

Assignment 2

Dew Point Generator Controller and Sensor Data Logger

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Contents

1	Intro	3
2	System Design Overview	3
2.1	Hardware Design	3
2.1.1	Load Cell and ADC Integration	3
2.1.2	SDI-12 Sensors and Communication Interface	4
2.1.3	Power Supply and Voltage Regulation	4
2.1.4	Data Logging and Storage	5
2.1.5	DAC Integration	5
2.2	Communication Protocols and OSI Model Layers	5
2.2.1	SDI-12/UART/RS485 Communication	7
2.2.2	SPI Communication (SD Card)	8
2.2.3	I2C Communication (DAC)	9
2.2.4	Analogue Inputs and Outputs	10
2.3	Command-line Interface	10
3	Discussion	11
3.1	Technical Challenges and Solutions	11
3.1.1	SDI-12 Sensor Communication Issues	11
3.1.2	Load Cell Signal Scaling and Stability	11
3.1.3	I2C Bus and DAC Communication Issues	12
3.2	Recommendations	12
4	Conclusion	13
5	Appendix	13

List of Figures

1	Block diagram of the system	4
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2	Photo of Board	5
3	Photo of System Setup	6
4	Flowchart of Program	7
5	SDI-12 timing from SDI-12 Support Group (2019)	9

List of Tables

Intro

This report documents the design and implementation of an embedded system developed to serve as both a scientific data logger and a smart interface with an analogue dew point generator. The system utilizes the RP2040 microcontroller and various sensors, including SDI-12 environmental sensors and a load cell, to collect and process data for use in climate modelling applications. The project aims to provide a reliable and efficient solution for monitoring and controlling environmental parameters, particularly in the context of research on tropical plant behaviour under varying climate conditions.

The LI-610 Dew Point Generator is a precision instrument designed to produce a stable stream of gas with a precisely controlled dew point. It uses Peltier thermoelectric coolers to regulate the temperature of water reservoirs, ensuring the air stream is fully saturated with water vapor. This precise control of dew point is critical in environmental research, as it helps prevent condensation inside climate-controlled chambers, which could disrupt experimental conditions and data accuracy.

Accurate and continuous monitoring of environmental parameters is essential for tropical plant research, but traditional data collection methods are labor-intensive and prone to error. Moreover, physical presence in climate-controlled rooms can disturb experimental conditions. Commercial solutions like those from Campbell Scientific are often expensive and use closed-source technology, limiting accessibility and customization options for researchers. This project addresses these limitations by providing an open-source, cost-effective alternative that enables remote monitoring and control of environmental parameters. By integrating various sensors and offering a smart control interface for the dew point generator, the system allows researchers to simulate different climate conditions and monitor plant responses without entering the controlled environment, ensuring data integrity while maintaining flexibility and affordability.

System Design Overview

The system was designed around the RP2040 microcontroller, acting as the central processing unit for interfacing with a variety of sensors and control devices. The design incorporates the SF-5M sap flow sensor, LT-1T leaf temperature sensor, and MT-603 load cell to measure various environmental parameters. Each of these sensors use different communication protocols, requiring careful consideration of power requirements, signal integrity, and communication compatibility. A photo of the board is shown in fig. 2 while fig. 1 shows an overview of all the communication systems involved in the design.

Hardware Design

Load Cell and ADC Integration

The MT-603 load cell requires an ADC (Analogue-to-Digital Converter) for signal conversion, as its output is an analogue signal representing weight measurements. Therefore, one of the RP2040's ADC pins was utilised to convert the load cell's voltage output into a digital signal in which the microcontroller can process. An instrumentation amplifier was also added to amplify the small voltage changes from the load cell, improving the resolution and accuracy of the measurements. This ADC integration allowed for precise scaling and calibration of the load cell to achieve accurate data representation.

