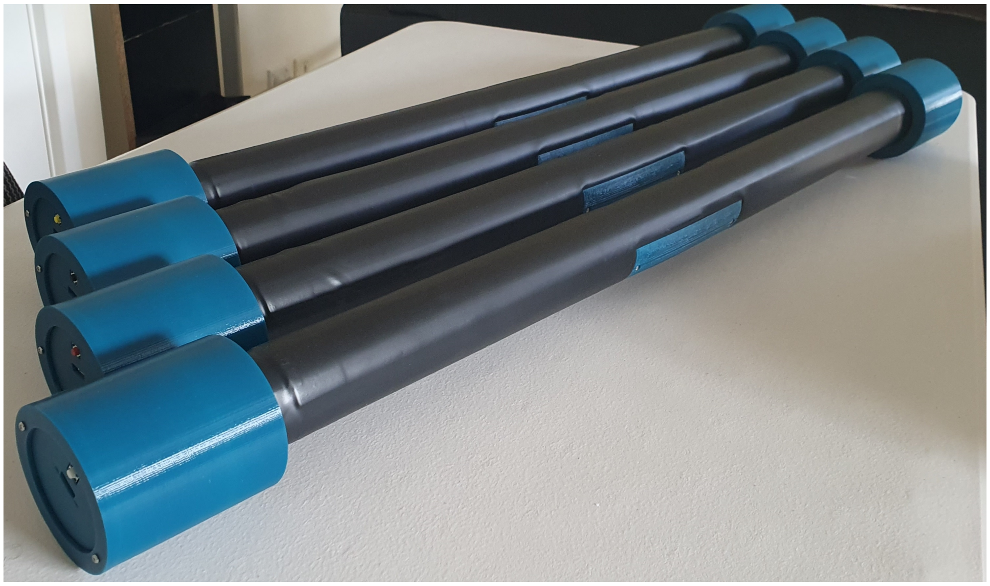

Fig. 5.10 Four fully assembled Soprano T-Stick 5GW.

The assembly reduces the soldering required to only the wires for the button and FSR. The rest of the assembly only consists of gluing parts, cutting pipes, and adding heat shrink. The simplified assembly makes it easier for a non-skilled technician to build. Therefore, it is easier to build more performance-ready T-Sticks without needing an experienced technician, as was done for previous T-Sticks. Four fully assembled Soprano T-Sticks 5GW are shown in figure 5.10.

5.4 Summary

The T-Stick 5GW uses a custom ESP32-S3 board which incorporates an IMU, fuel gauge and the ESP32-S3 WROOM 2 module. The touch sensor uses a flexible PCB instead of copper tape and connects to the touch board using a FFC connector. The Trill Board and Enchanti Touch board, can be used interchangeably to process the touch data from the touch sensor. These changes reduce the need for soldering in the assembly process, drastically reducing the assembly process's difficulty. The new assembly process incorporates lessons learned from maintaining the 4G T-Sticks and improves the maintainability of the T-Stick 5GW. The 3D printed components improve the maintainability of a fully built T-Stick 5GW by allowing easy access to components for artist and technicians.

Chapter 6

Verification and Validation

In this chapter, I will discuss the results of testing the T-Stick 5GW. The T-Stick was tested against the requirements listed in Chapter 4.

6.1 Verification and Validation Scheme

6.1.1 Pairwise Analysis

I use pairwise analysis to rank the requirements in order of importance. I do this for both the user requirements and the technical requirements. To do a pairwise analysis, I compare each requirement to the others and see which is more important. I then add the results and rank the requirements by their total score.

Table 6.1 Pairwise Analysis Table

	U1	**U2**	**U3**	**U4**	**U5**	**U6**	**Score**	**Rank**
U1	N/A	0	0	0	1	1	2	4
U2	1	N/A	1	1	1	1	5	1
U3	1	0	N/A	1	1	1	4	2
U4	1	0	0	N/A	1	1	3	3
U5	0	0	0	0	N/A	1	1	5
U6	0	0	0	0	0	N/A	0	6

Table 6.1 shows the results from the analysis. On the left column, I compare if Req. X is more

critical than Req. Y. If it is more important than I put in 1, otherwise it is a 0.

The weighting is calculated by taking the total score for each requirement and dividing it by the total number of requirements minus 1. I then add 1 to the weight.

