Single-Chip micro-Mote Observatory

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Abstract

The Single-chip micro-mote (SCμM) is a complete system-on-chip that features physical dimensions 2x3 mm^2. A flagship feature of SCμM that researchers are interested in utilizing is its low-power design, achieved by omitting a crystal reference. Replacing this reference with an Inductive-Capacitive (LC) tank circuit introduces performance challenges, including phase noise, frequency drift, and clock drift, which require further investigation to address effectively. To reduce the possibility of confounding results, a standardized testing approach must be established so that more reliable and rigorous testing can be performed. The focus of this work is to develop a baseline testing configuration utilizing low-cost USB devices to monitor the analog, digital, and radio-frequency components of SCμM. The result of this work is the aforementioned observational setup, capable of performing automated tests, as well as testing user-provided SCμM programs.

CCS Concepts

• **Hardware → PCB design and layout**; **Analog, mixed-signal and radio frequency test**; **Built-in self-test**; • **General and reference → Reliability**; **Evaluation**; • **Software and its engineering → Software libraries and repositories**; **Software configuration management and version control systems**; **API languages**; **Scripting languages**; **Hypertext languages**.

Keywords

SCμM, Crystal-Free, Observatory, Automation, Test

1 Introduction

The Single-chip micro-mote (SCμM) is a single piece of silicon measuring just 2x3 mm^2 [1] [2]. Within this small footprint is a complete system-on-chip (SoC) capable of sensing, computation and wireless communication. Due to SCμM's size and complexity, an array of testing equipment is needed to accurately monitor all performance metrics of the chip. To aid the distributed work towards improving SCμM's design and potential applications, a standardized development and testing environment is needed. This environment or experimental observatory would enable researchers to reduce differences in testing environments from confounding results. Furthermore, the implementation of remote access to the host PC the observatory is connected to would allow for further dissemination of SCμM development and would allow for even greater reproducibility in performance results.

2 Background

SCμM features a crystal-free transceiver and ARM Cortex M0, which allows SCμM to be compatible with 802.15.4 and Bluetooth Low Energy (BLE) [1] wireless communication protocols. The standards compliant radio can be used to implement a sensor network using the openWSN project. [2] The first official SCμM debuted in 2016 and has received continuous development. The development is spread across a number of laboratories around the world.

This distributed development environment introduces significant consistency challenges for experimental setups and device configurations. Differences in wiring or even environmental factors between laboratories can lead to varying measurement results, making it difficult to compare findings and ensure reliable progress. Furthermore, the experimental nature of the device itself adds considerable variability to the test results. This is due to the SCμM's sensitivity to temperature fluctuations and inherent process defects, which can lead to unexpected behavior and make a reliable performance evaluation difficult. These factors underscore the critical need for a robust and standardized testing solution. By implementing a standardized layout and connections, such a solution can help remove variability between testing locations, ensuring more consistent and reproducible results across diverse development sites and device iterations.

2.1 Existing Solutions

The SCμM observatory represents the first known implementation of an accessible, automated framework for validating SCμM die functionality. While a related resource—the SCμM test code repository—offers a collection of sample programs to showcase basic SCμM features, it primarily serves as an entry point for new users and provides limited diagnostic feedback in the event of test failures. In contrast, the observatory addresses this gap by offering a comprehensive validation suite, integrated debugging instrumentation, and automated reporting, making it a more robust platform for both development and evaluation. Additionally, the observatory is configured such that end users may fork and modify the code-base for catering the system for SCμM-adjacent chips.

3 Observatory Layout

The observatory provides a rigid enclosure that aids with transportation, improves protection, and creates a controlled testing environment. This isolation helps ensure consistent and reproducible results by managing ambient conditions and minimizing human interference. A collection of test equipment within the enclosure offers comprehensive evaluation capabilities. Each device performs a specific function and work in concert to allow the observatory to generate inputs or measure outputs to thoroughly stimulate and assess the Device Under Test (DUT). All testing equipment communicates upstream through a single powered USB hub that connects to a host PC. The only cables that enter the observatories testing environment are the host PC USB connection and the USB hub's 12V DC power connection. A level 1 block diagram can be seen in Figure 1, depicting the interconnections between devices within the observatory as well as the connection to the host PC.

