Take Five: Improving Maintainability and Reliability of the T-Stick

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ABSTRACT

The T-Stick, an interface with a lifetime of nearly 17 years, has undergone multiple changes over time. Over the first decade and a half of its existence, the T-Stick was manufactured in various sizes (four) and copies (> 30 units). Despite the relatively large numbers in the context of in-house academic interfaces, many T-Sticks were made fairly artisanally, with graduate students manufacturing their own devices. Despite this strategy's clear pedagogical advantages, the reliability of these devices was not always a priority, leading to the need for repairs and downtime during extended use. In this paper, we present the design for the 5th generation of T-Sticks, the T-Stick 5GW, designed to improve the reliability and maintainability of the interface to reduce faults dramatically during extended periods of use. The main change in this new generation is the use of a custom-made ESP32-S3 board, which integrates a fuel gauge and IMU. In addition, the touch sensor is printed on a flexible PCB and interfaces with the touch board using a 32-pin FFC connector, substantially reducing the need for soldering parts. Requirements relating to the instrument's reliability/availability and manufacturing are described in detail and were evaluated analytically, showing the effectiveness of the new design. Further reliability testing is ongoing through the use of the latest generation in musical performances.

Author Keywords

T-Stick, DMI, evaluation, reliability

CCS Concepts

•Applied computing → Sound and music computing; •Hardware → Hardware reliability;

1. INTRODUCTION

The T-Stick is a musical interface introduced in the mid-2000s [8]. For more than 17 years, the interface has existed in a state of perpetual upgrades, downgrades, and sidegrades [10]. 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 constructed to more than two dozen 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.

Indeed, as an instrument designed in a lab focusing on research and pedagogy, the T-Stick has sometimes suffered from reliability, robustness, and manufacturing issues. Major redesigns done in 2018 and 2021 have resulted in an increase in failures such as wire shorts, faulty microcontrollers and sensor boards, and batteries not charging [11]. These issues were due to component choices and sub-optimal manufacturing, resulting in poor field reliability.

Since around 2017, with the increase of interest in the use of T-Sticks in different performance situations, e.g., [4], a drive for standardization and reliability has been initiated so that the interface can be used in sustained musical performance practice.

Buxton's notion of the "artist spec" highlights the high-performance standards of tools for artists [1]. "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. "Artist spec" has been viewed as a requirement [6, 12, 9] which can be tested by using their instrument/tool in performances, and in terms of long-term support [14].

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.

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 [8] and continues the standardization work of the 4G series of T-Sticks [10]. Initially

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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 [7]. The T-Stick 5GW features improvements in the reliability and manufacturability of the device 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 interface but greatly simplify assembly and improve reliability. Five copies of the T-Stick 5GW were made and evaluated.

2. DESIGN REQUIREMENTS

The goals of the fifth generation of T-Sticks are listed below:

Goal 1 Improve/redesign the current cap sensing solution for greater spatial resolution and faster sampling

Goal 2 Redesign the T-Stick to be easier to construct and maintain

Goal 3 Improve battery and power management system

Goal 4 Improve sensor management system

Goal 5 Improve the quality of existing signals

Goal 6 Improve feedback to end-user

Goals 1, 2, 5, and 6 are inherited from the original T-Stick project, while Goals 3 and 4 are in response to particular problems in the 4G T-Sticks. We chose a set of technical requirements to evaluate the new T-Stick design, which can also be used by future designers proposing new versions of the interface. In this paper, we will focus on the requirements relating to reliability (Req. 4) and manufacturing (Req. 5), which are derived from goals 2 and 6.

2.1 Reliability and Availability Requirements

The reliability and availability requirements focus on the reliability targets the T-Stick must be able to achieve, listed below:

Req. 4.1 Robustness to jabs.

Req. 4.2 Robustness to shakes.

Req. 4.3 Practice/Performance Interruption Rate (PIR) of $< 1\%$.

Req. 4.4 Practice/Maintenance Ratio (PMR) of at least 1.

