# Reliability Centered Approaches for Digital Musical Interface Design

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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 is used to design the T-Stick 5GW, the fifth generation of the T-Stick a gestural controller designed in the mid-2000s by Joe Malloch and Marcelo Wanderley. The T-Stick 5GW is evaluated agaisnt a series of technical metrics and potential design improvements are discussed. Finally, potential applications to other projects are summarised.

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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 typically designed using, a wide array of technologies, such as game controllers, laptops, microcontrollers and sensors have been used in a wide array of applications. Several such interfaces have been presented at conferences such as the New Interfaces for Musical Expression (NIME) and used in performances by a variety of artist and musicians.

There are several issues limiting the long term usage of DMIs. A large number of DMIs are presented at the NIME conference every year, but only 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 existing repertoire, there is the issue of accessing the instrument, the software and the mappings used. 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 never transitioning to stable and responsive instruments.

Reliability and robustness are an important component 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 a labs can suffer from reliability, robustness, and manufacturing issues. A prototype instrument with reliability issues may be tolerated 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 having to design reproducible instruments that have low failure rates.

Several approaches to the design and evaluation of Digital Musical Instruments (DMIs) have been used to various levels of success. However, the lack of proper engineering solution and approaches have been noted in (Wanderley & Depalle, 2004) and (Malloch & Wanderley, 2017). A greater focus on engineering approaches can lead to instruments that are more robust and provide a common basis for the evaluation of DMIs.

In this thesis, I will propose a systems engineering framework to the design and evaluation of gestural controllers, using the design and development of the T-Stick 5GW as a case study. The T-Stick is a musical interface designed in the mid-2000s (Malloch & Wanderley, 2007) by Joe Malloch in collaboration with Marcelo Wanderley and Dr. Andrew Stewart. The T-Stick 5GW is the first 5th generation of the T-Stick which combines the reliability and performance of the 2nd generation T-Sticks built by Joe Malloch with the accessibility of the 4th generation T-Sticks designed by Alex Nieva and Edu Meneses.

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 introduces the design approach for the design of the T-Stick 5GW. Chapter 5 will explain the design of the T-Stick 5GW. Chapter 6 will cover how the T-Stick 5GW was evaluated.

# Chapter 2

# 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), yet very few papers attempt to quantify the reliability of the instrument. In this chapter, we will discuss the concepts of reliability and availability from a reliability engineering perspective and how they can be applied to DMI design.

## 2.1 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, we can break down reliability into 3 separate elements. First, there is the function. Every component in an instrument is doing some sort of action, whether it is supplying power, acting as a structural component, or acquiring sensor data. When we discuss reliability it is important to acknowledge what function each component is doing and what failure exactly is. This may differ from component to component. The second element is the conditions the instrument is meant to operate under. This includes but is not limited to the temperature of the components and environment, and typical mechanical stresses such as impacts, vibrations shakes. If the instrument needs to operate outdoors, things like humidity are also a factor. It also includes whether the instrument is used continuously or intermittently. The final part is time. For most complex systems we assume that failures a random (Lienig &

Bruemmer, 2017), meaning that the failure rate is constant over time however that may not be the case for your instrument or individual components within your instrument.

Reliability can be expressed as a function $R(t)$ which represents 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 $\lambda$ this can be expressed as an exponential function.

$$R(t) = e^{-\lambda t} \tag{2.1}$$

We can look at the expected value of Equation 2.1 to find the mean time until failure ($MTTF$). This is equal to the reciprocal of the failure rate $\lambda$.

$$MTTF = \frac{1}{\lambda} \tag{2.2}$$

We note that 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 2.2 is the point where you expect that 63% of the devices would have failed. We can see this by plugging in the MTTF back into Equation 2.1.

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

## 2.2 Reliability Handbooks and Analytical Tools

Information about the reliability of particular components can be hard to find for a variety of reasons. Suppliers may not make the information public, existing information is not relevant to your use case or the component is too new and no data exists. Several popular reliability handbooks have been used in the past 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 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 enchancement." FIDES (Charpenel et al., 2003) is an analytical reliability tool which uses the mission profile of the product and environmental conditions to estimate the reliability of the product.

### 2.2.1 Availability Modelling

A basic example of availability modelling is presented in (Niyonsenga & Wanderley, 2023), involving calculating the average uptime (Availability) using the reliability and maintainability of individual components. However, we can consider more advanced models that are 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. We are 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.

To build an availability model I draw from the commonly used availability metric in the aerospace industry *Dispatch Reliability*(DR). 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. We can also consider the *Dispatch Interruption Rate* (DIR) which is $1 - DR$.

It is the probability that a flight will be interrupted. DIR Models incorporate 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 than 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 couple of major 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 airplanes live directly compared to instruments where the manufacturer has no direct control over the maintenance actions of a musician. However even with these limitations I believe that Dispatch Interrupt Rate modelling can apply 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 their strings, brass players will keep their slides, and valves well lubricated and woodwind players will have extra reeds, in case of a reed fails. Furthermore, more generally people already undertake regular maintenance actions for their electronics, most notably charging it regularly, and cleaning it if it gets too dirty. We can assume that an interested musician who is committed to performance will take the time to do maintenance as long as it is within their abilities.

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

*Practice Interruption Rate* is the average failure rate for performances/practices involving the DMI. In other words, if I am planning to use a DMI for a performance/practice session what is the likelyhood 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.

The practice interruption rate ($PIR$) can be computed as follows. Using the mean time to failure of the T-Stick ($MTTF_p$) we divide that by the performance time ($t_p$) to get the *mean performances between failure* ($MPBF$).

$$MPBF = \frac{MTTF_p}{t_p} \tag{2.3}$$

We can then compute the practice interruption rate ($PIR$) by taking the reciprocal of the mean time between performances.

$$PIR = \frac{1}{MPBF} \tag{2.4}$$

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 we consider the mean time to repair ($MTTR_c$) of each component and the failure rate of each component ($\lambda_c$). We can then take a weighted average of all the repairs by taking into account each component's contribution to the total failure rate of the T-Stick ($\lambda_{tstick}$). For the $MTTR_c$ of each component, we will assume a worst-case scenario where no spares are available. Therefore we will the time to acquire new components as part of the mean time to repair.

$$MTTR_p = \sum_{c=0}^{n} \frac{\lambda_c}{\lambda_{tstick}} (MTTR_c) \tag{2.5}$$

To compute PMR we divide the $MTTF_p$ by the mean time to repair ($MTTR_p$).

$$PMR = \frac{MTTF_p}{MTTR_p} \tag{2.6}$$

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 is the number of performance hours per hour of maintenance.

## 2.3 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 you are not an expert artist it is difficult to understand these requirements, and they may differ from artist to artist. 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 "artist spec".

Although several papers cite Buxton's "artist spec" to either justify why robustness is important (Bartindale et al., 2016) or as a particular design goal they are aiming for (Tremblay et al., 2021) few specify exactly what they mean by artist spec or how their tool achieves it.

In 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 over the course of long-term use and designed to withstand the rigors 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.

We see that “reliability and stability” as defined by Sullivan and Wanderley merge several aspects of reliability, robustness and availability. Sullivan and Wanderley define stability similarly to how a reliability engineer might define reliability or robustness. Sullivan and Wanderley’s definition of “reliability” is much closer to the concept of availability. They fold in the concepts of maintainability and repairability into the definition of “reliability” making its scope wider than simply failure rates.

