Survey on Harness Design for CubeSats: Understanding the Constraints of CubeSats Design and Toward an Optical Wireless Bus for CubeSats

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Abstract

CubeSats of nanosatellites have attracted the attention of space scientists and engineers seeking to observe the space environment and develop innovative technologies in space engineering. The CubeSat is a class of miniaturized satellites with a form factor based on a 10 cm cube. However, the dimensional constraints of CubeSats restrict the embedding of relatively large mission devices, such as attitude control systems, into the satellites. Moreover, the harness used to transfer the data and supply power to the mission devices also occupies physical space to embed the mission devices. Therefore, this research surveys earlier studies on nanosatellite harness design. In addition, we consider the possibility of an optical wireless harness for the satellite bus system to achieve a more effective and reliable design for the CubeSats.

Keywords:

1. Introduction

Space developments recently have been gathering attention to provide services such as worldwide wireless communication, launch vehicles, and data analysis of remote sensing by artificial intelligence. The satellites are categorized by mass of the satellites, such as large satellites, microsatellites, and nanosatellites [1]. The category for microsatellites and nanosatellites is chosen actively for providing satellite-based services to construct their service systems because both kinds of satellites contribute to the development costs of the satellites and launch costs to orbits. Especially the small satellites (~180 kg) and their onboard devices have attracted space engineers, space researchers, and the space market because the micro/nanosatellites reduce the development costs and development period [2].

Moreover, universities and venture companies develop and operate CubeSats of nanosatellites for innovative technology demonstration and space or earth observation. The CubeSat is a miniaturized satellite with a 10cm cube (The basic unit size (1 Unit) of the CubeSat is a cubical shape with 10 cm × 10 cm × 10 cm. The physical size of the CubeSats depends on the mission requirements, and the total unit size varies from 1U to 12U. Fig. 1 shows the typical configurations of the CubeSats. The 1U, 2U, and 3U CubeSat are implemented as a single string of 1U

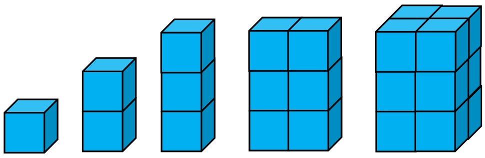
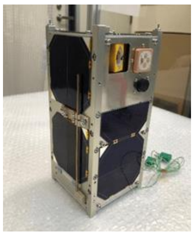
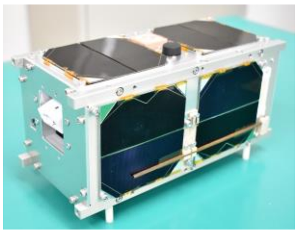


Fig. 1 Typical configurations of CubeSats



(a) KOSEN-1



(b) KOSEN-2

Fig. 2 Flight models of KOSEN-1 and KOSEN-2

CubeSat. On the other hand, 6U CubeSat is implemented as double lines of 3U Cubesat.

The physical size of the CubeSats is small compared with conventional satellites such as communication satellites and weather satellites [2]. However, many universities, research institutions, and venture companies attempt new and challenging technologies such as attitude control systems, inter-satellite communication, and space tether. Although launch services into space are necessary for the satellites, the major launch vehicles such as Epsilon Launch Vehicle (Japan Aerospace Exploration Agency, JAXA) [3], Polar Satellite Launch Vehicle (the Indian Space Research Organization, ISRO) [4], and Vega [5] and Ariane [6] (European Space Agency, ESA). The CubeSats usually are onboard as piggyback satellites, and the multiple CubeSats are onboard in a single launch. The PLSV-C37 by ISRO successfully launched 96 CubeSats in a single launch (The flight of PLSV-C37 carried 104 satellites in total in a single launch) [7], [8].

We belong to the KOSEN space collaborative group and have attempted CubeSat development twice: KOSEN-1 and KOSEN-2. Unfortunately, we faced various problems caused by the wire harnesses through two satellite developments and the function tests. The wire harnesses are used to connect electrical components to supply power and transfer control signals and mission data. Therefore, we considered that we needed to devise a different approach for harnessing to assemble the satellites.

