ON-BOARD DATA HANDLING FOR CUBESAT USING RASPBERRY PI

by

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Endorsement

I, Muhammad Hakiim Bin Zainudin hereby declare that I have checked and revised the whole draft of dissertation as required by my supervisor.

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DECLARATION

This thesis is a result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

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Date:

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ON-BOARD DATA HANDLING FOR CUBESAT USING RASPBERRY PI

Abstract

Outer space is such a mysterious place, full of questions, and we humans tend to seek for the answers. That’s why human develop space exploration. From this development, satellite was born. The development of satellite alone help human in many ways. Satellite has become a device that very important to human in so many fields. Nowadays, satellite has evolved, to smaller size, and cheaper in price. It is called CubeSat. A CubeSat is a small cube with size of 1U which is 10cm x 10cm x 10 cm, and consist of power supply, on-board controller, payload and transmitter. On-board data handling helps to control the satellite automatically. It also helps a satellite to gather various data from payload and collect information about the condition of the satellite. There’s a lot of data handling being developed right now such as Arduino, Raspberry Pi and Basic-X24. Arduino and Basic X-24 widely used in CubeSat on-board data handling but Raspberry Pi still in development. Raspberry Pi hold a lot of potential to become one of the on-board data handling for CubeSat. There’s only a few of CubeSat that contain Raspberry Pi that really go to space such as Pi-Sat. Raspberry Pi can be said a lot more powerful in term of processing power but has a few problems in the development to launch in space because Raspberry Pi not generally build to go to space. Raspberry Pi always need a modification to sustain harsh environment of space.

PAPAN PENGENDALIAN DATA UNTUK CUBESAT MENGGUNAKAN RASPBERRY PI

Abstrak

Ruang angkasa merupakan tempat yang misteri dan penuh dengan tanda tanya. Kita manusia yang selalu cenderung mencari jawapan. Oleh sebab itu, manusia cuba memajukan penerokaan ruang angkasa. Dari perkembangan ini, satelit dilahirkan. Perkembangan satelit semata-mata membantu manusia dalam pelbagai cara. Satelit telah menjadi alat yang sangat penting untuk manusia dalam banyak bidang. Pada dewasa ini, satelit telah mengecil, kepada saiz yang lebih kecil, dan harga yang lebih murah. Ia dipanggil CubeSat. A CubeSat adalah kiub kecil dengan saiz 1U iaitu 10cm x 10cm x 10 cm, dan terdiri daripada bekalan kuasa, pengawal di atas kapal, muatan dan pemancar. Papan pengendalian data membantu mengendalikan satelit secara automatik. Ia juga membantu satelit untuk mengumpulkan pelbagai data dari muatan dan mengumpulkan maklumat mengenai keadaan satelit. Terdapat banyak papan pengendalian data yang sedang dimajukan sekarang seperti Arduino, Raspberry Pi dan Basic-X24. Arduino dan Basic X-24 digunakan secara meluas dalam pengendalian data papan atas CubeSat tetapi masih dalam pembangunan. Raspberry Pi mempunyai banyak potensi untuk menjadi salah satu pengendalian data di papan atas untuk CubeSat. Terdapat hanya beberapa CubeSat yang mengandungi Raspberry Pi yang benar-benar pergi ke angkasa seperti Pi-Sat. Raspberry Pi boleh dikatakan jauh lebih berkuasa dari segi kuasa pemprosesan tetapi mempunyai beberapa masalah dalam pembangunan untuk melancarkan ruang angkasa kerana Raspberry Pi tidak biasanya dibina untuk pergi ke ruang angkasa. Raspberry Pi sentiasa memerlukan pengubahsuaian kerana angkasa merupakan persekitaran yang bahaya.

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Chapter 1

Introduction

1.0 Background

A satellite is an artificial object which has been intentionally placed into orbit. Such objects are sometimes called artificial satellites to distinguish them from natural satellites such as the Earth's Moon.

On 4 October 1957, the Soviet Union launched the world's first artificial satellite, called Sputnik 1. The Sputnik 1 launched into low Earth orbit for the technology demonstration(Swenson, 1997). This event marked the beginning of satellite era. Since then, about 6,600 satellites from more than 40 countries have been launched. Approximately 500 operational satellites are in low-Earth orbit, 50 are in medium-Earth orbit (at 20,000 km), and the rest are in geostationary orbit (at 36,000 km). A few large satellites have been launched in parts and assembled in orbit. Over a dozen space probes have been placed into orbit around other bodies and become artificial satellites to the Moon, Mercury, Venus, Mars, Jupiter, Saturn, a few asteroids, a comet and the Sun.

