

Miniaturized Solutions for CubeSat Servicing and Safety Requirements

Jacob Willis^{ID}, *Student Member, IEEE*, Patrick Walton, Doran Wilde^{ID}, *Senior Member, IEEE*, and David Long^{ID}, *Fellow, IEEE*

Abstract—Small spacecraft require systems to facilitate safe preflight and launch operations. These include access ports to test software, charge batteries, and monitor spacecraft health after assembly, as well as inhibits to prevent inadvertent operation during servicing, integration, transport, and launch. For CubeSats, the requirements for these features are primarily governed by the CubeSat Design Specification (CDS). The size, weight, and cost of existing, off-the-shelf access port, inhibit, and remove-before-flight implementations can be prohibitive for low-budget, miniaturized spacecraft. This article aims to reduce the size, weight, and cost of CDS-required servicing and safety features. This is achieved by integrating these features into a single system using off-the-shelf, consumer-scale electrical components, including a type-B universal serial bus (USB) mini connector and an FTDI USB to multiseri al protocol integrated circuit.

Index Terms—Access port, CubeSat, remove-before-flight (RBF), servicing and safety.

I. INTRODUCTION

WHILE designs for spacecraft are primarily governed by intended flight operations, designs also take into account the requirements for servicing and safe handling before flight, and safety during launch. Pre-flight spacecraft operations typically include assembly, testing, storage, transport to the launch site, and integration with the launch vehicle.

The preflight operations of small spacecraft conforming to the CubeSat standard are of particular interest thanks to the reduced costs and development time of CubeSats [1]. Because of their small size, CubeSats are inexpensive to launch, resulting in development programs that are more tolerant of the risk incurred by using low-cost components designed for consumer devices instead of the space environment [2]. CubeSat costs are also reduced through standardization, which lowers the nonrecurring engineering costs required in developing a new CubeSat system and launching it on a variety of vehicles. This standardization is primarily governed by the CubeSat Design Specification (CDS), managed by Cal Poly, San Luis Obispo [3].

Table I lists the CDS requirements which govern the design of CubeSat subsystems for servicing and safety.

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The authors are with the Department of Electrical and Computer Engineering, Brigham Young University, Provo, UT 84602 USA (e-mail: long@ee.byu.edu).

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Remove-before-flight (RBF) and deployment switch mechanisms are required to inhibit electrical power, so human servicers and the launch vehicle are protected from inadvertent operation during integration and launch [4]. Systems to delay radio frequency (RF) transmission, and the actuation of deployables, such as antennas and solar arrays, are also required. Exterior data and power interface ports (access ports), if included, are required to fit within the specified areas of the CubeSat surface. These ports enable technicians to install software, charge batteries, monitor system health, and validate performance during assembly, storage, ground maintenance, and transport [4]–[6].

Many components used to satisfy the requirements of the CDS are bulky, making them difficult to package within a CubeSat's limited surface and interior [7]. This reduces overall performance by consuming space that could be used for other subsystems, such as solar panels [8]. This can be improved by using miniaturized components and by combining the functionality of multiple subsystems. For example, the RBF pin and deployment switch circuitry are often combined [9]–[11]. However, the access port often consists of a variety of different connectors dedicated to charging, programming, diagnostics, or testing [12]–[14], although some connectors combine functionality for multiple operations [15].

The Passive Inspection CubeSats (PICs) mission developed by Brigham Young University needed low-cost, miniaturized implementations of CDS-required servicing, and safety features. Each of the two satellites (individually referred to as a "PIC") tightly packs six wide-angle cameras, 4 Ah batteries, six 1U solar panels, a flight computer, radio, and antennas, in a 10-cm cube [16]. The unique requirements of the PICs mission required a custom bus with tightly integrated CDS-required servicing and safety systems. When development for the PICs mission began, commercially available implementations of the nonflight design features were too large and expensive to fit within the mission design constraints. Although at least one similarly sized system has since been developed [17], no designs of these miniature systems are available for reimplementation as part of a custom circuit board.