In this paper, we survey on the satellite harness designs to consider the new different approaches to building the CubeSat for achieving highly reliable satellites. We also propose a new approach to constructing CubeSats' computer system using optical wireless communication technology. We consider some issues for implementing the optical wireless bus for the CubeSats. The remainder of this paper is as follows: Section 2 explains lessons learned from satellite developments of KOSEN-1 and KOSEN-2; Section 3 describes reviews of constraints of satellite design on CubeSats and safety regulations for satellite onboard; In Section 5, we explain the results of the survey on wired and wireless harness for satellites; In Section 5, we propose the optical wireless bus for the CubeSats and explain the basic concept of the proposed bus system; In Section 6, we conclude the survey on the CubeSats' harness and introduction to the optical wireless bus.

2. Lessons learned from satellite developments of KOSEN-1 and KOSEN-2

We have attempted to develop the two CubeSats: KOSEN-1 [9] and KOSEN-2 [10]. Fig. 2 shows flight models for launch vehicles onboard. The developments and technology demonstrations in space for KOSEN-1 and KOSEN-2 are selected for Innovative Satellite Technology Demonstration-2 (KOSEN-1) [9] and the same Demonstration-3 (KOSEN-2) [10] by JAXA. KOSEN-1 aimed to demonstrate an antenna expansion technology for Jupiter's radio observation. KOSEN-1 was launched by JAXA's Epsilon Launch Vehicle No. 5 in November 2021. KOSEN-2 aimed to demonstrate data transmission for sea crustal data from a marine buoy to KOSEN-2 at low orbit. KOSEN-2 was attempted to launch into space by JAXA's Epsilon Launch Vehicle No. 6 in October 2022. However, the launch of the Epsilon Launch Vehicle No. 6 failed the flight by a second motor trouble during the flight [10].

We faced various problems caused by harnesses through satellite developments and function tests. The satellites consist of onboard computers, batteries, chassis, harnesses, and mission devices. The main computers and sub-microcontrollers are interconnected and control the mission devices through electronic signals and electrical wires. The onboard computer boards, mission devices, and batteries are installed into the chassis of the CubeSats.

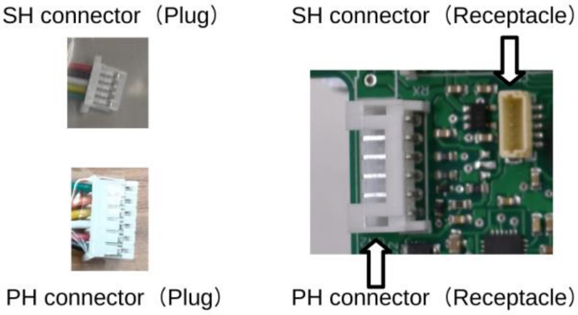
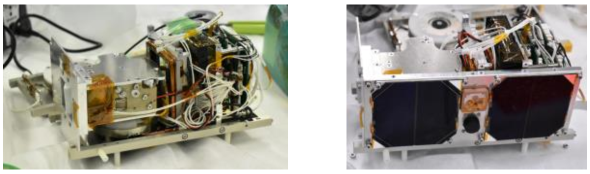


Fig. 3 Typical example of connectors and receptacles (J.S.T.Mfg.Co.,Ltd.)



(a) Before the body structure panel installation

(b) After the body structure panel installation

Fig. 4 The harness installation of KOSEN-2 flight model.

Fig. 3 shows a typical example of connectors used to interconnect the satellite mission devices.

The mission devices, electronic circuit boards, and batteries are installed into the chassis. The various kinds of harnesses are used for interconnecting the mission devices. Fig. 4(a) shows the actual harness installation of the KOSEN-2 flight model before the body structure panel installation. The workers need to be careful about damaging harnesses while installing the body structure panels and mounting the mission devices. Fig. 4(b) shows KOSEN-2 after the body structure panel installation. Eventually, the six panels are mounted around the chassis of the satellite.

