Cureus Journal of Engineering
https://doi.org/10.7759/s44388-025-00039-6

Original Article

Automated Serial Peripheral Interface-Enabled Test Validation and Characterization Environment

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Received: August 26, 2025 | Review began: September 08, 2025 | Review ended: February 21, 2026 | Published: March 22, 2026

Abstract

Ensuring the stability and precision of voltage references is critical in the domain of automotive electronics, where consistent analog-to-digital conversion is essential. Zener diodes, commonly employed as voltage reference sources, suffer from thermal instability, which can degrade the overall system accuracy. Traditional validation methods are often manual, time-consuming, and susceptible to human error. This paper presents a fully automated test and validation framework that integrates Standard Commands for Programmable Instruments-based control of instrumentation with Serial Peripheral Interface-based communication between embedded microcontrollers. The system is capable of performing comprehensive temperature-based characterization of Zener references. Furthermore, a digital correction algorithm is implemented to mitigate temperature-induced voltage deviations. Curve-fitting techniques are used to model thermal behavior, and Horner's method is adopted to optimize the computational efficiency of the correction function. The corrected values are validated against actual measurements to confirm improved voltage stability. The results demonstrate the framework's potential for rapid, accurate, and repeatable validation of reference components in automotive environments, offering significant advancements in both test automation and system reliability. Experimental validation was performed on multiple Zener-based reference sources across a temperature range of -40°C to +125°C. The uncorrected voltage references exhibited thermal drift in the range of ±8-10 mV, corresponding to a stability variation of approximately ±0.12%. After applying the proposed digital correction algorithm, the residual drift was reduced to ±1.5 mV, achieving an improvement factor of nearly 6×. Curve-fitting and Horner's method-based polynomial evaluation reduced computational complexity by ~40% compared to conventional polynomial implementations, enabling efficient real-time execution on resource-constrained embedded controllers. Overall, the automated framework achieved >95% repeatability across repeated test cycles, while reducing manual intervention time by more than 70% compared to traditional validation methods.

Categories: Electronics Design and VLSI, Embedded Systems and IoT, Automotive Safety and Crashworthiness

Keywords: test automation, spi communication, temperature compensation, horner's method, automotive electronics

Introduction

Accurate and stable voltage regulation across varying thermal environments is a critical prerequisite in the design of high-reliability electronic systems, particularly those interfacing with precision analog front ends, high-resolution data converters, and temperature-sensitive sensor arrays [1]. Zener diodes, widely employed as voltage reference elements or overvoltage protection devices, exhibit inherent temperature-dependent behavior, most notably, a measurable drift in their breakdown voltage with ambient temperature variations [2]. If left uncompensated, this thermal susceptibility can

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introduce significant deviations in the reference voltage, thereby degrading the integrity of downstream signal acquisition and processing blocks in applications such as precision instrumentation, automotive electronic control units, and calibration-grade metrology platforms.

Traditional mitigation strategies typically rely on empirical correction factors or temperature-compensated biasing circuits [3]. While effective in limited scenarios, these approaches are constrained by low adaptability and limited resolution, particularly in dynamic environments with rapid or unpredictable thermal fluctuations. Furthermore, reliance on manual testing procedures often introduces latency and operator-induced variability, making such methods unsuitable for high-throughput validation pipelines.

To overcome these limitations, we propose an integrated characterization and compensation framework that combines automated thermal-electrical measurement, high-speed digital communication, and embedded algorithmic correction. The experimental setup utilizes programmable thermal forcing systems to impose controlled temperature gradients on the device under test (DUT), while precision digital multimeters (DMMs) or source measure units (SMUs) capture the corresponding voltage response with sub-millivolt accuracy. This acquisition process is fully automated using Standard Commands for Programmable Instrument (SCPI)-compliant control scripts, enabling rapid thermal cycling and real-time data collection without human intervention [4].

On the digital processing front, the system architecture incorporates a microcontroller platform equipped with a high-speed Serial Peripheral Interface (SPI). This interface facilitates real-time emulation of analog-to-digital converter (ADC) behavior, enabling low-latency data transfer and efficient downstream signal processing. The acquired voltage temperature pairs are analyzed using curve-fitting techniques such as high-order polynomial regression or piecewise linear interpolation to generate a mathematical model of the diode's thermal response. These models are subsequently embedded in firmware, allowing the system to apply real-time voltage correction based on live temperature readings from integrated sensors [5].

The resulting closed-loop, self-calibrating reference module can adapt to instantaneous thermal variations with minimal latency and high accuracy. This approach not only improves the thermal stability of Zener-based voltage references but also enables scalable deployment in mission-critical domains including aerospace systems, medical instrumentation, and autonomous vehicle platforms where predictable analog behavior is indispensable. By transitioning from static correction paradigms to a dynamically adaptive compensation framework, the proposed methodology significantly enhances voltage reference fidelity under real-world operating conditions, thereby extending the operational range and long-term reliability of temperature-sensitive electronic subsystems [6].

Materials And Methods

Python automation for Zener characterization

The proposed methodology involves the development of a fully automated test framework using Python to characterize Zener diodes across a range of temperatures. The automation is achieved through the use of SCPI (Standard Commands for Programmable Instruments) to interface with both the Keithley 6.5-digit DMM and the Therostreamer temperature chamber, as shown in Figure *1*. It is concluded that these medium-term deviations limit the predictability of a voltage standard's output. Python scripts are used to remotely control the test environment setting specific temperature points, initiating stabilization delays, and triggering precise voltage measurements from the test chip. These measurements are then automatically logged into an Excel sheet, allowing data collection for different Zener trim codes and temperature values without manual handling. This automation greatly improves the efficiency, accuracy, and repeatability of the validation process, enabling high-throughput data acquisition that supports further stages such as digital correction algorithm development and SPI-based system-level testing [7].

- Use SCPI commands to control DMM (6.5-digit) and Thermostreamer remotely via Python scripts.

- Establish communication over GPIB/LAN using libraries like PyVISA.

- Set temperature via Thermostreamer.
- Take voltage measurements from the test chip using the DMM.
- Log data into an Excel sheet.
- Integrate temperature vs. voltage data for multiple Trim Codes.
- Optimize Python code for minimal human intervention and increased test efficiency.

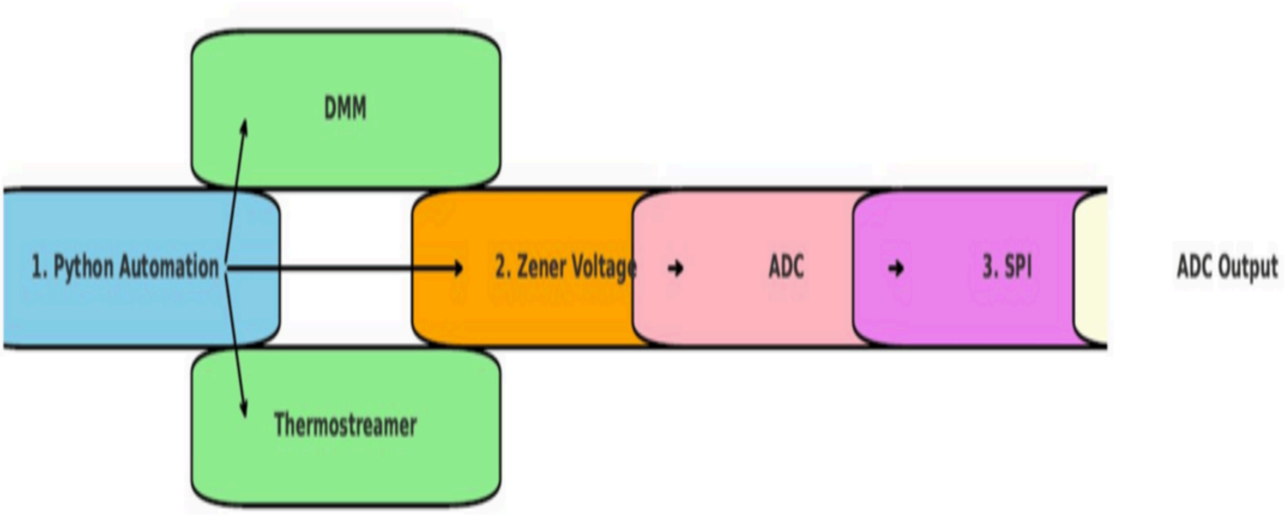

FIGURE 1: Proposed Methodology of Test Setup

DMM, Digital Multimeter; ADC, analog-to-digital converter; SPI, Serial Peripheral Interface

SPI master-slave test setup for ADC data transfer

The SPI operates as a synchronous data bus, employing distinct lines for data transfer and a dedicated clock signal to maintain synchronization between communicating devices. In this project, the SPI-based data transfer system is implemented to emulate real-time communication between an ADC and a processor, utilizing two STM32F446RE microcontrollers one configured as the SPI Master and the other as the Slave. A 4.5 MHz Data Ready pulse generated by the Slave triggers an interrupt on the Master, signaling the availability of ADC data as shown in Figure *2*. Upon detecting the falling edge of this pulse, the Master asserts the Slave Select (NSS) line low, thereby initiating the SPI transaction. During this transaction, the Master transmits a command byte (0x01) via the MOSI line, and the Slave responds with a simulated ADC data byte (0xA5) via the MISO line. The implementation supports both 8-bit and 16-bit data frames, with the SPI configured through register-level bare-metal C code. The system clock of the microcontroller was set to 92 MHz, while the SPI peripheral was operated at a clock frequency of 11.5 MHz [8-10].