From a reliability and robustness perspective I believe that the Practice Interruption Rate and the Practice/Maitenance Ratio of an instrument serves as a good metric for evaluating whether a DMI meets “artist spec”. Unlike reliability and robustness, PIR takes into account maintenance and repairability, therefore giving a more comprehensive view of the stability of the instrument. 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 gives an indicator of the amount of performance hours an artist should expect per hour of maintenance, which is an indicator of the amount of maintenance workload an instrument will require.

# Chapter 3

# T-Stick

The T-Stick is a musical interface introduced in the mid-2000s (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. This 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 gone down 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.

In this chapter I will summarise the history of the T-Sticks major design changes, discussing the goals and motivation for each major change and discuss the ongoing issues that motivated and informed the design of the T-Stick 5GW.

## 3.1 1st - 3rd Generation T-Sticks

## 3.2 4th Generation T-Sticks

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.

The fourth generation of T-Sticks were initially designed in 2018 (Nieva et al., 2018). This generation of T-Sticks also represents a permanent shift in the communication protocol of T-Sticks to WiFi communication using either Open Sound Control (OSC) or libmapper (Malloch et al., 2014).

### 3.2.1 Hardware

The T-Stick can be split into three subsystems: a communication system, power system, and sensor system. The current architecture of the 2nd gen 2021 models is shown below.

The communication system handles the T-Stick's connections with external devices. This is handled by either libmapper or OSC. The system handles sending and receiving signals. The power system delivers power to the rest of the subsystems as well as handles the charging and discharging of batteries. The sensor system handles the input of the user as well as basic signal processing. The raw and processed signals are sent to the control system to be interpreted.

## 3.3 Understanding the Problem Space

Starting from around 2017, the drive to both standardize the T-Stick and use it as a pedagogical tool has led to a decrease in the average reliability of the instrument in comparison to the 2G

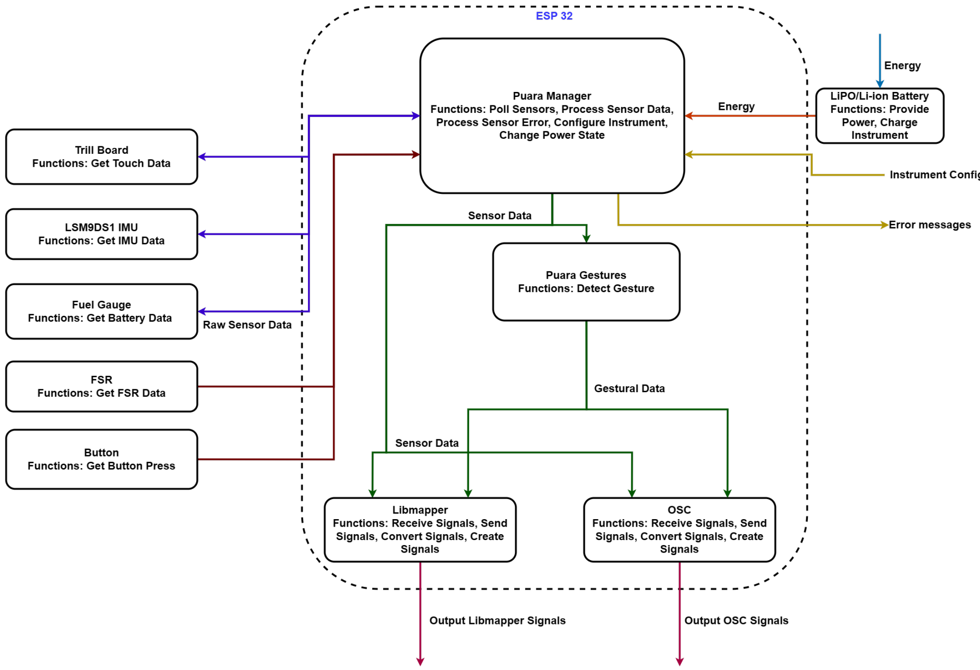


**Fig. 3.1** System Architecture of 4th Generation T-Sticks

T-Sticks.

The Sopranino T-Stick was built as part of class projects in 2018, 2019 and 2021. Due to the wide variety of soldering and electronics experience, these T-Sticks had large variations of quality and required multiple hours of maintenance just to ensure that they functioned reliably in performances. The most recent batch of class built T-Sticks in 2021, took 4 months of work, working 5-10 hours a week to get to working state. Even with that amount of work the Alto and Tenor T-Sticks are still not fully functional.

In addition to build quality issues, the 4th generation of T-Sticks were almost exclusively focused on Sopranino T-Sticks. Although two Sopranos, one Alto, and one Tenor T-Stick were built, it is clear that most of the design effort, testing, and evaluation were done on Sopraninos, with little consideration for longer T-Sticks. This is a reflection of a larger issue that T-sticks took too long to build and fix for use as a class project. Sopraninos take anywhere from 6 - 12 hours to build and that is the smallest T-Stick. Longer T-Sticks such as the Alto and Tenor take multiple days.

The current T-Stick firmware has one major problem when it comes to robustness. It does not handle failure of any component well. As discussed in Section 2.1 robustness can be considered reliability over changing conditions. The current T-Stick firmware is unable to handle failures of sub-components such as sensors and WiFi even when those failures are temporary. These failures result in either no through messages being sent over Wi-Fi or very little messages being sent over Wi-Fi

Moving away from design and maintenance issues, the hardware documentation of the T-Stick is also lacking. Although we have some documentation on the hardware of older T-Sticks this documentation is exclusively just the list of components, the design schematic, and build instructions. Important information such as, why particular design decisions were made, why certain components were selected, what technical requirements were prioritised, and why said requirements were prioritised can be hard to find.

This makes continuity of design incredibly difficult as students move on from projects taking all of their knowledge, assumptions and experience with them. This leads to a cycle of upgrades, downgrades and side-grades as knowledge is lost and found again, interesting design ideas are proposed but never followed-up on and the primary design goals constantly shift and change leading to certain aspects of T-Stick development to linger or get worse over time. 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 gone down 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.

This is the environment that the project for the 5th generation of T-Sticks came from. The current designs of the T-Stick are too difficult to build and maintain leading to low reliability. Lack of effective handover and documentation makes design continuity hard to maintain over time. I would argue that in this environment it is a remarkable achievement that there are still functioning T-Sticks in the lab and that they have not been completely relegated to being yet another prototype on a shelf for students to walk past.

# Chapter 4

# Design Approach

The design approach I undertook for this thesis was inspired by Systems Engineering Design approaches. This was used for the as it provided a systematic way to analyse the T-Stick and the environment it must operate in and my existing familiarity with the design approach from both my undergraduate and work experience. This chapter will describe the major 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 lice cycle stages of a system. This encompasses concept, development, production, utilization, support and retirement. In this paper 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 entire life cycle of the system. They tend to be less resistant to change and are typically used in organisations to tackle large complex systems (INCOSE, 2015). The Vee-model is an example of such a framework.