Instead of a strict reliability target, we evaluate the robustness of the T-Stick against the two main stresses the T-Stick has to deal with: jabs and shakes.

The Practice Interruption Rate is an analytical requirement used to validate the component choice and design decisions made in terms of their impact on the availability of the T-Stick. A basic example of availability modeling is presented in [11], involving calculating the average uptime (Availability) using the reliability and maintainability of individual components.

We are only concerned with a measure of the instrument's availability when a performer needs it. Downtime outside of performances or practice is not relevant in our case.

To build an availability model, we draw from the commonly used availability metric in the aerospace industry *Dispatch Reliability*(DR) [3]. 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 the maintenance time of components, regular maintenance intervals, available stock of replacement components, 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 maximize their Dispatch Reliability while minimizing their costs.

Similarities to digital musical instruments can be drawn from this approach. DMIs 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 significant differences. DIR modeling is done by airplane companies that control multiple aspects of the airplanes directly compared to instruments where the manufacturer has no direct control over the maintenance actions of a musician or the rate at which the musician uses the instrument. However, despite these limitations, we believe that Dispatch Interrupt Rate modeling can apply to musical instruments. Consider that professional musicians regularly maintain their acoustic and/or electric instruments. Brass players will keep their slides and valves well lubricated, woodwind players will have extra reeds if a reed fails, and electric guitarists will probably have extra 9V batteries or spare power supplies for their pedals. Furthermore, more generally, people already undertake regular maintenance actions for their electronics, most notably charging and cleaning them often. We can assume that an interested musician committed to performance will take the time to do maintenance as long as it is within their abilities.

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* ($MPBF$).

$$MPBF = \frac{MTTF_p}{t_p} \tag{1}$$

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

$$PIR = \frac{1}{MPBF} \tag{2}$$

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 each component's mean repair time ($MTTR_c$) and its failure rate (λ_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 (λ_{tstick}). For the $MTTR_c$ of each component, we will assume a worst-case scenario where no spares are available. Therefore, we will take the time to acquire new components as part of the mean time to repair.

$$MTTR_p = \sum_{c=0}^{n} \frac{\lambda_c}{\lambda_{tstick}} (MTTR_c) \tag{3}$$

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

$$PMR = \frac{MTTF_p}{MTTR_p} \tag{4}$$

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.

2.2 Manufacturing Requirements

The manufacturing requirements are a series of constraints on the manufacturing technologies and outline the documentation required for the design. They relate to the physical design documentation, the assembly of the device, and the sourcing of parts and materials. They are listed below:

Req. 5.1 Include a bill of materials.

Req. 5.2 Include schematics.

Req. 5.3 Include assembly instructions.

Req. 5.4 Mean assembly time less than 5 hours[1].

Req. 5.5 The final assembly and repair possible using only a soldering iron, wire stripper/cutter, heat gun, saw, and hex key.

Req. 5.6 Use of common, readily available parts and materials.

These requirements are not as technical as the reliability requirements but add significant constraints to the available manufacturing technologies and assembly procedures. In particular, Reqs. 5.4 and 5.5 place constraints on the type of manufacturing allowed for the final assembly. Having the final assembly and repair be possible only using standard tools found in an electronics lab and mechanical lab also puts constraints on the design.

3. SYSTEM ARCHITECTURE

Figure 1 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 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.

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 resistor (FSR) are made. The board's layout is shown in figure 2b.

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 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, we are improving the overall reliability of all the passive components and, consequently, the board.

4. T-STICK ASSEMBLY

Older 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, then the T-Stick was closed again. This design has several benefits from a maintainability standpoint, making 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 many components and wires in a small space. However, this meant that the heat shrink that covered the T-Stick and the endcaps became essential structural components. Therefore, it was not easy to thoroughly test that all the

[1]Not counting the time to gather parts and materials.
[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/
[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.
[10]https://www.espressif.com/en/module/esp32-s3-wroom-2-en
[11]https://www.espressif.com/en/products/longevity-commitment
[12]Derating is a technique of using components at a lower power/voltage/current rating than they are designed for [13].