This article presents a custom, repeatable implementation of the CDS-required servicing and safety features, created to fit within the size and cost constraints of the PICs mission. This implementation is illustrated in Figs. 1 and 2, and its features are listed in Table I in conjunction with the requirements that they satisfy. This implementation reduces the cost and size of the CDS-required access ports, deployment switches, RBF pin, and RF inhibits, primarily by integrating the RBF pin

TABLE I
DESIGN FEATURES REQUIRED BY THE CDS FOR PRE-FLIGHT SAFETY

Design Feature	Requirements	CDS [3] Section	PICs Implementation
Software Access Port	Confined to access port region.	3.3.6	Section II-A
Deployment Switches	Stationed at end of rail standoff, disconnects all spacecraft power during integration, launch, and deployment.	3.3.1 - 3.3.5	Section III-A
RBF pin	Confined to access port region, inhibits spacecraft power during handling and integration, removable after integration into dispenser.	3.3.6 - 3.3.7	Section III-B
Power Access Port	Confined to access port region.	3.3.6	Section II-B
RF Transmission Inhibit	Disables radio transmission during integration, launch, and deployment.	3.3.9	Section III

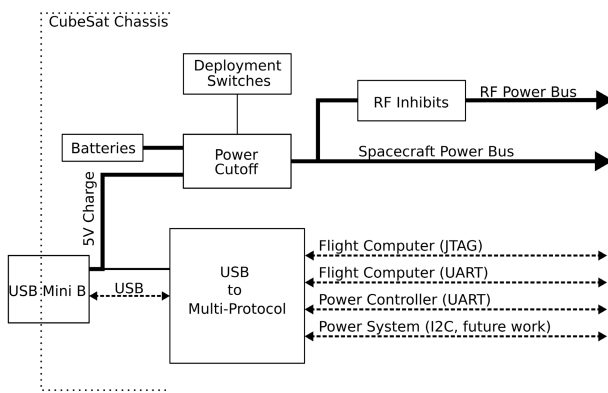


Fig. 1. High-level block diagram of the access port, RBF pin, deployment switches, and RF transmission inhibits.

and access port into a single connector using off-the-shelf, consumer-scale components.

II. SOFTWARE AND POWER ACCESS PORT

Once a CubeSat is assembled, control electronics are difficult to reach, but still need to be accessed for programming, testing, and charging. In addition, after integration into the CubeSat deployer, access to a CubeSat is limited to a designated area on its +X face [3]. Connectors for data and power access are commonly put in this area to allow for monitoring and charging during assembly, testing, and after integration. The RBF pin must be accessible and located within this area (see Figs. 3 and 4). To conserve surface area for the solar cells and cameras, a PIC's data access, charging, and RBF pin functions are incorporated into a single universal serial bus (USB) mini Type-B connector. The data and power access port functions are described here, whereas the RBF pin is described along with other power inhibit functions in Section III.

A. Software Access Port

The PICs design integrates multiple microcontrollers with a main system flight controller to meet computing and control requirements. The main system flight controller is a system on module (SOM) based on the Microsemi SmartFusion2, which includes an FPGA and an ARM Cortex-M4 processor. This processor is responsible for controlling the six payload cameras, as well as monitoring and responding to each of the eleven STMicroelectronics ARM Cortex-M0 microcontrollers via an inter-integrated circuit (I²C) bus. These eleven low-power microcontrollers take care of low-level tasks such as individual battery monitoring or controlling system power distribution.

To support debugging and programming flexibility for a PIC, the FT4232 by Future Technology Devices International is used in the access port as a USB bridge for digital serial data. It converts up to four serial ports to virtual endpoints running over a single USB interface. Two of the serial ports are a "MultiProtocol Synchronous Serial Engine" (MPSSE), which can be configured via USB to support UART, JTAG, SPI, or I²C protocols. The other two serial ports support UART and GPIO, which allows for software-controlled signaling (bit-banging). All the UARTs support standard baud rates up to 12 Mb/s [18]. The multiple serial ports broken out by the FT4232 communicate with different parts of the system, allowing greater ease in reprogramming and system monitoring during development. The access port on the PIC uses three of the four FTDI ports: two as UARTs, and one as JTAG. The use of these connections is described below.

1) *UART Console*: One of the FT4232 UARTs is used for accessing the Linux terminal on the main system flight computer. Through this connection, system diagnostic programs can be run, data can be transferred, and the flight computer can be reprogrammed.