Table 6.2 Pairwise Analysis Results for user requirements

ID	User Requirements	Weighting
U2	Improve the reliability and robustness of the T-Stick	2.00
U3	Improve battery and power management system	1.80
U4	Improve sensor management system	1.60
U1	Redesign the T-Stick to be easier to construct and maintain	1.40
U5	Improve quality of existing signals	1.20
U6	Improve feedback to end-user	1.00

From these results, the User requirements can be ranked in this order. Table 6.2.

1. U2: Improve the reliability and robustness of the T-Stick
2. U3: Improve battery and power management system
3. U4: Improve sensor management system
4. U1: Redesign the T-Stick to be easier to construct and maintain
5. U5: Improve the quality of existing signals
6. U6: Improve feedback to end-user

This order makes sense based on my priorities for the maintenance and robustness of the T-Stick over the sensor quality and accuracy. Also, I believe that outside of requirement U1 (improving capsense), the other user requirements can be enhanced by better firmware and, hence, are not the main priority. The pairwise analysis process is repeated for the technical requirements listed in section 4.3. Doing this gives me the following list of the most important technical requirements.

1. Req 4.1: The T-Stick will have a Practice Interruption Rate (PIR) of 1%.
2. Req 3.5: The sensor system will continue operating regardless of the states of the sensors.

3. Req 3.6: The sensor system will have a calibration mode which enables the artist to calibrate the sensors manually.
4. Req 3.2: The sensor system will have an average error of less than 1%.
5. Req 1.2: Continuous signals will have a wireless signal rate of at least 100Hz and no slower than 50Hz.
6. Req 4.2: The T-Stick will have a Performance/Maintenance Ratio (PMR) of at least 1.
7. Req 1.4: The packet loss will not be above 2.5% under good networking conditions.
8. Req 2.3: The power system will be able to measure the battery's state of charge with an average error of less than 10%.
9. Req 3.3: The sensor system will be able to detect when sensors are not communicating.
10. Req 5.5: The mean time to assemble one T-Stick, not counting the time to gather parts and materials, will be less than 5 hours.

Once again, this order reflects my priorities of improving maintenance and reliability. Two of the key Reliability requirements (4.1 and 4.2) are in the top 10 requirements alongside requirements relating to failure management (3.5, 3.6 and 3.3) and better power management). Table 6.3 shows the weighted scores for the top 10 technical requirements.

Table 6.3: Pairwise Analysis Results for technical requirements

ID	**Requirements**	**Weighting**
4.1	The T-Stick will have a Practice Interruption Rate (PIR) of 1%	2.00
3.5	The sensor system will continue operating regardless of the states of the sensors	1.88

3.6	The sensor system will have a calibration mode, which enables the artist to calibrate the sensors manually.	1.88
1.1	Continuous signals will have a wireless signal rate of at least 100Hz and no slower than 50Hz.	1.85
3.2	The sensor system will have an average error of less than 1%.	1.85
4.2	The T-Stick will have a Performance/Maintenance Ratio (PMR) of at least 1	1.85
1.4	The packet loss will not be above 2.5% under good networking conditions.	1.69
2.3	The power system will be able to measure the battery's state of charge with an average error of less than 10%.	1.65
3.3	The sensor system will be able to detect when sensors are not communicating.	1.62
5.5	The mean time to assemble one T-Stick, not counting the time to gather parts and materials, will be less than 5 hours.	1.62

6.2 Results

6.2.1 Communication System Results

The Communication System was tested by connecting the T-Stick to a PC and recording the packets received by the instrument for four scenarios: 1) libmapper + OSC for 1 IP address, and 2) libmapper + OSC for 2 IP addresses, 3) OSC for 1 IP address, and 4) OSC for 2 IP addresses. An additional output was added to the T-Stick, which outputted a continuous sequence to estimate packet loss. For scenarios 1 and 2, libmapper was enabled but was not actively used.

The maximum and average throughput, latency, and jitter were measured for each scenario. The throughput of the T-Stick was defined as the rate at which individual messages were received.

The */raw/fsr* signal was used as the test signal to measure throughput.

The results are shown in table 6.4.