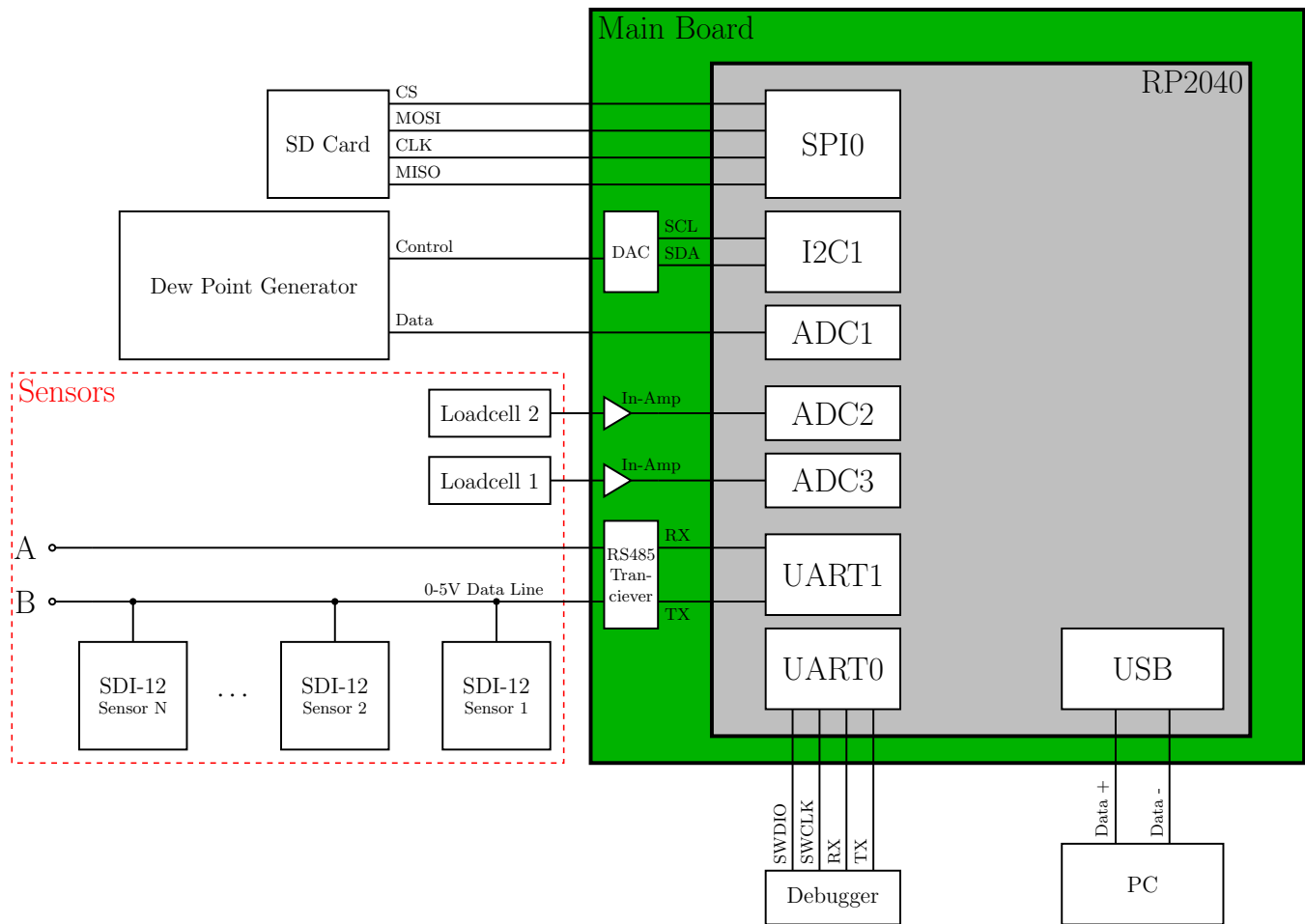


Fig. 1. Block diagram of the system

SDI-12 Sensors and Communication Interface

The SDI-12 protocol was implemented because it is the standard communication protocol for the environmental sensors integrated into this system. However, SDI-12 differs from typical UART communication in that its bit values are inverted and requires strict timing. To address this, the project leveraged the RP2040's UART capabilities in conjunction with an RS485 transceiver. The RS485 transceiver is suitable for this application due to its robust line-driving capabilities, noise immunity, and compatibility with inverted logic levels. By using only the non-inverting line of the differential pair (data line B), and setting the voltage reference at 2.5V, the design effectively maps the inverted SDI-12 signals to conventional UART high and low values, allowing reliable sensor communication.