2) *JTAG FPGA Programming*: The FPGA on the flight computer is typically programmed with Microsemi's FlashPro

series of JTAG programmers. The FlashPro 5 uses an FT4232 as its internal USB to JTAG converter. Microsemi makes the configuration for the FT4232 available, allowing hardware developers to integrate FlashPro programming functionality directly into their system [19]. The hardware required for this functionality is integrated into the PICs access port circuitry.

3) Power System UART: This UART is connected to the main electrical power system (EPS) controller, one of the eleven low-power microcontrollers, which is responsible for monitoring the state of the power system and for controlling power distribution. Having a direct UART connection to the main EPS controller allows the system power levels and configuration to be monitored independently of the main flight computer.

Using the FT4232 multiprotocol to USB converter reduces a PICs access port hardware to a single USB connector. While the FT4232 device is used for the presented access port, other devices could provide similar functionality and benefits. Reducing the digital signals in the access port to a single USB connection provides easy access and saves CubeSat surface area that would otherwise be consumed for additional connectors.

B. Power Access Port

The PICs power system was designed to accept a charging voltage of 5 V, which corresponds to the power voltage of the USB protocol. The charging voltage is supplied directly through the single USB mini connector in the access port. This functionality is described further in Section III. As shown in Fig. 1, the USB power goes into the power cutoff circuitry (see Fig. 5) and the FT4232 integrated circuit. The FT4232 can only be powered by the USB power, preventing it from causing unnecessary battery drain during the flight.

III. POWER INHIBITS

For mission safety, the CDS [3] requires power inhibits that prevent all powered CubeSat systems from activating beginning with the time the CubeSat is integrated into the launch vehicle until it is separated from the launch vehicle on-orbit (see Table I). Two components are required to ensure this safety protocol: the deployment switches (see Section III-A) and the RBF pin (see Section III-B). The CDS also requires 1–3 independent inhibits to prevent RF transmission until long after deployment. The deployment switches count as one of these inhibits; additional RF inhibits used on a PIC are not discussed here.

A. Deployment Switches

The deployment switch ensures that the CubeSat is unpowered and inactive during pre-launch activities and launch. The CDS requires that a CubeSat must have, at a minimum, one deployment switch located at the end of a corner rail stand-off [3]. For additional safety, a PIC includes two deployment switches at the end of opposite corner rails.

Each deployment switch has two states: actuated (pressed) and unactuated (unpressed). The switches are in the actuated state while the CubeSat is held within the CubeSat

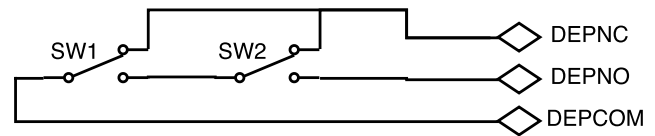


Fig. 2. Harness wiring for deployment switches.

dispenser [20]. With both deployment switches in the actuated state, the EPS in the CubeSat is disconnected from the rest of the CubeSat and the voltage on the power bus is zero (see power cutoff block in Fig. 1). When at least one deployment switch goes into its unactuated state, during CubeSat deployment, the power system is connected to the rest of the CubeSat.

A potential hazard with this design is that mechanical vibration during launch might cause the deployment switch, and thus the power system, to prematurely transition from actuated to unactuated. The CDS requires a debounce delay to mitigate this risk. The PICs deployment switches are designed such that the switches must be continuously unactuated for a minimum of 50 ms before the power system engages. This is enforced by a simple resistor-capacitor (RC) timing circuit, shown in Fig. 5, that is placed between the deployment switches and the gate of Q1, the MOSFET transistor that controls the power to the CubeSat. The resistive component of the timing circuit is composed of resistor R3 in series with resistor R4 and the on-resistance of transistor Q2; the timing circuit capacitor is C1. The values of these components are chosen to enforce the 50-ms delay in turning on transistor Q1 that controls the power to the CubeSat. The timing was verified by circuit simulation.

The PICs deployment switches are DG series sub-miniature snap action switches manufactured by ZF Electronics. Fig. 2 shows the harness wiring for the deployment switches, and Table II shows the connection that occurs for each of the four switch states. The connections DEPNC, DEPNO, and DEPCOM, that refer to the normally closed (NC), normally open (NO), and common (COM) pins of the deployment switch, attach to a three-pin header installed on a EPS circuit board, as shown in the schematic in Fig. 5. The wiring configuration of the two deployment switches requires only one of the switches to be unpressed to enter the unactuated state; this provides redundancy to ensure the CubeSat powers on if one of the switches breaks or gets stuck in its actuated state.