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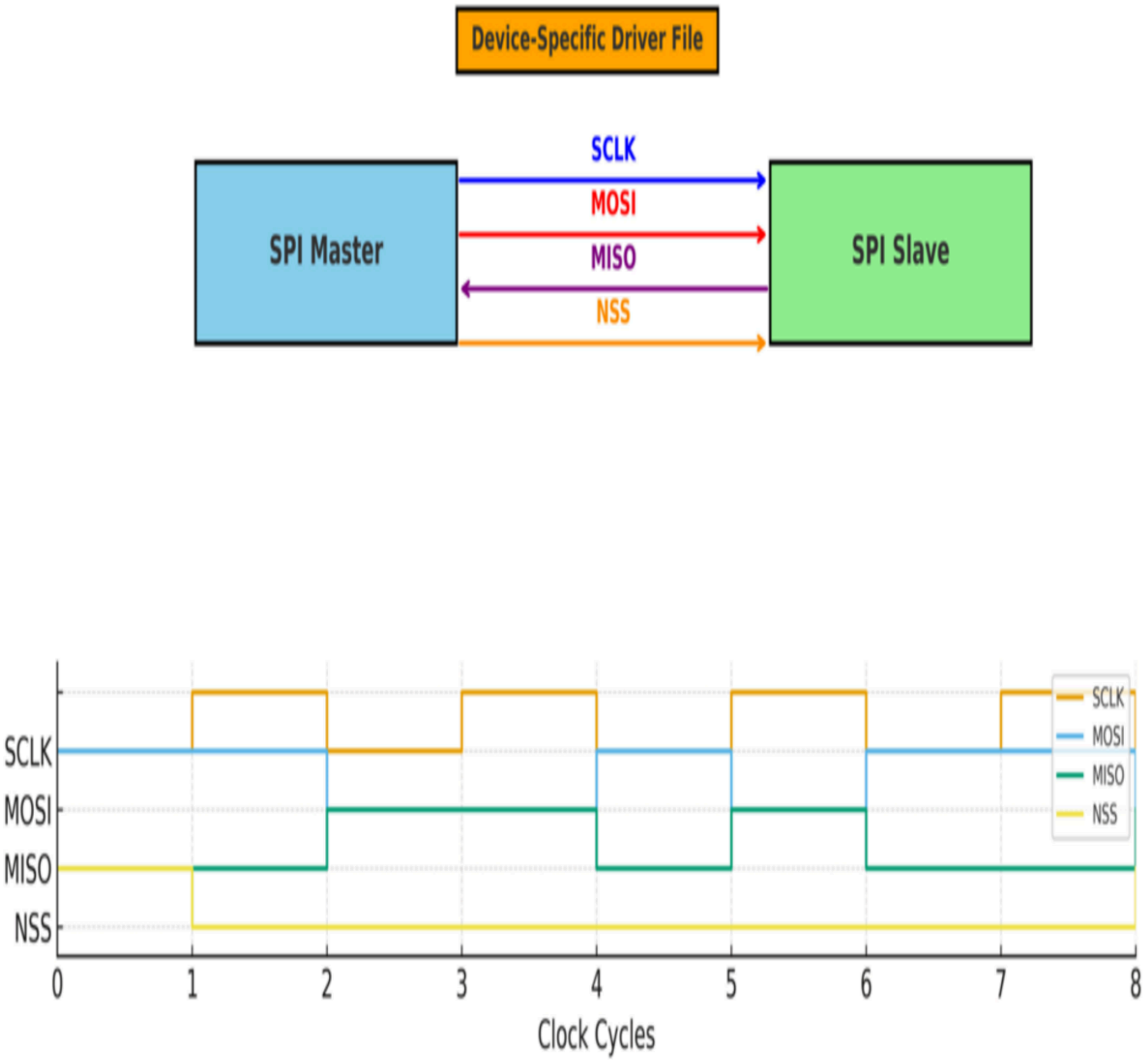

FIGURE 2: Software Stack for SPI Driver Implementation

SPI, Serial Peripheral Interface

SPI using Direct Memory Access (DMA)

A Direct Memory Access (DMA) Controller solves this by allowing I/O devices to transfer data directly to memory, reducing CPU involvement. In the context of SPI-based ADC data transfer, DMA is implemented to enhance the speed and efficiency of communication between the Master and Slave microcontrollers. Without DMA, the CPU is required to continuously poll the SPI status registers (TXE and RXNE) to transmit and receive data, introducing a latency of around 0.28 microseconds per transaction. By using DMA, the SPI peripheral automatically transfers data between memory and the SPI data register without CPU intervention, as shown in Figure *3*.