The satellite has been used for ages to gain and collect information that we can't normally get from the ground. Satellites are used for many purposes. There are various types of satellite include astronomy satellites, atmospheric satellites, communication satellites, navigation satellites, spy satellites, remote sensing satellites, search and rescue satellites, space exploration satellites, and weather satellites. Besides, International Space Stations and human spacecraft in orbit are also satellites. In modern days, satellites are a very important device without a majority of human realizing it.

As time goes on, satellite becomes smaller and simpler. Researchers start to develop new kind of satellite which is small and simple enough to make. This development leads to introduce new kind of satellite such as Mini-satellite, Nano-satellite, micro-satellite and pico-satellite.

Table 1.1: Types of small satellites and their weight

Satellites	Wet mass
Mini-satellite	101 – 500 kg
Microsatellite	11 – 100 kg
Nano-satellite	1 – 10 kg
Pico-satellite	≤ 1 kg

The CubeSat is a miniaturized satellite type for space research and application. The CubeSat is made up of one or more 10 x 10 x 10 cm cubic units. It all started in 1999, California Polytechnic State University (Cal Poly) and Stanford University developed CubeSat specifications to promote and develop the skills necessary for creating small satellites intended for low Earth orbit operations. Professors Jordi Puig-Suari of Cal Poly and Bob Twiggs of Stanford also proposed a reference design for the CubeSat. Their mission was to enable graduate students to design, build, test and operate limited capabilities of artificial satellites within the limited time and financial constraints of a graduate degree program. In June 2003, the first CubeSats launched and were placed into orbit on a Russian Eurockot(Bethesda MD (SPX), 2016). Nowadays, CubeSat has been built by a hobbyist, students, researchers, and even entrepreneur. CubeSat has evolved from its original mission which is to act as a tool to help teach students about the process involved in developing, launching, and operating spacecraft. One of the driven factors is the price. The cost to build a satellite also has decreased a lot than it used to be. CubeSat is a small device and much simpler satellite which helps a lot of researchers to build a CubeSat in doing their research in the space without using a lot of money. There are many projects that used CubeSat to gain data from the space. With the existence of CubeSat, students in university also can build their own satellite without costing university or college huge amount of money.

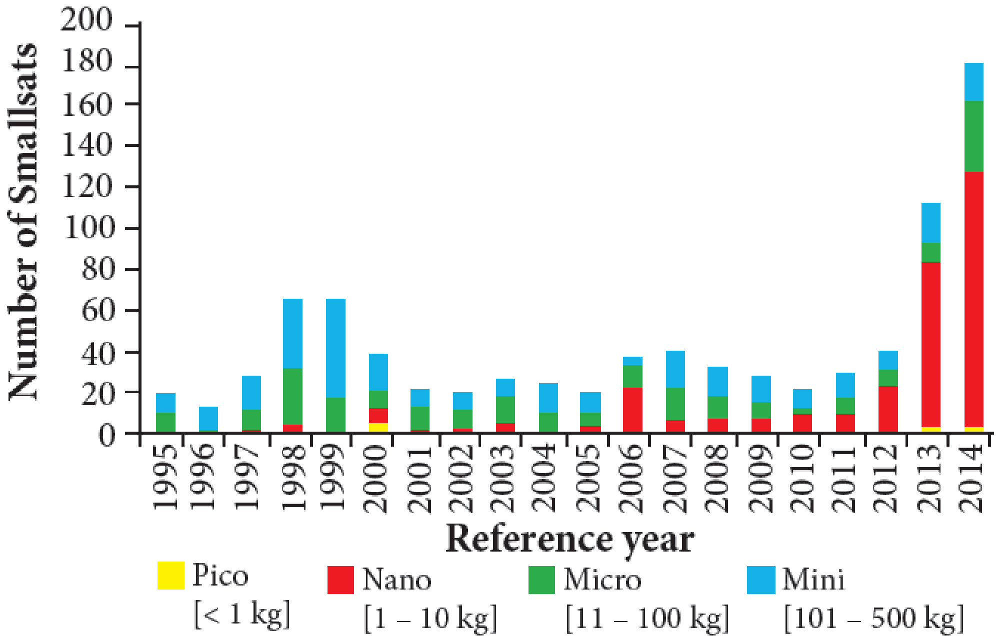

Figure 1.1: The number of small satellites sent into the orbit in recent years(Wekerle *et al.*, 2017)

This figure 1.1 shows how small satellites increasing popularity in the recent years. Starting from 2007 the number of Nanosatellite has increased drastically. CubeSat also categorized into Nanosatellite(Wekerle *et al.*, 2017).

