Development of Mission Control Unit Prototype for Small Class Satellite Payloads

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***Abstract*—In this paper, Mission Control Unit (MCU) prototype for small class satellite payloads is developed with the goal of providing schools and institutions to low cost design that could be easily integrated and augmented for mission–specific needs. Basic design platform has been developed to demonstrate the proof of concept model of MCU for small satellites by using commercial off-the-shelf (COTS) components. Many commercial companies have emerged to cater this objective however most of them provide expensive on-the-shelf solution, therefore this paper proposed a low cost, compact platform design. This paper presents the design of payload-ready prototype unit of mission control subsystem that is built on Arduino based microcontroller with wireless transmission by using COTS components. This platform is intended mainly for educational purposes, specifically to expose high school and university students or researchers to satellite engineering concept. Other than that, it is developed to provide platform for spacecraft developers, researchers and others to test their scientific missions or perform their research with reduced costs. In addition, the end-product of this project can be used for public outreach mission involving local communities of amateur radio operators and school students. This project has produced a prototype that is compatible with 2U CubeSat platform standard, requires no external wiring with all subsystems, and can be customized to perform many mission themes over amateur radio band.**

***Index Terms*—CubeSat; Mission Control Unit; Nanosatellite; Satellite Sensor.**

I. Introduction

Today, satellite becomes an important role in daily life. The significance of low-cost small satellites used for scientific research and application continuously grows in the fields of earth observation, precise climate monitoring, geoinformatics, mobile and personal communications, urban sprawl prediction etc [1]. Recently, there are several researches done by researchers to promote a way to efficiently construct small inexpensive satellite by using commercial technology.

According 2016 Nano/Microsatellite Market Assessment by SpaceWork [2], it shows that nanosatellite launches have grown by an average of 39% per year since 2010. The development of nanosatellites having mass between 1 to 10kg is a significant trend in the area of space science and engineering research. With the development of nanotechnology, cube satellites (CubeSats) have achieved great success. These small satellites provide an opportunity to prove new technological innovations at a fraction of the cost of traditional large satellite programs. With that trade in cost, numerous challenges came out while trying to fit components that enable the critical capabilities of large satellites in size, weight and power constrained environment.

In general, CubeSat is described as a class of nanosatellites ranging from 10x10x10cm^3, and upwards in 10cm increments of length [3]. It is comprised of several subsystems that play a crucial role in carrying out the small satellite mission. These subsystems, including communication system, power supply and data handling should be able to work together as one system in order for the mission to be successful. Appropriate system integration is required to ensure the compatibility among subsystems.

The idea behind developing a low-cost small satellite using COTS hardware for terrestrial monitoring has been presented previously. In [4], the task for all connected subsystems is controlled by two controllers; each controller has specific task to execute. However, the cost of dual processor design is more expensive compared to a single controller. In addition, the power usage and space allocated can be reduced by using single controller that can improve the efficiency of the design.

Since the introduction of low scale satellites, many companies have emerged to support small satellites-related projects, proven by establishment of many university spin-off companies worldwide. However, the commercial companies provide an expensive on-the-shelf solution, which is a big disadvantage for the universities, specifically due to the limited source of funds to start up their own space program [5]. In some countries, explorations in space related research are still limited due to the high cost of designing, developing, testing and launching a satellite. To develop it on their own, knowledge in developing and integrating all the subsystems are very important and requires lot of times [6].

Therefore, for prototyping purposes, this research proposed a low cost MCU platform design, integrated with multiple sensors developed by using commercial off-the-shelf (COTS) components to replace the expensive space grade components which can greatly reduce the overall development cost [7-11]. Specifically, this paper focuses on designing the proof of concept model of mission control unit (MCU) for nanosatellite by using COTS components with wireless transmission at UHF band. The prototype can be improved and upgraded to produce a space qualified spacecraft model in future.

In this research works, many research questions are formed. For example, the capability of the proposed Arduino-based microcontroller in performing scientific mission shall be verified. Another question raised is due to the compact standardized 1U to 3U CubeSat structure that need to be followed, which may increase the complexity of the circuit design and assembly phase.