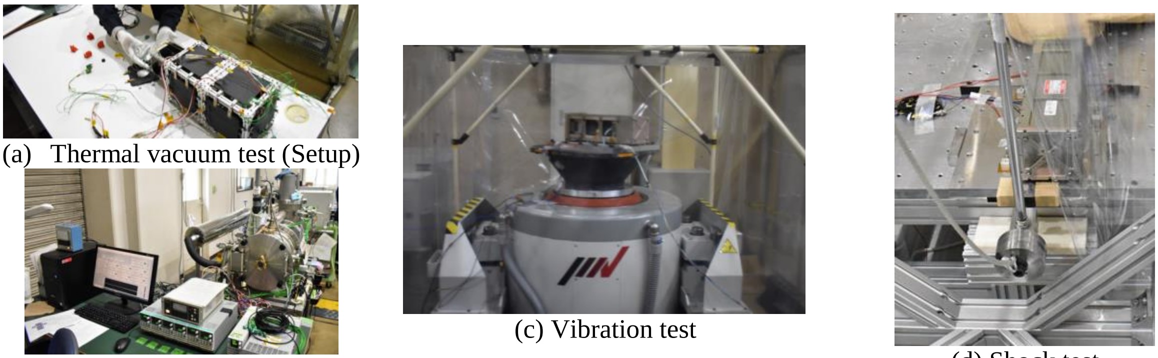
We recognized that some electrical mission devices of KOSEN-1 and KOSEN-2 did not work properly during the functional tests of the satellites. We found that the connectors' engagement between plugs and receptacles made the contact failures. Eventually, the mission devices worked adequately after replacing the connectors with new ones. However, we lost the effort to solve the contact failures of the harnesses during the satellite production. Therefore, we conceived that we needed to devise a different approach for harnessing to assemble the CubeSats more effectively and accurately.

3. Constraints of satellite design for CubeSats

The satellites for flight models onboard to launch vehicles must satisfy various requirements such as the budget for the satellite developments, mission requirements, and safety regulations for the launch vehicles. Epsilon Launch Vehicles User's Manual [11] is an example document on safety requirements for onboard satellites. The design standard document for the CubeSats is available [12] and many user manuals of the launch vehicles follow the CubeSat Design Specification. For the CubeSats, the vacant space for the main mission devices and their related devices occupies the internal space for the physical size. However, the physical size of the CubeSats and the various kinds of mission devices are embedded into the CubeSats in high density. The essential components of the satellites, such as onboard-computer boards, batteries, and wire harnesses, are essential devices for satellite implementation.

Although the physical size and the mass of the CubeSats are small, the CubeSats need to pass a safety regulation for launch vehicles. The launch vehicle service providers require safety inspections for the satellites. The safety inspections of the launch vehicles aim to prevent CubeSats' malfunction during the rockets' flights. The typical example of the CubeSats' malfunction during the flight is accidental radio emissions because the erroneous radio emissions interfere with monitoring and controlling the rocket's flights.

The designs and test results of the CubeSats need to satisfy the safety inspections for onboard launch vehicles. The tests for flight models for the launch vehicles involve various tests such as mass property tests, vibration tests, shock tests, and thermal vacuum tests. Fig. 5 shows the typical example of proto flight tests by KOSEN-2. Interface control documents define the test conditions for boarding the launch vehicles. Fig. 5(a) and Fig. 5(b) show the thermal vacuum test. The thermal vacuum test mainly aims to inspect the functions of the satellite under the vacuum state and the heat environment in space. Fig. 5(a) shows the setup for the thermal vacuum test, and the satellite is installed into the special enclosure that heats the satellite with manual control or programmed control. The satellites are installed and tested in the thermal vacuum chamber (Fig. 5(b)). Fig. 5(c) shows the vibration tests for the CubeSats. The vibration tests inspect the



(a) Thermal vacuum test (Setup)