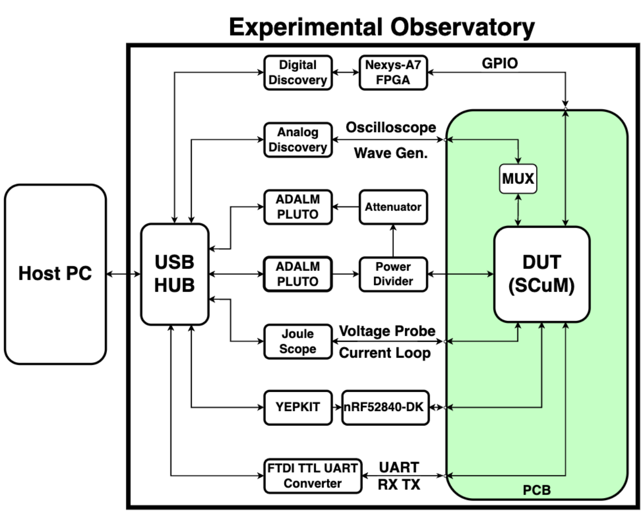

Figure 1: Level 1 block-diagram of the SCμM observatory

A custom PCB serves as the central interface, connecting testing equipment to the DUT and ensuring signal integrity. It is designed to accommodate the SCμM development board, Sulu V2.0 REG, which is mounted on a pin-compatible footprint for reliable electrical contact and stable operation during testing, which can be seen in Figure 2.

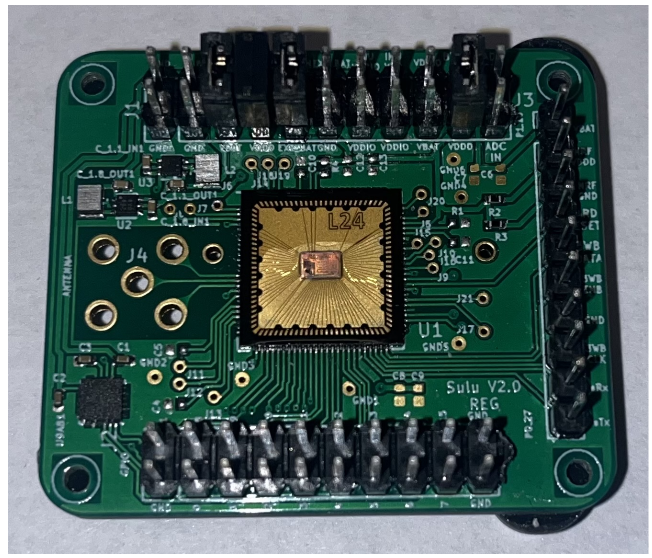

Figure 2: SCμM ver. 3C mounted atop the Sulu V2.0 board.

3.1 The Box

The observatory structure consists primarily of a plastic enclosure that has minimal external connections. A top-down image of the internal components comprising the observatory can be seen in Figure 3. This enclosure fulfills several important functions that improve the consistency of test results generated by the observatory.

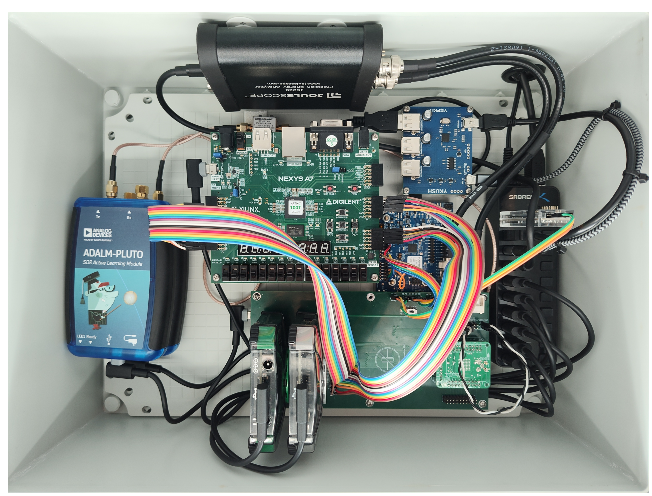

Figure 3: Top-down image of the inside of the observatory.

First, the rigid and protective enclosure allows for the transportation of a fully assembled testing environment to any location. The enclosure provides mounting options for all test equipment as well as the DUT. Rigid mounts improve the reliability of the testing environment. Once all connections are established, the observatory can be enclosed, preventing unintended errors that might arise from exposed cabling. A goal of the project is to facilitate automated testing. Automated testing is often performed unattended. So, it is key to ensure that the observatory's various testing devices remain connected while unattended to enable this goal.