II. System Design and Methodology

There are several aspects that have to be considered in designing a successful system. The selection of hardware components is the key for successful design in order to satisfy all the design requirements. In this section, the design of MCU is presented and described into three parts which are system overview, hardware and software development.

A. System Overview

A generic MCU based on proof of concept platform satisfying the basic mission requirements is developed. This platform consists of all subsystems required to support scientific instruments as well as payload data acquisition and mission requirement.

The primary energy source is required to supply all the subsystems in order for the mission to be successful. Given the constraints in the size of standard 2U chassis, the selection of power supply is a major aspect that has to be considered while designing hardware architecture. Lithium-ion battery is the most suitable for this design due to robust structure and compact size. The lithium-ion battery is required to provide sufficient power to the on-board system as planned.

The mission requires a minimal amount of on-board memory storage facility to store a scientific payload and state-of-health data. Therefore, COTS memory devices are being used to serve that purpose. This memory device is interfaced with the microcontroller to log science and health related data continuously. The data stored in this memory will be sent to ground station by communication subsystem and can be analyzed for research purposes.

The communication subsystem has to downlink the scientific (payload) and health data of the satellite unit to ground station. An amateur band communication system is chosen to serve that purpose, designed with the same protocol and modulation technique used by the low cost Ham radio transceiver at the ground. The transceiver selected can interface with the microcontroller.

The main responsibility of the microcontroller is to execute all operations and interface with all subsystems and components by receiving and sending command and science data. It ensures the efficient execution of various autonomous algorithms and maintains synchronization between numerous peripherals which drive the connected sensor. The selection of the microcontroller with low cost and minimal power consumption that support all subsystems and component interface is needed for on-board computer (OBC) system. The complete system integration of Onboard Data Handling (ODHS) subsystems is shown in Figure 1. The interface and data flow is represented in block diagram for easier understanding.

The selection of microcontroller requires several General-Purpose Input/output (GPIO) pins and peripheral modules for serial communication such as several ports of Universal Asynchronous Receiver/Transmitter (UART), Inter-Integrated Circuit (I2C) and Serial Peripheral Interfaces (SPI). In addition, it also has equipped with Input/output (I/O) pins for analog-to-digital (ADC) and digital-to-analog (DAC) conversions. Besides that, the microcontroller based board with built-in regulator that can be used to generate power of 5V and 3.3V for supplying the COTS components is the best suit for this design as it minimizes the space.

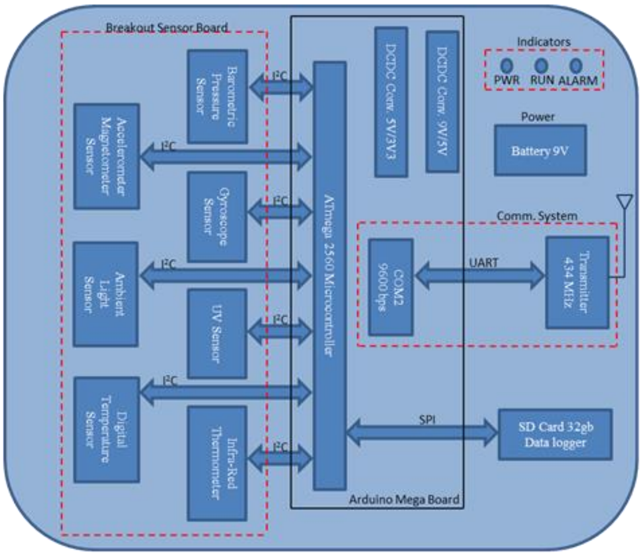


Figure 1: System Interface Diagram of System Overview

B. Hardware Development

In this part, hardware components chosen are described. Besides, the schematic circuit and the printed circuit board design are presented.

1) Sensor Interfaces

There are many sensors integrated with the MCU to allow various scientific data to be collected and analyzed. Essential sensors to determine and calculate satellite attitude are also integrated to ensure accurate satellite positioning. The lists of sensors are described as follows:

i. 10 degree-of-freedom (DOF) Inertial Measurement Unit: To determine the magnetic field relative to the earth so that its attitude determination and control algorithm can be verified. Also contains accelerometer, gyroscope and barometer.

ii. Ultra Violet (UV) Sensor: To predict the tilt of the satellite by outputting analog signal (voltage) that is linearly related to the measured UV intensity (mW/cm^2) through I2C interface.

iii. Infrared/ Digital Thermometer Sensor: To monitor the health of connected subsystems or devices by giving warning signs when the temperatures of connected devices are near to the faulty threshold level.

iv. Luminance Sensor: To measure luminance in diverse lighting conditions, providing exposure control in camera specifically. It is integrated to the system to support future development which is integration of camera module.