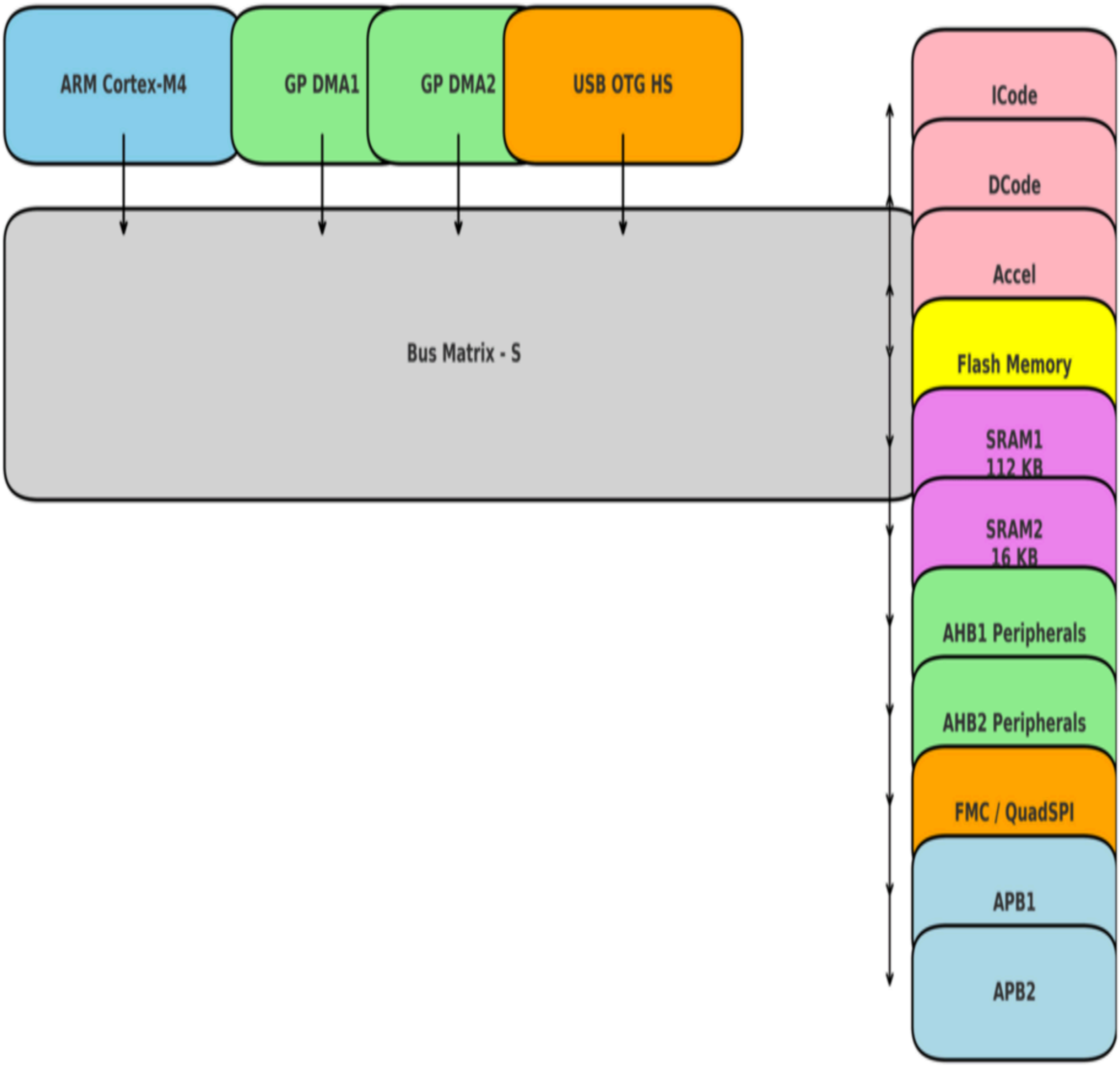

FIGURE 3: DMA Along with Cortex-M4 Core and Other Peripherals

DMA, Direct Memory Access

This enables continuous, high-speed data transfer in the background while the CPU performs other tasks or remains idle, significantly reducing processing overhead, eliminating latency, and supporting a more real-time and responsive system that is ideal for high-frequency ADC data acquisition and validation environments.

Piecewise polynomial fitting and Horner's method

To correct the temperature-induced drift in Zener voltage, a piecewise polynomial curve fitting approach is implemented. The measured voltage data across various temperature points is divided into multiple segments, each covering a specific temperature range (e.g., 0-59°C, 60-119°C) as shown in Figure 4.

For each segment, a second-order polynomial is fitted to model the voltage variation, and the polynomial coefficients are stored in a Lookup Table (LUT). During runtime, the current temperature is used to select the appropriate segment, and the corresponding polynomial is evaluated to compute the corrected voltage. This segment-wise fitting provides higher accuracy compared to a single global polynomial and is well-suited for hardware-based implementation in embedded systems.

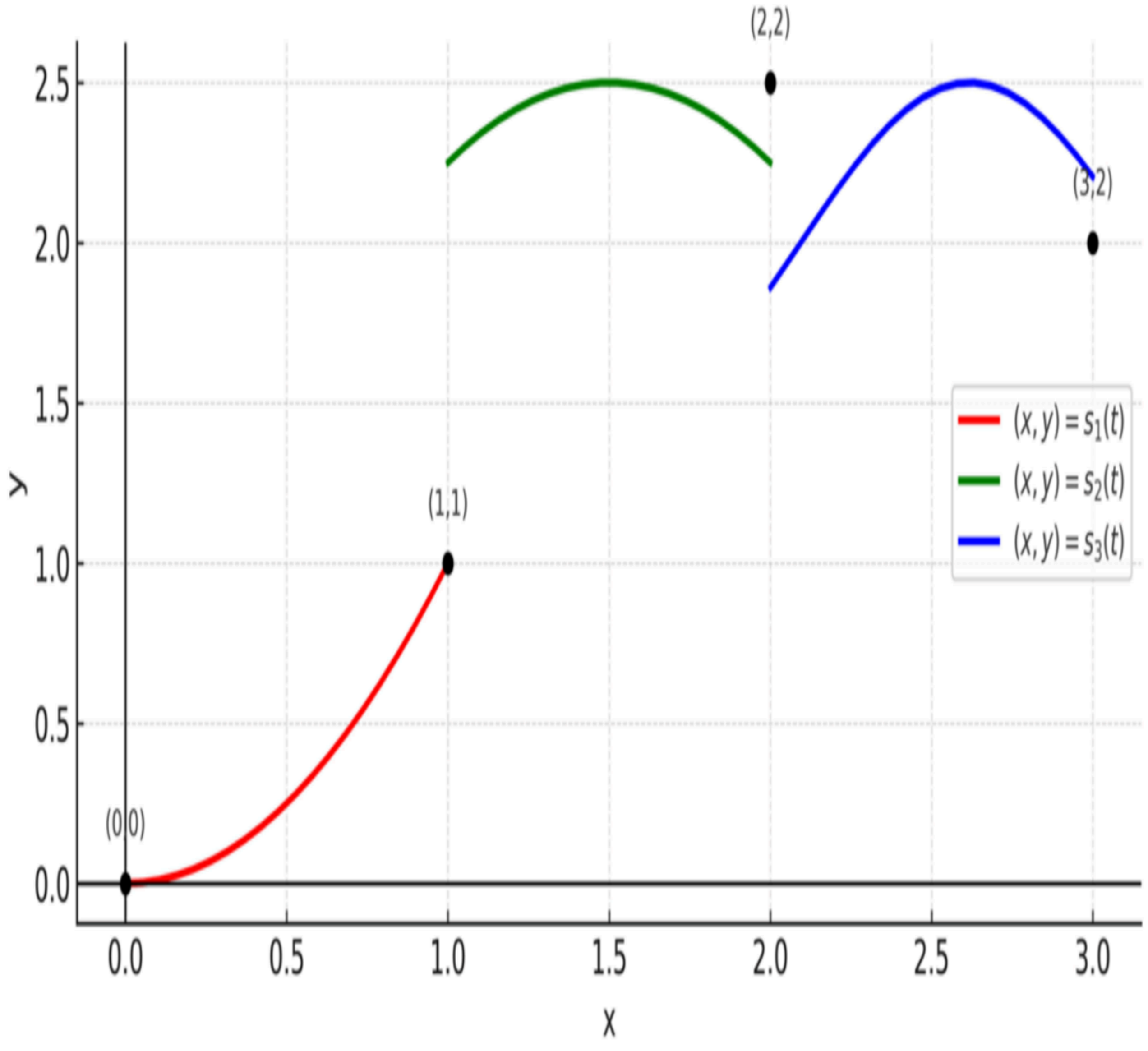

FIGURE 4: Piecewise Polynomial Curve Fitting for Accurate Temperature Compensation

To enhance the computational efficiency of polynomial evaluation, Horner’s Method is implemented for the temperature compensation algorithm, instead of using the standard quadratic form, reducing the number of required multiplications and additions. This method not only speeds up software-based evaluation in Python and embedded C but also minimizes logic gate usage in hardware implementations such as FPGA or ASIC. Horner’s Method results in lower latency, reduced power consumption, and improved numerical stability, making it an optimal choice for real-time, resource-constrained applications in automotive validation systems.

Software and hardware used

The development and testing workflow in this project relied on a carefully chosen suite of software tools tailored for both embedded and automation tasks. STM32CubeIDE was used as the primary environment for firmware development on the STM32F446RE microcontroller. It enabled bare-metal programming, peripheral configuration, and register-level debugging essential for SPI protocol testing. For the automation layer, PyCharm served as the integrated development environment for writing Python scripts that controlled external instruments using SCPI commands. This scripting enabled synchronized data acquisition and thermal cycling. Additionally, Verilog code was developed and tested using tools such as Cadence, Yosys, and GTKWave for digital logic simulation and waveform analysis, particularly for prototyping future FPGA-based acceleration modules.

In terms of data management, Microsoft Excel was integrated into the Python automation flow for seamless data logging. The real-time voltage readings from the DMM were captured and formatted into Excel sheets for easy post-processing and visualization. This setup provided a low-friction way to analyze large volumes of data collected during temperature sweeps or SPI-based measurements. By exporting time-stamped measurements directly into structured formats, the process of correlation and validation became significantly more efficient, especially during debugging or test case reviews.

On the hardware front, the project utilized several key instruments. A Keithley DMM was the primary tool for capturing high-accuracy voltage or current values from the device under test. Temperature variation was applied using a Theriostreamer, capable of delivering controlled air flows ranging from -40°C to +150°C, thereby simulating real-world environmental conditions. For embedded protocol validation, STM32F446RE Nucleo boards were used in master-slave SPI configurations to implement and test custom data exchange schemes. This hardware setup enabled closed-loop testing of the system’s responsiveness and reliability across a wide range of operating conditions.

Zener characterization using Python automation scripts

The implementation of Zener characterization is carried out using Python scripts integrated with SCPI (Standard Commands for Programmable Instruments) to control and communicate with the Keithley 6.5-digit DMM and the Thermostreamer. Shunt mode references are typically less accurate than Series mode, but require lower operating current. The Python automation script sets the desired temperature point on the Thermostreamer, waits for stabilization, and then triggers the DMM to measure the Zener voltage from the test chip. In the Zener characterization setup, Python acts as the central automation tool that interfaces with both the test instruments and data logging systems.