In addition, the enclosed structure allows researchers to have greater control over the temperature of the testing environment. Consistent temperature is important, as highlighted in [4], temperature variations present challenges in radio communication. On-chip oscillators, which are sensitive to temperature fluctuations, can experience frequency drift when the temperature changes. The enclosed environment provides greater temperature stability for the DUT by reducing the effects of transient fluctuations in the room temperature by providing insulation.

3.2 The Devices

To achieve a modular, cost-effective, and automatable testbed for SCμM development, the observatory integrates a variety of USB-interfaced devices. Selection criteria included device compatibility with SCμM workflows, support for Python-based automation, and the availability of vendor APIs. Each device was selected to fulfill a distinct measurement or stimulus function, enabling flexible, scriptable testing across analog, digital, and RF domains.

3.2.1 Analog Discovery 2. The Analog Discovery 2 (AD2) was selected for its integrated dual-channel oscilloscope and waveform generator. Although the Analog Discovery 3 offers updated hardware, it was excluded due to incomplete support in the existing Python API at the time of development. Extending the API for AD3 functionality was determined to be out of scope for this project.

3.2.2 Digital Discovery. The Digital Discovery enables precise monitoring of digital signals and is used to observe GPIO activity and protocol-level interactions. It was integrated into the observatory for use cases that require accurate timing and multi-line digital capture.

3.2.3 Adalm-Pluto SDR. The ADALM-PLUTO SDR is used to stimulate and observe SCμM's RF transmissions and receptions. It provides a flexible, scriptable RF interface for conducting frequency sweeps, signal detection, and power-level measurements, making it suitable for evaluating the SCμM radio in a controlled environment.

3.2.4 JouleScope. JouleScope is used to monitor SCμM's power consumption during operation. It offers precision current and voltage measurement capabilities, enabling real-time profiling of SCμM's energy usage under different test scenarios.

3.2.5 YepKit USB Hub. The Yepkit programmable USB hub enables remote power cycling of the SCμM chip. This feature is critical for automating testing routines that require controlled resets or power state transitions.

3.2.6 nRF52840-DK Board. The Nordic nRF52840-DK board serves as both a power source, and a calibration [3] and programming interface for the SCμM chip. It allows the observatory to flash firmware and maintain power delivery during test cycles.

3.2.7 Nexys A7 FPGA. A Nexys A7 FPGA from Digilent was implemented in the observatory simply to provide end-users with FPGA capabilities. In this design, the FPGA is programmed such that the input ports are netted to corresponding output ports. This is done by writing the bitstream file to the onboard 128MiB DDR2 SDRAM, a non-volatile memory device, ensuring the FPGA is programmed correctly on each power-up.

3.3 The PCB

The observatory uses a custom PCB, created with KiCAD, to provide flexibility and ease of use by offering a standardized reconfigurable set of circuits to aid in the automated testing of SCμM. PCB source files are available in the GitHub repository link found at the end of this paper. Creating a standard circuit between the DUT and the observatory's various testing equipment helps reduce confounding errors between different tests or testing locations. The PCB layout provides easy-to-access connections for the Analog Discovery, Digital Discovery, JouleScope, Serial UART TTL device, nRF52840-DK, and an FPGA.

The observatory's PCB employs both manual and automated reconfiguration methods to provide a wide range of testing capabilities to researchers. It includes a set of USB-controlled MUXs that can route the Analog Discovery's two oscilloscope inputs to 32 different pins on Sulu. A single wave generator from the Analog Discovery can be routed to any of Sulu's 16 GPIO pins. A Raspberry Pi Pico development board is integrated into the PCB. This microcontroller unit (MCU) translates incoming commands into control signals. This MCU was chosen for its low cost, surface-mount capability, and drag-and-drop programming method. For power consumption measurements, the PCB uses pin headers with jumpers to select a voltage reference. A current consumption measurement loop can be constructed between a pair of pins and the Sulu development board.