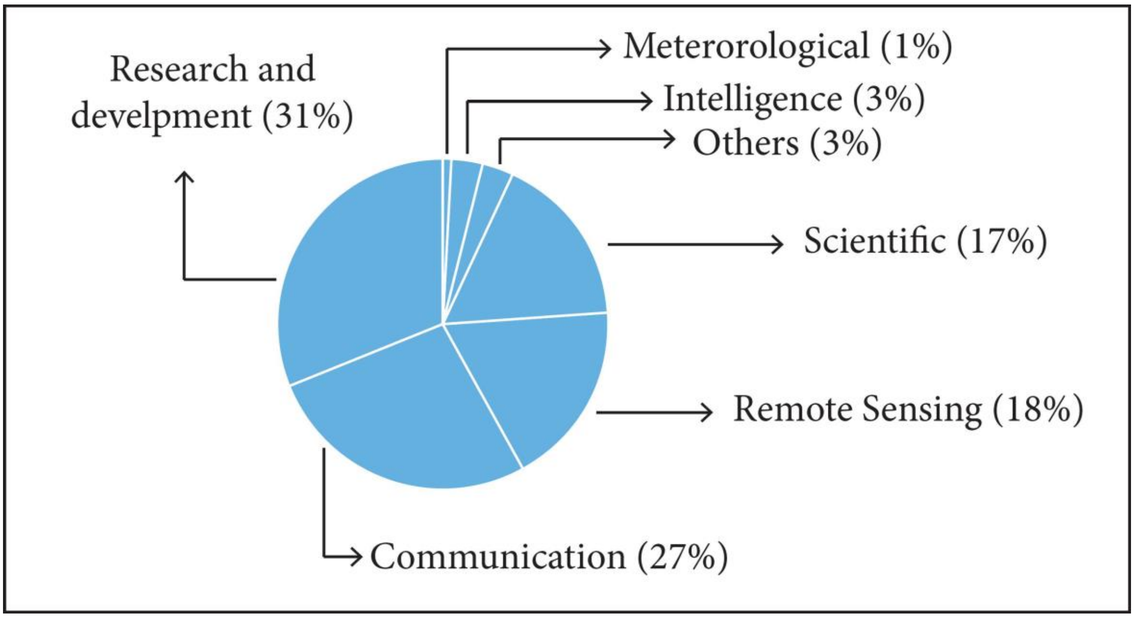

Figure 1.2: CubeSat mission category(Wekerle *et al.*, 2017)

Figure 1.2 shows the mission of the CubeSat that has been sent to space in recent years. Small satellites have been used majorly for research and development.(Wekerle *et al.*, 2017) This project also categorized into research and development, and scientific research.

University Sains Malaysia also plans to build a CubeSat and launch it to space. University Sains Malaysia collaborates with ANGKASA (National Co-operative Movement of Malaysia) in developing and launching this CubeSat into space. This CubeSat named MySat. MySat will be the first CubeSat from Malaysia to be launched into space. MySat mission is to measure the amount of electron in ionosphere. Based on figure 2, Ionosphere is the ionized part of the Earth's upper atmosphere, about 50 km to 250 km altitude.

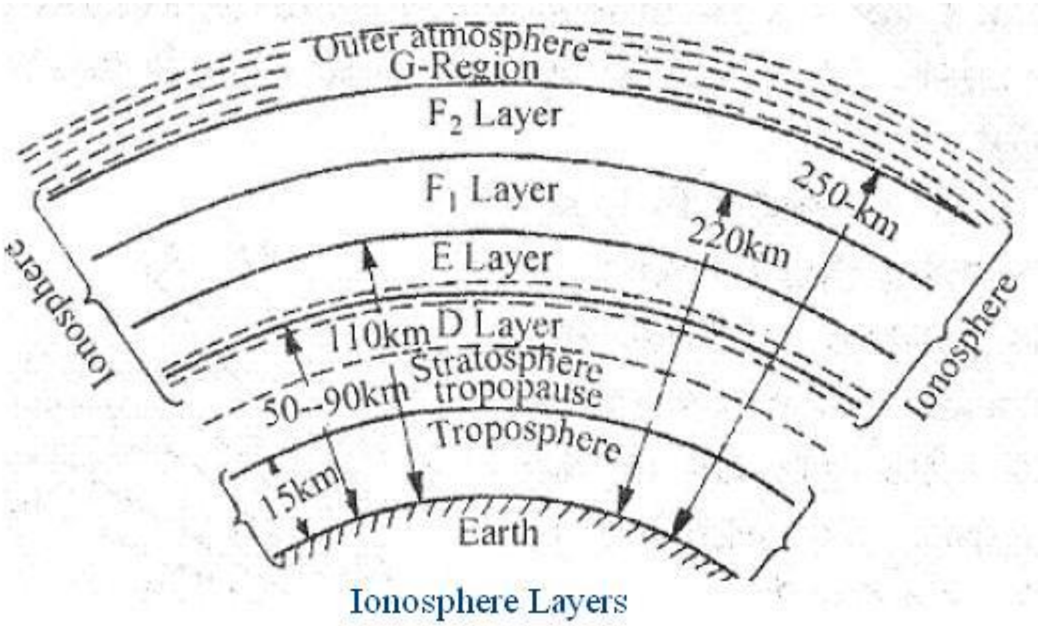

Figure 1.3: The location of the ionosphere

At first, many will question University Sains Malaysia on why we even need to calculate the amount of electron in the ionosphere and what will we get by doing this. In 1960s, ionosphere disturbances regarding with earthquakes were identified. Kim and Pulinets et al suggested that there will be disturbance of electron density based on strong vertical electric field at the earth's surface. Basically, we can predict the occurrence of earthquake in certain places by using this CubeSat.