Using libraries like PyVISA and openpyxl or pandas, Python scripts send SCPI commands to control devices such as the Keithley DMM and the Thermostreamer. These scripts automate the process of setting temperature points, waiting for thermal stabilization, and then capturing the corresponding Zener voltage from the test chip, as shown in Figure *5*.

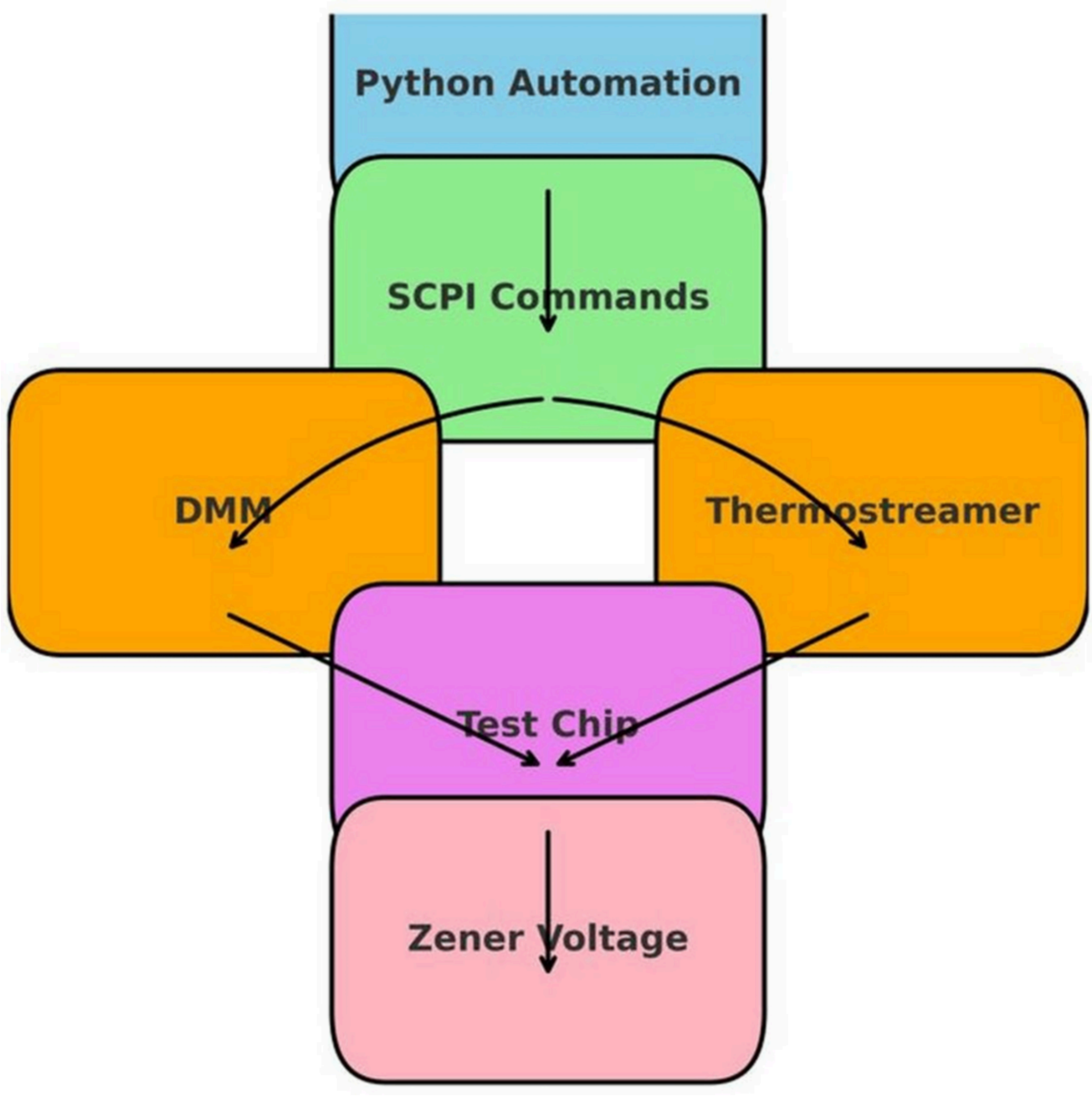

FIGURE 5: DMM and Thermostream Automation Implementation Flow

DMM, Digital Multimeter

The results are logged in real-time into an Excel sheet for further analysis. This process is repeated for a range of temperature points and various trim code values, allowing automated collection of voltage-versus-temperature data without manual intervention. This setup ensures high efficiency, repeatability, and accuracy in characterizing the temperature-dependent behavior of Zener diodes.

Data ready enabled SPI master-slave communication

To emulate real-time ADC communication behavior, a dedicated SPI link is established between two STM32F446RE microcontroller boards, where one board functions as the SPI Master and the other as the SPI Slave. This setup is used to simulate an ADC-to-processor data transmission scenario. The SPI Slave board is configured to generate a 4.5 MHz "Data Ready” (DRDY) pulse, a digital signal that informs the Master that fresh ADC-like data is now available and ready to be read. The DRDY signal is connected to a GPIO pin configured as an interrupt input on the Master board. The Master continuously monitors this pin and is programmed to detect the falling edge of the DRDY pulse. When a falling edge is detected (i.e., a transition from high to low), it triggers an external interrupt on the Master, prompting it to begin an SPI communication sequence.

Immediately upon recognizing the DRDY falling edge, the Master drives the NSS (Slave Select) line low, which selects the SPI Slave and enables the data exchange process. This manual NSS handling allows precise control over the communication window and ensures that the Slave is ready to transmit valid data. During the SPI transaction, the Master sends a command byte (e.g., 0x01) over the MOSI (Master Out Slave In) line. Simultaneously, the Slave, which has preloaded simulated ADC data (e.g., 0xA5) into its SPI data register, responds by sending this value over the MISO (Master In Slave Out) line. The SPI is configured in full-duplex mode, allowing both transmission and reception to occur simultaneously over a shared clock (SCLK), which is generated by the Master as shown in Figure *6*.

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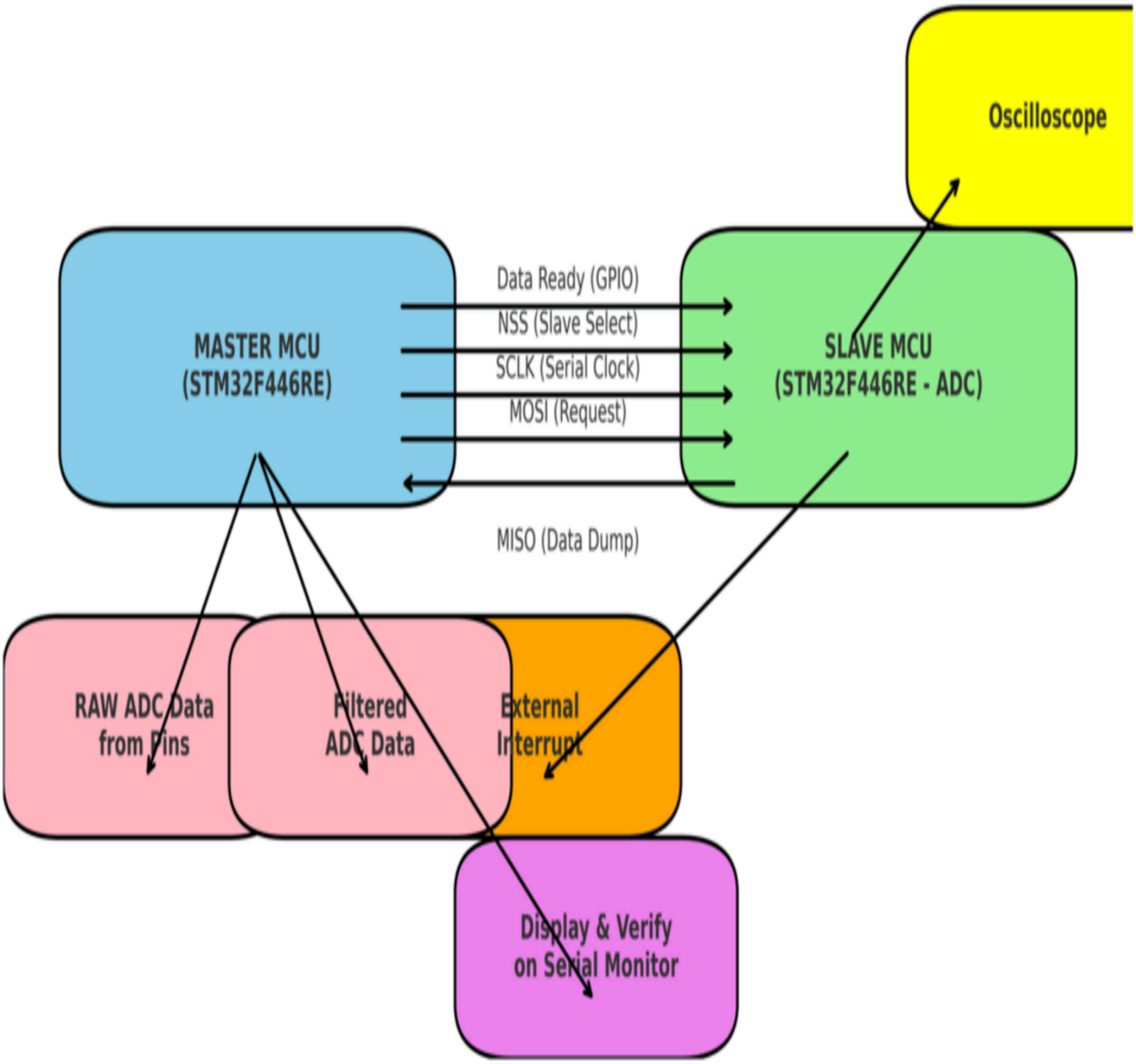