Power Supply and Voltage Regulation

Due to the diversity of communication protocols and components used in the system (such as ADC for the load cell, SDI-12 for sensors, and I2C for the DAC—multiple), the following voltage levels were required on the PCB: 12V, 5V, and 3.3V. Each voltage level was supplied through dedicated regulators to ensure stable power delivery to each module. The careful placement of decoupling capacitors was critical to minimize voltage ripple and noise, ensuring stable operation of the entire system.

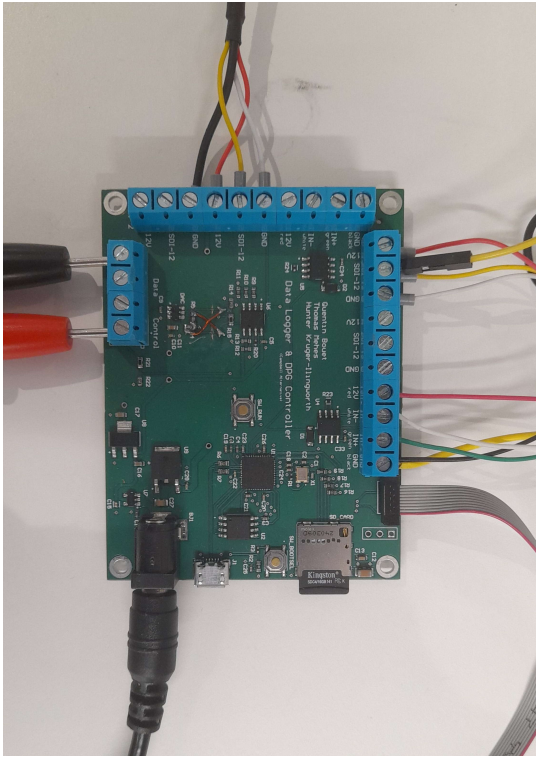


Fig. 2. Photo of Board

Data Logging and Storage

An SD card module was added to the schematic, utilising the SPI interface as defined in the RP2040 datasheet. This module enables reliable data storage and allows easy access to logged data for further analysis. The SPI bus operates at a clock speed of 1 MHz, which is suitable for reliable data transfer with the SD card.

DAC Integration

Initially, a solution consisting of Pulse Width Modulation (PWM) along with a low pass filter was considered to convert to generate the required analogue signal for the dew point generator. However, this method proved unreliable and inaccurate when tested with a Raspberry Pi Pico. As a result, the MCP4716 DAC (10 bits) was integrated to provide fine-grained control of the dew point generator. Proper bypass capacitors were placed near the V_{DD} pin to minimize induced noise and ensure stable operation. The DAC was designed to communicate with the RP2040 over the I2C bus at a standard mode speed of 100 kHz.

Communication Protocols and OSI Model Layers

In designing the embedded system, several communication protocols were implemented to interface with various sensors and peripherals. Understanding how these protocols map onto the OSI model layers, particularly the physical and data link layers, is crucial for ensuring reliable and efficient data transmission. This section explains the OSI model implementation for each protocol used: SDI-12/UART/RS485, SPI, I2C, and analog inputs and outputs.

