A Standardized Solution to Command & Data Handling Between Modular Bus and Payload for the Future CubeSat Missions

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ABSTRACT

The traditional CubeSats development model is a one-off build designed to accomplish a specific mission using proprietary hardware and software. The specific mission requirements and associated development costs result in a lack of reproducibility for CubeSats. The Naval Academy Standard Bus (NASB) advances the concept of CubeSat modularity with a design that physically separates a fully-functional standalone 1U bus from an independently-developed 1U or 2U customer payload module with a 10-pin wiring harness serving as the sole electrical interface between bus and payload modules. Residing within the standard bus module the main onboard computer (OBC) handles uplink and downlink communications and connects the NASB to the payload module through two interface boards: the Bus Board and the Payload Interface Board (PIB). Ground commands received by the NASB pass through the Bus Board to the PIB in the payload module, through which they are communicated to the payload via universal asynchronous receiver/transmitter (UART) protocol. Messages and stored data generated by the payloads are stored on a secure digital card within the PIB, to be passed on to NASB and downlinked to the ground station. This modular design allows for independent development of payloads, shortening CubeSat development timeline by eliminating the need for bus development in parallel with payload development.

1 INTRODUCTION

The burgeoning interest in CubeSat development for operational missions underscores the need to expedite the transition from design to launch. While commercial vendors have introduced "modular" capabilities to streamline the development process, these solutions have not sufficiently addressed the time constraints faced by academic institutions. Despite the adoption of "standard" components to enable modularity, the integration with payload components often results in bespoke, time-consuming builds that impede efficient project execution and lack future repeatability by necessitating customization of hardware and software within the CubeSat shell.

An early instance of enhancing CubeSat modularity through standardized bus design emerged with the MISC-series CubeSat bus in 2010. The MISC series bus compartmentalized the housing structure, attitude control system, and flight motherboard within a 1.5U volume, featuring an open architecture for pluggable processing modules. Additionally, it provided a 1.5U payload bay and pin-map for seamless payload integration [1]. Adopted by the federal government as the "Colony I" CubeSat bus, based on the MISC-2 model, it became the standard bus for future government CubeSats. This adoption reduced costs, development time, and expedited technological advancements and on-orbit experimentation [2]. Despite its hardware modularity focus, the MISC-series bus required customized software and bus functionality, leading to concurrent payload and bus development and integration

[1]. Subsequent efforts have been made to further enhance modularity in CubeSats and larger small satellites, such as the Tactical Satellite Program (TacSat) by the Naval Research Laboratory (NRL) [3]. However, this traditional modularity approach still involves a labor-intensive design process with extensive customization, resembling more of a one-off satellite design rather than a repeatable one [4-6]. Despite incorporating standard components or structures, the integration of payloads to bus components in previous modular satellites demanded customization for a significant portion of the overall satellite system, including mechanical and electrical interfaces and software.

In order to alleviate these challenges in the university-education setting, the Naval Academy Satellite Bus (NASB) is pioneering a paradigm shift in CubeSat modularity by introducing a design that physically separates a fully-functional standalone 1U bus from an independently-developed 1U or 2U customer payload module. This innovative approach allows for integration with a payload module through a straightforward mechanical and electrical connection process, reducing integration time to a matter of hours. At the heart of this standardized solution lies the command and data handling (C&DH) architecture, which leverages inexpensive commercial-off-the-shelf (COTS) components. The main onboard computer (OBC) within the bus module orchestrates uplink and downlink communications, interfacing with the payload module through dedicated interface boards: the Bus Board on the NASB and the Payload Interface Board (PIB) in the payload module. A simple 10-pin wiring harness serves as the sole electrical conduit between the Bus Board and the PIB. Ground commands dispatched to the NASB are seamlessly relayed to the payload module via the Bus Board and the PIB, employing the universal asynchronous receiver/transmitter (UART) protocol for communication. Subsequently, messages and stored data generated by individual payloads are securely stored on the PIB's digital card, ready to be transmitted back to the NASB and downlinked to the ground station. This modular architecture is underpinned by standardized electrical connections, UART communication protocol, and command formats between modules, ensuring interoperability and ease of integration.