Table 6.4 WiFi Throughput Results

	Average Throughput	**Maximum Throughput**
Scenario 1	$103.6 \pm 0.6Hz$	$139.9Hz$
Scenario 2	$96.3 \pm 4.8Hz$	$102.0Hz$
Scenario 3	$120.0 \pm 0.5Hz$	$155.8Hz$
Scenario 4	$111.5 \pm 0.8Hz$	$144.0Hz$

In scenarios 1, 3, and 4, the communication system was able to achieve a consistent throughput higher than 100Hz for sending messages over WiFi (Reqs. 1.1). However, the communication system's error messaging capabilities are still limited to sending error messages over a serial monitor (Reqs. 1.5).

Table 6.5 WiFi Latency and Packey loss Results

	Latency (ms)	**Packet loss (%)**
Scenario 1	$4.1 \pm 2.8ms$	0.01%
Scenario 2	$5.1 \pm 6.0ms$	0.33%
Scenario 3	$2.7 \pm 2.5ms$	0.00%
Scenario 4	$3.4 \pm 3.1ms$	0.12%

The T-Stick 5GW's wireless latency is below 10ms for all scenarios, with a maximum latency of 5.1ms for scenario 2. The network jitter was passable, below 5ms for all scenarios except scenario 2. The packet loss under good network conditions was at most 0.33%.

6.2.2 Power System Results

The ESP32 boards underwent several charge and discharge cycles over weeks to test the fuel gauge's accuracy and any power instability issues. The T-Stick can be powered on by wired power and via its lithium-ion battery (Reqs. 2.1), and the average battery life with a 2000mAh battery is 11-13 hours (Reqs. 2.2). The fuel gauge results indicate that the T-Stick 5GW's power system can estimate the remaining battery life and battery percentage with an error of less than 3% meeting requirements 2.3 and 2.4. Non-linearity in the battery life estimate can be seen in the last 3% of the battery life. This non-linear region is exaggerated when the battery has been in deep sleep for a long time. However, this only affects the estimate in the last 3% of the battery life estimation and, therefore, does not affect the T-Stick's ability to meet requirement 2.3. These results match the data from Analog Devices, which states that the error is below 3% 97% of the time for their fuel gauge.

6.2.3 Sensor System Results

The sensor system requirements were largely not met by the current hardware and firmware of the T-Stick 5GW. The polling rate for continuous signals is 105Hz (Reqs. 3.1). Requirements 3.3, 3.4 and 3.5 regarding error management of sensors have not been implemented in the firmware of the T-Stick. The T-Stick 5GW firmware gives access to calibration parameters but provides no easy means for users to calibrate their instruments (Reqs. 3.6). Requirement 3.2 on sensor accuracy was not formally analyzed, but the lack of calibration of the IMU for the sensor fusion makes those signals unusable for artistic use due to poor accuracy of the yaw signal.

6.2.4 Manufacturability

The T-Stick 5GW met all of the standard manufacturing requirements. The physical documentation includes the bill of materials, schematic, and assembly instructions (cf. Reqs. 5.1, 5.2, and 5.3, respectively). The build time is under 5 hours (cf. Req. 5.4) and only uses commercially available parts and common tools such as hex keys, screwdrivers, and tape (cf. Req. 5.5).

6.2.5 Reliability and Maintainability Results

The T-Stick's mean time to failure ($MTTF_p$) was computed analytically using the FIDES Reliability Tool. As discussed in Chapter 3, FIDES is an analytical reliability tool that uses the product's mission profile and environmental conditions to estimate the reliability of the product. A link to the Excel sheet with all of the parameters for the model is found in the appendix A. A couple of assumptions were made about the mission profile of the T-Stick.

1. The T-Stick is performed monthly for a two-hour concert.
2. The T-Stick is only charged once the battery dies or before a concert.
3. The artist practices daily for 1 hour a day.
4. The artist flashes their T-Stick a couple of times a year to update the firmware.
5. The artist transports the T-Stick carefully so it doesn't experience large vibrations or shocks.
6. The artist leaves the T-Stick in deep sleep when not in use.

The following mission phases were identified: 1) Flashing, 2) Transport, 3) Practice, 4) Performance, and 5) Charging. The T-Stick experiences the highest temperatures during the flashing and charging states and the strongest vibrations during transport.

The $MTTF_p$ was computed to be 37,747 hours or approximately 4.3 years. Table 6.6 shows the results from the reliability analysis. Note that the mean time to repair also considers the time it takes to get new components, assuming there are no spares.