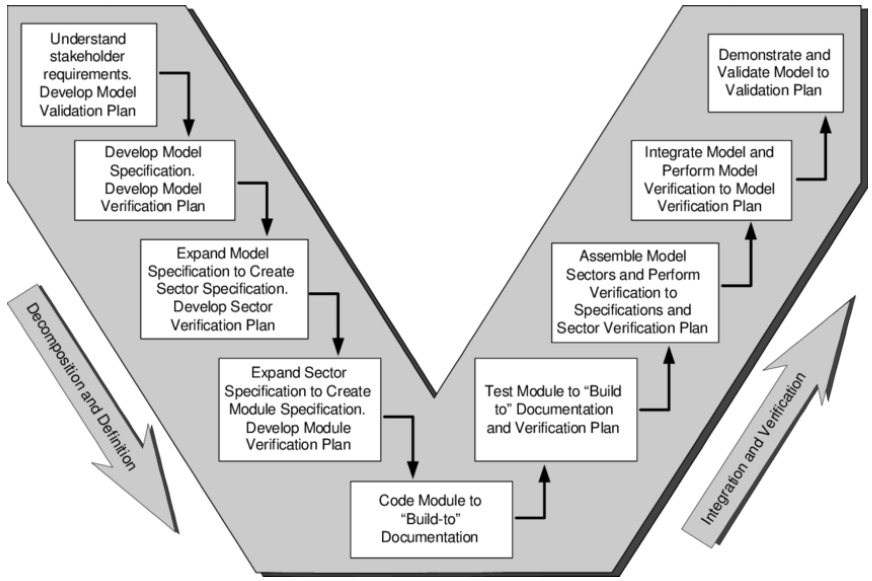


**Fig. 4.1** Vee-Model Process

The Vee-model is a sequential systems engineering process that involves going through a specified set of plans. These involves 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 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. These models better account for systems where experimentation is needed to develop a better product. Examples of these processes include the Spiral Model for systems. In general, these models can be seen as going 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 important 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 takes these requirements and considers what the system must be do to be able to achieve these requirements. These functions may also be allocated to subsystems. Once these two stages are done concepts are generated and system architectures are developed for each concept.

### 4.1.3 Verification and Validation

The Verification and Validate phase ensures that the product meets all of the technical requirements and relevant regulations and the stakeholder requirements. We can use the following verification methods for requirements (SEBoK, 2021).

**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 that we wanted 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. On board sound synthesis (even primitive would work for 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)

We can broadly split these items into four categories: Better sensor resolution and speed, improved reliability/robustness, improved maintainability, and additional features that would be interesting to try out or add to the T-Stick. When making requirements we will focus on items that fit the first three categories but not the third. Although some of the ideas are interesting and worth exploring, the primary goals are of this project are to improve reliability and maintainability, improve the hardware documentation and improve the 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 common 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 on the specific types of sensors, or exactly how the namespace should be outlined. Instead it should be thought of as a document that future T-Stick designers can look out and from the guidelines design a T-Stick-like instrument. A full copy of the design guidelines can be found in the appendix (INSERT REFRENCE TO APPENDIX).

## 4.3 Technical and User Requirements

From the items presented in Section 4.2 we derive 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 |

From the user requirements, we 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.

Requirements 1.1 - 1.4 specify the technical performance of the communication system. All of these requirements specify the worst acceptable performance. Designs that significantly exceed this performance are viewed more favourably. Requirement 1.5 and its sub-requirements outline

**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 will be 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 2ms. | 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 |

the functions the communication system must do to meet the user requirements (U6).

### 4.3.2 Power System Requirements

The Power System of the T-Stick handles delivering power to all components of the T-Stick and measuring the remaining power when the T-Stick is on battery power. Hardware components such as regulators, and fuel gauges, as well as software components such as 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 able to be powered by both batteries and USB. | Demonstration |
| 2.2 | The power system will be able to 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 state of charge of the battery 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

use both battery power and USB power for operation. 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 seen as the minimum battery life needed for a T-Stick to be able to do an entire performance of a battery. 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 of the T-Stick manages the initialisation, communication, and analysis of sensors in the T-Stick. This includes all the sensors excluding sensors related to power management and the software components that communicate with the sensors and process 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 which enables artist to manually calibrate the sensors. | 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 artist to trust the signals from the sensor system and to address user requirement U5. Requirements 3.4 - 3.6 relate to user requirements U4 and U6, relating to improving sensor management and improving feedback to the end user. Requirement 3.7 exists to ensure continuity with previous T-Sticks in particular the T-Stick 4GW.

### 4.3.4 Reliability and Availability Requirements

As the name suggests this section contains all requirements relating to reliability and availability. These requirements address user requirement U2 for improving the reliability and robustness of the instrument. This includes a PIR and PMR target for the T-Stick. The robustness requirements are to ensure the T-Stick can handle elevated levels of shaking and jabbing for short periods of time 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 hours/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 the manufacturing of T-Sticks 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. We specify this to

**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 common readily available parts and materials. | Demonstration |

ensure better interoperability with current and future T-Stick designs.

# Chapter 5

# Designing a new T-Stick

In the past two chapters we have discussed reliability and availability analysis and modelling and the design derived a series of requirements for evaluating the performance of new and current T-Stick prototypes. In this chapter I will go through the design of the 5th generation of T-Sticks. This will include going through initial prototypes, key 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 straight forward functional flow block diagram.

The sensors must be initialised, and then regularly polled for their raw sensor data. Any sensor errors must be processed and then converted to error messages to be sent to the user. In the fourth generation of T-Sticks this function is not fully developed 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 output signals via OSC or libmapper and interpret any user inputs/signals such as using the serial monitor to reboot the T-Stick.

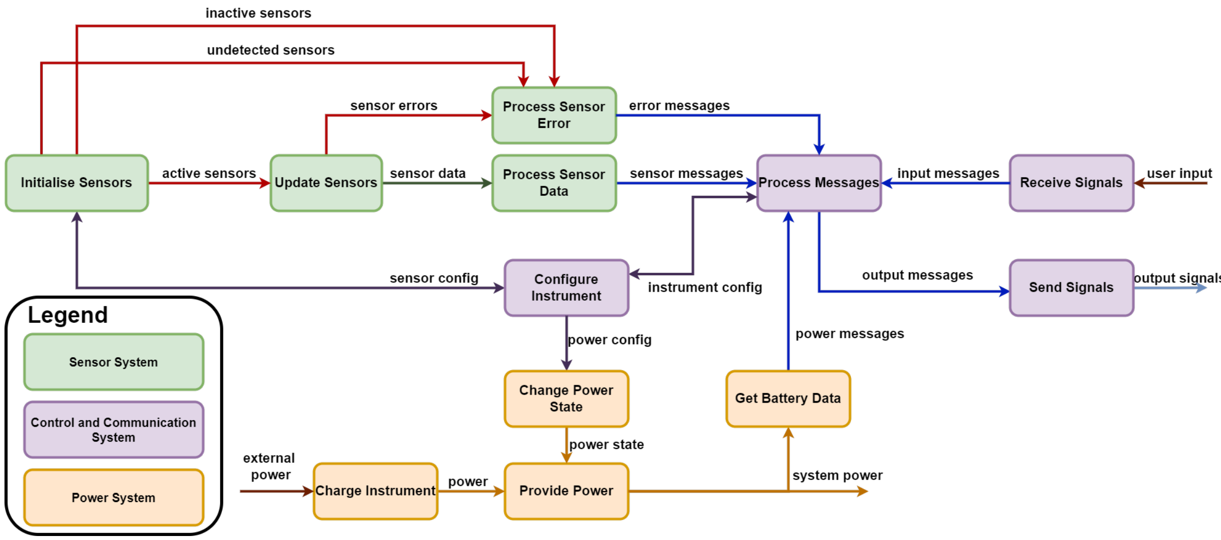


**Fig. 5.1** Functional Flow Block Diagram of the T-Stick, Legend on the bottom left shows which functions are in which system

## 5.2 Early Prototypes

### 5.2.1 Prototype 1: DIY Plus

Initial design ideas of the 5th generation of T-Sticks were focused on simplifying the design process, and removing the need to individually solder each T-Stick together. To do this I considered using JST-SH connectors to connect the different sensors to the microcontroller. To do this I was going to leverage Sparkfun's Qwiic Connectors/Adafruit's StEMMA QT connectors. Both of these 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. In addition, a fuel gauge such as the MAX17048 was considered to improved the accuracy of the battery life estimation.