Payload C&DH requirements are communicated to payload developers through an interface control document (ICD), which also specifies standardized commands and protocols. This paper provides a comprehensive exposition of the command and data handling architecture that enables the independent development of payload modules, in addition to the detailed mechanical interfacing and structural design aspects facilitating rapid integration for a holistic solution to CubeSat modularity and interoperability challenges.

2 INTERFACE DESIGN

The NASB Project revolutionizes the process of CubeSat development and launch with a “next-level modularity” approach. This approach consists of integrating a customer’s independently-developed 1U or 2U Payload Module (PM) with a self-sufficient 1U standard bus (NASB) via one specified electrical interface and standardized physical connections. A ICD establishes a set of PM guidelines, which include physical, electrical, and software requirements for payload design teams (customers) to successfully integrate with the NASB. The standard bus eliminates the need for satellite subsystem development to focus design efforts on the Payload Module (PM), shortening the transition time from design to launch.

The big picture mission and long term goal is to have the Service Academies student teams build a NASB as a part of their engineering curriculum and use the design capstone class for development or integration of an appropriate payload. For example, USNA teams in the Spacecraft Systems Laboratory Course (EA467) in the USNA’s Aerospace Engineering Department would assemble one standard bus using the well-defined Assembly Procedures, thus creating a stockpile of buses. This stockpile of buses can then be rapidly integrated to put sensors and payloads into orbit.

2.1 Design Overview

The NASB module is a 1U standalone CubeSat, which contains all of the satellite subsystems required for an operational mission. The unique "next-level modularity" design feature of the NASB is its ability to integrate with up to a 2U of independently-developed payload module that do not have typical satellite life-support systems (e.g., power generation, communication, etc.). A sample NASB-based CubeSat with a 2U Payload Module is shown in Figure 1. The internal layout of NASB is also shown in Figure 1.

Bus subsystem functions provided by the NASB include: an Electrical Power System (EPS); a Command and Data Handling System (C&DH); a passive Attitude Determination and Control System (ADCS); an On-Board Computer (OBC); and a complete structural system. If additional subsystems (e.g., propulsion, thermal control system) or active subsystems (e.g., reaction wheels, magnetorquers, environmental control) are mission-critical, they must be incorporated into the Payload Module.

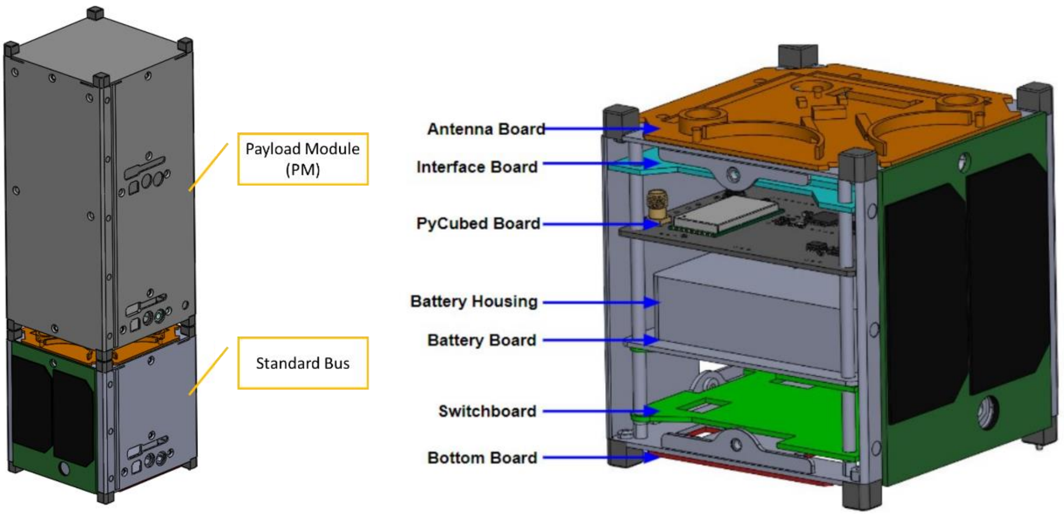

Figure 1. (Left) Notional 3U NASB-based CubeSat. (Right) Internal Layout of NASB.