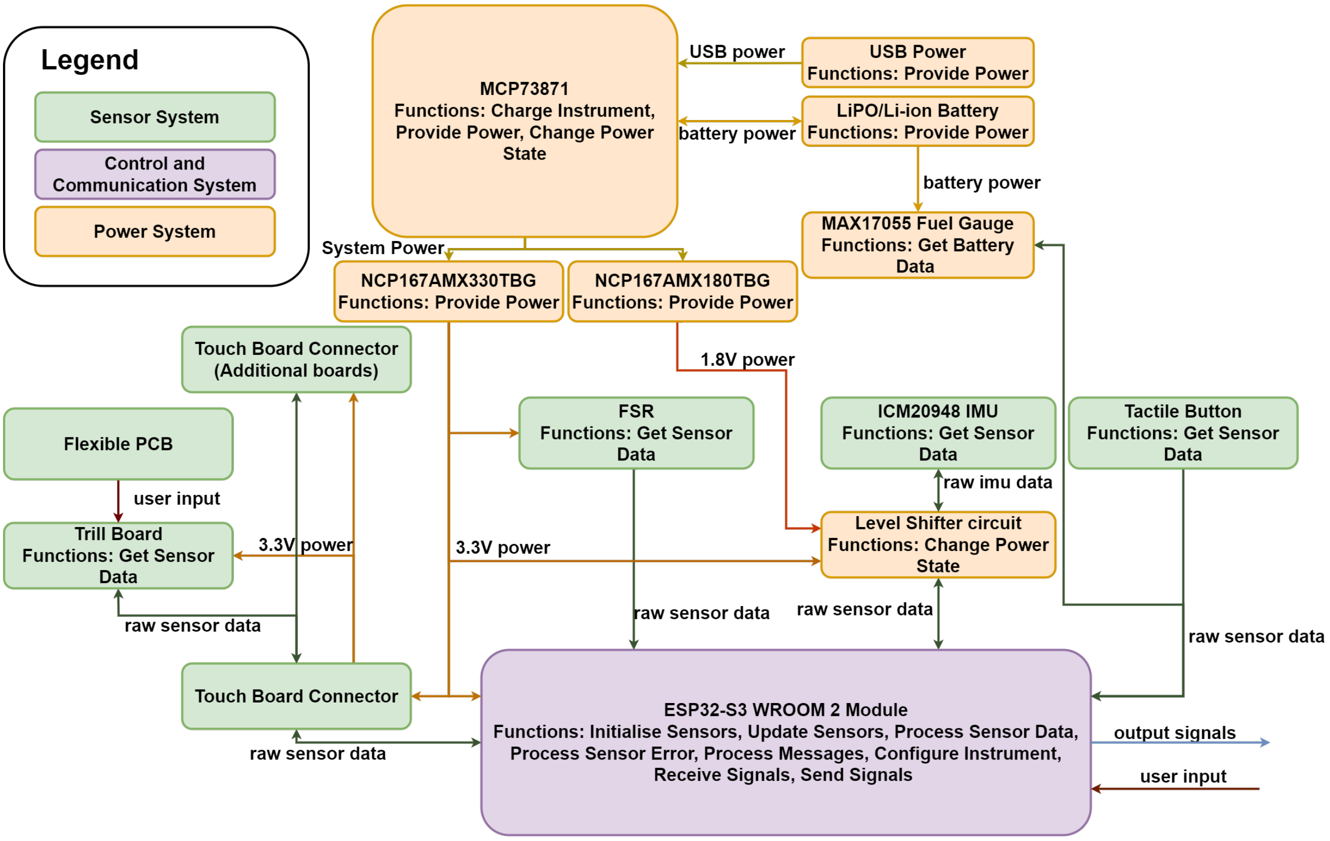
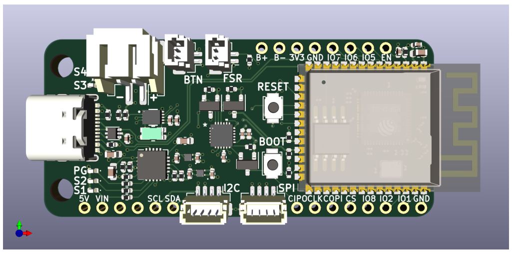
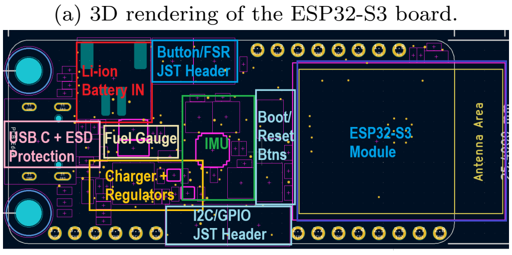