2) Memory Interfaces

The data logger shield is chosen to log the science and state-of-health (SOH) data of the satellite and time stamp the data with the current time. This shield is OBC compatible and can support MicroSD card interface works. A 3V lithium cell battery is used as an alternate power source to continuously keep the time when primary source is interrupted or unavailable. This shield communicates with OBC via two distinct serial interfaces, SPI and I2C. The four-wire SPI is used for MicroSD card interface and I2C for RTC communication.

3) Power Subsystems

The power subsystem uses 9V Li-ion battery to provide system power. The power system built-in on the OBC provides two regulated voltage of 5V (+/- 1%) with maximum current draw 800mA and 3V (+/- 1%) up to 150mA current. The total power required for overall subsystem is less than 1W.

4) Communication Subsystems

The UHF communication system is selected for communication between the CubeSat and ground station. There are several important parts or devices chosen for a successful communication which are:

i. Transceiver – semi-duplex low power transceiver with forward error correction. The transceiver can provide up to 20mW (10 levels) transmitted power, and have satisfied the low power, cost effective and small size constraints that lead to the selection. This unique module offers simple serial port interface to OBC by UART or transistor-transistor logic (TTL) interfaces. For satellite communication, the ground station requires UART/TTL to RS232 converter to connect the transceiver to a PC or laptop. The UART/TTL to RS232 converter is also available off the shelf.

ii. Antenna – a duck-type rubber antenna, which has a gain of 2.5dBi and operates in UHF frequency band.

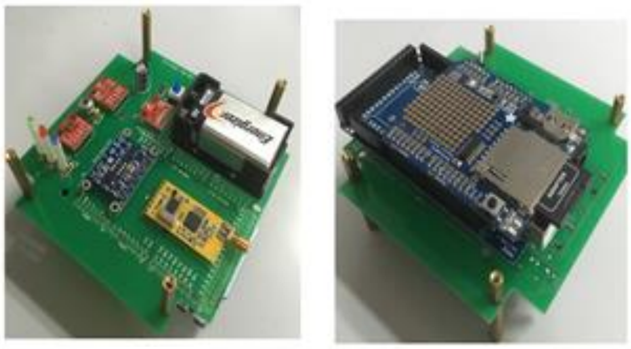
5) Onboard Computer

The onboard computer (OBC) acts like a brain to the whole system and is expected to perform many activities by monitoring and controlling every function of any satellite. The microcontroller board based on Atmega2560 is chosen to provide onboard computing. The board provides GPIO pins; 54 digital I/O (14 can be used as PWM output) and 16 analog inputs. In addition, it offers 4 UARTs, I2C, SPI and USB connection to interface with external devices or components.

A prototype board is constructed and populated with subsystem modules and components. Figure 2 shows the picture of the complete breakout board of the MCU on donut board. The function of this breakout board is to verify the functionality of the integrated subsystems in schematic circuit that have been designed. The performance of this breakout board is analyzed to improve the schematic circuit diagram.

Figure 2: Breakout Board on Donut Prototyping Board

The complete board of MCU is fabricated after all the subsystems and components have been integrated as one system and are successfully tested, and have satisfied all the design requirements. Figure 3 shows the prototype board in printed circuit board (PCB). There are two PCBs developed to integrate all subsystems and components.



(a) (b)

Figure 3: Prototype Board in PCB: (a) Board 1 (b) Board 2

C. Software Development

Due to small number of operating modes and simplicity of the mission, simple loop architecture rather than an operating system is used. This loop is written in Arduino IDE, run to continuously monitor the telemetry and satellite location (determined by magnetometer, barometer and gyroscope) and to call appropriate sub-functions as necessary. Figure 4 shows the main loop of software flowchart.