In addition to the use of cables to connect sensors, the touch array was going to be replaced by a flexible PCB which would connect to a Trill Flex (LINKTOBOARD) through its 32 pin FFC 0.5mm pitch connector. This would easily allow doubling the touch sensor density from 1 sensor every 2cm to 1 sensor every centimeter while reducing the build time.

These changes would have improved manufacturing of the T-Stick by lowering the time to build the T-Stick which would improve the performance of the T-Stick for requirement 6.4. In

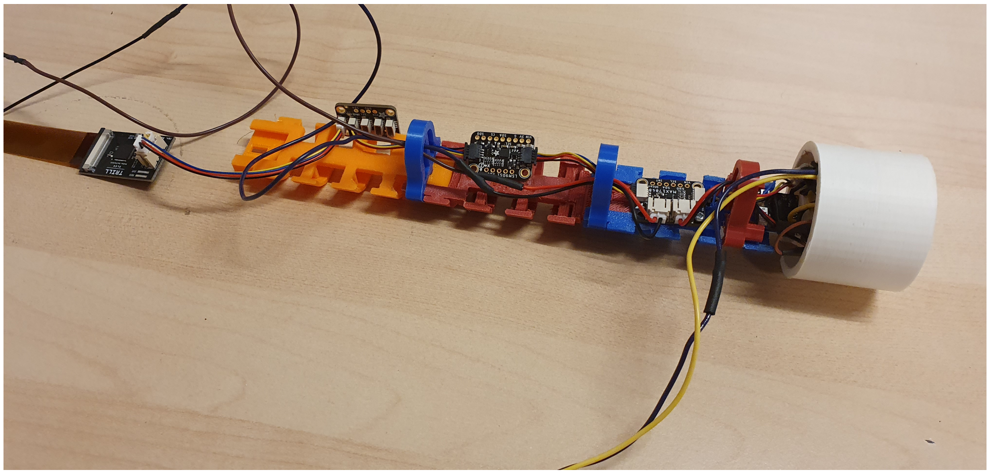

**Fig. 5.2** Example of T-Stick DIY Plus Design

addition, this assembly would be easier to do even for those without soldering experience which would improve the reliability requirements 4.3 and 4.4, as the T-Sticks overall would be more robust to shakes and jabs. In addition as cables are easier to maintain. If the interior of the T-Stick is assembled such that the cables are easy to access it wouldn't be unreasonable to assume that a musician could check before performances that the cables are secure. Which 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. We would also need to find an ESP32 board that has a jst-sh 4 pin header on the board. This design is still 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, the introduction 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.

Finally, although this would improve robustness and reliability, and the introduction of a fuel gauge would improve the power system requirements, specifically requirements 2.3, 2.4, and 2.5 regarding battery life, voltage and capacity estimates no other requirements would be addressed. Specifically, sensor system and control and communication system reliability would not be addressed. These requirements would need to be addressed in firmware.

### 5.2.2 Prototype 2: Prosumer

As the drawbacks of my initial idea for the hardware design of the T-Stick 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 the robustness requirements.

A custom ESP32 board would have several benefits from a manufacturing perspective. Recall that in Section 3.3 I mentioned that really the T-Stick has a manufacturing problem that manifests itself in severe reliability issues while in use. A custom ESP32 board can have a majority of the sensors that are used in the T-Stick in a single small ESP32 board. This outsources the manufacturing to an external organisation who is specialised in the manufacturing, and reduces the bill of materials for final assembly with the negative of increasing the costs and design complexity. The idea would be to have the ESP32 board to have all the necessary senosrs 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, already added on the board. The IMU was changed from the LSM9DS1 9 DOF IMU used in the current T-Sticks to a 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 producing 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 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 is shown in figure 5.3. Extension touch boards for longer T-Sticks were also designed and shown in figure 5.4.

Five boards were ordered, and were tested. Out of the five boards, one board has a fuel gauge that does not respond consistently to I2C communication. In addition, the LEDs which

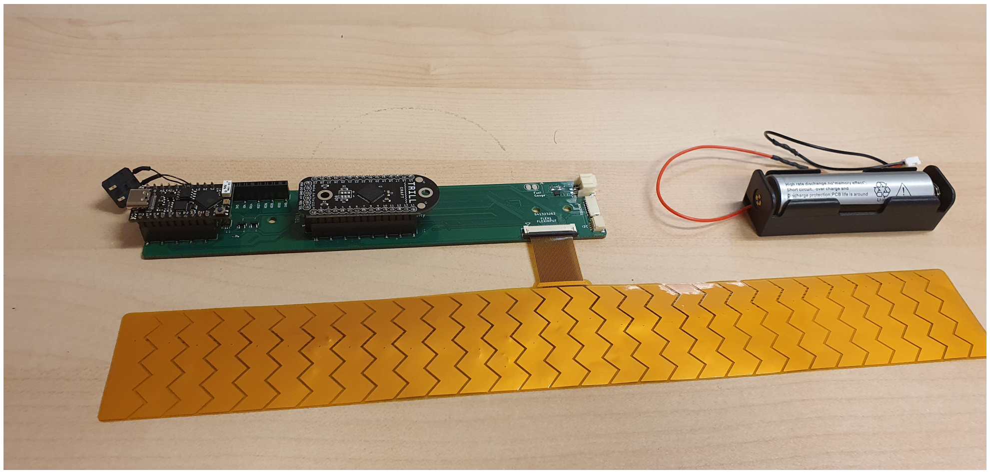

**Fig. 5.3** T-Stick Prosumer Board, including TinyPico and Trill Craft Board

were added for visual indication that the sensors worked, draw more current from the battery even while the T-Stick is in sleep mode. This idea improved on the previous idea by simplifying construction further. For a single Sopranino T-Stick you only need a single board and 3 additional cables. Compared to connecting multiple cables between sensors boards. However, this design significantly increases the design complexity of the T-Stick. The benefit of using development boards is that you do not need to understand what is happening on the board, you just need to understand the inputs and outputs on the board. This means if the boards need to be replaced, all you need to do if find a similar board that has the same or similar sensor, with the same inputs and outputs on the board.