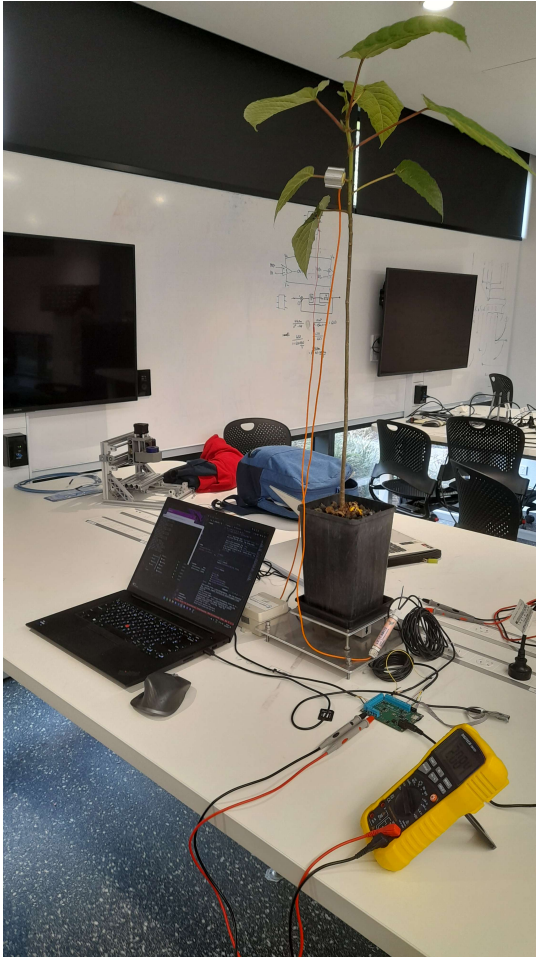


Fig. 3. Photo of System Setup

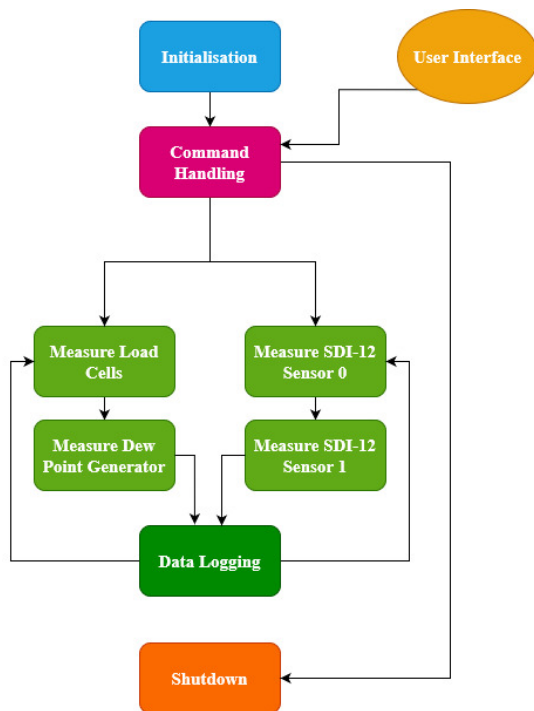


Fig. 4. Flowchart of Program

The program sequentially takes measurements from each SDI-12 sensor while simultaneously collecting data from faster sensors, such as load cells and the dew point generator, during the waiting periods for SDI-12 responses. Instead of using interrupts, the program relies on flag-based polling to gather data. Since the system is monitoring a living plant, where rapid changes are not expected, precise timing is not critical. fig. 4 shows a diagram illustrating the process.

A more extensible system would ask all the sdi12 sensors on the data line what their address is and dynamically get data from all of them regardless of how many sensors there are. The hardware design is highly extensible (screw in terminals allow you to plug in however many you want) but the software would need to be developed more to fully realise this extensibility (mention specific commands that could be used to get all the sensors address)

oh on this note i think a quick mention of the sdi12 uart data format would be good

SDI-12/UART/RS485 Communication

Physical Layer

SDI-12 communication is managed using UART1 on the RP2040 microcontroller, with specific GPIO pins defined for transmission (TX on GPIO 8), reception (RX on GPIO 9), and data line drive enablement (GPIO 15). The SDI-12 protocol operates over a single data line with negative logic levels, where a logic '0' is represented by a voltage high, and a logic '1' by a voltage low. The RS485 transceiver adapts the UART signals to meet these requirements.

The RS485 transceiver is suitable for this application due to its robust communication capabilities:

- Noise Immunity: RS485 uses differential signaling, enhancing noise immunity and allowing reliable

communication over long distances, which is essential in environmental monitoring setups.

- **Line Driving Capability:** It can drive long cables with high capacitance, ensuring signal integrity between the microcontroller and sensors.
- **Inverted Logic Handling:** The transceiver accommodates the inverted logic levels required by SDI-12 devices.

By using only the non-inverting line of the RS485 transceiver and setting appropriate voltage references, the system effectively adapts the standard UART interface to meet the physical layer requirements of the SDI-12 protocol.

Data Link Layer

At the data link layer, the SDI-12 protocol defines the communication between the data recorder (master) and the sensors (slaves). It operates at 1200 baud with 7 data bits, even parity, and one stop bit. The protocol specifies a set of ASCII commands for initiating measurements, requesting data, and managing sensor addresses.

In the current implementation, the system communicates with two SDI-12 sensors whose addresses are hardcoded. This approach simplifies the software but limits the system's scalability and flexibility. SDI-12 allows for up to ten sensors on a single data line, each with a unique address. A more extensible system would implement a discovery process using the SDI-12 "Address Query" command (!) to identify all connected sensors dynamically. This would enable the system to communicate with any number of sensors without prior knowledge of their addresses, fully utilizing the hardware's capability for extensibility.