FIGURE 6: SPI Master Slave Implementation

During the transaction, the Master sends a command byte (e.g., 0x01), and the Slave responds with a predefined ADC data byte (e.g., 0xA5). The SPI communication is handled using register-level C code with appropriate initialization of SPI pins, clock settings, and control registers, ensuring accurate and synchronized full-duplex data exchange. This method mimics actual hardware ADC behavior and supports real-time system-level validation.

SPI using DMA

As a high-speed, full-duplex, synchronous serial bus, the SPI bus has been widely used in the field of communication. To optimize the performance of SPI data transfers, DMA is implemented in the STM32 microcontroller setup. The DMA controller is configured to automatically handle data movement between memory and the SPI data register without CPU involvement. For transmission, data is fetched from memory and pushed to the SPI peripheral when the transmit buffer is empty; for reception, incoming data is captured and written directly to memory once the receive buffer is full. This eliminates the need for CPU polling of SPI status flags, which previously caused a latency of 0.28 microseconds. The DMA-based implementation improves system efficiency, supports high-speed data dumping, and ensures non-blocking, continuous SPI communication ideal for real-time validation workflows.

Piecewise polynomial curve fit for temperature compensation

To correct the temperature-induced drift in Zener voltage, a piecewise polynomial curve fitting approach is implemented. The measured voltage data across various temperature points is divided into multiple segments, each covering a specific temperature range (e.g., 0-59°C, 60-119°C). For each segment, a second-order polynomial is fitted to model the voltage variation, and the polynomial coefficients are stored in a LUT. During runtime, the current temperature is used to select the appropriate segment, and the corresponding polynomial is evaluated to compute the corrected voltage. This segment-wise fitting provides higher accuracy compared to a single global polynomial and is well-suited for hardware-based implementation in embedded systems.

Horner’s method for improving system efficiency

To enhance the computational efficiency of polynomial evaluation, Horner’s Method is implemented for the temperature compensation algorithm. Instead of using the standard quadratic form $V = T(aT + b) + c$, reducing the number of required multiplications and additions. This method not only speeds up software-based evaluation in Python and embedded C but also minimizes logic gate usage in hardware implementations such as FPGA or ASIC.

Naive Polynomial Evaluation:

$$P(t) = at^2 + bt + c \tag{1}$$

Horner’s Method:

$$P(t) = t\,(at + b) + c \tag{2}$$

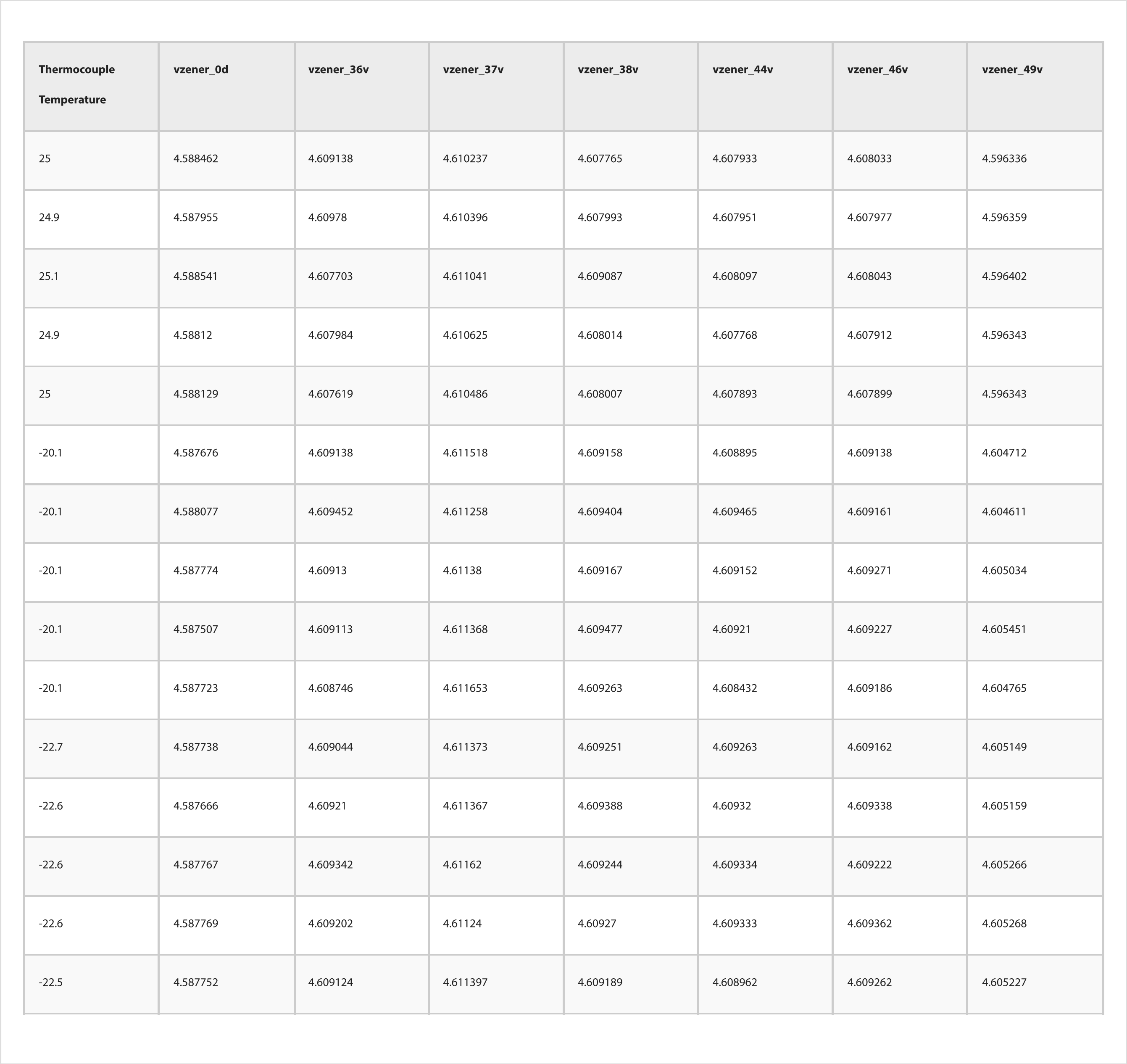
Horner’s Method results in lower latency, reduced power consumption, and improved numerical stability, making it an optimal choice for real-time, resource-constrained applications in automotive validation systems. Both floating- and fixed-point implementations can be improved using Horner’s method, as it requires fewer clock cycles. The complete test setup must be cohesively integrated and validated to ensure seamless data acquisition and control across all subsystems - namely, thermal characterization, ADC reference voltage supply, analog-to-digital conversion, and SPI-based digital communication. This integration phase is critical for identifying and mitigating any latency, signal-integrity issues, or synchronization errors that may be introduced during the transition from analog-domain measurements to digital data logging. In practice, the characterization system driven by Python automation regulates the thermal cycling through the Thermostreamer while simultaneously capturing high-resolution voltage readings from the DUT via a precision DMM. Once the analog reference voltage is applied to the ADC, the resulting digital output is transmitted via the SPI protocol to an STM32-based microcontroller system. Any delay or corruption in this transmission, particularly at higher SPI clock speeds or under temperature-induced stress conditions, could compromise the fidelity of the measured data. Therefore, real-time monitoring of the SPI data frames, coupled with timestamped analog readings, is essential to ensure data consistency and timing correctness. Furthermore, cross-verification between the analog values logged by the DMM and the digitized ADC outputs helps quantify the system’s accuracy and stability under varying operating conditions, ultimately determining the robustness and reliability of the entire measurement chain.