(b) Thermal vacuum test (Testing)

(c) Vibration test

(d) Shock test

Fig. 5 Typical example of the proto flight test (KOSEN-2)

satellites under the vibration environments during the flights of the launch vehicles. The vibration tests simulate environments that assume various kinds of vibration caused by launch vehicles during the flights. Fig. 5(d) shows the impact tests for the satellites. The impact test aims to inspect whether the satellites endure the shocks for a fairing separation during the rocket's flight. In satellite developments, test conditions are defined in the rocket interface control documents. Therefore, the satellite development teams also need to consider the CubeSats' designs to pass the safety inspection regulations and their missions [13], [14].

4. Related work on satellite design for CubeSats

Space engineers and space scientists have studied extensively and deeply the design approaches of the CubeSats. However, the satellite developers need to devise the designs, assembly, and tests of the CubeSats because of the many design constraints require for the satellites.

The dimensions of the CubeSats are standardized by the design specification documents [12]. Therefore, the components such as electronic circuit boards also have modularity and compatibility with other components. The various components are available in the website shop [15]. Electronic circuit boards, such as onboard computers [16] and electrical power systems [17], are carefully considered for interconnectivity between the boards and stackable structures. The stackable modularity for the electronic circuit boards is a practical approach for the CubeSat design for high modularity. The PC/104 standards are used for stacking the electrical boards for the CubeSats [18]. Although the PC/104 standards are practical for interconnection among the electrical boards, the PC/104 socket is significant for the size of the CubeSats. The pins for the PC/104 sockets increase as the number of mission devices increases installed into the satellite. Using CPLDs for interconnecting the mission devices successfully reduced the wiring among electronic circuit boards [19]. The study [19] used CPLDs for routing the data and control signals for the mission devices. Using the CPLD approach and stackable electrical boards reduces the wire harness's mass and space.

For the reduction of the satellite's mass, the optical fibers are used for the signal transfer instead of the electrical wires [20]. The study [20] considered the optical fiber connectors and cables for spacecraft. Optical fibers overcome the data rate limitation and wire harness's mass. The proposed optical fiber was examined in the tests of the engineering model, and the test was passed without performance degradation and failures of the fibers.

Using PC/104 standards and optical fibers for the CubeSats would be the candidate solutions for overcoming the constraints of the CubeSat design. However, satellite engineers and researchers have also studied the other approach to the wireless harness. Although the related studies aim to wireless harness technologies for ICT equipment [21]. The study [21] investigates microwave radio propagation in the ICT equipment to design the wireless harness. The study is the first step in constructing the ICT equipment by connecting the internal devices with the wireless harness. The study analyzed microwave radio propagation for ISM 2.4 GHz band. The communication for ICT equipment is up to a couple of meters at most. The study reported that the proposed modeling technique using a frequency-

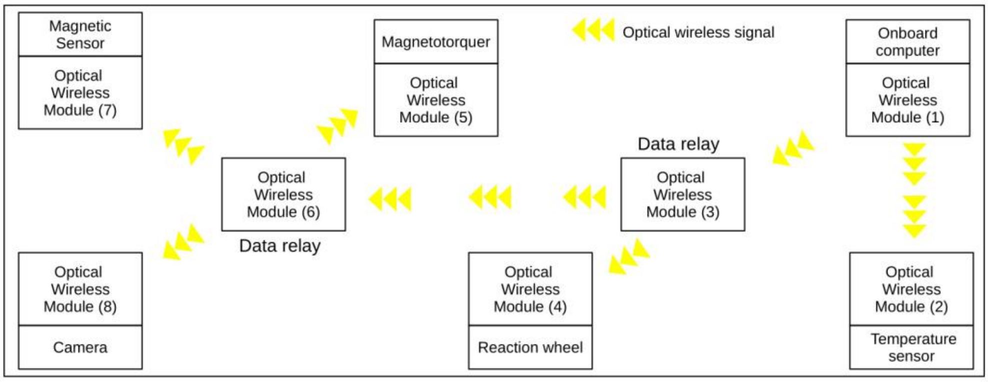


Fig. 6 Overview of the optical wireless bus. The numbers inside of the parentheses indicates module identifiers.

dependent path loss exponent expressing the near- and far-field propagation succeeded in extracting attenuation factors for the frequency and the propagation distance from the measured data.