B. RBF Pin

The RBF pin disables internal power when inserted into the spacecraft. The RBF pin is normally inserted when the CubeSat is being stored or transported. The CubeSat is delivered for launch with the RBF pin inserted to keep the satellite from turning on during integration. The RBF pin must not protrude more than 6.5 mm from the CubeSat's rails so that the spacecraft may be loaded into the CubeSat dispenser without interference. The RBF pin is removed from the spacecraft after its deployment switches are actuated by the spacecraft's insertion into the CubeSat dispenser. After the RBF pin is

TABLE II
SPACECRAFT POWER STATE GIVEN DEPLOYMENT SWITCH STATE

Switch 1	Switch 2	Connection	Spacecraft Power
Pressed	Pressed	DEPNO↔DEPCOM	OFF
Pressed	Not Pressed	DEPNC↔DEPCOM	ON
Not Pressed	Pressed	DEPNC↔DEPCOM	ON
Not Pressed	Not Pressed	DEPNC↔DEPCOM	ON

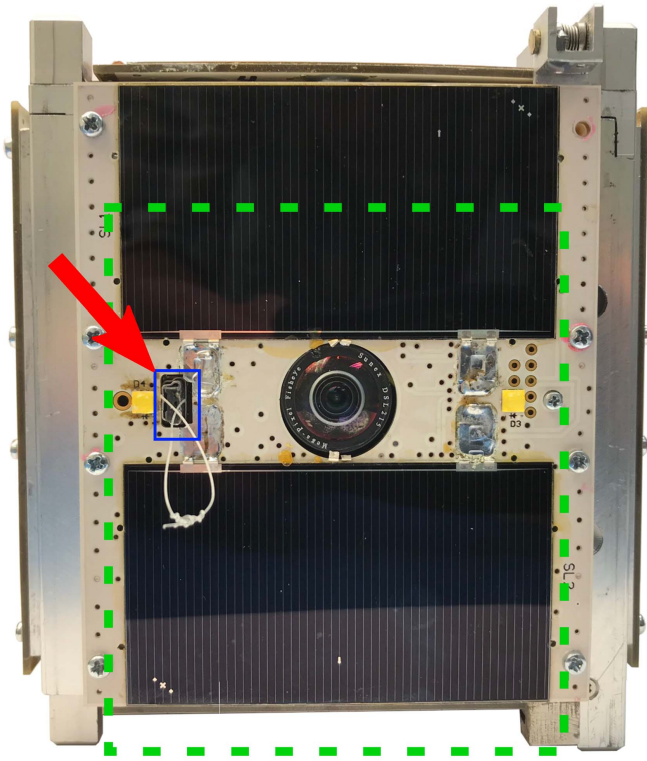


Fig. 3. Location of the Access Port on a PIC. The dashed green line encloses the access port area [3] allowed by the CDS. The solid blue box pointed to by the red arrow encloses the actual access port area on a PIC, shown with the RBF pin inserted. A nylon string is attached to the RBF pin for easy removal while fitting within the CDS-mandated envelope.

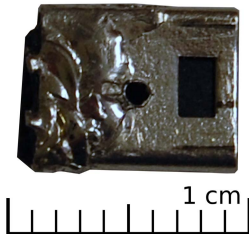


Fig. 4. Custom-built RBF pin created by modifying a USB mini plug.

removed, the deployment switches continue to disable power until the satellite is released on orbit.