Table 6.6 PIR Model Outputs

Property	**Value**
Mean time to failure (hrs)	37,747.58 hrs
Mean time to repair (hrs)	124.7 hrs
Practice Interruption Rate (%)	0.02%
Practice/Maintenance Ratio (hrs)	302.6

As seen from table 6.6, the interruption rate of the T-Stick is 0.02% and the Practice/Maintenance ratio is 302.60 performance hours per maintenance hour. The analytical examination reliability results indicate that the T-Stick passes Reqs. 4.3 and 4.4, respectively.

Five T-Stick 5GW copies were made and subjected to increasing severity jabs and shakes. The jabs and shakes were done manually. In addition, the T-Stick was also dropped from about 1 meter of the floor onto hard flooring several times to see if it induced any failures. Unlike the T-Stick 4GW-2021 models, the T-Stick 5GW did not suffer failures from jabs and shakes with maximum magnitudes of 100m/s/s, operating smoothly throughout the entire operation. The T-Stick 5GW suffered from a lack of robustness towards impacts when dropped from 1 meter, but the failures were temporary. After a power cycle, the instrument continued to operate normally.

6.3 Discussion

6.3.1 Performance against Technical Requirements

The T-Stick 5GW meets most of the technical requirements. Of the top ten technical requirements, the T-Stick 5GW meets seven of them. Those that are not met are all sensor system ones (Reqs. 3.1, 3.2, 3.5). This was expected, as this initial design phase focused mainly on the power system, reliability and maintainability of the T-Stick. The power system outperformed its modest requirements by a fair margin, indicating a cheaper, less accurate solution can be considered for future applications. More testing and analysis are required to verify and validate the sensor system requirements. In addition, validating the reliability requirements via testing is needed to increase the certainty that the T-Stick meets user requirement 2.

6.3.2 Reflections on the Design Process

In chapter 4, I describe the design framework I decided to use to update the T-Stick. I picked this framework for two reasons. It would provide a systematic way to analyze the T-Stick and the environment it had to operate in, as well as being a process I'm already familiar with. The Systems Engineering design process had many benefits when designing the T-Stick 5GW. The process helped me navigate a new design context, music technology, and design prototypes in academia.

Being a 17-year-old instrument, the T-Stick inherits a lot of constraints from previous designs. There is an implicit requirement that the new T-Sticks should be able to perform pieces made by previous T-Sticks. This is rarely the case due to changing namespaces and changing sensors. New sensors may have different ranges or sensitivities, and as the T-Stick firmware changes, the namespace of the signals has also changed. This means that an artist trying to perform an old T-Stick piece on a new T-Stick needs to spend a lot of time transposing the piece for a new T-Stick.

Due to the methodology, I had to spend much more time than expected in the requirements analysis and definition phase. Months were spent outlining and defining the requirements and discussing them with artists. As a result of the time spent on requirements, the prototyping and testing phase of the project was much shorter than I would have liked. The sensor requirements suffered the most from this setback. Improvements in communicating sensor errors to the user could not be fully implemented (Reqs 3.3 - 3.5), Sensor accuracy and precision tests could not be done on every sensor, and not enough time was left to improve on the firmware and reduce latency for sensor data collection (Reqs. 3.1). Plans to verify the reliability requirements through testing had to be scrapped due to the time it took to receive prototypes.

The idea of using a PCB for all electronic components was floated quite early in the project. Using custom PCBs would improve the reliability of the connections between components and lower the number of manufacturing defects, solving some of the critical issues of the 4G T-Sticks. However, using custom PCBs opened the question of whether a new PCB design was needed each time a new development board was used in the T-Stick. From 2018 to 2023, both the ESP32 boards used for the 4G t-sticks (Tinypico and Lolin D32 Pro) and the Sparkfun LSM9DS1 board were discontinued, and the Trill board got a new version with a slightly different layout. To avoid designing a new PCB each time I needed to change development boards, I decided to make a custom ESP32-S3 board with all the sensors on one board. This decision ate up a significant amount of design time, as the lead time for assembled custom PCBs was about 3 - 4 weeks.