The related study [22] also attempted constructing the wireless harness with ZigBee technology. The ZigBee is a technology and standard for constructing wireless sensor networks, and the study applied the ZigBee to a vehicle. The study reported viable technology for implementing an intra-car wireless sensor network. Two related studies reported that the wireless harness with IEEE 802.15.4 or ZigBee reduced the power requirements [23] and the satellites' power consumption [24].

The related study [25], [26], [27], [28] for the 3U CubeSat also attempted to construct the wireless harness called SKITH (SKIpTheHarness) of the InnoCube project. In the InnoCube project, Skith adopted the 2.4 GHz band for communication among the front-end modules. The Skith supports a data rate of up to 1 Mbps with GFSK modulation and transmission power up to 19 dBm.

Other related studies [29], [30] introduced the Ultra Wide Band (UWB) technology for substituting the wire harness to the wireless harness. The UWB is a personal wireless network technology for short-range communication (≤ 10 m). In the UWB technology, the modes communicate with very high-speed data rate and using wideband frequency (≥ 500MHz), compared with other related technologies such as ZigBee and Bluetooth. Furthermore, for the communication among the modes, the advantages of the UWB are low power, robustness for multipath fading, and reliability for communication errors. Therefore, earlier studies have investigated the applicability of spacecraft and vehicles for intra-interconnection for electrical devices.

The studies [31], [32] adopted a different approach to implementing the wireless harness for the satellites. The studies [31], [32] attempted to construct the wireless harness by optical wireless communication. There are various kinds of advantages of optical wireless communication for the wireless harness against radio wave communication. The optical wireless harness can avoid Electromagnetic Compatibility (EMC) in communication intra-spacecrafts and implement simplified circuits compared with RF circuits. Furthermore, the satellite development need not have RF licenses for optical wireless communication. The RF emissions during the launch vehicle's flight affect to monitor and control of the rocket. The study [31] described the development history of ten years on the optical wireless harness for spacecraft. However, in-orbit experiments on the optical wireless harness [31], [32] have still been challenged.

5. Optical wireless bus for CubeSats

5.1. *System overview of optical wireless bus*

In the previous section, we reviewed various papers on wireless harnesses for spacecraft and IoT equipment. Some studies on the wireless harness technology by UWB or ISM 2.4 GHz band demonstrated the feasibility of constructing the satellite bus system. However, the use of the wireless harness by radio waves usually are restricted by RF licenses and rocket interface control documents. The optical wireless communication for the mission devices would be the candidate for constructing the internal bus system for spacecraft. Optical wireless communication is available for spacecraft without RF licenses. Furthermore, optical wireless communication can avoid the restriction on erroneous RF emissions in launch vehicles' flights.

We propose the optical wireless bus based on the optical wireless harness to construct the bus system for the CubeSats based on the reviews of the earlier studies. The entire bus of the satellite consists of sensors and mission devices distributed in the satellite chassis. Fig. 6 shows the overview of the proposed optical wireless bus. The proposed optical wireless bus aims to interconnect the mission devices through optical communication, and each device transmits the mission and control data mutually.

Each mission device or sensor connects directly with an optical wireless module (OWM), and the OWMs control the devices. The transmission and reception of the optical signals of the OWMs would be realized with LEDs (Transmission) and photodiodes (Reception). Each OWM exchanges the mission and control data through optical wireless signals. The OWMs for the data relay act as router nodes for relaying the data. The OWMs ((3) and (6)) for the data relay receive the data from other OWMs, and the OWMs ((3) and (6)) relay the data to other OWMs ((7) and (8)).