2.2 Bus-payload Integration

The NASB provides structural interfaces, baseplates, and spacer mechanisms to facilitate modular assembly for the Payload Module (1U or 2U). The bus and payload module are integrated into one complete 2U or 3U CubeSat. Integration between NASB and Payload Module requires five steps. First, the male Payload electrical cable is inserted into the fixed female electrical receptacle on the NASB (Figure 2). The size, type, pin-map, and orientation for this interface connection is specified in the ICD. Second, each solar panel on the CubeSat is attached to its corresponding electrical cable on the NASB wall. Third, the newly-connected solar panels are placed vertically into the solar panel clips on the NASB. Finally, the bus and payload are fastened together using two bolts that secure the mechanical connection between the two modules (Figure 3).

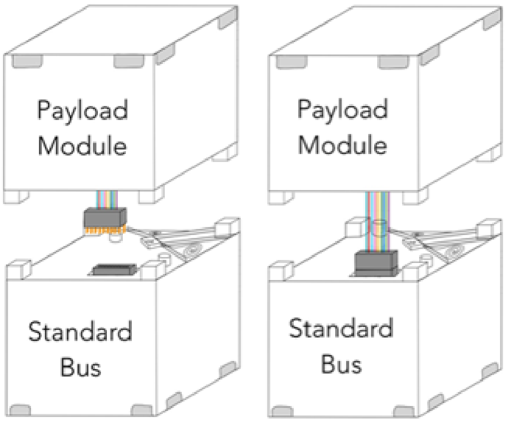

Figure 2. Depiction of electrical interface.

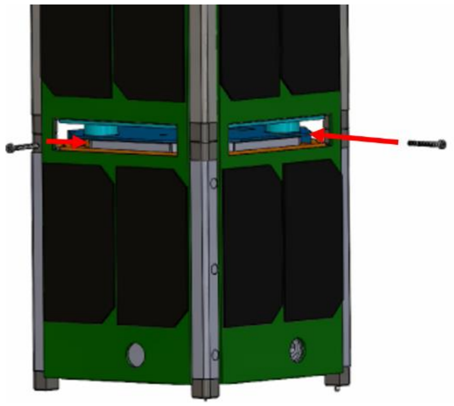

Figure 3. Mechanical interfacing shown.

2.3 Mechanical Interface

NASB was designed to meet CubeSat dimensions and features outlined in the CubeSat Specification Drawings (CSD), as well as the fit-check outlined in the CubeSat Inspection and Fit-check Procedure (CIFP). The Payload Module must meet the physical properties specified in both the CSD and CIFP independently and prior to delivery for integration with NASB. By design, the mass of the 1U NASB is 1.5kg and its center of mass (CM) is 1 cm below its true geometric center along the Z-axis (per standard CubeSat axes). The ICD specifies constraints on the Payload mass and CM in order for the final assembled CubeSat to be within the acceptable range in the CSD and CIFP. Per the NASB ICD, the Payload Module has no protrusions on the surface of the four side walls (X-axis and Y-axis) to accommodate surface-mounted solar panels, and no protrusions on the bottom surface (-Z) to facilitate the physical and electrical connections between the NASB and the payload. The top surface (+Z) is available for payload developers to modify, and the 2U Payload Module can accommodate a 7.6 cm x 6.0 cm area for outside access, with a corresponding reduction in total power due to loss of solar panel surface area to accommodate the access portal.

The physical interface that connects the NASB to the Payload Module is an interlocking set of two connection posts: solid posts mounted to the top of the NASB insert directly to hollow posts mounted to the bottom of the Payload Module (shown in Figure 4). The two solid 4 mm connection posts on the NASB stand on the lower diagonal of the top of the chassis. The NASB posts were designed to support a 4 kg 3U CubeSat by one post, without compromising the structural integrity of the modular CubeSat. The ICD specifies a set of two hollow aluminum connection posts on the Payload Module, which slide onto the connection posts of the NASB. This simple design protects the joint between the bus and payload module assembly from the forces experienced during launch and orbit insertion. Set screws in a tapped hole on the Payload Module posts secure the posts of the NASB Bus to those of the Payload Module. It is important to note that the poly-picosatellite orbital deployer (P-POD) launch mechanism (or similar rail-based deployer) absorbs most of the vibration loads the satellite will experience during launch, reducing the need for this physical interface to support launch structural stresses.