Our RBF pin design allows the same USB mini connector used for data access to be used for the RBF pin as well. To make an RBF pin, a USB mini plug (see Fig. 4) is modified

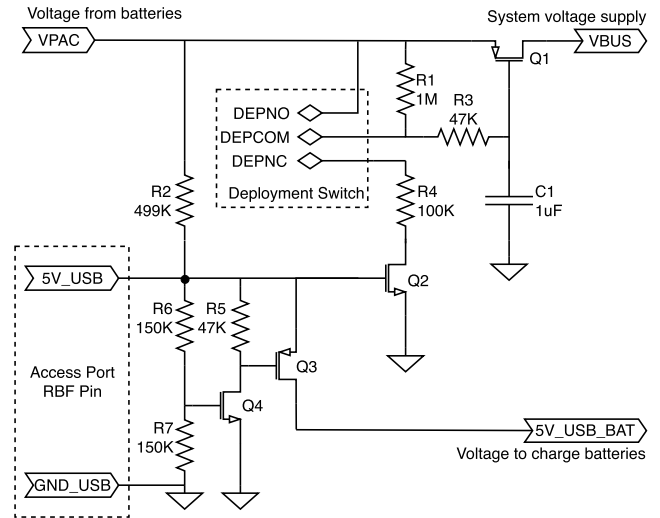


Fig. 5. RBF, deployment switch, and charging circuitry.

by wiring pins 1 and 5 (VCC and GND) to each other. When this small modified plug is inserted into the access port, the CubeSat's power system circuitry detects it and disables the flow of power to the rest of the satellite. The circuitry to detect the RBF pin is described in Section III-C2. When a standard, unmodified 5-V USB cable is inserted into the port, external power is supplied for charging batteries and data transfers can occur.

C. Circuitry to Detect State of CubeSat Power Inhibits

The four states of the CubeSat power system are summarized in Table III, the circuitry that controls these power system states is shown in Fig. 5, and the operation of this circuit is described below. Signals from Fig. 5 are written in *bold italics*.

1) Testing and Charging: While testing or charging, the USB mini connector is connected to a standard USB cable through which a supply voltage of 5 V is provided to the satellite. This 5-V supply appears at the circuit input **5V_USB**. The gate of N-transistor Q4 is pulled-up to 2.5 V through the resistor divider R6–R7, turning on Q4. When Q4 is on, the gate of P-transistor Q3 is pulled to ground, turning on Q3 as well. Q3 provides a current path from the power supply **5V_USB** to the battery charging system so the batteries can be charged from the external voltage supply. If the deployment

TABLE III
DESCRIPTION OF POWER SYSTEM STATES

State	Description	Spacecraft Power
Testing and Charging	The USB mini connector is connected to a standard 5 volt USB cable for battery charging, diagnostics, and testing. All diagnostics within the P-POD are done while the deployment switches are unactuated. In this mode, power is supplied from the 5 volt USB supply. To supply enough current for charging, a powered USB hub is used.	5V (from USB)
RBF Pin Inserted	The RBF pin is inserted into the USB mini connector.	0V
Deployment Switches Actuated	The spacecraft is loaded into a CubeSat dispenser, awaiting launch, with deployment switches actuated. The RBF pin is removed. Batteries may be charged using a 5 volt USB cable while in the dispenser, however, no power is delivered to the electrical power system of any other part of the satellite.	0V
Deployed, Normal Operation	Nothing is plugged into the USB mini connector and at least one of the deployment switches is unactuated for more than 50 ms. The PIC is fully powered from the on-board battery system. In this state, the CubeSat performs its mission.	Battery (3.6-4.2V)

switches are actuated then **DEPNO** is connected to **DEPCOM**, P-transistor Q1 is turned off, and no power is supplied to the EPS bus **VBUS**. This means the satellite power system is disabled, even while the batteries are being charged. If the deployment switches are not actuated then **DEPCOM** is connected to **DEPNC** causing Q1 to be turned on so that power is supplied to the satellite through the EPS bus **VBUS**. Thus, the satellite can be tested and monitored through the USB data port.

2) **RBF Pin Inserted**: When the RBF pin is inserted, the power and ground of the USB connector are shorted together through the modified USB plug. This forces the voltage at the circuit input **5V_USB** to be 0 V. As a result, transistors Q4, Q3, and Q2 are all turned off. Because Q3 is off, battery charging is disabled. Because Q2 is off, there is no path to ground from the gate of Q1. Whether the deployment switches are actuated or not, the gate of P-transistor Q1 is pulled high, Q1 is turned off, and the satellite power bus **VBUS** is disconnected from any power source.