5.2. *Implementation of optical wireless bus*

There are some technical issues with achieving the optical wireless bus. For the first issue, we need to design communication links among the OWMs for applying optical wireless communication to the CubeSats. However, the lighting LEDs of the OWMs consume the power of CubeSats for transmitting the signals. Furthermore, we need to consider the energy balance for power generation and power consumption for the operation of the CubeSats. Therefore, we investigate the communication links among the OWMs to realize the wireless optical bus.

For the second issue, we need to design the OWMs and implement the OWMSs as a module that can install into the CubeSats. We can implement the OWMs as printed circuit boards (PCB), including the transmission and reception circuits. Furthermore, the PCBs of the OWMs need to include microcontrollers for communication and controlling the mission devices or sensors. The transmission and reception circuits would be more straightforward than RF circuits because the optical wireless circuits for the proposed bus would not require high-frequency oscillation circuits. However, we need to consider the microcontrollers for the OWMs carefully because of the processing speed, storage space for programs, and input pins and output pins for analog circuits or digital circuits for mission devices and sensors. Therefore, selecting the microcontrollers for the OWMs depends on these requirements.

For the third issue, we need to design and standardize the communication protocol for the OWMs. The interconnectivity of the OWMs plays an essential role in the development of CubeSats. We need to consider various perspectives for the communication protocol, such as a physical layer, the data link layer, and the network layer. We need to define the modulation methods and data speed rate for the physical layer. We need to define the data frame, including error correction and header fields. In the end, we need to implement the communication protocol as a program for the microcontroller.

5.3. *In-orbit experiment plan and satellite development plan*

We develop the optical wireless bus and need to demonstrate the proposed bus in orbit. We have already obtained the opportunity for the in-orbit experiment as a CubeSat of KOSEN-3 (2U). KOSEN-3 is selected as Innovative Satellite Technology Demonstration-4 by JAXA. The primary mission of KOSEN-3 aims to demonstrate the pulsed plasma thruster system to maintain the orbit. KOSEN-3 will be launched by Epsilon S Launch Vehicle in the 2024 fiscal year. For the in-orbit experiment, the KOSEN-3 project is developing the satellite for the flight model. We consider and develop the engineering (EM) model of KOSEN-3 to verify the satellite design that complies with the safety requirements of the JAXA's Epsilon Launch Vehicle.

The optical wireless bus is still under development in the KOSEN-3 project. The optical wireless bus would contribute to the satellite itself and the development process of the satellite. The optical wireless bus would reduce the wired harness to interconnect the mission devices and sensors. However, the satellites require the harness for the power supply at the current development progress. The contactless power transmission technology can be the candidate to reduce the wired harness for power supply to the internal devices of the satellites. Other advantages of the optical wireless bus also can reduce the mass of the satellite by reduction of the wired harness.

Furthermore, the connection reliability of the connectors for interconnecting the mission devices or sensors would be improved because the mission devices or sensors exchange only the signals of the mission data or control data by wireless communication. Finally, the optical wireless bus enables us to change the design of the fitting out because of the mount position of the mission devices or sensors without changing the harnesses. The satellite development team can attempt various designs to fit out of the internal devices in the development process. The optical wireless bus would contribute to the rapid development of the satellite compared with the conventional development by the wired harness.

6. Conclusions

We reviewed the earlier studies on the harness for the CubeSats and discussed the constraints of the CubeSats' designs. Therefore, we proposed the optical wireless bus for the satellite bus system. The optical wireless bus comprises the optical wireless modules that communicate with other modules. The optical wireless modules are connected directly to the mission devices or sensors to transmit the mission data or control data for the satellite operation. In addition, we considered the possibility of an optical wireless bus for the satellite bus system to achieve a more effective and reliable design for the CubeSats. We explained that the optical wireless modules could be implemented with simplified circuits and microcontrollers compared with high-radio frequency circuits. For future work, we will implement the optical wireless bus for KOSEN-3 and demonstrate the usefulness of the optical wireless bus in orbit.

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