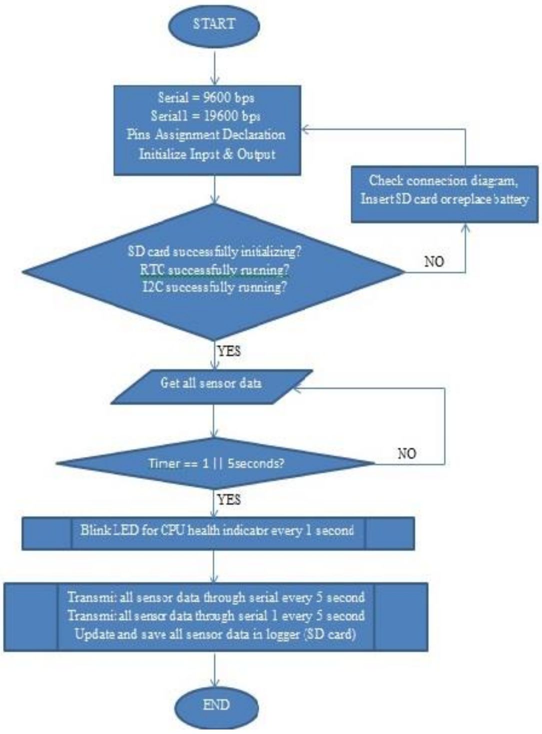


Figure 4: Software Flowchart

There are three major sub-functions which are science, communications and fault response.

The science function is called periodically in the main loop of the programming code. This function collects science data continuously and records into memory device for a length of time until housekeeping is required. The sciences functions are also periodically monitors the health sensors and call the fault response function if necessary. The fault response function is activated if any other function detects abnormal health reading.

The communications function is called continuously since the real-time telemetry is applied in communication subsystem. The transceiver at ground station is capable to receive science data at any time determined by the missions of interest. The function sends science data to the ground in real-time until the signal is terminate or interrupt. Same as science function, the communications function monitor satellite health and can call the fault response function is needed.

III. Results and Discussion

The primary requirements on the structure are to satisfy the external requirements placed on the design, as well as to provide adequate interfaces to each subsystem to ensure safe passage through all phases of the mission. Another requirement is to ease the fabrication and assembly of both the satellite structure and the satellite as a whole system. The structure consists of two parts which are beams and panels that made from Polylactic Acid (PLA) material. Figure 5 shows the complete MCU boards assembled in 2U structure that are stacked parallel to the bottom face arrangement. The top layer board consists of power subsystem, attitude determination subsystem, communication subsystem, components, sensor modules and indicators. The Onboard Data Handling (ODHS) subsystem is located at the second layer which is stacked to the top layer board that consists of OBC and real time data logger.

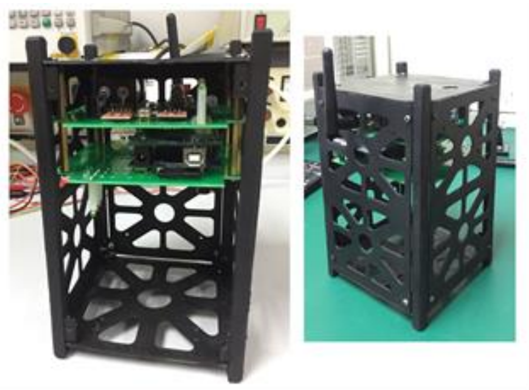


Figure 5: Complete MCU Assembled in 2U Structure

To verify the design as a successful system, the MCU required downlinking the science data based on one ground station at 9600bps baud rate periodically. The preliminary analysis of the data received from the MCU is conducted at ground station. Figure 6 shows the serial monitor of science data received at ground station. There are two tests conducted to verify the system performance.

Figure 6: Serial Monitoring Science Data

A. Frequency Verification Test

The radio frequency specification supported by the transceiver module used in this design is between 418MHz to 455MHz. A simple test is performed to verify the efficiency and accuracy of transceiver propagation. Figure 7 shows the diagram of the indoor frequency verification test setup. Serial cable is connected to the PC instead of wireless communication between MCU and ground station to ensure the science data received is similar as in wireless medium. During this test, the MCU will transmit the data periodically at setup frequency of 434MHz to spectrum analyzer and PC.