Results And Discussion

Python automation data logging with SCPI commands

The Zener voltages obtained from the test chip can be systematically recorded across a wide range of temperatures and multiple trim code configurations by leveraging a fully automated Python-based framework. Each trim code, corresponding to a unique register setting in the chip, results in a different Zener output voltage. By integrating SCPI commands with Python scripts, this process becomes hands-free, allowing for precise control of both the temperature chamber (Thermostreamer) and the DMM without manual intervention.

As the temperature is swept across defined intervals (e.g., from -40°C to +150°C), the Python script triggers the DMM to measure the voltage after each stabilization period. These measurements, tagged with temperature and trim code metadata, are automatically logged into an Excel sheet using libraries like openpyxl or pandas. This not only accelerates the entire characterization workflow but also ensures repeatability, data consistency, and easy post-processing, significantly reducing human error and labor, while enabling high-throughput validation for production-scale testing. Hence, after running the Python Code, the Excel sheet is generated with the voltage measured at the set temperature point. The temperature is also controlled with the help of Python Automation scripts for the Thermostreamer as shown in Table *1*.



Thermocouple Temperature	vzener_0d	vzener_36v	vzener_37v	vzener_38v	vzener_44v	vzener_46v	vzener_49v
25	4.588462	4.609138	4.610237	4.607765	4.607933	4.608033	4.596336
24.9	4.587955	4.60978	4.610396	4.607993	4.607951	4.607977	4.596359
25.1	4.588541	4.607703	4.611041	4.609087	4.608097	4.608043	4.596402
24.9	4.58812	4.607984	4.610625	4.608014	4.607768	4.607912	4.596343
25	4.588129	4.607619	4.610486	4.608007	4.607893	4.607899	4.596343
-20.1	4.587676	4.609138	4.611518	4.609158	4.608895	4.609138	4.604712
-20.1	4.588077	4.609452	4.611258	4.609404	4.609465	4.609161	4.604611
-20.1	4.587774	4.60913	4.61138	4.609167	4.609152	4.609271	4.605034
-20.1	4.587507	4.609113	4.611368	4.609477	4.60921	4.609227	4.605451
-20.1	4.587723	4.608746	4.611653	4.609263	4.608432	4.609186	4.604765
-22.7	4.587738	4.609044	4.611373	4.609251	4.609263	4.609162	4.605149
-22.6	4.587666	4.60921	4.611367	4.609388	4.60932	4.609338	4.605159
-22.6	4.587767	4.609342	4.61162	4.609244	4.609334	4.609222	4.605266
-22.6	4.587769	4.609202	4.61124	4.60927	4.609333	4.609362	4.605268
-22.5	4.587752	4.609124	4.611397	4.609189	4.608962	4.609262	4.605227

TABLE 1: Excel Sheet Generated by Python Automation for Zener Voltage Measurement

SPI master-slave ADC data transfer

The communication between the SPI Master and Slave is initiated by a Data Ready pulse generated by the Slave at a frequency of 4.5 MHz. This pulse serves as an interrupt signal to the Master, indicating that the Slave has ADC data ready for transmission. The SPI transaction begins at the negative edge of the Data Ready pulse, at which point the Master pulls the Slave Select (NSS) line low to enable the Slave device as shown in Figure 7.

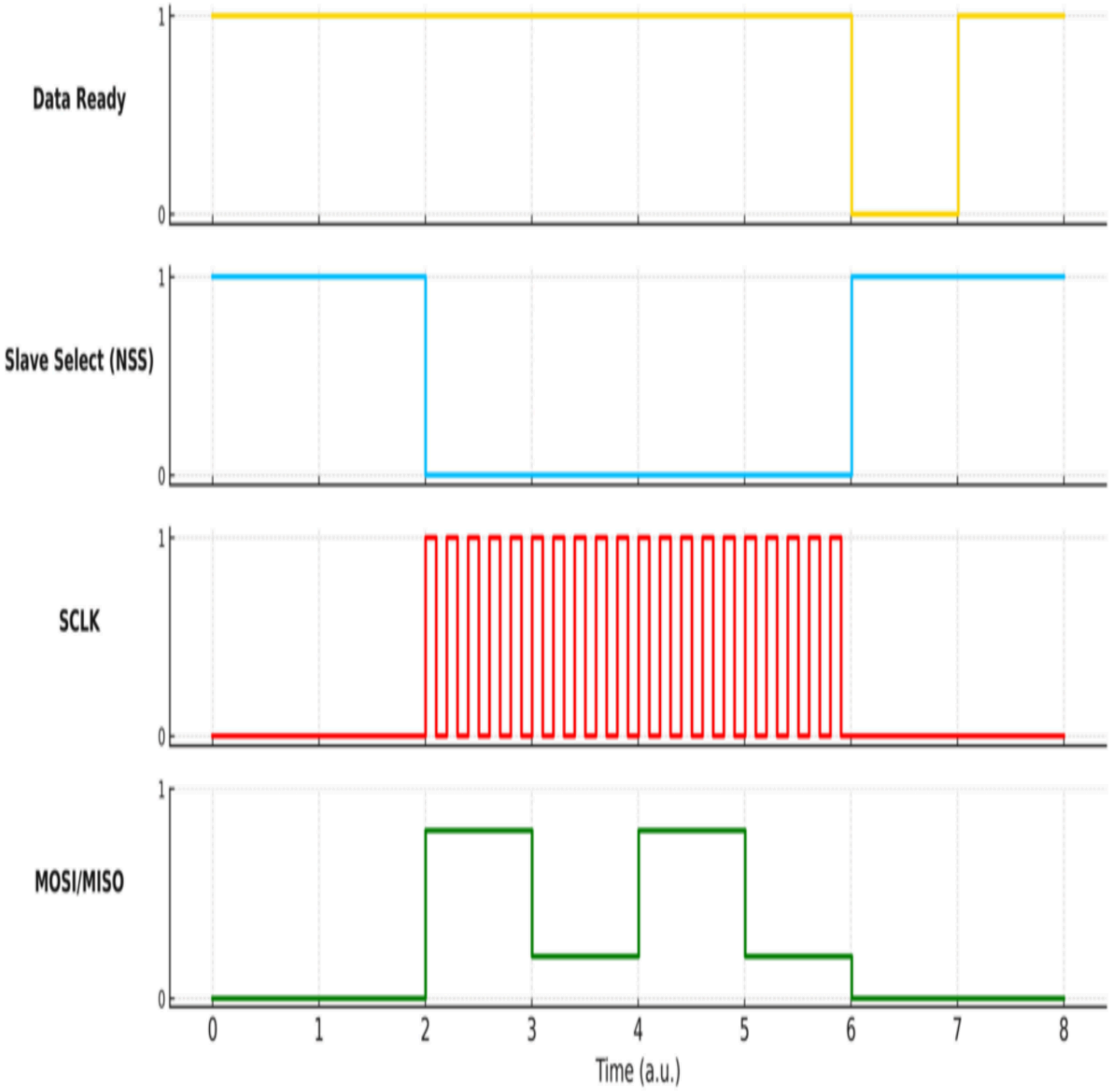


FIGURE 7: Interrupt-Based SPI Transaction for an 8-bit Data Frame Format

The communication between the SPI Master and Slave is initiated by a Data Ready pulse generated by the Slave at a frequency of 4.5 MHz. This pulse serves as an interrupt signal to the Master, indicating that the Slave has ADC data ready for transmission. The SPI transaction begins at the negative edge of the Data Ready pulse, at which point the Master pulls the Slave Select (NSS) line low to enable the Slave device. The data exchange follows an 8-bit frame format, where the Master first sends a command byte 0x01 (binary: 00000001) to request the data. In response, the Slave transmits the ADC data as a data byte 0xA5 (binary: 10100101) back to the Master, completing the SPI transaction as shown in Figure *8*.