The benefits from a reliability standpoint are clear. It significantly reduces the most common form of failure, i.e., solder joint failures between boards, and simplifies assembly, further reducing failures. These reliability benefits come at a cost to maintainability and manufacturability. Requirement 5.6 states that the T-Stick must be built using standard, readily available parts. This was judged as a necessary trade-off to comply with reliability requirements judged more critical to the long-term use of the device. Using standard components, simple tools, and having the design documentation available are needed so that another person can create a T-Stick.

However, I believe that the extra time in the requirements analysis phase was a good use of time as defining the technical requirements of the T-Stick has benefits that will outlive this project. They serve as a starting point for future technical evaluations of the instrument and help future designers understand what went into designing the T-Stick 5GW. The requirements outline what is currently lacking from the T-Stick 5GW and where the project should go from here.

6.3.3 Limitations of current Design

Although this design made several significant improvements over the previous T-Stick design, there are aspects in which the current T-Stick is still outperformed by the earlier iterations, mainly touch sensor speed, system latency, and throughput. The Trill Board can only scan all its channels in 1.7ms at the fastest setting. That speed is roughly 40% slower than the 2nd generation T-Sticks. Although the custom touch solution, the EnchantiTouch board, has sub 1ms touch sensor speed, the latency introduced by the I2C interface still makes the board much slower than the 2G T-Sticks, which had a sub-millisecond latency for touch sensing.

Given that the T-Stick 5GW uses WiFi as a means of communication, I was never going to surpass the system latency of the T-Stick 2G due to the overhead of the WiFi communication protocol. However, several aspects of the T-Stick 5GW from a hardware and firmware perspective could be improved to reduce system latency. Sensors are still largely polled in the T-Stick 5GW rather than taking advantage of interrupt routines, slowing down the main loop. The IMU and touch sensor could use SPI instead of I2C for communication, significantly decreasing communication latency. However, using multiple sensors on the same SPI bus is more complicated as they each require their own selection pin, increasing the complexity of the design. Newer protocols such as MIPI I3C[1], address the slower data speed of I2C and should be considered for future designs.

The throughput of the T-Stick 5GW is, at best, 120Hz, which is ten times slower than the T-Stick 2G. Although this represents an improvement over the 4GW T-Sticks, this is mostly due

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[1] https://www.mipi.org/specifications/i3c-sensor-specification

to firmware improvements to optimize the Open Sound Control sending. Better firmware can increase the throughput, but a 10-fold increase is unlikely.

There are several requirements that the T-Stick 5GW still does not meet or require further testing. As noted in the previous section, the sensor system requirements require additional work to verify the accuracy and precision of the sensors and to improve and measure the latency for sensor collection. As can be seen from the reliability requirements, the current design represents a significant improvement in reliability and robustness compared to the T-Stick 4GW. The power system is also improved with better battery life estimation, far exceeding our modest requirement for an error of less than 10%.

As mentioned in section 4, no reliability testing was done to validate the analytical results for the mean time to failure. The FIDES reliability handbook has several limitations (Gaonkar et al., 2023) that can lead to overly optimistic predictions. However, the environmental conditions of the T-Stick use are not extreme. An indoor venue at room temperature with low relative humidity does not substantially strain electronic components. This lowers the risk that the hardware reliability of the boards will be much lower than the predicted reliability. The test against jabs and shakes ensures that the most common stresses of the T-Stick do not cause premature failure, and the design for maintainability ensures that the artist can quickly fix the two most common failure modes without needing a technician: cables getting loose and batteries dying. However, note that the FIDES model does not consider software failures. Poor firmware may cause additional failures that are not considered in this model.

6.4 State of the Current Design

The T-Stick 5GW represents a major improvement in the reliability, robustness, and assembly process of the T-Stick. Most of the major technical requirements were met except for the sensor system requirements. Although the design fares worse in terms of latency and throughput in comparison to the 2G T-Sticks, the new design represents a good step forward for the WiFi Based T-Sticks, creating a solid foundation for future improvements in firmware features to address missing sensor requirements and further testing to verify performance requirements.

Chapter 7

Conclusion and Future Work

DMIs, due to their separation of the controller interface from the sound-producing unit, provide the opportunity to explore new and interesting artistic expression. However, interfaces presented at conferences such as the International Computer Music Conference and the International Conference on New Interfaces for Musical Expression can be limited in their long-term use due to poor reliability and robustness. In this thesis, I proposed a methodology inspired by system engineering to design the T-Stick 5GW to improve the reliability and robustness of the interface and derive reliability and robustness metrics for DMIs.