The prosumer board is complex enough that a custom ESP32 board is not a significantly more complex tasks design task and 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. The shift from a single expert technician to being built by graduate students predictably decreased the average

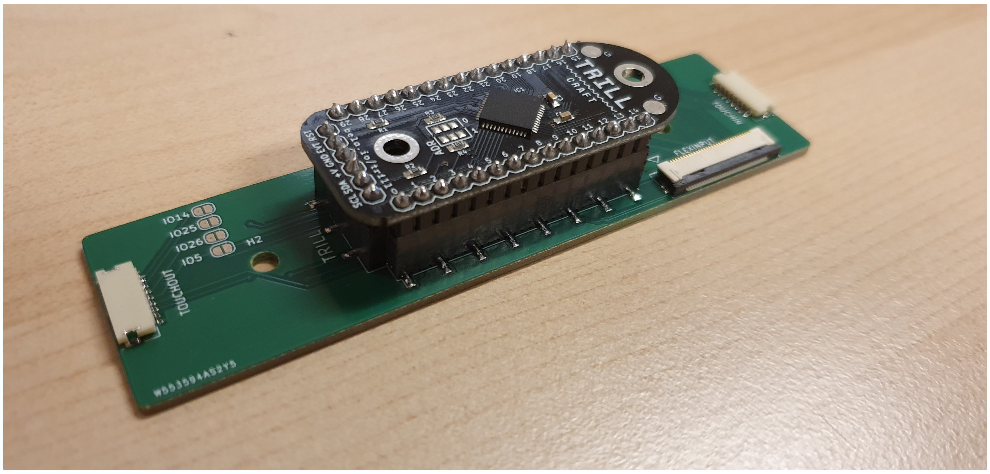


**Fig. 5.4** Extension Touch Boards for longer T-Sticks

build quality of the 4G T-Sticks, and therefore, their reliability in performance was, on average, less than that of the 2G T-Sticks that were built by the original designer. This decrease is due to a mismatch between the difficulty of the assembly and the skill level and time of the builders. The T-Stick 5GW assembly attempts to bridge this gap by greatly simplifying the assembly so that builders with limited soldering experience can still build performance-ready T-Sticks. Two assembly process were tested in the end for assembling the T-Stick.

Traditionally T-Sticks have used a split pipe design for their assembly. The ABS pipe was cut along its long side and the parts were assembled and then the T-Stick was closed again.

[INSERT PICTURE OF SPLIT OPEN T-STICK]

This design has several benefits from a maintainability stand point. It 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 as well as the endcaps were all important structural components. Therefore, it was not easy to fully test that all the components are working properly inside the tube before final application of the heat shrink. Also splitting the pipes length wise is a time consuming process increasing the total build time.

In 2021 a closed pipe design was used. This meant 3d printing an internal skeleton for the components and sliding that skeleton into the pipe. This had significant improvements from a reliability stand point. It standardised board placement and connections, it lowered the chances of components moving within the pipe and provided a means of testing the components before applying heat shrink. However, it was significantly less maintainable. Accessing components without cutting wires or accidentally breaking other interconnections ranged from difficult to impossible.

The first iteration of the 5GW design opted to iterate on the closed pipe design as we believed that the reliability benefits offset the losses to maintainability. Furthermore, we believed it was possible to offset the loss of maintainability with some design changes to the internal skeleton.

**Fig. 5.5** First fully assembled prototype for the T-Stick 5G

The main innovations of this design mostly designed by a colleague Travis West was a regularly spaced M3 mounting holes so that we can create mounting brackets for any sensor or controller we use, and the seperation of the internal endcap and the external endcap. The is to say that the pipe will have an endcap glued unto it that the internal skeleton will be screwed to. This should help with removing the internal skeleton without having to remove the heat shrink, reducing waste and making it possible for artist to check and fix minor issues on their T-Sticks.

**Fig. 5.6** Internal Skeleton for T-Stick 5G prototype

However, this design was abandoned because of two factors: 18650 batteries are very tall, taking up most of the vertical room in the pipe making fitting them very difficult, and the touch sensor had to be pressed against the pipe so hard that pulling and inserting the skeleton not only became very difficult but also risked breaking other structural components. In addition every time you needed to pull the the skeleton out, you needed to unplug the FSR, further degrading the connector and decreasing it's long term reliability.

## 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, and a touch board that has a pinout for the Trill Craft board as well as, two JST-SH 4 pin connectors to daisy chain multiple touch boards together.

The 3D printed skeleton was also redesigned to make it easier to 3D print. The outer cap now is split into two sections. An inner cap which is glued on to the tube and an outer cap which connected to the 3D printed skeleton via a screw. These changes make it easier to remove the T-Stick from the inside of the tube for maintenance without having to disassemble the entire T-Stick.

This has the added benefit of allowing artist to more easily troubleshoot their instruments.

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 previous 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 5.7 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[1]. 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[2] series are used to step down the system power to 3.3V and 1.8V respectively. Maxim Integrated's MAX17055[3] is used as a fuel gauge.

Either the Trill Craft board[4] or a custom touch board such as IDMIL's EnchantiTouch[5] 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[6] and the EnchantiTouch being a PSoC 4100S Max device[7]. 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[8], which receives the 1.8V power from one of the regulators. Three MOSFETs are used to convert the 1.8V logic from

[1] https://www.microchip.com/en-us/product/mcp73871
[2] https://www.onsemi.com/products/power-management/linear-regulators-ldo/NCP167
[3] https://www.analog.com/en/products/max17055.html
[4] https://shop.bela.io/products/trill-craft
[5] https://github.com/IDMIL/EnchantiTouch
[6] https://www.infineon.com/cms/en/product/microcontroller/legacy-microcontroller/legacy-8-bit-16-bit-microcontroller/psoc-1/
[7] 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/
[8] This is due to the fact that the LSM9DS1 is no longer actively supported by STMicroelectronics.

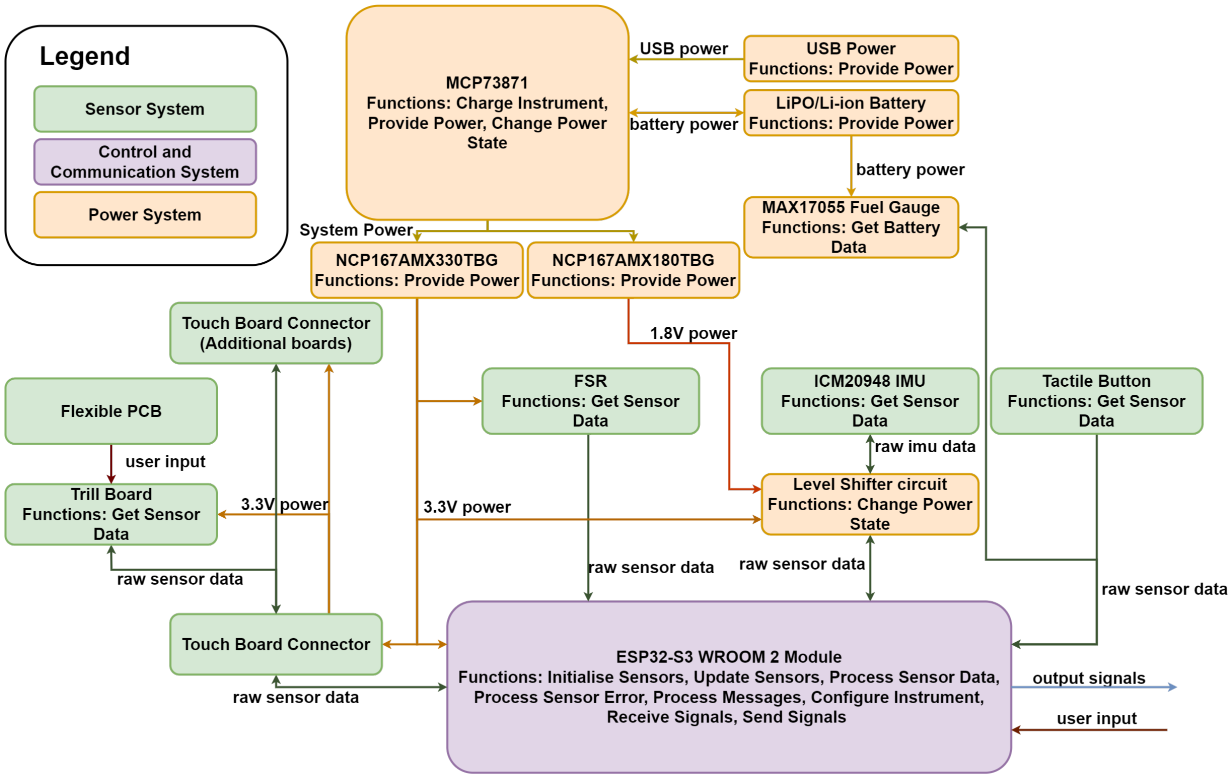


**Fig. 5.7** Hardware Architecture Diagram for the T-Stick 5GW, Legend on the top left shows which components are in which system.

the ICM20948 to 3.3V to communicate with the ESP32-S3.