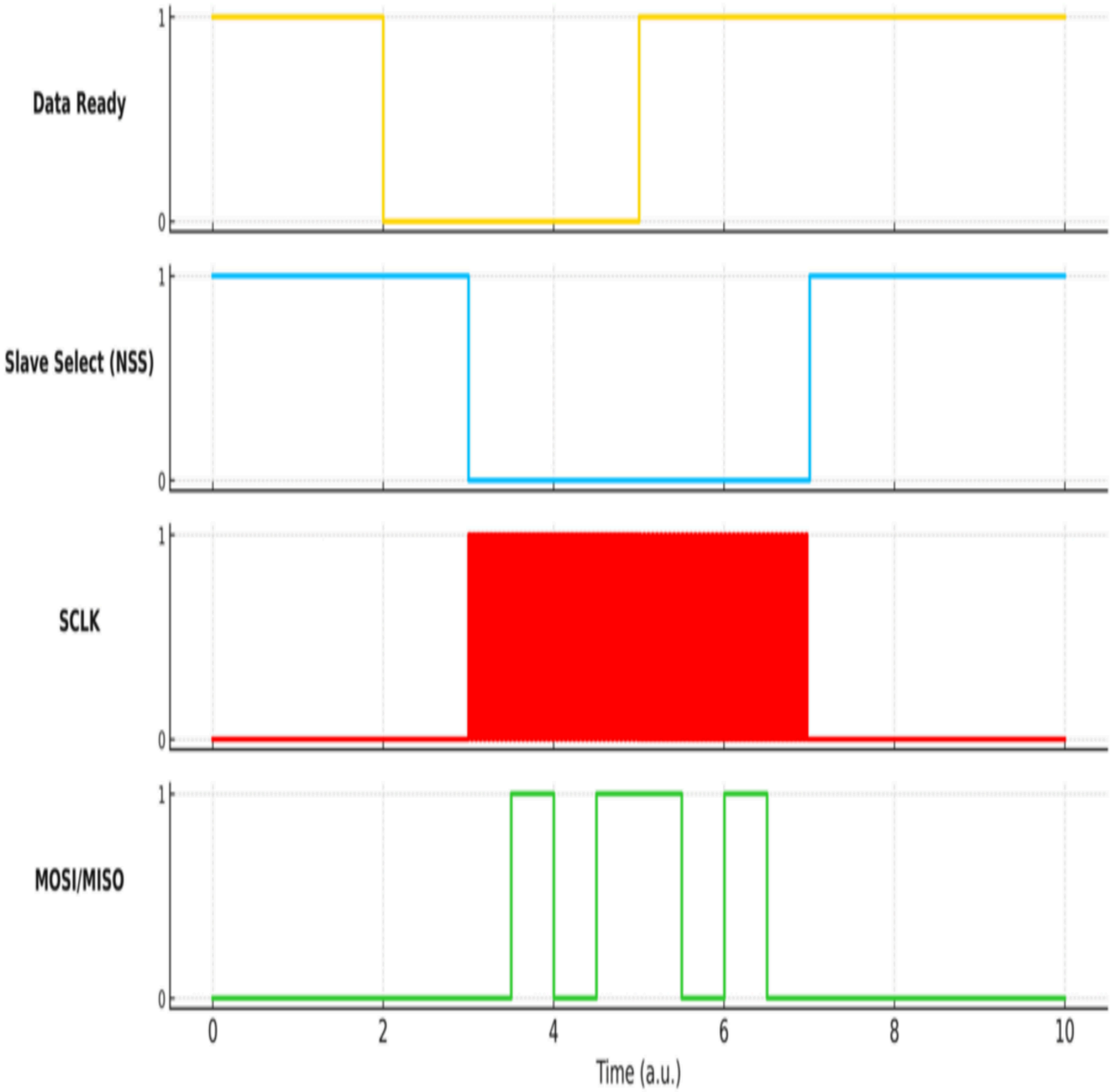


FIGURE 8: Interrupt-Based SPI Transaction for 16-bit Data Frame Format

SPI transaction with DMA enabled

The implementation of DMA-based SPI transactions significantly improved system performance by eliminating the CPU polling delay, which previously introduced a latency of 0.28 microseconds during each data transfer. With DMA, data are transferred directly between memory and the SPI peripheral without CPU intervention. This enables faster and more efficient SPI communication, as the CPU is free to handle other tasks concurrently while the DMA controller manages the data flow as shown in Figure *9*.

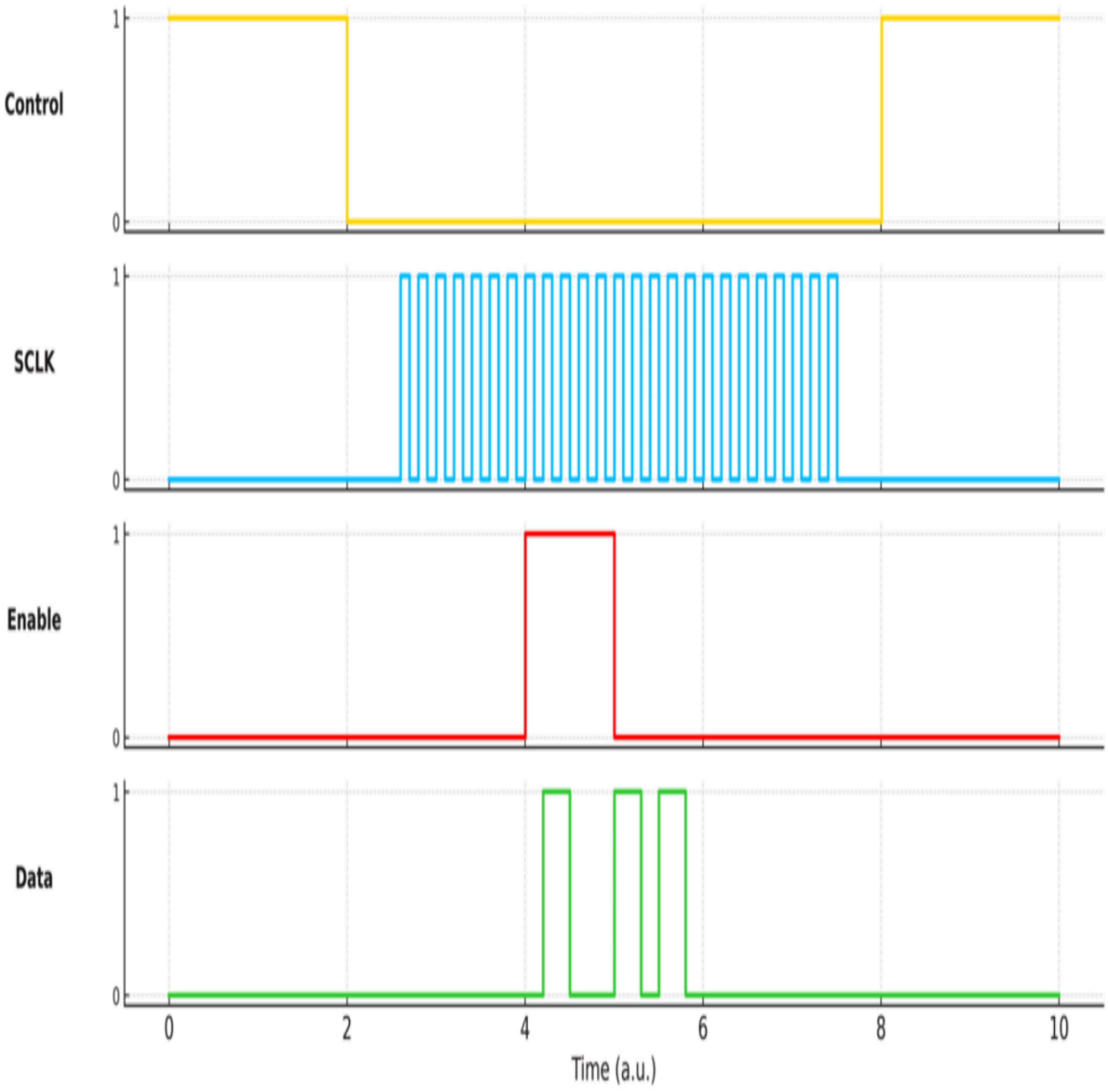


FIGURE 9: DMA-Enabled SPI Transaction for Faster Access

As a result, the overall throughput of the system increased, SPI transactions became more responsive, and the setup was better suited for real-time and high-speed data acquisition, such as continuous ADC data dumping in validation environments.