Sulu's 16 GPIO pins can make permanent connections with the Digital Discovery's high-speed inputs. Along the connection path between Sulu's GPIO and the Digital Discovery is a 2x16 pin header that can break this connection. This header allows an FPGA to be connected in place of the Digital Discovery or in series with it. A jumper is used to create the direct connection to the Digital Discovery in the event that no FPGA is required. BNC connections are provided for secure connections with the JouleScope. The PCB also accommodates an option to omit the BNC connectors and substitute pin headers.

There are five sets of pin headers on the PCB, not including the previously mentioned headers used for the FPGA connection and JouleScope configuration. The first header labeled "5V_in" is one of the two options available to power the PCB, labeled "V_op+." A switch labeled "Observatory Power V_op+ Select" can be set to select this "5V_in" source or the DC+ supply of the Analog Discovery. The second is a header labeled "nRF_Connections." All connections from the nRF52840-DK programming board are found here. Third, a header labeled "Serial" breaks out the Sulu RsTx and

RsRx pins with the serial UART TTL device. The fourth, labeled "Sulu Header," makes available the Sulu J1 header. This header is used in conjunction with jumpers to configure various inputs on SCμM. It is on this header that current loops can be formed with the 1.1V and 1.8V supplies using jumper wires. The fifth header, labeled "GPIO Expand" provides access to all 16 GPIO pins as well as the 1.8V source on Sulu and the "V_op+" power source provided to the Observatory.

The PCB, in conjunction with the various programmable testing equipment, allows fully automated programming and testing of SCμM through the Sulu development board. Using this hardware platform with the provided example scripts, a test can be created that will download a pre-compiled binary file, upload the binary to SCμM, and then evaluate the devices performance.

3.4 Development Environment

The current development environment for the SCμM observatory is based on Python and operates on a Windows host system. Python was selected for its accessibility, readability, and wide-spread adoption within the research community. All test procedures and scripts are written in Python.

To interface with measurement and test equipment, vendor-provided Python libraries were utilized whenever possible. However, an exception was encountered with the Digilent Analog Discovery 2 (AD2). The available Python API did not support the full range of required features. As a result, certain AD2 functionalities were accessed via the Digilent WaveForms C-based SDK, interfaced through Python using the ctypes module. This hybrid approach allowed the team to maintain a Python-based testing framework while still leveraging lower-level hardware control when necessary.

For tests involving control of the SCμM chip, C was used in conjunction with the Keil compiler to flash SCμM. This multi-language approach ensures that the observatory remains flexible and compatible with the SCμM platform while enabling comprehensive automation of test routines.

4 Tests

Users are expected to develop their own test scripts tailored to specific experimental needs, leveraging the provided Python APIs and example scripts. To demonstrate the observatory's capabilities and to serve as references for future users, two representative test scripts were developed. These scripts highlight different modes of operation and measurement scenarios supported by the platform.

4.1 Validation Test

The validation script evaluates key functionalities of the SCμM chip by executing a custom test program in conjunction with a suite of four observatory-defined tests. These tests assess the SCμM's capabilities in GPIO operation, serial communication, and RF transmission. Additionally, they validate the accuracy of both the high-frequency (HF) and low-frequency (LF) on-chip clocks, as well as the internal voltage reference (V_{ref}) levels. Throughout the testing process, power consumption is monitored using a JouleScope to capture voltage and current behavior over time. A detailed breakdown of each test is provided in the following subsections.

4.1.1 Analog Test. The analog test verifies the performance of SCμM's analog subsystems. It begins by using the Analog Discovery 2 (AD2) oscilloscope to measure the internal reference voltages, confirming that the 1.1V and 1.8V rails fall within ±0.1 V of their expected values. The test then proceeds to validate the high-frequency (HF) and low-frequency (LF) on-chip clock outputs using the AD2's measurement capabilities, ensuring that both oscillators operate within ±40 ppm of their nominal frequencies.

4.1.2 GPIO Test. Digital I/O functionality is verified using a pulse-based validation procedure implemented with the Digilent Digital Discovery. Upon initiation, the SCμM chip outputs a pulse across its digital I/O pins. The Digital Discovery's logic analyzer captures these signals over a fixed observation window. Each pin is individually evaluated and considered functional if it maintains a high logic level for a predefined duration, confirming proper output behavior and signal integrity.