The test result measured by spectrum analyzer is shown in Figure 8. Based on the observation, the peak transmitted power is detected at 434MHz with 12.37dBm power received. The result indicates that the frequency received is similar as the setup frequency of 434MHz at the receiver.

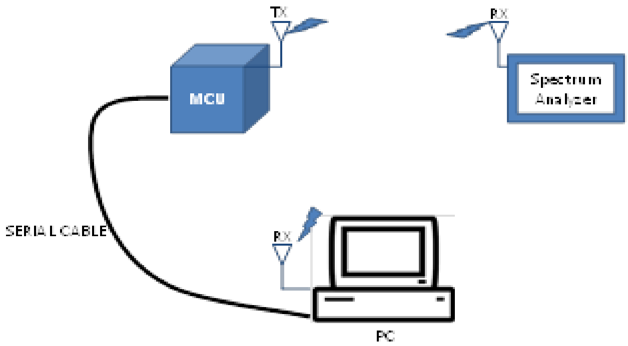


Figure 7: Frequency Verification Test Setup

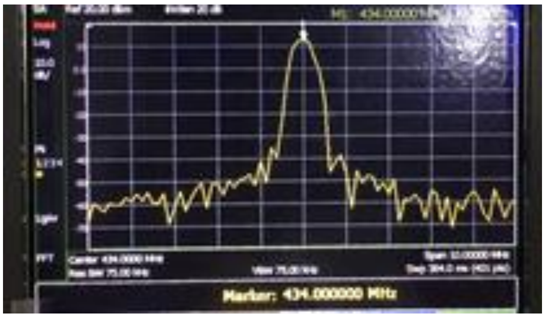


Figure 8: Operating Frequency

B. Maximum Signal Propagation Test

Requirements of antennas for space use are very stringent and measurement methods need to be continuously refined to be able to accurately verify them. The antenna radiating properties such as radiation pattern, gain and cross polarization need to be considered during antenna test range. The type of range test can be setup indoor (anechoic chamber) or outdoor (free space). Figure 9 shows the test setup for maximum signal propagation test used in this design.

Figure 9: Maximum Signal Propagation Test Setup

An outdoor test setup is chosen to determine the maximum range of the propagation signal between the two antennas. The Friis transmission equation as shown in equation (1) and (2) below will be used to determine the maximum distance of the signal propagation [12].

$$P_r = P_t G_t G_r \left(\frac{C}{4\Pi R f_O} \right)^2 \quad (1)$$

$$P_r(dB) = P_t + G_t + G_r + 20\log\left(\frac{\lambda}{4\Pi R} \right) \quad (2)$$

The result of data obtained in spectrum analyzer shown in Figure 10 is collected to calculate the transmitter power output. It is accomplished by calculating the free space path loss (FSPL) and using the gain of transmitter and receiver antenna equal to 2.5dBi. The calculated parameters used in Friis equation are tabulated in Table 1.

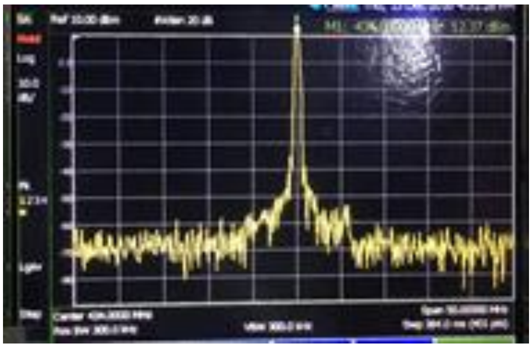


Figure 10: Measurement of Received Power

Table 1
Test Result Parameters used in Friis Equation

Ranges (m)	Average P_{RX} from Spectrum Analyzer (dBm)	Path Loss (dB)	P_{TX} (dBm)
3	-11.74	-29.37	12.63
6	-18.38	-35.75	12.37
9	-21.68	-39.27	12.59
12	-25.08	-41.77	11.69
15	-26.29	-43.71	12.42
18	-28.89	-45.30	11.41

The commercial specification of the transceiver transmit power is 13dBm. Based on the results obtained in Table I, the transmit power calculated is approaching to 13dBm and it is verified that the transceiver is a low power transceiver module device with transmit power of 13dBm. There are some inconsistencies in the data due to the non-ideal semi-indoor measurement setup. The results are expected to be more consistent and reliable if it is performed inside huge anechoic chamber or wide outdoor areas such as football field. The results gathered from semi-indoor setup are subjected to various wave propagation conditions such as reflection and diffraction.