3) **Deployment Switch Actuated**: When the deployment switches are pressed, wire **DEPNO** is connected to wire **DEPCOM** (see Fig. 2), and the gate of P-transistor Q1 is pulled to the battery voltage **VPAC**, turning off Q1. No voltage is supplied to the EPS bus **VBUS** and the satellite power system is disabled without the need of the RBF pin. Note that if **5V_USB** is powered, the batteries may be charged while the deployment switches are actuated. This allows the spacecraft battery system to be recharged while in the CubeSat dispenser.

4) **Deployed, Normal Operation**: Once the satellite is placed in the dispenser, the RBF pin is removed. When nothing is plugged into the USB access port, the external voltage source input **5V_USB** floats. Because of resistors R2, R6, and R7,

the voltage at **5V_USB** rises to 0.38 times the battery voltage **VPAC**. The battery voltage is at least 3.2 V, resulting in a minimum of 1.2 V at the gate of N-transistor Q2, turning on the transistor. R2, R6, and R7 also cause the voltage at the gate of Q4 to be 0.20 times the battery voltage **VPAC**. The battery voltage is at most 4.2 V, resulting in 0.8 V or less at the gate of N-transistor Q4. This turns off transistors Q3 and Q4 and disconnects the current path to charge the batteries through the access port. The batteries may still be charged from the solar cells through another path.

While in the dispenser, the power system is disabled by the deployment switch as was discussed in Section III-A. However, after the satellite is released from its launch dispenser, the deployment switches become unactuated and wire **DEPCOM** is connected to wire **DEPNC** (see Fig. 2). The gate voltage of P-transistor Q1 is grounded through the **DEPCOM** to **DEPNC** connection and through transistor Q2.

Resistors R3 and R4 in combination with capacitor C1 create a turn-on delay causing it to take about 50 ms to turn on transistor Q1 after the deployment switch is deactivated. It takes much less time to turn Q1 off again if the deployment switch is reactivated since the gate is pulled to a high voltage using only resistor R3 and capacitor C1. This delay prevents the system from turning on inside the dispenser if the deployment switch is deactivated momentarily. When the deployment switch is deactivated and stays deactivated for 50 ms, the transistor Q1 is turned on, enabling battery power to the rest of the spacecraft.

IV. RESULTS

The completed access port and inhibit circuitry implemented for a PIC is shown in Fig. 6. In comparison to commercially available implementations, the design presented in this article

TABLE IV

COMPARISON OF THE PICs ACCESS PORT AND RBF PIN IMPLEMENTATION WITH OFF-THE-SHELF ACCESS PORT IMPLEMENTATIONS

	PICs	Pumpkin [21]	GOMSpace [15]	Endurosat* [17]
Approximate CubeSat Surface Area	0.5 cm ²	11 cm ²	20 cm ²	0.67 cm ²
Protocols supported	USB (I2C, SPI, JTAG, UART)	USB	USB (4x UART)	USB or custom (2-signals)
Connector 1 Purpose	USB mini <i>Data, charging, RBF</i>	USB-B <i>Data</i>	USB mini <i>Data, charging</i>	4 pin header <i>Data, charging</i>
Connector 2 Purpose	NA	DC Barrel Jack <i>Charging</i>	14 pin header <i>Power control, RBF</i>	Custom pin <i>RBF</i>
Connector 3 Purpose	NA	Custom pin <i>RBF</i>	NA	NA