The main microcontroller was changed from the ESP32 Series to the ESP32-S3 WROOM 2 Module[9]. 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[10]. In addition, using a module over a bare ESP32-S3 chip reduces the complexity of the PCB design. No changes are made to the tactile button and force sensing resistor (FSR). The layout of the Board is shown in figure 5.8b.

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 difficult, despite potentially saving space and making routing traces easier. Furthermore, it allowed us

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

to use components with voltage and power ratings higher than what they would experience on the board[11]. This improves the reliability performance of the component in comparison to using them at their rated power/voltage/current. By using passive components such as resistors and capacitors at a higher power/voltage rating we are improving the overall reliability of all the passive components and, consequently, the reliability of the board.

### 5.3.2 T-Stick 5GW Assembly

The highly integrated nature of the custom ESP32-S3 board means that rather than having three separate boards for the fuel gauge, IMU, and the ESP32-S3 they are all on a single board. This means that, there are only three components that have to 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. We can instead design 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 5.9.

The 3D-printed components were designed with removable doors. The doors can be removed whenever a battery needs to be replaced, or the boards need maintenance. Threaded inserts are used for all the parts that will need to 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 longer longevity assuming it is properly inserted.

As shown in figure 5.10, 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.

[11]Derating is a technique of using components at a lower power/voltage/current rating than they are designed

The assembly reduces the amount of soldering required to only soldering the wires for the button and FSR. The rest of the assembly is only consisting 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 the need for an experienced technician, as was done for previous T-Sticks. Four fully assembled Soprano T-Sticks 5GW are shown in figure 5.11.

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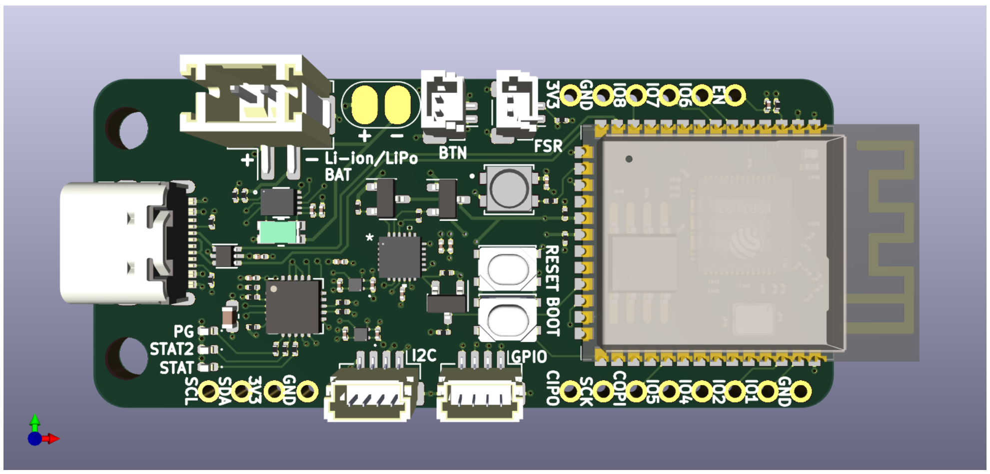
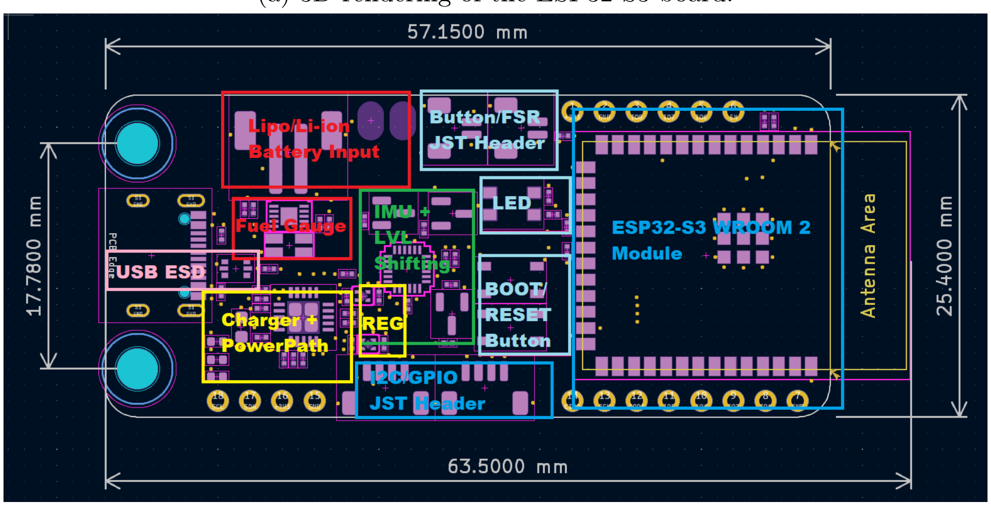
for (Silverman, 2011).




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




(b) PCB layout, comments highlight important components.