Piecewise Polynomial Fitting

The result of the piecewise polynomial fitting is a segmented and more accurate model of how Zener voltage varies with temperature. Instead of using a single global polynomial over the entire temperature range which may not capture localized variations accurately the range is divided into smaller temperature segments (e.g., 0-30°C, 30-60°C, etc.), and a separate 2nd-order polynomial is fitted for each segment using actual measurement data as shown in Figure *10*.

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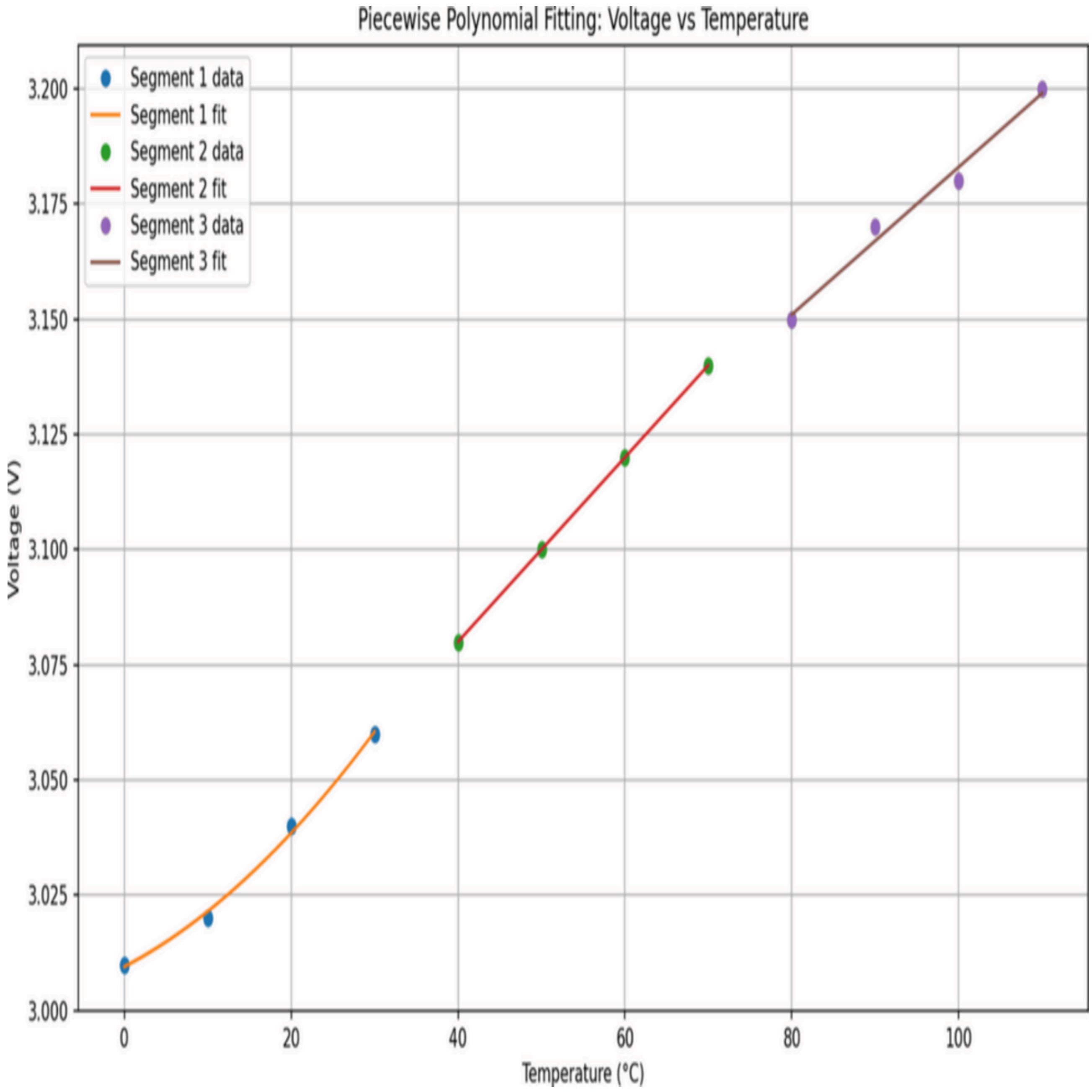

FIGURE 10: Piecewise Polynomial Fit of Sample Data

This approach improves the fit precision within each temperature band, effectively capturing nonlinear voltage drift due to temperature dependencies. The fitted coefficients (a, b, c) for each segment are stored in a LUT, enabling efficient and accurate digital correction during real-time operation. When a temperature is measured, the corresponding segment is selected, and the fitted polynomial is evaluated using those coefficients, providing a corrected voltage value.

Horner's method and improving system efficiency

The result of applying Horner's method in the Zener voltage correction algorithm is a significant improvement in computational efficiency and reduction in hardware complexity. This restructuring reduces the number of multiplications and additions required from 4 multiplications and 2 additions in the standard form to just 2 multiplications and 2 additions using Horner’s method. Hence, Horner’s method reduces the execution time of the Polynomial Correction Equation and improves the efficiency of the system. The application of Horner’s Method in the Zener voltage correction algorithm leads to a substantial improvement in computational efficiency and a corresponding reduction in hardware complexity. By reorganizing the polynomial evaluation process, Horner’s method minimizes the number of arithmetic operations needed. This optimization translates directly to faster execution times and lower power consumption, which are crucial factors in embedded systems and real-time measurement applications. The standard polynomial evaluation involves several multiplications and additions, which not only increase computational load but also require more processing time and resources.

Horner’s method cleverly restructures the calculation into a nested sequence of operations, effectively reducing the total multiplications and additions needed. Since multiplication operations are more resource-intensive and slower compared to additions, cutting down the number of multiplications significantly improves performance. This reduction in arithmetic complexity leads to quicker processing of the correction algorithm, making it well-suited for time-critical applications where rapid and accurate voltage adjustments are necessary.

Furthermore, the decreased computational demand simplifies hardware implementation by lowering the resource footprint in microcontrollers or FPGA logic. This enables the system to conserve power and allows more efficient allocation of processing capacity for other concurrent tasks. Overall, Horner’s method enhances the efficiency and speed of the voltage correction algorithm, thereby improving the system’s responsiveness and stability under varying temperature conditions without sacrificing accuracy or reliability.

Conclusions

Accurate voltage referencing under varying thermal conditions is essential for maintaining the performance and reliability of precision electronic systems, particularly in automotive and industrial applications. This work presents a comprehensive methodology for automated characterization and digital correction of Zener-based voltage references. By integrating SCPI-controlled instrumentation with embedded SPI communication and temperature-dependent compensation algorithms, the system ensures precise, real-time monitoring and correction of voltage drift.

The implementation of polynomial curve fitting and lookup table-based correction, optimized through Horner’s method, significantly improves computational efficiency and hardware compatibility. Experimental results demonstrate notable improvements in voltage stability across a wide temperature range, validating the effectiveness of the correction model. Moreover, the use of DMA-enhanced SPI communication ensures high-throughput, low-latency data acquisition, mimicking real-world operating conditions. This integrated solution not only streamlines the testing and validation process but also enables the deployment of real-time correction mechanisms within embedded platforms. The approach offers a scalable, low-cost alternative to commercial validation systems, with strong potential for extension to broader applications involving temperature-sensitive analog components.

The study shows that piecewise polynomial fitting with lookup tables significantly improved Zener diode voltage stability across -40°C to +150°C, effectively correcting thermal drift and aligning the reference output closely with ideal values. For SPI communication, moving from CPU polling to DMA eliminated the 0.28 µs per-transfer latency, enabling near-continuous high-throughput data streaming at the 11.5 MHz SPI clock, which closely matched real-time ADC requirements. Finally, applying Horner’s method to the polynomial correction cut the arithmetic from 4 multiplications and 2 additions to just 2 multiplications and 2 additions, halving the multiplication load, thereby reducing execution time, hardware complexity, and power consumption while maintaining accuracy.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Sowmya KB

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Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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How to cite this article:
KB S, Sreekar Mulukutla S (March 22, 2026) Automated Serial Peripheral Interface-Enabled Test Validation and Characterization Environment. Cureus J Eng 3 : es44388-025-00039-6. DOI https://doi.org/10.7759/s44388-025-00039-6