Development of an Innovative Payload Interface Board for CubeSats

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ABSTRACT

This paper presents a modular, general-purpose payload interface board for rapidly integrating experiment hardware with existing CubeSat control electronics. The PayLoad Support Board (PLSB) provides four configurable power and data interfaces based on the MikroBUS™ standard on a custom-printed circuit board conforming to the CubeSat 1U physical standards. The MikroBUS™ standard has over 1,400 compatible off-the-shelf sensors, interfaces, transceivers, displays, motor drivers, data storage devices, clocks, and other electronic modules, all with a standard socket configuration. Standard 3.3V and 5V power options are provided to each of the interface's four sockets, and SPI, I2C, and UART communication lines are present for data transfer between the payloads and the STM32L552 or RP2040 microcontrollers, which provide processing for the payload data. Hardware prototypes have been assembled in both flight-ready and non-flight-ready configurations. The non-flight variation is targeted at high school and undergraduate students who can develop their engineering skills and inexpensively test a variety of payload concepts before committing to critical design for flight.

INTRODUCTION

With the barrier of access to low Earth orbit (LEO) continuing to lower over time **(1)**, many new companies and research institutions are taking advantage and placing their payloads into orbit. Additional gains are possible as the cost and time of development continue to be improved.

Our lab's goal is to reduce the complexity and the amount of custom-engineered solutions required to develop flight systems. One common subsystem that is often overly complex and designed on a mission-by-mission basis is the interface between payloads and the flight system. Such an interface typically provides power and communication from the power distribution subsystem and the command and data handling (C&DH) subsystem to the payload. A dedicated microcontroller may also allow preliminary processing of data collected by the payload, separate from the main C&DH processor. The time and resources spent designing a unique payload interface board could be better used in other aspects of the program if a reconfigurable interface option was available. This paper focuses on the design of a modular, general-purpose payload interface board (PLSB), which includes power and communication interfaces as well as an onboard processing unit.

DESIGN AND IMPLEMENTATION

After identifying the PLSB's purpose and functions, specific top-level requirements were generated. The most important top-level requirements are identified in **Table 1**.

Table 1: PLSB's Top-Level Requirements

ID	Requirements
REQ-01	The PLSB shall allow for flexible customization and integration of experiment hardware.
REQ-02	The PLSB shall provide the necessary interfaces to support a variety of payloads.
REQ-03	The PLSB shall facilitate the rapid integration of experiment hardware with existing CubeSats.
REQ-04	The PLSB shall align with the physical dimensions so as to fit within a 1U (10 cm x 10 cm x 10 cm) CubeSat.
REQ-05	The PLSB shall be able to locally store and process payload data and controls.
REQ-06	The PLSB shall distribute power from a stable and regulated power source to the payload(s).
REQ-07	The PLSB shall support communication between the payload(s) and an onboard processing unit using at least UART, SPI, and I2C protocols.
REQ-08	The PLSB shall be able to withstand the expected launch loads and operational environment of Low Earth Orbit (LEO).
REQ-09	The PLSB shall meet the necessary environmental requirements. This includes outgassing restrictions, thermal limits, and radiation tolerance.
REQ-10	The PLSB shall use interfaces that are common with existing CubeSat buses' connectors and protocols to enable straightforward integration.

The MikroBUS™ Standard

In an attempt to simplify the design and integration process for payloads using the PLSB, a standard interface that offers multiple power and communication lines was selected. As a result, a trade study (**Table 2**) was conducted to determine which interface standard to incorporate in the PSLB. Various evaluation criteria were used with various weights (the scale is from 1 to 5, with 1 being the worst and 5 being the best) that most aligned with the requirements of the PLSB. While several alternative options (including USB and Ethernet) were considered, the MikroBUS™ standard was ultimately selected.

Table 2: PLSB to Payload Interface Trade Study

Evaluation Criteria	Weight	MikroBUS	USB	Ethernet
Communications	20%	5	3	2
Power Delivery	20%	4	3	2
Compatibility	10%	5	3	2
Physical Traits	10%	4	3	2
Reliability	10%	3	4	4
Cost	10%	5	3	3
Complexity	10%	4	2	1
Power Requirements	10%	4	4	2
TOTAL		4.3	3.1	2.2

The MikroBUS™ interface came out on top for a number of reasons. Looking at the communications offerings first, Ethernet and USB do not natively support UART, SPI, and I2C, which are communication protocols that many off-the-shelf sensors and laboratory-developed payloads use to communicate with the data processor. The use of a USB-to-X converter or an X-to-ethernet bridge requires added complexity to pass UART, SPI, or I2C data through these types of interfaces.