2.4 Electrical Interface

The Payload Interface Board (PIB) serves as the electrical interface between NASB and the payload system, distributing power to the payload components and acting as the communications hub for command, data transfer and data storage between the NASB and the Payload Module. The PIB includes software needed for the NASB to communicate with the Payload Module; this software can be customized by the payload developer but the ICD requires the Universal Asynchronous

Receiver/Transmitter (UART) communication protocol. The PIB contains three surface-mounted 10-pin connectivity headers for use by payload components. Three solid state switches and three latching relays are used to control the three switched power outputs to the payloads (3.3V, 5V, and the nominal battery voltage of approx. 7.4V).

The main microprocessor of PIB is a Feather M0 Adalogger with an SD card for data file storage. Although provided by the NASB, the PIB is physically located in the Payload Module on the bottom (-Z axis) plate, and connects to the payload components by a 10-pin connector shown in Figure 4. Payload developers either use the PIB as their on-board computer or interface with the PIB using an additional Payload Module OBC.

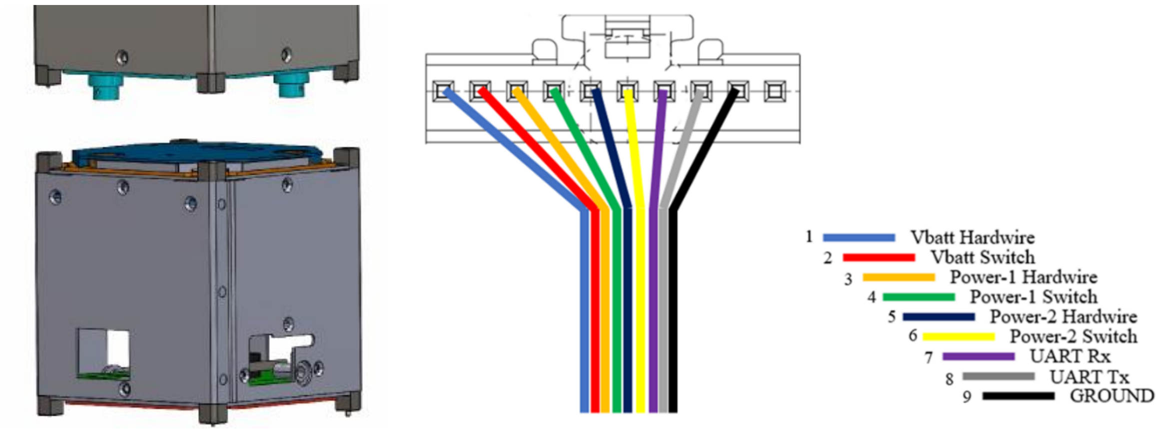

Figure 4. Depiction of mechanical (left) and electrical (right) interfaces.

2.5 Software Interface

There are three types of ground communications available for payload missions: commands, messages, and data downloads. Commands are instructions sent from the ground station to the satellite, which may pertain to housekeeping or mission functions. Messages are packets of information transmitted from the satellite to the ground station, and include satellite health information and command acknowledgement. Data downloads are payload specific and reflect the payload missions, e.g., measurements, images, science results. The three main categories of data handling for NASB is described here, and a more detailed command list specific to how data are handled in the current mission's payload module is detailed in the Mission Overview section.

Commands: The ground station directly commands the Payload Module via the UHF radio. A command packet is limited to 150 Bytes. When NASB receives a command directed at the payload, NASB strips overhead from the command packet and passes the core packet to PIB, which communicates the information to the payload via UART. The command pass-through to the payload occurs in real time, with minimal delay. The payload processes the command upon its receipt.

Messages: The payload downlinks messages to the ground station via the UHF radio. The maximum message packet size is 150 bytes. The payload sends a message packet to the PIB via the UART channel with a "M:" header. PIB removes the "M:" header, adds a sequential number and appends it to a file named "message.txt" where it is stored on the SD card until it receives a message command from the ground station with that number as its argument. As an example, when the PIB receives a command "Downlink message number 534," it retrieves the 534th message line from message.txt and passes it to the NASB, where it is transmitted to the ground station.