Figure 1: Hardware Architecture Diagram for the T-Stick 5GW, Legend on the top left shows which components are in which system.



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



(b) PCB layout, comments highlight important components.

Figure 2: PCB Layout of the ESP32-S3 board, figure 2b highlights important components and regions on the board.

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.

In 2021, a closed pipe design was adopted after initial trials in the early 2010s. This implied 3d printing an internal skeleton for the components and sliding that skeleton into the pipe. This version of the interface had significant improvements from a reliability standpoint. It standardized 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 significantly less maintainable. Accessing components without cutting wires or accidentally breaking other interconnections ranged from difficult to impossible.

4.1 Final T-Stick 5GW Design

A significant portion of the T-Stick 4GW's reliability problems were due to poor assembly, which was caused by a mismatch between the difficulty of the assemblage and the skill level and time of the builders. The T-Stick 5GW design attempts to bridge this gap by greatly simplifying the assembly so that builders with limited soldering experience can still build performance-ready T-Sticks.

The highly integrated nature of the custom ESP32-S3 board means that rather than having three separate boards, the fuel gauge, IMU, and the ESP32-S3 are all on a single board. 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 Enchanti-Touch 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 them all. Instead, we can 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 3.

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 need to be regularly

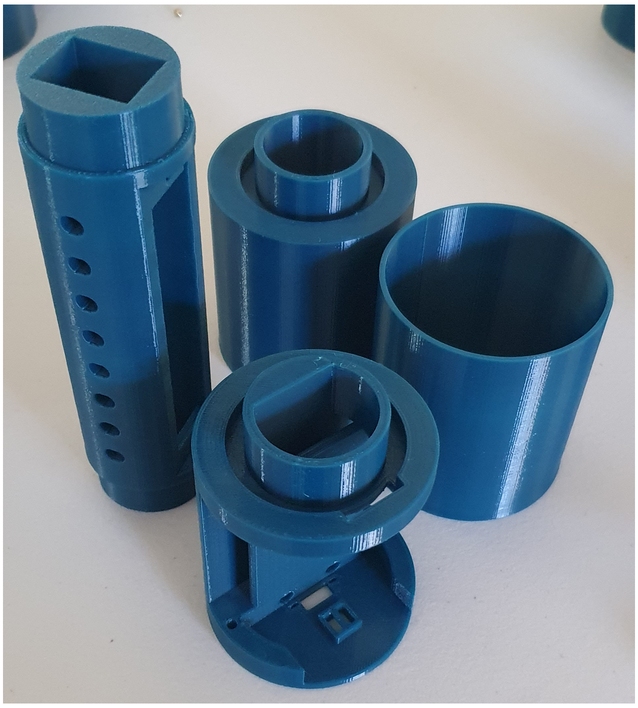


Figure 3: Components for the second version of the assembly, the touch board bed, and ESP32-S3 endcap are shown.

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.

Figure 4: Partially assembled Soprano T-Stick 5GW. The touch board bed and endcap are glued onto the plastic pipe.

As shown in figure 4, 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.

The assembly reduces the amount of soldering required to only soldering 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 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.