Both the USB and Ethernet interfaces have options to deliver more power than the MikroBUS™ standard, but this comes at the cost of a less electrically efficient system. Converting the Ethernet's 48 V into something usable by the payload results in additional circuitry to step down the voltage, leading to additional complexity for payload developers. The USB interface's standard operating voltage is much easier to work with. Having only one power line in its interface increases the likelihood of needing to step up or step down the voltage based on the specific requirements of the scientific instruments.

MikroBUS™ **(2)** is an open-source standard that consists of three types of direct communication protocols (SPI, UART, and I2C), two power lines (3.3 V and 5 V which can deliver up to 10 W each), and six additional pins (PWM, Interrupt, Analog Input, Reset, and Chip Select). These pins are laid out in a standard format to allow all MikroBUS™ boards to be compatible with all MikroBUS™ sockets. **(Figure 1)**.

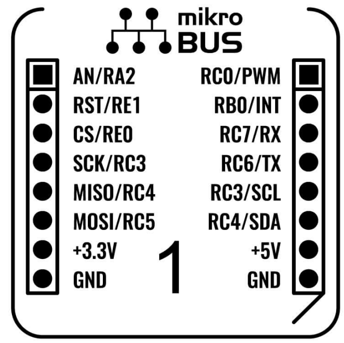

Figure 1: MikroBUS™ Standard Pin Layout (2)

The MikroBUS™ standard has a high degree of compatibility due to its use of common voltage lines and the multiple common communication protocols that it supports. The MikroBUS™ standard has been applied to over 1,400 add-on boards. These add-on boards incorporate sensors, interfaces, transceivers, displays, motor drivers, data storage devices, and clocks. While the off-the-shelf sensors come in a few fixed-sized boards (**Figure 2**), custom boards can be designed as large or as small as necessary.

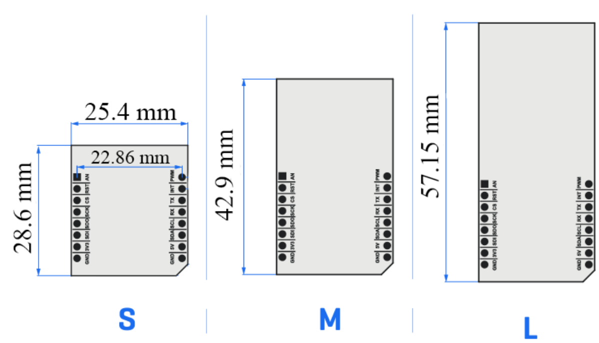

Figure 2: MikroBUS™ Fixed-Size Standard Pin Layouts (2)

The standard interface consists of two 0.1-inch 1x8 pin female-male sockets. The complexity of this standard is low because of the direct power and communication lines provided.

Processing and Data Storage

Having selected a standard interface, the next step is to select a compatible microcontroller. Multiple options were examined for use in data processing and payload control on the PLSB. The microcontroller has to support 27 GPIO pins and provide I2C, SPI, and UART communication protocols. Other key performance parameters considered (**Table 3**) included chip size, power draw, processing speeds, cost per chip, and previous development experience. These criteria and their associated weights were evaluated based on their alignment with the requirements of the PLSB. This trade was conducted during the global chip shortage in 2021, so purchasing availability was a significant factor that was also considered.

Table 3: Microcontroller Trade Study

Evaluation Criteria	Weight	STM32L552	RP2040	PIC32MX	MSP430F5
Features	**20%**	5	4	3	3
Development Support	**10%**	5	4	4	4
Purchasing Availability	**20%**	2	4	3	2
Chip Size	**10%**	3	2	4	3
Processing Speeds	**5%**	4	4	3	2
Power Draw	**10%**	5	4	3	5
Cost	**5%**	3	5	3	4
Previous Experience	**20%**	5	4	2	2
TOTAL		**4.1**	**3.9**	**3**	**2.9**

The STM32L552 evaluated well, but due to its poor availability, a second microprocessor, the RP2040, was selected for parallel development (**Figure 3**). These two microcontrollers provide high performance, a high level of feature availability, and good development support.