Application Layer

A custom driver was developed for the SDI-12 sensors, adhering to the SDI-12 protocol. Specific issues with the byte framing of the SDI-12 protocol were addressed by using the `uart_set_format()` function to configure the communication format correctly (data bits were set to 7, stop bits were set to 1, parity option was set to `UART_PARITY_EVEN`), allowing the RP2040 to receive the inverted data without additional circuitry.

The `uart_set_break()` function was used to assert a break condition on the UART transmission, where it was first set to true then to false immediately after (the UART break in this case happens to be about the same time as the SDI-12 break). The following functions were then used to send an SDI-12 command to the sensors: `uart_write_blocking()`, `uart_tx_wait_blocking()`. In order to read the sensor responses, the `uart_is_readable()` is used along with `tight_loop_contents()`, which improves CPU efficiency. The response was then parsed to get the data. The timing of the SDI-12 protocol is shown in fig. 5.

SPI Communication (SD Card)

Physical Layer

The SPI protocol is used for communication with the SD card module. SPI is a synchronous serial communication interface that operates in full-duplex mode. It uses four signals:

- **MOSI (Master Out Slave In):** Transfers data from the master to the slave.
- **MISO (Master In Slave Out):** Transfers data from the slave to the master.

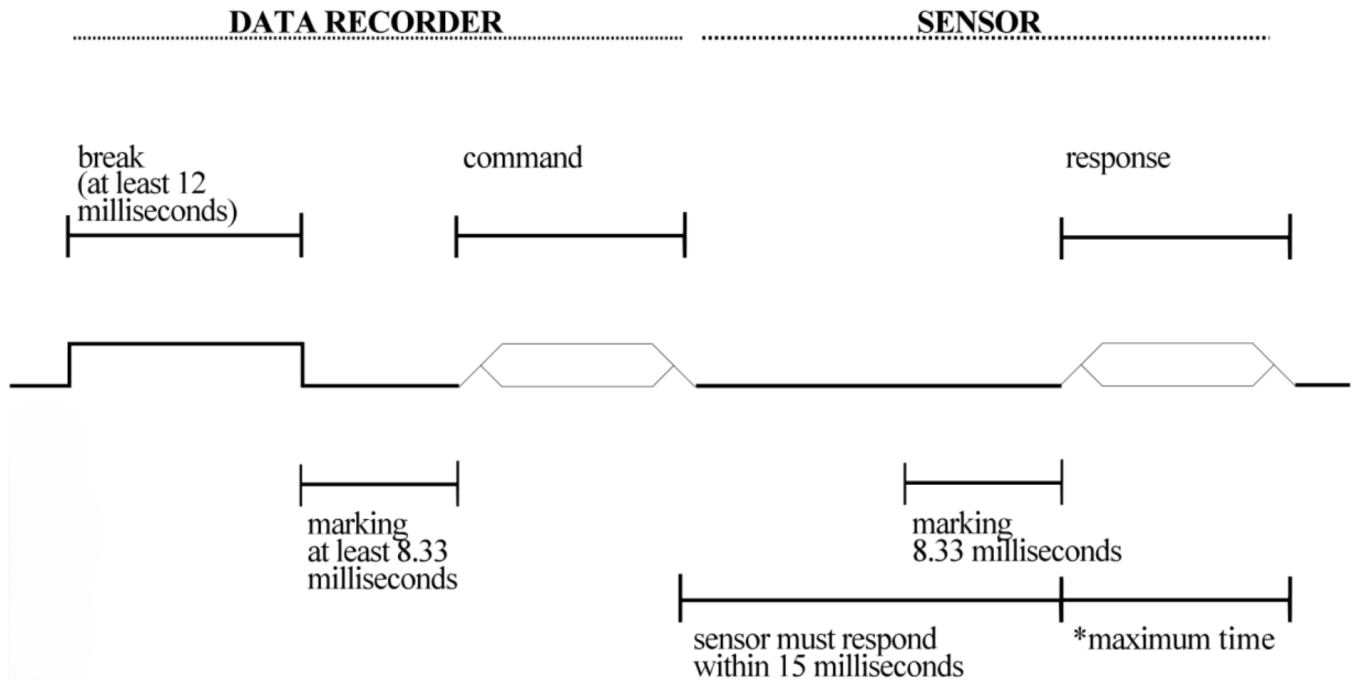


Fig. 5. SDI-12 timing from SDI-12 Support Group (2019)

- SCK (Serial Clock): Synchronises data transmission between the master and slave.
- SS (Slave Select): Enables the slave device for communication.