**Fig. 5.8** PCB Layout of the ESP32-S3 board, figure 5.8b highlights important components and regions on the board.

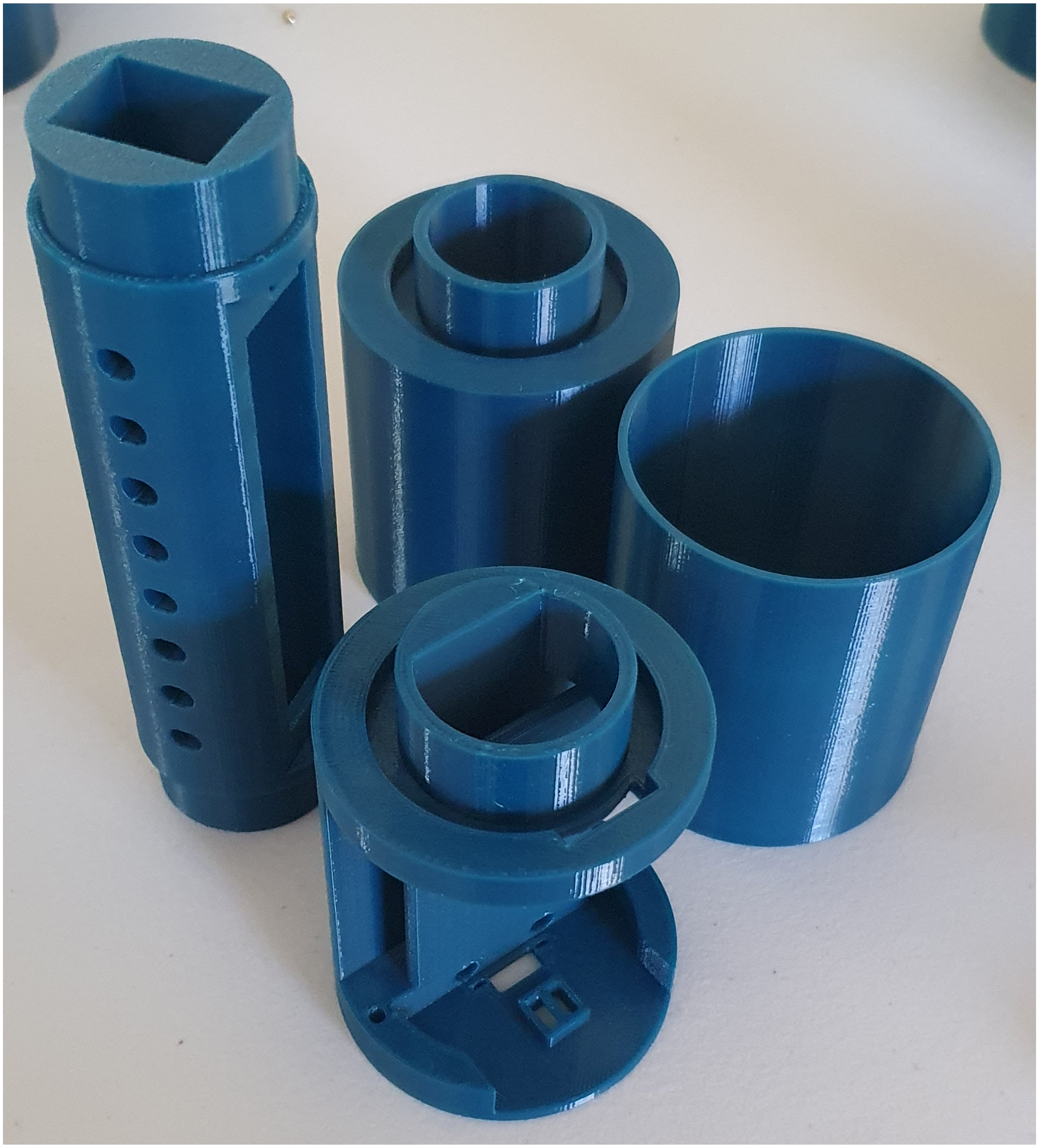


**Fig. 5.9** Components for the second version of the assembly, the touch board bed, and ESP32-S3 endcap are shown.

**Fig. 5.10** Partially assembled Soprano T-Stick 5GW, the touch board bed, and endcap are glued onto the plastic pipe.

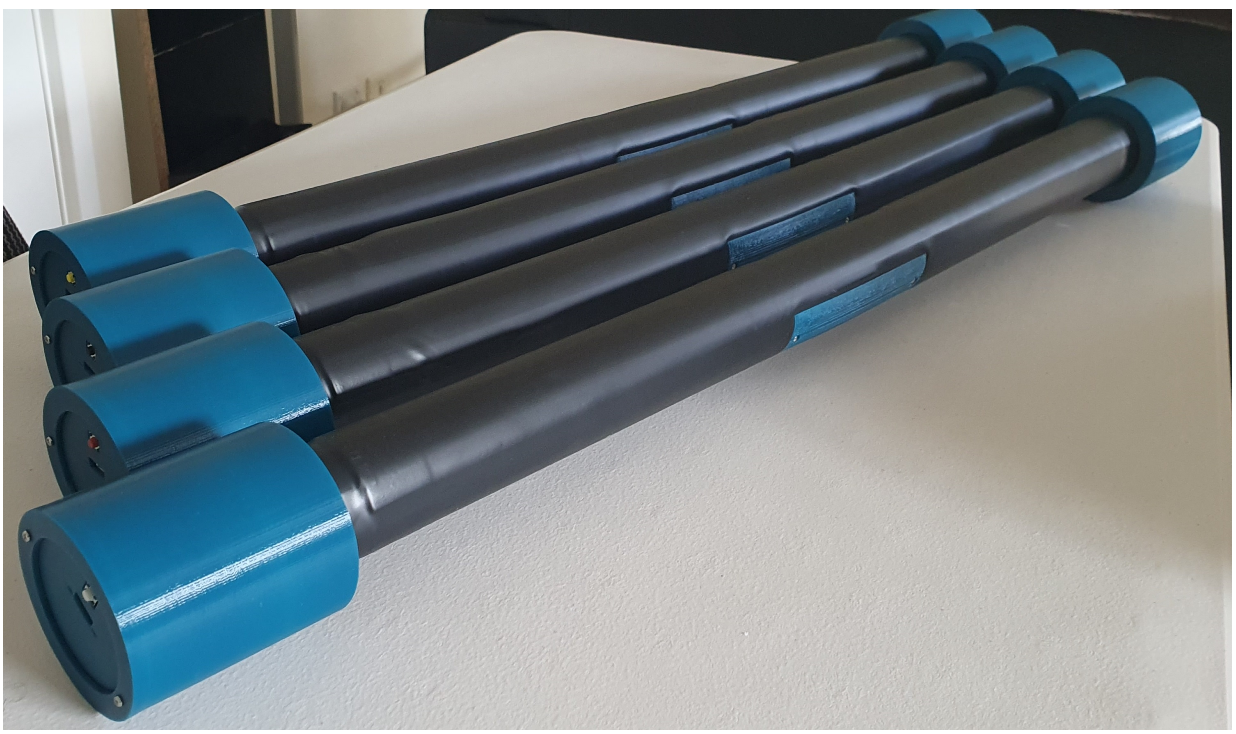


**Fig. 5.11** Four fully assembled Soprano T-Stick 5GW.

# Chapter 6

# Verification and Validation

In this chapter, we 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

We develop a verification and validation scheme for the T-Stick to help sort the relative importance of the requirements and to compare different designs and concepts.

### 6.1.1 Pairwise Analysis

We use pairwise analysis to rank the requirements in order of importance. We do this for both the user requirements and the technical requirements. To do pairwise analysis we compare each requirement to each other and see which one is more important. We then add the results up and rank the requirements by their total score.

Table 6.1 shows the results from the analysis. On the left column we compare if Req. X is more important than Req. Y. If it is more important than we put in 1, otherwise it is a 0.

The weighted score is calculated by taking the total score for each requirement and dividing it by the total number of requirements minus 1. We then and add 1 to the weight. We will use this

**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 | | 1 | 1 | 3 | 3 |
| **U5** | 0 | 0 | 0 | 0 | N/A | 1 | 1 | 5 |
| **U6** | 0 | 0 | 0 | 0 | 0 | N/A | 0 | 6 |

value in combination with the technical requirements when scoring prototypes in the evaluation stage.

**Table 6.2** Pairwise Analysis Results for user requirements

| ID | User Requirements | Weighting |
|---|---|---|
| **U2** | Improve the reliability and robustness of the T-Stick | 2 |
| **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 quality of existing signals
6. U6: Improve feedback to end-user

This order given makes sense based on my priorities on 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 improved by better firmware and hence can be done at another time.

This process is repeated again for the technical requirements listed in section 4.3. Doing this we get the following list of requirements as 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 manually calibrate the sensors.
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 will be 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 state of charge of the battery 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 on improving the 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). This tracks with the user requirements ranking. In particular U2, U3 and U4. However, the manufacturing requirements are quite low given that they all derive from U2. 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 manually calibrate the sensors. | 1.88 |
| 1.1 | Continuous signals will have a wireless signal rate of at least 100Hz and will be 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 state of charge of the battery 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 |

### 6.1.2 Technical Performance Metrics (TPM)

We will score each requirement on a score between 0 (lowest) and 1 (highest) depending on how well the prototype meets the requirements. Like the requirements analysis each section will have their own page detailing the Technical Performance Metrics (TPMs) and why they are designed that way.