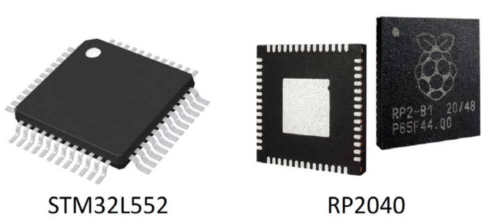

Figure 3: STM32L552 and RP2040 Chips

After selecting the microcontroller, compatible programming languages were evaluated. There are many options available, but the most relevant were assessed to be MicroPython, C, and Rust (**Table 4**),

Table 4: Pros and Cons Chart for Programming Language Selection

Programing Language	Pros	Cons
MicroPython	• Easy to learn. • Large and active developer community. • A wide variety of libraries are available. • Rapid prototyping turnaround time. • Dynamic memory allocation.	• Interpreted nature lowers performance compared to compiled languages. • Lack of memory safety guarantees • Lack of control over low-level hardware (in comparison)
C	• Large and mature ecosystem. • Provides fine-grain control and optimization opportunities. • Well-established development environments. • Efficient memory usage.	• Steeper learning curve for new programmers. • Memory leaks are possible due to bad programming. • Lack of built-in abstractions and high-level features. • Requires more effort for rapid prototyping.
Rust	• Strong memory safety guarantees. • Zero-cost abstractions • Growing ecosystem of libraries and frameworks.	• Steepest learning curve. • Smaller support ecosystem. • Strict compiler checks slow down code development initially. • Restrictive ownership/ borrowing rules. • Long development and compiling times.

By providing a variety of development languages for the PLSB, everyone from a high school student to an industry professional can use the PLSB with their level of programming skill for whatever their use case may be. The student who is just learning how to program can use the MicroPython development tools to quickly prototype many different payload interfaces, while the industry professional can program in Rust to get additional performance out of the payload and the microcontroller. C is a great middle ground between the two in terms of functionality and difficulty, perfect for a college undergraduate student working on a senior design project.

Data collected by the payload and processed by the microcontroller is stored on a commercial-grade microSD card. The microSD card is sized for the mission requirements. Based on the available testing results for radiation-based failures **(4)**, a commercial-grade MicroSD card that is radiation resistant will range in storage sizes from 4 GB to 32 GB, which is sufficient for most mission profiles. Once data is collected by the payload, it can be stored on the microSD card until it is ready to be processed by the PLSB's microcontroller, after which it is returned to the microSD card on the PLSB until it is time to downlink the science data.

PLSB Programmable Circuit Board Layout and Design

With the requirement that the PLSB be capable of operating within a 1U CubeSat, its footprint must be contained within an approximately 90mm by 90mm space. To allow for cable runs, spaces approximately 60 mm by 5 mm in size are cut out from the maximum-sized footprint on each of the four sides. All corners are rounded to enhance structural integrity. Application of these design rules resulted in the default shape of the board.

The backbone connector is a 50-pin connector that acts as the harness for the entire CubeSat and is placed on the board to connect the rest of the CubeSat's power and communication lines to the PLSB. These lines are run throughout the board to connect the backbone's power and communication pins to the MikroBUS™ interfaces and the microprocessor that will be used for payload data processing.

Because many of the off-the-shelf MikroBUS™ components abide by the standardized sizing (**Figure 2**), the design of the PLSB takes into account the differences between the small, medium, and large add-on boards. A total of four interfaces were provided on the PLSB. The 2 x 2 square interface configuration (**Figure 4**) maximizes the amount and size of the MikroBUS™ interfaces available to the user.