4.1.3 Serial Baud Rate Test. Due to inherent process variations in SCμM's silicon fabrication, slight deviations in serial communication timing may occur, requiring per-die baud rate calibration. To characterize these discrepancies, a serial baud rate validation test was developed. In this test, a host computer transmits a character to the SCμM chip via an SH-U09C5 USB-to-TTL UART converter across a sweep of standard baud rates. For each rate, if the SCμM correctly echoes the received character, that baud rate is marked as compatible. This procedure enables identification of the subset of baud rates reliably supported by a specific SCμM instance.

4.1.4 RF Test. RF testing within the observatory is comprised of two separate tests. The first test validates the expected functionality of both the transmitting and receiving Adalm-Pluto SDRs and reports the efficacy of the devices by verifying a predetermined control signal was both accurately transmitted and received. Due to the bandwidth of the Adalm-Pluto RF receiver being just 20MHz, the second test works in tandem with SCμM to ensure the Adalm-Pluto's LO is adjusted accordingly to effectively monitor its RF transmission performance, then reports the results to the user both graphically and numerically. SCμM's transmitter is controlled by three 5-bit Digital to Analog Converters (DAC(s)) – coarse, mid, and fine. During this test the transmitter increments through each of the triplet-pair DAC codes comprising the 802.15.4 wireless communication standard, transmits 480 packets containing all zeros at each frequency, and sends a trigger pulse to indicate to the development environment that the next carrier frequency is being transmitted, prompting the Adalm-Pluto LO to adjust. Each time a trigger pulse is detected, the Adalm-Pluto receives the transmitted signal data as complex pairs, a Fourier transform is performed to identify the received carrier frequency, and the discerned tone is assigned with the corresponding DAC triplet-pair values, effectively creating a look up table. This is presented to the user in the results report for a qualitative analysis of the transmission performance of SCμM. Additionally, a .csv file is generated including the exact measured frequency information for the user to review more thoroughly. Users interested in observing ranges other than the 802.15.4 standard may do so by implementing the corresponding increments to the compiled binary as well as modifying the incrementing variables in the RF Test loop for their desired operating range.

4.1.5 Power Monitoring. Power monitoring during validation is performed using the JouleScope. At the start of the test, the JouleScope begins recording voltage and current data, continuously capturing measurements throughout the execution of the script. After the validation sequence completes, the collected data is parsed to extract average, minimum, and maximum power values. These results provide insight into SCμM's operational power behavior under test conditions.

4.2 Nightly Test

To demonstrate the observatory's utility in a continuous integration and validation workflow, a Nightly Test script was developed. At a user-defined interval, this script queries a specified Git repository for a configurable list of SCμM binaries. If changes are detected in any of the tracked binaries, the updated binary is automatically retrieved, flashed onto the SCμM chip, and subjected to the analog validation test. Test results are compiled into a report and delivered to the user via email, enabling automated regression detection and early identification of performance drift.

5 Results

The result of this work is a unified testing configuration designed primarily to perform routine testing of SCμM's performance. Additionally, the observatory is capable of facilitating user-defined experiments. After assembling the observatory, the user only needs to edit the configuration file to match the USB device connections and run a few command-line commands to complete the observatory setup. Once the setup process is complete, the user can expect to be provided results of how SCμM is performing in a comprehensive HTML report at their selected interval, and may elect for this report to be emailed to an account of their choice. Below are example results of what a user of this observatory may expect to be provided with.

5.1 Radio Self-Test

The results of the radio self-test inform the user that the radio equipment within the observatory are operating correctly by reporting back the BER along with associated frequencies and power levels. For any instances where the BER is not zero, the test fails, ending the validation script and prompting the user to verify the radio devices.

Radio(RF)	Passed
Bit-Error-Rate (BER)	0.0
Set Transmission Freq.	2.405 GHz
Actual Transmission Freq.	2.405 GHz
Received Freq.	2.405 GHz
Abs. Freq. Offset	1457.8 Hz
Set Tx Power Gain	-20 dB
Transmitted Power (PSD)	84.29
Received Power (PSD)	81.61
Abs. Power Offset	2.68

Table 1: Summary of radio hardware self-test results, focusing on frequency accuracy and transmission power.

5.2 Program Upload

The results of the program upload test inform the user whether or not the binary file was correctly programmed to SCμM. If the program was not correctly programmed, the test fails, ending the validation script and informs the user that the program did not load successfully.