Data Download: Payload data is stored in the Payload Module's PIB as a sequentially numbered file in a Data Folder on the SD card in the form "5.txt." The payload downloads data to the ground station via radio waves in the S-band. The maximum data file size is 30 kB, which is the file size that can be downlinked in one minute at S-band. Data files are stored until the ground station sends a command requesting the downlink: "Downlink 5." The NASB passes the command through to the PIB, which downloads the file to the ground station on the next pass.

3 MISSION OVERVIEW

The first iteration of this modular CubeSat model is USNA-16. USNA-16 contains the 1U NASB and a 2U PM with payloads developed independently by student CubeSat developers in other university settings.

3.1 Background

The mission of the USNA-16 is to create the first USNA modular CubeSat, which contains a 1U NASB and a 2U PM. USNA-16 integrates two external payloads into the PM via the PIB, 10-pin connector and mechanical modular structure. The United States Air Force Academy (USAFA) payload, FALCON-RAD, houses a dosimeter to measure and record radiation data on orbit, with a focus on studying the South Atlantic Anomaly. The University of Maryland (UMD) payload consists of a customized UHF radio which their students will use to communicate with remote ground stations. An aluminum ballast within the PM demonstrates the ability to carry a third external payload on board and ensures the correct location of the center of mass within the PM.

In addition to standard CubeSat qualifications for ground testing and environmental testing, which both the NASB and payloads must individually achieve, USNA-16 imposes additional qualifications on the fully assembled CubeSat. Firstly, after a successful visual inspection of the mechanical interface between the NASB and PM, USNA-16 must undergo an additional vibration test as a 3U CubeSat. Secondly, after a successful visual inspection of the 10-pin connector electrical interface, the power, voltage and current outputs of both the NASB and PIB must demonstrate the effectiveness of the electrical connection between the bus (USNA component) and payloads (external component); external payloads connected to the PIB for must qualify their electrical system as well as their communication system, specifically data transfer from the payload to the PIB and data storage on the PIB.

3.2 Description of USNA-16 Payload Interface

As previously described, a standard PIB software provides three methods of operational communication: messages, commands, and data download. A message is information from the payload through the NASB to the ground station, which is not scientific data; an example of a message is a status check on the functionality of the payload. A command is an instruction to perform a task, from the ground station through the NASB to the payload; an example of a command is a “turn on” instruction after the CubeSat reaches orbit. Data download is the transfer of scientific information from the payload through the NASB to the ground station; an example of a data download from USNA-16 is a file of dosimeter readings from FALCON-RAD. Although messages, commands and data downloads are communications that pass between the NASB and payload, the PIB is the integral component that directs communications traffic for mission success.

The PIB software facilitates communication between the NASB and payloads through predefined sets of commands embedded within its code. The GPS timecodes sent from the NASB and received by the PIB are identified by their characters “$G” at the beginning of the code; start and end bytes “ff” are added to the timecodes transmission to the payloads.

The PIB software code comprises specific definitions, each containing commands callable by a main function while loop. Three main function definitions are implemented: "check_command," "store_message," and "store_data." Each definition contains its own set of functions that enables the PIB to control communications efficiently. Each function has an identifier: “C:”, “I:”, “A:”, “F:”, “T:”, “M:”, “D:”.

The "check_command" definition manages communication between the NASB and the PIB, and interprets incoming commands from the ground station to transfer data or regulate power to the payloads. There are five identifiers within the check_command definition: “C:”, “I:”, “A:”, "T:" and “F:”. The “C:” identifier signifies a general command from the ground station through the NASB and PIB to the payload. The “I:” identifier signifies power commands sent from the ground station through the NASB to the by the PIB, controlling the power switches attached to the PIB to regulate the voltage received by the payloads (between 3.3V, 5V, and Vbatt (7.4V nominally)). The “A:” identifier signifies the "send messages" command from the ground station through the NASB to the PIB, resulting in the download of the messages.txt file from data storage on the PIB through the NASB to the ground station. The “F:” identifier signifies the "send data" command from the ground station through the NASB to the PIB, resulting in the download of specific files of data from data storage on the PIB through the NASB to the ground station. The “T:” function serves as an identifier for the GPS timecodes sent from the BUS to the PIB, which have start and end bytes “ff” added to them before being transmitted to the payloads.