In this system, the SPI bus operates at a clock speed of 1 MHz, suitable for reliable data transfer with the SD card.

Data Link Layer

At the data link layer, the SPI protocol manages the exchange of data bytes between the microcontroller and the SD card. It does not define a specific frame format or error-checking mechanism, relying on higher-level protocols for these functions. The FatFs file system library is employed to handle file operations on the SD card. FatFs provides functions for reading, writing, and managing files, ensuring data integrity and proper formatting according to the FAT file system standards.

Application Layer

The FatFs API was integrated to enable read/write operations on the SD card, using the SPI protocol. This allowed for structured data logging and easy retrieval of information. Functions were implemented to write data in CSV format, facilitating compatibility with data analysis tools.

I2C Communication (DAC)

Physical Layer

The I2C protocol is used for communication with the MCP4716 DAC. I2C is a synchronous, multi-master, multi-slave, single-ended serial communication bus. It uses two bidirectional open-drain lines:

- SDA (Serial Data Line): Transfers data between devices.
- SCL (Serial Clock Line): Provides the clock signal for synchronisation.

Pull-up resistors are used on both lines to maintain the high logic level when the bus is idle. In this system, the I2C bus operates at a standard mode speed of 100 kHz.

Data Link Layer

At the data link layer, the I2C protocol handles addressing and data transfer between the master (RP2040 microcontroller) and the slave device (DAC). Each device on the I2C bus has a unique 7-bit address. The protocol defines start and stop conditions, acknowledgments, and data byte transfers. The software includes drivers to configure the DAC's settings, such as reference voltage and gain, and to send digital values that the DAC converts into analog voltages. This allows precise control over the dew point generator.

Analogue Inputs and Outputs

Physical Layer

Analog inputs and outputs are used to interface with devices like the load cell (MT-603) and the dew point generator (LI-610). The load cell produces an analog voltage proportional to the applied weight, which is connected to the RP2040's ADC pins. An instrumentation amplifier (e.g., INA826) is used to amplify the small signal from the load cell. The dew point generator accepts a 0–5 V analog input for control, which is provided by the DAC's output.

Data Link Layer

In the context of analog signals, there is no formal data link layer as in digital communication protocols. However, signal conditioning and conversion processes serve similar functions. For analog inputs, the signal from the load cell is amplified and filtered before being digitized by the ADC. For analog outputs, the DAC converts digital values from the microcontroller into precise analog voltages to control the dew point generator's settings.

Application Layer

A software interface for controlling the dew point generator was implemented using the I2C protocol to communicate with the DAC. This interface allows precise voltage adjustments to the generator, with preliminary tests confirming accurate output predictions based on command inputs. The I2C communication was established using standard mode at 100 kHz, which is compatible with the MCP4716 DAC.

The careful selection of communication interfaces and voltage levels, along with robust software integration, allowed the system to operate seamlessly and efficiently, providing a reliable solution for monitoring and controlling environmental parameters.

Command-line Interface

A command-line interface was implemented to allow the user to interact with the system. A terminal driver was developed to handle user input and execute commands and manages a buffer for multi-character commands. A command in this context is represented as a data structure called `Command`, which encapsulates the command type and an optional floating-point argument. The 'Command' struct contains:

- the type of command issued by the user (e.g., `help`, `set_voltage`, `get_data`, `shutdown`)
- an optional argument for commands that require additional information, such as a voltage value for `set_voltage`

This class provides methods for:

- Handling input character by character.
- Parsing and executing user commands by interpreting the `Command` structure.
- Resetting and managing the internal command buffer used for building commands from user input.

Discussion

This section will discuss the implications of the design choices, critically assessing their effectiveness and potential areas for improvement.

The main issue will be having the interrupts not “collide” with each other since the low baud rate increases the probability that other things will interrupt the middle of a communication session with one of the SDI-12 sensors.