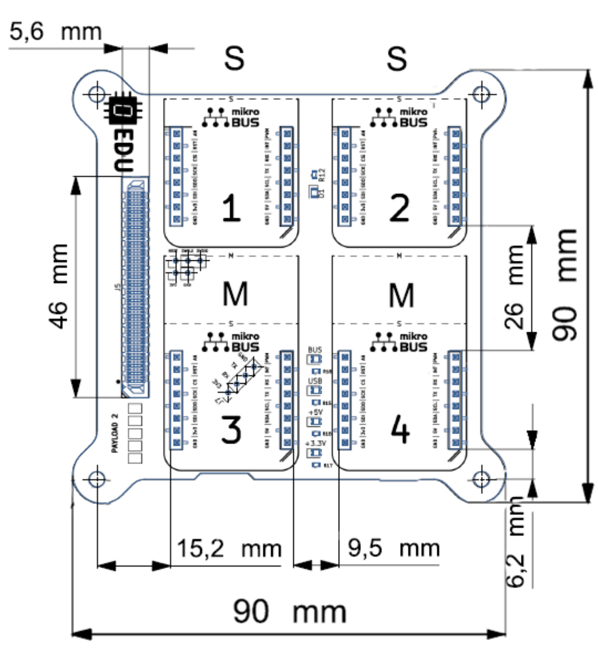

Figure 4: PLSB MikroBUS™ Interface Locations

With the 2 x 2 square configuration of MikroBUS™ interfaces, compatibility of four small add-on boards, two small and two medium add-on boards, or two large boards, is possible. The ability to mix and match add-on board sizes to fit the users' needs is a significant advantage unique to this configuration. The only restriction is that custom-sized MikroBus™ add-on boards must stay clear of the backbone connector to meet the CubeSat's integration requirements (**Figure 5**).

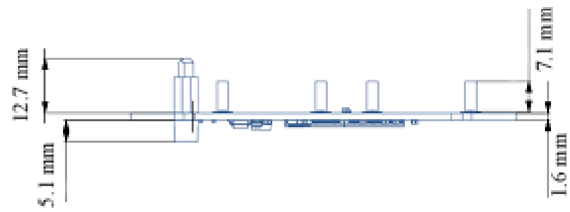

Figure 5: PLSB Height Dimensions

The back of the PLSB (**Figure 6**) provides space for the selected microcontroller. Additionally, all supporting connectors are located on this side of the board, including a USB C interface to program the microcontroller and a microSD card interface to store payload data. The final PSLB design was incorporated into a four-layer PCB.

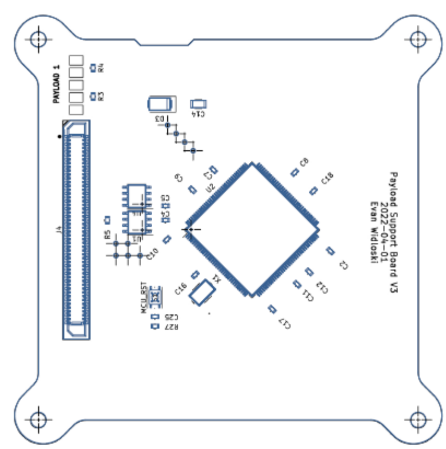

Figure 6: PLSB Back of Board View

HARDWARE PROTOTYPE

The flight-qualified version of the PLSB (**Figure 7**) uses automotive-grade components to ensure that the board can survive the launch environment and operate successfully in LEO.

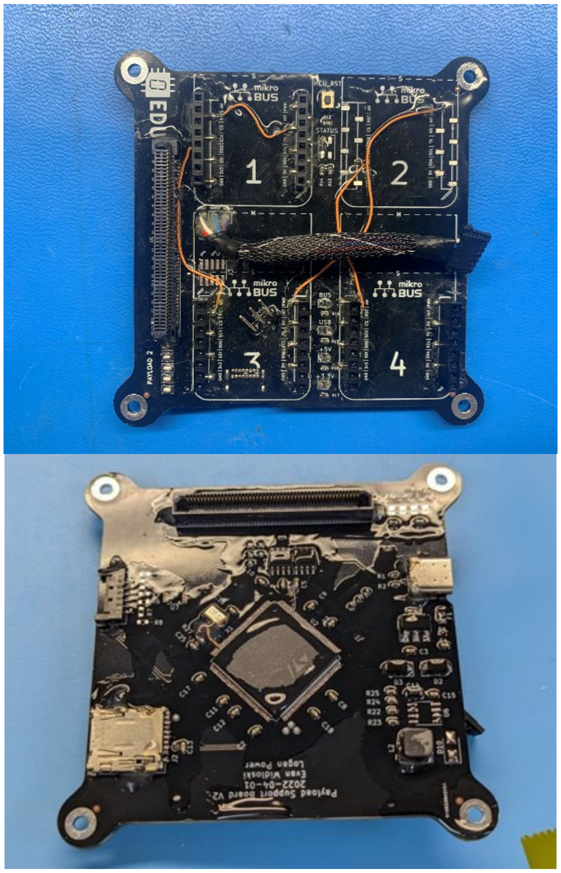

Figure 7: Flight PLSB

The non-flight variation of the PLSB sacrifices some of the automotive-grade components that the flight variation uses to save on manufacturing costs. The non-flight variation of the PLSB is perfect for prototyping designs and can also be emulated by using an off-the-shelf Click Shield from MikroBUS™ (**Figure 8**) during the payload development process.