5.3 Radio Communication

The results of the radio communication test inform the user of the operating transmission frequencies of SCμM based on the triplet pairs for the DAC controlling its radio. This plot provides a qualitative method of ensuring SCμM's radio is functioning correctly, and the user should refer to the provided .csv for exact frequencies observed. The below plot was generated based on the base test that increments the coarse and mid DACs to operate at ranges defined by the 802.15.4 range.

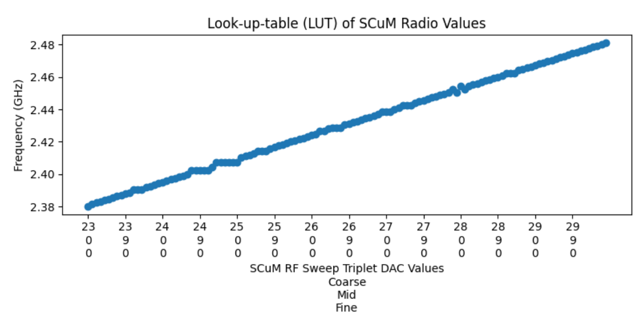

Figure 4: Look-Up-Table (LUT) of SCμM's transmission frequency for corresponding DAC triplet pairs.

5.4 Digital Input/Output

The results of the digital input and output test inform the user of the performance of SCμM's GPIO pins. Pins are toggled in an ascending pattern starting from GPIO 0, and if any of the pins do not provide a pulse signal, the pin is deemed to have failed. An individual pin that fails does not warrant the test to halt.

5.5 Analog Validation

The results of the analog verification test inform the user of the voltage references found on SCμM, as well as the LF and HF clock signal frequencies. Any measurements falling outside of the acceptable range results in a fail status. For these measurements, a failing status does not warrant the test to halt.

Analog Validation	Failed
1.1V Reference Voltage	Passed
Measured Voltage (V)	1.112
1.8V Reference Voltage	Failed
Measured Voltage (V)	2.177
HFCLK Clock Signal	Failed
Measured Frequency (Hz)	111728.1
ppm	-994413.6
LFCLK Clock Signal	Failed
Measured Frequency (Hz)	145310.0
ppm	-992734.5

Table 2: Summary of voltage and clock reference results.

5.6 Serial Communication

The results of the serial communication test inform the user of the baud rate associated with SCμM. A failing status for this test indicates serial communication with SCμM was not confirmed.

Serial Communication	Passed
300 BPS	Failed
9200 BPS	Failed
19200 BPS	Passed
38400 BPS	Failed
57600 BPS	Failed
115200 BPS	Failed
230400 BPS	Failed
460800 BPS	Failed
921600 BPS	Failed

Table 3: Summary of serial baud rate results.

5.7 Power Consumption

The results of the power consumption test inform the user of the power consumed during the operation of the validation script. This test does not feature a traditional pass or fail result as it has been implemented simply for monitoring the power consumption of the observatory.

Power Consumption	Passed
Voltage Average (V)	1.123
Voltage Minimum (V)	1.121
Voltage Maximum (V)	1.124
Current Average (mA)	0.061
Current Minimum (mA)	0.012
Current Maximum (mA)	0.080

Table 4: Summary of power consumption results.

6 Conclusion

The completion of the SCμM observatory furnishes the first iteration of a standardized testbed for analyzing the chips complete performance. Research labs worldwide are interested in using SCμM and further developing the SoC, but converging on congruent results has proven difficult due to discrepancies in testing equipment and configurations. The observatory was designed to be simple, yet robust, through rigorous testing of off-the-shelf USB instrumentation. By use of the observatory, more reliable SCμM performance results may be acquired. A significant attribute of this design is its low-cost when compared to the typical price associated with chip development suites. This was achieved by use of low-cost USB devices and optimizing them for the expected outputs SCμM was designed for. Furthermore, the observatory is configured such that its users may elect to have routine tests performed on the cadence of their choice, as well as elect for the results report to be emailed directly to them. The culmination of this work yields the first complete test suite designed for SCμM, and provides a central base in which future permutations may be designed for more focused SCμM performance studies. Future work may be done to implement the monitoring of environmental factors such as temperature and humidity, which prove to have a significant impact on the performance of SCμM.

GitHub

For more detailed information regarding this work including code, PCB schematics, BOM, etc., please refer to the GitHub link below.

https://github.com/HailStorm32/WEST-Lab-Capstone

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