Technical Challenges and Solutions

SDI-12 Sensor Communication Issues

During the testing of the SDI-12 sensors, initial attempts to communicate using RS485 transceivers failed due to improper framing of byte streams. The strict timing requirements and inverted logic levels of the SDI-12 protocol made it difficult to achieve reliable communication using standard UART settings. This issue was addressed by applying the `uart_set_format()` function, which allowed the RP2040 to handle the SDI-12 protocol's timing and framing more accurately.

Additionally, a `custom is_timed_out()` function was created to automate character reception without using traditional sleep methods, ensuring precise byte timing and avoiding data loss during transmission. The RS485 transceiver's ability to handle inverted logic and differential signaling enhanced noise immunity and improved communication reliability over long distances.

Load Cell Signal Scaling and Stability

The MT-603 load cell exhibited a significant dead zone and provided inconsistent readings due to mechanical vibrations in the experimental setup. An instrumentation amplifier was used to amplify the load cell's signal, improving sensitivity. However, environmental noise and mechanical oscillations still affected the readings.

Software-based noise reduction techniques, such as averaging past data points using an exponential moving average, were implemented to mitigate the effect of oscillations. This software solution was preferred over hardware filtering due to the constraints of the existing apparatus.

I2C Bus and DAC Communication Issues

During the process of integrating the DAC, software implementations from GitHub were tested, but scanning the I2C bus showed no devices detected. This pointed to a hardware issue. Upon further inspection, it was discovered that the SDA and SCL pins were swapped on the RP2040, and the pull-up resistors for the DAC were incorrectly sized.

To address this, the traces were manually cut and re-soldered to correct the pin connections. Smaller pull-up resistors were also added to compensate for the track capacitance, which had caused the rising edges of the clock signal to appear more triangular than square. After these modifications, the I2C bus functioned correctly, and basic software confirmed the DAC's operation. This highlighted the importance of thoroughly reviewing the final PCB layout before submission, as the initial errors could have been avoided.

Recommendations

A potential solution is to implement an SDI-12 command queue, which would manage sensor requests efficiently. Alternatively, a system similar to real-time operating systems (RTOS) could be used, where tasks are prioritized and managed with mechanisms like task prioritization and mutexes. This approach would ensure smoother task allocation, preventing conflicts and improving response handling for both fast and slow sensors.

Based on the design process and challenges encountered, several recommendations can be made for future engineers who might revise this work:

1. **Implement Dynamic Sensor Discovery:** To enhance the system's scalability and flexibility, incorporate the SDI-12 "Address Query" command (!) to dynamically discover all connected sensors. This would eliminate the need for hardcoded sensor addresses and allow the system to support any number of SDI-12 sensors without software modifications.
2. **Develop Robust Error Handling:** Improve the software to handle communication errors, sensor timeouts, and unexpected responses. Implementing retries, acknowledgments, and exception handling will make the system more reliable in field conditions.
3. **Optimise Hardware Design for Extensibility:** Ensure that hardware interfaces, such as screw terminals and connectors, are designed to accommodate future expansions. Consider modular designs that allow for easy addition or replacement of components.
4. **Thorough PCB Layout Review:** Implement a rigorous design review process before finalising the PCB layout. This includes checking pin assignments, signal integrity, and component placements to prevent issues like swapped pins or incorrect resistor sizing.
5. **Enhanced Signal Conditioning:** For analogue inputs like the load cell, consider implementing hardware filtering and shielding to reduce noise and improve signal stability. This might include adding low-pass filters or using differential signal processing techniques.
6. **Documentation and Standardisation:** Maintain comprehensive documentation of both hardware and software components. Adhering to coding standards and providing clear comments will facilitate future development and maintenance.

7. Power Management: Explore power-saving features and strategies, especially if the system is to be deployed in remote locations where power availability is limited.

By addressing these areas, future iterations of the system can achieve greater robustness, scalability, and ease of use, ultimately enhancing its value for environmental research applications.

Conclusion

This section will summarize the project's outcomes, reflecting on the objectives achieved and providing final thoughts.

Appendix

References

SDI-12 Support Group, *SDI-12: A Serial-Digital Interface Standard for Microprocessor-Based Sensors*, SDI-12 Support Group, River Heights, Utah, Jan. 2019, version 1.4. [Online]. Available: <http://www.sdi-12.org>