The "store_message" definition handles communication between the payloads and the PIB, executing various functions and health checks on payload modules. Messages received from the payloads are stored on the PIB's SD Card until requested by the bus through the corresponding function within the "check_command" definition. The "M:" identifier executes the storage of a message from the payload on the PIB SD Card.

The "store_data" definition facilitates communication between the payloads and the PIB, enabling the payloads to transmit data to the PIB for storage in a file within the data folder on the PIB SD Card. Data is retained on the SD Card for the NASB to download using the corresponding function within the "check_command" definition. The "D:" identifier executes the storage of data from the payload on the PIB SD Card.

3.3 USAFA FALCON-RAD Data Flow and Handling

FALCON-RAD captures and processes data with high precision. Each radiation measurement from the dosimeter is formatted to ensure accuracy and reliability. This includes a breakdown of data components, comprising a 22-byte line preceded by 2 synchronization bytes and followed by 2 checksum bytes, facilitating seamless communication from the PIB to the interface board on the NASB. The actual data payload consists of 18 bytes, supplemented by an additional 8 bytes for GPS time confirmation, culminating in a total of 30 bytes per line. In the event of errors detected through the checksum process, the PIB promptly discards the erroneous line to maintain data integrity.

Data storage on the PIB is organized to facilitate efficient retrieval and management. Data is stored in numbered files within a designated folder named 'data', with each document sequentially titled in the format (01.txt). Each text file is subdivided into individual lines of data, with each line subjected to a checksum validation process to ensure correctness. Each line of data corresponds to one measurement, occupying 30 bytes, thus maintaining consistency and coherence in data storage and management procedures.

A streamlined data transfer facilitates communication between the ground station and the payload. Commands dispatched from the ground station to the NASB are routed to the payload, encapsulating the relevant dataset number within the command. Data retrieval from each orbit is automatically initiated when USNA-16 is within range of the ground station.

3.4 UMD Data Flow and Handling

Because the UMD payload is a communications radio, the payload beacons telemetry and receives and executes ground station commands. Data storage and data transfer are not in the operational mission of this payload.

3.5 Data Budget

The data budget for the USNA-16 mission is summarized in Table 1. One packet is 30 bytes, made up of: 1) 18 bytes (no overhead) from third-party payload development; 2) 8 bytes from the PIB timestamp, condensed into two integer values; 3) 2 synchronization bytes; and 4) 2 checksum bytes With 20 bytes from the UMD telemetry packet, USNA-16 will produce approximately 703 kB of data per day, which is within the downlink limit of 1 MB/day specified by the USNA NASB ICD.

Table 1: Data Budget

Payload	Packet size (bytes)	Packet frequency (s)	Total data (kB/day)
UMD	20	every 10 s	~3
USAFA	30	every 5 s - every 1 s in SAA	700
TOTAL	--	--	~703

4 CONCLUSION

The Naval Academy Standard Bus (NASB) heralds a new era in educational CubeSat technology, offering a standardized platform for payload integration. Its first iteration and on-orbit demonstration is USNA-16, a 3U CubeSat that includes two external payloads. The central interface, the Payload Interface Board, is an optimized interface system that enables easy integration of external payloads to NASB. PIB achieves these goals by providing power regulation/distribution and standardized data handling functions between NASB and a payload through a single wiring harness connection. The standardized data handling process is established through an Interface Control Document (ICD) that is supplied to the payload developers. For any given launch opportunity, if the payload module meets the requirements in the ICD and passes qualifications, it can be rapidly integrated with NASB for launch. If the payload module does not fit the requirements in the ICD or fails to qualify, the NASB will launch without a payload as an educational mission utilizing the onboard communications system. By standardizing CubeSat buses and facilitating payload integration, the NASB creates a model for the mass manufacture of a modular 1U satellite bus which can support a 1U or up to a 2U customer payload, decreasing both the development time and cost for educational satellite missions.

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