*Not available at start of PICs development

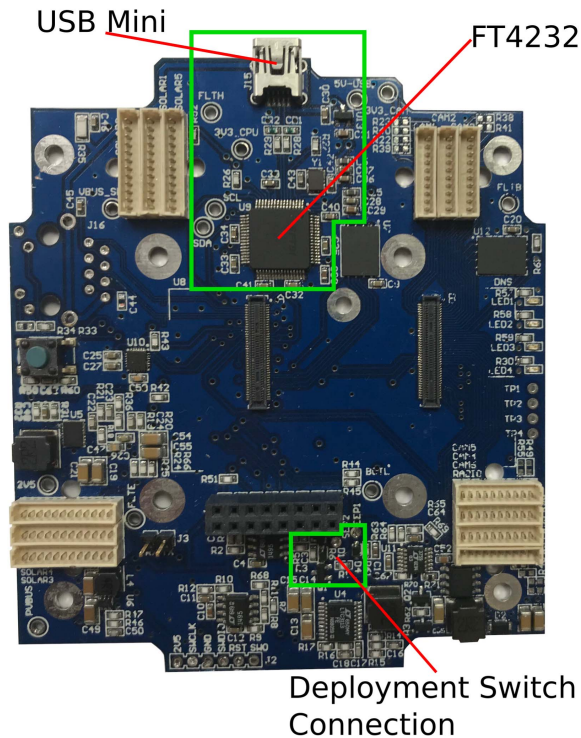


Fig. 6. PICs EPS and command and data handling board. At the top is the USB mini connector used for power, data and RBF and the FT4232 multiprotocol integrated circuit. At the bottom is the deployment switch connection surrounded by the circuitry for disabling the CubeSat using the RBF pin and deployment switches.

reduces the size and increases the features of the access port and RBF pin. This is summarized in Table IV. While the charging and data access features of a PICs access port design are included in other systems, none of the systems integrate the RBF pin with the data connector. A comparison of cost is not

made due to the different methods of integrating access port circuitry; the PICs circuitry is integrated on a single printed circuit board (PCB), whereas other systems may spread the access port and RBF circuitry across multiple internal and external PCBs. The approximate cost for the components of a PICs access port is 20USD.

Although the presented design was developed for the PICs mission, it can be adapted for other CubeSat missions. This RBF pin and access port combination is much smaller than alternatives, so it can easily fit within the openings available in off-the-shelf structures and solar boards. Additionally, the need for small-footprint data and power access, as well as safety inhibits, is not unique to CubeSats. This design may be included in a custom, multipurpose circuit board, or dedicated access port circuit board for use on a variety of spacecraft form factors or with other types of unmanned vehicles.

V. FUTURE WORK

During subsystem and system testing of the PICs, the access port was used heavily, and many possible improvements to it were found which have not been implemented. The most significant improvements are listed below.

- 1) It was found that a single USB cable and the 500-mA current limit on a standard PC USB port is not capable of powering a PIC, leading to battery drain during testing. This was resolved by using a 2000 mA powered USB hub between the computer and the PICs access port. Since the development of the PICs access port, the universal serial bus Type C (USB-C) standard [22] has gained traction. The USB-C standard allows for up to 65 W of power to be delivered through a single plug, and a USB-C connector has a higher signal count than a USB mini connector. Replacing the USB mini connector with

a USB-C compliant connector would make it possible to have high power charging, and to complement the USB connection to the CubeSat with another high-speed protocol, such as Ethernet, through a similarly sized access port.

- 2) With the current implementation, it is not possible to monitor the CubeSat through the access port while it is operating on battery and solar power, as USB battery charging occurs whenever a USB cable is connected to the CubeSat. An internally powered monitoring state may improve testing by allowing the power system to operate as it would in flight. A future implementation could disable USB charging by adding a transistor between Q3 and **5V_USB_BAT** (see Fig. 5) which can be disabled using the GPIO on the FT4232.
- 3) It was originally intended that the fourth port on the FT4232 be used for communicating with the eleven microcontrollers on the Power System I²C bus (see Fig. 1), allowing each to be reprogrammed or monitored while the CubeSat is fully assembled. Due to limited development time, this capability was not implemented for the PICs mission. Adding this feature would make it possible to reprogram microcontroller firmware without disassembling and re-assembling a PIC.

VI. CONCLUSION

Spacecraft systems that support safety and preflight development are critical to mission success. The CDS sets the requirements for the systems used to ensure safety and to facilitate servicing for CubeSats. The design of these systems significantly impacts spacecraft size, weight, cost, and development time. Existing off-the-shelf implementations are relatively large, heavy, and expensive. This reduces CubeSat performance by consuming volume and surface area that could be used for other components.

The presented design reduces volume, weight, and cost by incorporating off-the-shelf components originally developed for consumer electronics, notably the USB mini port and multiprotocol FTDI integrated circuit. This is achieved by integrating the access port and RBF pin functionality into a single USB mini port. The USB mini port provides charging and RBF functions while passing data to the FTDI integrated circuit which provides UART and JTAG connections to the main processor and a UART connection to the EPS microprocessor. This combined power and data port facilitates charging, testing, and programming of subsystems while consuming a very small area. These advantages help miniaturized spacecraft to be developed quickly and for less cost than would be possible using off-the-shelf CDS-required servicing and safety solutions.

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