The T-Stick 5GW continues the standardization process that started with the T-Stick 4G series while improving the robustness and maintainability of the interface following the original goals of the T-Stick project. The fifth-generation T-Stick, the T-Stick 5GW, represents a return to the initial goals of the T-Stick project in terms of reliability and uptime (J. W. Malloch & Wanderley, 2007) and continues the standardization work of the 4G series of T-Sticks (Nieva, 2018). The T-Stick 5GW features improvements to the reliability and manufacturability of the T-Stick while keeping the communication method the same as the 4G T-Stick. The new design features a custom ESP32-S3 board and replaces the touch sensor from copper strips with a flexible PCB for faster and easier manufacturing. These changes increase the total cost of the T-Stick but greatly simplify assembly and improve reliability. Five copies of the T-Stick 5GW were made and evaluated.

Preliminary verification and validation showed that the current design meets most requirements, except for the sensor system requirements. In addition, some of the reliability requirements were verified analytically and not through testing. The use of custom PCBs represents a reduction in the accessibility of the interface, especially in regions where getting custom PCBs fabricated and assembled is prohibitively expensive. Although the design process allowed me to get a better perspective of the technical requirements and constraints of the T-Stick, the additional overhead cut into the prototyping and design phase impacting the testing of several requirements.

7.1 Future Works

Future work for the T-Stick includes further testing and analysis of the sensor and reliability requirements, especially in performance settings. Further improvements to the wireless robustness and latency can be made by taking advantage of current and upcoming multi-protocol radios that support dual/tri-band Wi-Fi such as the CYW5551x series and CYW5557x series[1] from Infineon Technologies, the nrf7002 WiFi 6 Companion IC from Nordic Semiconductor[2] and the ESP32-C5 from Espressif[3]. In addition, new and upcoming microcontrollers from STMicroelectronics[4], Espressif[5] and Nordic Semiconductors[6] that support I3C can lower the sensor processing latency further improving the performance of the T-Stick.

The design process outlined in this thesis can be used for other DMIs that want to transition from a prototype to a fully functional interface. The process gives designers a better perspective of the technical requirements and constraints of their DMIs, provides a method for evaluating prototypes, and can facilitate the handover process to new designers.

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[1] https://www.infineon.com/cms/en/product/wireless-connectivity/airoc-wi-fi-plus-bluetooth-combos/wi-fi-6-6e-802.11ax/

[2] https://www.nordicsemi.com/Products/nRF7002

[3] https://www.espressif.com/en/news/ESP32-C5

[4] STM32H7Rx/Sx: https://www.st.com/en/microcontrollers-microprocessors/stm32h7r7-7s7.html

[5] ESP32-P4: https://www.espressif.com/en/products/socs/esp32-p4

[6] NRF54H20: https://www.nordicsemi.com/Products/nRF54H20

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Appendix A

FIDES Excel Spreadsheet link

FIDES Excel Spreadsheet for T-Stick 5GW: https://docs.google.com/spreadsheets/d/1oDh22Wsgz3_582e0YIR6Vq9RYPL4AjKq/edit?usp=sharing&ouid=110513555701382137815&rtpof=true&sd=true

Appendix B

T-Stick Design Guidelines

B.1 Purpose

To improve interoperability between present and future T-Stick implementations. Guide can be found online at: https://idmil.github.io/tstick-docs/#/T-Stick%20Design%20Guidelines

B.1.1 Identity Characteristics

These features might be part of what makes an object identifiable as a T-Stick, and not some other instrument or object. These features are not normative, and serve more to introduce vocabulary that can be used in subsequent remarks.

1. T-Stick is cylindrical.
2. T-Stick usually has a diameter such that it can be held in one hand.
3. T-Stick's outer cylindrical face has two sides; one side (termed "the top side") has a pressure sensor, and it is usually slightly squishy e.g. due to a layer of closed cell foam adhered on that side of the instrument. The other side (termed "the bottom side") has a (usually capacitive) fully multitouch touch sensor, and it is usually not squishy.