Figure 8: PI Pico Microcontroller Click Shield (4)

Applications for Research

The PLSB is well suited for use in the research environment given its customization capabilities, data processing capacity, communication options, ease of prototyping, and collaboration abilities.

As discussed, the PLSB has many different customization features that researchers can take advantage of, from the choice between the STM32 and RP2040 microcontrollers to the programming language used for the microcontroller. The PLSB also allows for customization in the researcher's choice of communications protocol (I2C, UART, or SPI) and the physical location of the payload. Should the need arise, multiple PLSBs can be stacked on the backbone connector to allow for a greater number of MikroBUS™ interfaces to become available if four are not sufficient. The PLSB has been successfully designed to allow a range of operating options that allow it to meet a wide variety of mission requirements.

Data processing on the PLSB allows researchers to process the data collected by the research payloads before downlinking to a ground station to reduce the downlink requirements. These features also allow for near-real-time analysis of the data, allowing for autonomous interaction with the payload as required.

Applications for Education

The PLSB has been designed to allow students in high school and college to have the experience of working hands-on with flight-worthy hardware, inspiring the next generation of students to take up careers in engineering, aerospace, and other STEM-related fields.

One of the primary skills that can be developed while working with the PLSB is programming. By making the PLSB compatible with multiple programming languages, students get the opportunity to start with the basics (e.g., MicroPython) and move through the different levels of programming and abstraction (e.g., C, Rust). Working with our partners at the University of Illinois 4-H Extension Program, educational material and pre-planned experiments are being made available to demonstrate the capabilities of the PLSB hardware.

CONCLUSION

The PLSB was designed as a standardized interface board that can provide both power and communication lines to a payload through a standardized interface. On-board processing enhances its capabilities further. The selection of the MikroBUS™ standard allows for the use of over 1,400 off-the-shelf sensors and other electronics, enabling users to get started with their scientific experiments faster than having to put together something from scratch. The open-source nature of the design standard further enhances the design experience, allowing for user-made payloads to be integrated just as easily as the off-the-shelf components. The layout of the PCB itself allows for up to four MikroBUS™ add-on boards to be used simultaneously, and multiple PLSB boards may be stacked on top of one another to further increase the number of interface slots that can be made available to payload designers.

Use of the PLSB in Future LEO Missions

The PLSB is slated for its first launch as part of an International Space Station exterior-attached payload in 2024. The PLSB will be flight-qualified while interfaced to a small set of advanced-technology solar cells (**Figure 9**). MikroBUS™ compatible boards will collect data from the cells, including voltage and current, and the data will be returned to Earth for subsequent analysis.

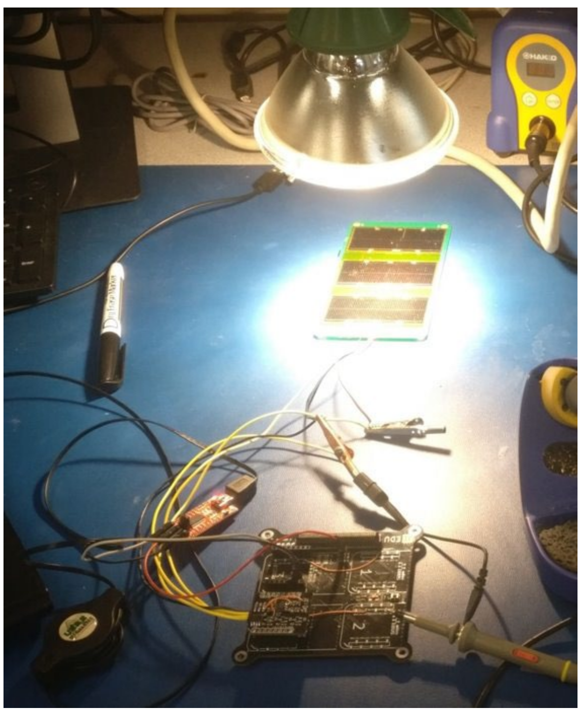

Figure 9: PLSB with the Solar Experiment

In the fall of 2023, Illinois high school students will get the opportunity to submit payload designs using the PLSB, and the winning design will be provided with the opportunity to fly on an upcoming CubeSat mission. The purpose of this contest is to promote STEM education in the field of space systems and bring attention to the educational opportunities made available by the Laboratory for Advanced Space Systems at Illinois.

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