The maximum distance signal propagation denoted as R (distance between two antennas) in Friis equation can be determined by using that formula. The maximum range supported by the transceiver is 1km at received sensitivity -113dBm. Further calculation and analysis is required to verify the distance supported by this device. The parameters showing maximum distance of signal propagation is shown in Table 2. From table 2, we conclude that the maximum distance that can be achieved by the transceiver is at 4.36km. It is because the received power at -113dBm behaves like a noise floor on spectrum analyzer and some spectrum analyzer can measure up to -80dBm.

Table 2
Measurement Result to Determine Maximum Distance

P_{RX} (dBm)	G_{TX} (dBi)	G_{RX} (dBi)	P_{TX} (dBm)	Maximum Distance (km)
-50	2.5	2.5	13	0.138
-80	2.5	2.5	13	4.36
-113	2.5	2.5	13	195

Tabulation of path loss data is also shown in Figure 11 showing the consistent variation of path loss as the distance increases. In addition, the comparison between RF performance of first prototype (donut board) and final product (PCB) is analyzed. Figure 12 shows the spectrum generated by transceiver on first prototype (donut board). From the observation, the spectrum produced is noisy and not clean as compared to final product (PCB) in Figure 10. In terms of RF, it shows significant improvement of signal for final product.

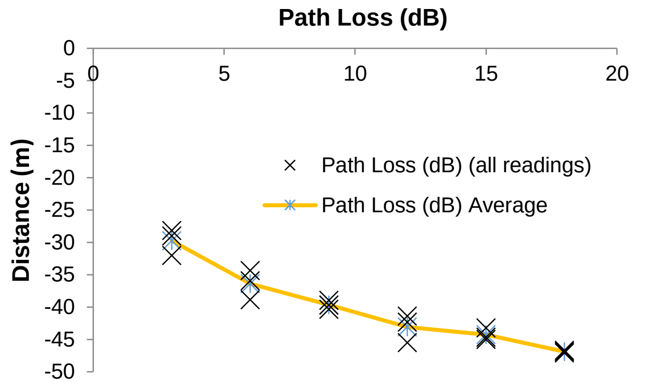


Figure 11: Tabulation of Path Loss Data

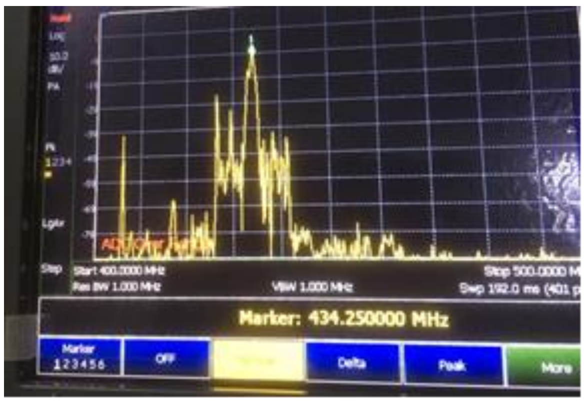


Figure 12: RF Performance of Donut Prototyping Board

IV. Conclusion and Future Work

In conclusion, a good performance and compact MCU prototype for educational purposes has been successfully developed, which can be used as a good platform to demonstrate satellite engineering principle as part of school or university curriculum. This product is beneficial to schools and universities that would like to start their space program.

By using this sensor-ready module, many parties will be able to explore the ability and application of small satellite. The end product for this project can also be used for public outreach mission involving local communities of amateur radio operators and schools or university students.

The current prototype is designed to have flexibility of having any sensors integrated to it in future. For example, a camera, GPS module or any experimental devices can be integrated to the Arduino Mega platform later on as part of the classroom exercise. The future work will include continued development of the prototype that can be improved and integrated with other subsystems to produce a space qualified spacecraft model. Higher gain antenna can also be designed to increase the maximum transmission range for better data collection.

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