4. T-Stick also senses information about the orientation and motion of the instrument in space, such as the direction in the global frame of reference it is pointing (i.e. "pitch and yaw", aka "altitude and azimuth", aka "heading and inclination" aka etc), usually using an inertial measurement unit (IMU), or magnetic-inertial measurement unit (MIMU).
5. T-Stick usually has a recipient port for a serial communications bus connection at one end of the pipe, usually USB. This end is termed "the proximal end" of the pipe, because it is often held closer to the heart of the T-Stick player. The other end of the pipe is termed "the distal end" of the pipe.
6. The ends of the pipe are usually closed off with end caps which sometimes have buttons, lights, and/or switches embedded in them, as well as the serial bus connector on the proximal end.
7. In addition to the pipe that makes up the main body of the instrument, a T-Stick often has an internal structure. Sensors may be attached to the pipe, the internal structure, the endcaps, or a combination of these parts.

B.2 Hardware Standards

These remarks are meant to be normative. Adherence to these remarks is meant to improve interoperability between present and future T-Stick implementations.

Many of the following standards are based on the dimensions of materials readily available in Canada where most T-Sticks are currently made. T-Stick builders in regions where available materials are sold with different base dimensions may wish to define local standards.

B.2.1 Coordinate Systems

The global coordinate system used in T-Stick implementations is a right-handed East-North-Up 3-dimensional orthogonal Cartesian coordinate system. The positive X axis points to the East. The positive Y axis points North. The positive Z axis points up.

The performance-local coordinate system used in T-Stick implementations is derived by a rotation of the global coordinate system about the Z axis, such that the performance-local X axis points from center stage to stage right (i.e. from left to right when standing on stage facing the audience), and the performance-local Y axis points from center stage to downstage (i.e. towards the audience).

The T-Stick-local coordinate system is used to give directions relative to the body of the T-Stick. The X axis points from the proximal end of the pipe to the distal end of the pipe. The Y axis is determined from a 90 degree counterclockwise rotation of the X axis about the Z axis. The Z axis points from the bottom side of the pipe to the top side of the pipe.

The reference origin is centered in the circular cross-section of the pipe, with X = 0 defined such that the origin lies in the cutting plane that defines the proximal end of the pipe before end caps are attached.

Dimensions must given in millimeters (mm). Alternative representations in other units such as inches (in), feet (ft), centimeters (cm), or other units may be given *in addition* to the dimension in mm when convenient to aid comprehension.

B.2.2 Consort Dimensions

T-Sticks can be made in a variety of sizes, shown in table 1.

All T-Sticks in this consort use standard **1 $\frac{1}{2}$" ABS pipe** (typically manufactured for use in plumbing fixtures) with an outer diameter of **42.164 mm (1.6600 in)** and an inner diameter of **35.179 mm (1.3850 in)**.

The base unit of length of a T-Stick is **304.8 mm (12 in, 1 ft)**. The different T-Stick sizes are all multiples of this base length. This length is chosen for maximum yield of T-Sticks from readily available lengths of pipe, which are normally sold by the foot.