Technical Performance Metrics (TPMs) represent how we will score the prototype against the requirement. This can be represented in the form of a graph from 0 to 1 with marginal values representing different splices of this graph. We will stick with simple TPMs that are either linear splices or a binary.

For example for Requirement 2.2 we can use a binary TPM where if the battery life of the T-Stick is more than 4 hours the prototype gets 1 point and if it is less than 4 hours it gets 0 points. Each requirement will be scored differently depending on their importance.

The final score for a T-Stick prototype is the score from the technical requirement times the weighting of the technical requirement times the weighting of the associated user requirements. For example for requirement 4.1 the related user requirement is U2. Therefore the score of requirement 4.1 will be multiplied by 2 which is the weighted score of requirement 4.1 and by 2 which is the weighted score for requirement U2. If a technical requirement has multiple user requirements the average of the weighted scores is used. Eq. 6.1 shows a simplified equation for calculating the total score for a T-Stick prototype.

$$score = \sum_{i}^{n} r_i \times wt_i \times wu_i \tag{6.1}$$

where $r_i$ is the score from the requirement, $wt_i$ is the weighting of the technical requirement and $wu_i$ is the weighting of the user requirement. All technical requirements not in the top 10 are given a weighted score of 1.

## 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 three scenarios: 1) libmapper only, 2) libmapper + OSC for 1 IP address, and 3) libmapper + OSC for 2 IP addresses. When libmapper was used all the outputs of the T-Stick were connected to multiple dummy devices in a 1 to 1 configuration to send as much data as possible. An additional output was added to the T-Stick which outputted a continuous sequence to estimate packet loss.

For each of the scenarios the maximum and average throughput, latency, and jitter were measured. The throughput of the T-Stick was defined as the rate 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

| | **Maximum Throughput** | **Average Throughput** |
|---|---|---|
| **Scenario 1** | | |
| **Scenario 2** | | |
| **Scenario 3** | 106Hz | |

In scenario 3 communication system was able to achieve a consistent 106Hz for sending messages over WiFi (Reqs. 1.1). The communication system's error messaging capabilities are still limited to sending error messages over a serial monitor (INSERT REQ REFERENCE).

INSERT ROUND-TRIP LATENCY RESULTS + JITTER

The wireless latency of the T-Stick 5GW is below 10ms with an average jitter of 2ms meetings requirements (INSERT REQ REFERENCE). The packet loss under good network conditions was

### 6.2.2 Power System Results

The ESP32 boards underwent several charge and discharge cycles over weeks to test both the accuracy of the fuel gauge 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 12-13 hours (Reqs. 2.2).

[INSERT GRAPHS OF CHARGE/DISCHARGE]

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. We see a small non-linearity in the estimate of the battery life 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.

### 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 errror management of sensors has 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 we note that the lack of calibration of the IMU for the sensor fusion makes those signals unusable for artistic use due to the sensor error due to drift.

### 6.2.4 Manufacturability

The T-Stick 5GW met all of the 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 mean time to failure ($MTTF_p$) for the T-Stick was computed analytically using the FIDES Reliability Tool. As discussed in Chapter 2, FIDES is an analytical reliability tool which uses the mission profile of the product 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 (INSERT REFERENCE TO APPENDIX). 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 is dead 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 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 6.5 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 6.5** 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 can be seen from table 6.5 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 were subjected to jabs and shakes of increasing severity. 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 4G models before it, the T-Stick 5GW did not suffer failures from jabs and shakes with magnitudes of about 100m/s/s, operating smoothly throughout the entire operation. It suffered from a similar lack of robustness towards impacts when dropped from 1 meter, but the failures were only temporary. After a power cycle, the instrument continued to operate normally.

## 6.3 Discussion

### 6.3.1 Reflections on the Design Process

In chapter 4 I describe the design framework I decided to use to update the T-Stick. The reasons I picked this framework were for two reasons. It would provide a systematic way to analyse the T-Stick and the environment it had to operate in as well as the being a process I'm already familiar with. The Systems Engineering design process had many benefits for designing the T-Stick 5GW. The process helped me navigate a new design context, music technology and designing prototypes in academia. Music Technology is a new field of study for me as I focused on robotics and control systems in my undergraduate. Given my lack of experience in music technology, I had to spend a significant amount of time to understand the major constraints and requirements in this field. In addition, given the multidisciplinary nature of the field there were many perspectives and interests to consider.

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 new T-Sticks.

Due to the methodology I chose and my lack of experience in the music technology field, I had to spend a lot more time than expected in the requirements analysis and definition phase. Months were spent outlining and defining the requirements and discussing 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. Some requirements could not be tested at the level of detail that 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.

Quite early in the project, the idea of using a PCB for all of the electronic components was floated, like previous versions of the T-Stick (2G). Using custom PCBs would have the benefit of improving the reliability of the connections between components and lowering 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 having to design a new PCB each time we needed to change development boards, we decided to make a custom ESP32-S3 board that had 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 common and 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 common 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 provide an outline of what is currently lacking from the T-Stick 5GW and where the project should go from here.

### 6.3.2 State of current design

Although this design made several major improvements over the previous T-Stick design there are aspects that the current T-Stick is still outperformed by the previous iterations, mainly touch sensor speed, system latency, and throughput. At the fastest setting the Trill Board is only able to scan all of its channels in 1.7ms. 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.

Given the T-Stick 5GW uses WiFi as the means of communication we were never going to surpass the system latency of the T-Stick 2G due to the latency of the WiFi communication protocol. However, there are still several aspects of the T-Stick 5GW from a hardware and firmware perspective that 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 which will greatly decrease communication latency.

The throughput of the T-Stick 5GW is 106Hz which is 10 times slower than the T-Stick 2G. Although this represents an improvement over the 4GW T-Sticks this is mostly due to firmware improvements to optimize the Open Sound Control sending. It is possible through better firmware the throughput can increase 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 further 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 the reliability and robustness in comparison to the T-Stick 4GW. The power system is also improved with better battery life estimation far exceeding our modest requirement for an error 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 pose a substantial strain on 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 easily fix the two most common failure modes without the need of a technician: cables getting loose and batteries dying. However, we note that the FIDES model does not consider software failures. Poor firmware may cause additional failures not considered in this model.

# Chapter 7

# Conclusion

Over the past 17 years, the T-Stick has undergone many design changes as a result of changing contexts, requirements, and the availability of new technologies. This paper presented the design work for the T-Stick 5GW which aims to continue the standardization process started with the T-Stick 4G series while improving the robustness and maintainability of the interface in accordance with 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 (Malloch & Wanderley, 2007), and continues the standardization work of the 4G series of T-Sticks (Nieva et al., 2018). Originally designed in 2018 with a later revision done in 2021, the 4G T-Sticks feature an ESP32 board and are the first fully wireless series of T-Sticks communicating over Wi-Fi using both Open Sound Control (OSC) and libmapper (Malloch, 2013). 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 passed the reliability and maintainability requirements we set out to achieve, though some of the reliability requirements were verified analytically and not through testing. We note, however, that 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. Future work involves conducting long-term reliability testing of the custom boards and the device.

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