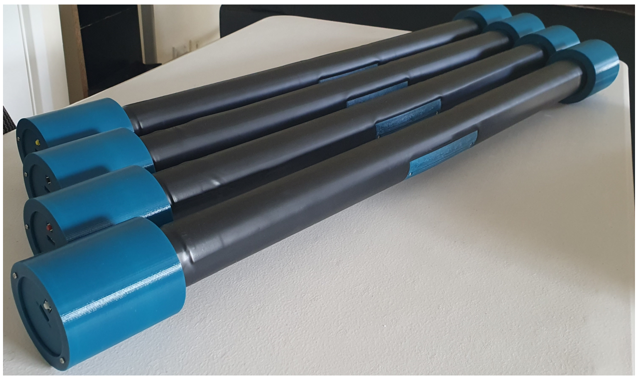


Figure 5: Four fully assembled Soprano T-Stick 5GW.

5. VERIFICATION AND VALIDATION

The new design was tested using two methods. First, an analytical reliability verification was carried out to test Reqs. 4.3 and 4.4. Second, five copies of the interface were built and tested to verify their resistance to jabs/shakes and dropping, cf. Reqs. 4.1 and 4.2.

5.1 Analytical Reliability Verification

The T-Stick's mean time to failure ($MTTF_p$) was computed analytically using the FIDES Reliability Tool [2]. The $MTTF_p$ was computed to be 37,747 hours or approximately 4.3 years. Table 1 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 1: 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 in table 1, 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.

5.2 Jab/Shake/Dropping Test

The devices 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, the T-Stick 5GW did not suffer failures from jabs and shakes with magnitudes of about $60m/s^2$, 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.

The T-Stick 5GW also met all the manufacturing requirements with a caveat for Req. 5.6, which we will discuss in more detail in the following section. The physical documentation includes the bill of materials, schematics, 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. DISCUSSION

Designing the T-Stick 5GW was a long process, with many ideas considered, some later abandoned and sometimes reconsidered. Here, we discuss the choice of designing a custom PCB for the ESP32-S3 and the limitations of the analytical reliability results.

6.1 Custom PCB

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 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 we needed to change development boards, we decided to make a custom ESP32-S3 board with all the sensors on one board.

All the components on the ESP32-S3 board can be bought from an electronics reseller, though it isn't practical to assemble the board manually. Although PCB fabrication and assembly services have gotten cheaper over the years, assembly costs are still relatively expensive and greatly increase the lead time for spare components. Due to the custom PCB components, the T-Stick 5GW costs around 50 CAD more to build than the T-Stick 4GW and the components can take 3 - 5 weeks to arrive once ordered. The cost can be slightly reduced by buying in bulk.

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. Recall that Req. 5.6 states that the T-Stick must be built using common, 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.

6.2 Analytical Reliability Test Limitations

As mentioned in section 5, no reliability testing was done to validate the analytical results for the mean time to failure. The FIDES reliability handbook has several limitations [5] 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. 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, we note that the FIDES model does not consider software failures. Poor firmware may cause additional failures that are not considered in this model.

7. CONCLUSION

Over the past 17 years, the T-Stick has undergone many design changes due to 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 new design included a custom ESP32-S3 board, which integrated an IMU and a fuel gauge for better battery life estimation. The touch sensor was redesigned, and the copper strips were replaced with a flexible PCB, which provided a faster and easier sensor assembly.

Preliminary verification and validation showed that the current design passed the reliability and maintainability requirements we set out to achieve. However, some reliability requirements were verified analytically and not through testing. We note, however, that the use of custom PCBs reduces 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.

8. ACKNOWLEDGMENTS

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9. ETHICAL STANDARDS

There are no observed conflicts of interest. All researchers participated consensually in the activities described in this document.

10. ENVIRONMENTAL STATEMENT

We acknowledge that all DMI prototyping efforts involve the consumption of electronic materials and resources and that this consumption has a permanent impact on the environment and communities involved in the production of these materials and resources.

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