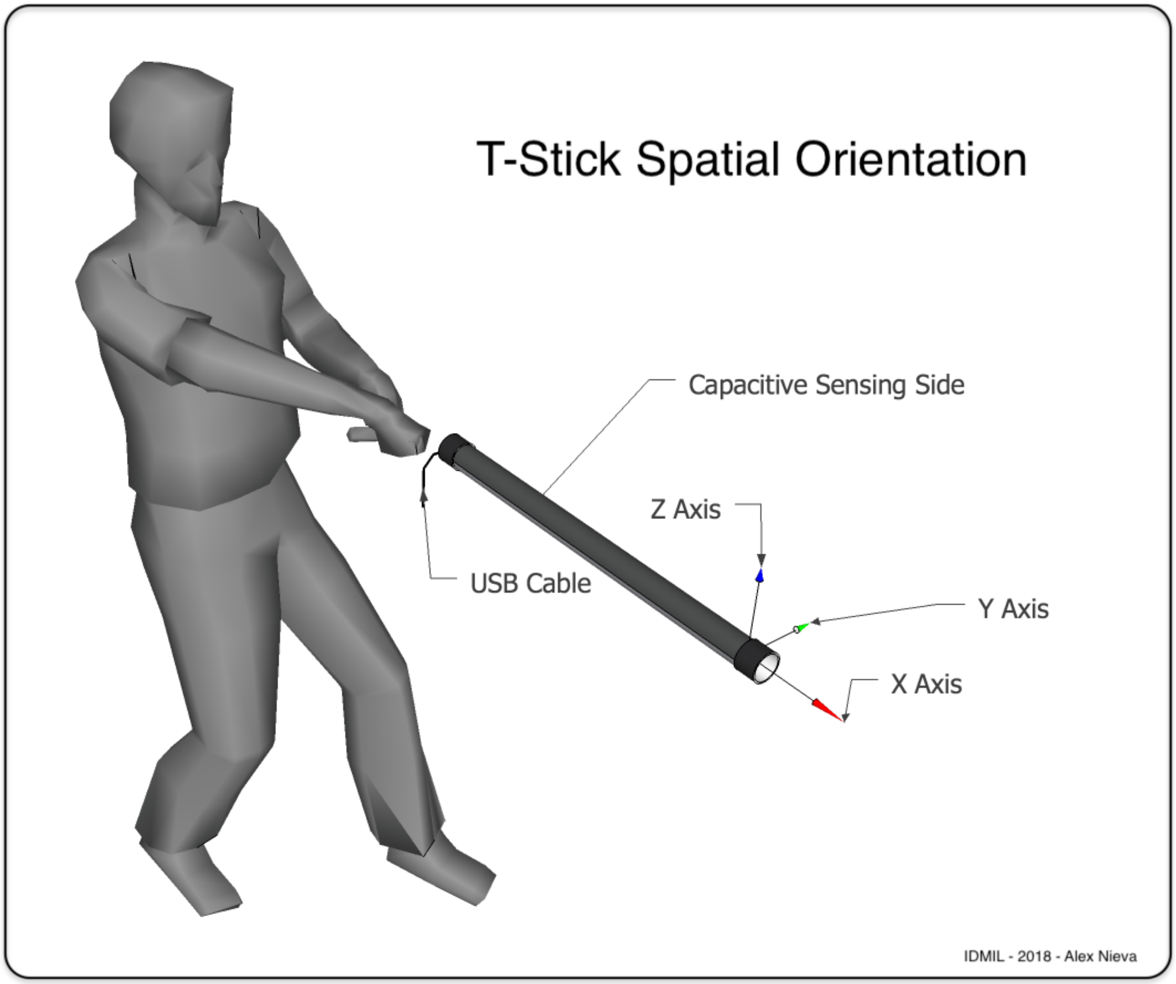

Fig. B.1 T-Stick Coordinate System

B.2.3 Mounting Holes

Mounting holes on the PCB and internal structure shall be spaced **12.7 mm ($\frac{1}{2}$ in)** apart along the X axis, starting **6.35 mm ($\frac{1}{4}$ in)** from the origin (i.e. from the proximal opening of the pipe). Adherence to this standard enables parts to be designed without strict coupling.

Table B.1 Current T-Stick Sizes

“Range”	**Length of pipe (without end caps)**
Sopranino	304.8 mm (12 in, 1 ft)
Soprano	609.6 mm (24 in, 2 ft)
Alto	914.4 mm (36 in, 3 ft)
Tenor	1219.2 mm (48 in, 4 ft)
Bass	1524.0 mm (60 in, 5 ft)
Contrabass	1828.8 mm (72 in, 6 ft)

B.2.4 PCBs

If PCBs are used the following characteristics should be followed to improve interoperability between designs.

1. PCBs shall not have dimension in the Y axis greater than **31.75 mm (1.25 in)**. 2. The bottom surface of PCBs should not have any surface mount components or through hole component legs.

B.3 Sensor Measurements

The T-Stick shall be able to measure or approximate the following properties:

1. Acceleration
2. Orientation
3. Pressure
4. Multi-finger touch
5. Taps
6. Jabs
7. Brushes
8. Rubs

It is recommended to use a similar set of sensors and algorithms as previous T-Stick designs to maintain similar behavior across T-Sticks. These properties should be able to meet the accuracy requirement (Requirement 3.2) outlined in Technical Requirements and Constraints.

B.4 Signal Namespace

If interoperability with previous T-Stick pieces is desired the following guidelines should be followed:

1. The T-Stick should use an existing namespace. Check previous designs for past and current namespaces. 2. If you wish for the T-Stick to be able to play older pieces the T-Stick firmware should have a built in translation layer for signals. External translation layers can be used but are not desired.