1.1 Problem statement

The CubeSat cannot operate with hardware alone. Users also cannot operate the CubeSat manually because of the distance between the CubeSat and the users. This means that CubeSat needs to operate automatically. It needs a subsystem that in charge of the hardware such as payload, sensor, and power supply. This subsystem also will schedule the tasks of the CubeSat. These tasks will be made by using programming.

This subsystem also needs testing to make sure it works perfectly according to the plan. Before launching the CubeSat, the functionality of the hardware and the software needs to be tested to make sure it can operate smoothly and achieve the missions. All the subsystems will be compiled into a system and the functionality of the software will be tested.

1.2 Objective

To build the subsystem to control My-Sat called on-board data handling based on Raspberry Pi. Raspberry Pi will be the main on-board computer that will be in charge to control other subsystems in the My-Sat such as Electric Power System (EPS), payload, sensors and communication subsystem. In developing on-board data handling for CubeSat, a program is needed to control all the subsystem in the CubeSat. On-board data handling can be called the brain of any satellite. On-board data handling the main function is to communicate through all the subsystems to make sure a mission run successfully. Its significant role is to store the data collected from the subsystems and payload and compile them to send back to the ground. The data that has been stored in the on-board data handling are consist of payload data, housekeeping data and telecommands data. The coding also responsible for scheduling the tasks of the My-Sat. This functionality of the coding also will be tested when the subsystems are ready.

In the same time, the on-board computer also needs to collect the information of the satellite. This task is known as housekeeping. Housekeeping data is crucial to monitor the condition of the satellite and how it operates in its daily life. On-board data handling to analyze the situation of the voltage and current supply because of it essential to keep the satellite works in the safe condition.

This strategy may save the satellite from being a shortage of electrical power. It helps the satellite to keep working within a wide range of electric supply. Besides, the satellite does not always operate at its best condition because at some point the satellite will go through the condition where there is no sunlight that reaches the satellite. This condition will affect the satellite because many simple satellites powered up by solar panels. This condition also normal to the satellite. It is called an eclipse. With on-board data handling that has been programmed, this problem can be tackled easily thus prolonged the satellite operation life. This is also one of the on-board data handling responsibilities.

Chapter 2

Literature review

2.1 Mission

Earthquake is a dangerous natural phenomenon that can affect many lives and manage to destroy building and infrastructure when it happens. Try to imagine if we can predict when and where an earthquake will occur, we can evacuate people and save them before it happens. There are some ways in detecting the earthquake, and one of them is analyzing ionosphere. DEMETER is a microsatellite that has been sent to space to study the ionosphere. The resulting conclusion made in DEMETER team publications suggests that there are real and obvious perturbations of electric and magnetic fields and electrons density in the ionosphere connected with the seismic activity, but they are rather weak and at the present stage of data processing could only be identified with the help of statistical analysis, because many other phenomena can perturb the ionosphere and generate similar and even greater disturbances there. Other conclusion points out that these perturbations may also occur within a few hours and a few days before an EQ and mostly in the close vicinity of the EQ epicentre (Korepanov, 2016). The electromagnetic waves directly propagating from the EQ epicentre have not been observed, in contrast to suggestions advanced in many papers. But the changes in wave propagation above the epicentres were confirmed and this was attributed to variations of ionospheric plasma density.

CubeSat is a cheap way to send satellite to space for space mission, science project or education purpose. CubeSats considerably decrease the cost and complexity of development and launch as compared to robust traditional satellites with redundant subsystems, as evidenced by observed dramatic increase in number of CubeSat launches over the last decade (Poghosyan and Golkar, 2017). It also has a few limitations by using CubeSat, power is one of them for 1U CubeSat. But, currently, power generation on 3U CubeSats can easily reach up to 20–30 W by using deployable solar panels. There also a huge range of battery with high capacity such as high energy density lithium ion and lithium polymer batteries that can be utilized as primary or secondary power source for CubeSat missions (Poghosyan and Golkar, 2017). Communication also become one of the problem for CubeSat. Early CubeSat missions used VHF and UHF radio frequency which provide low data rates as 1.2 and 9.6 Kbps. CubeSat nowadays, can achieve higher data rates up to few Mbps through S-band communication systems such as DICE 1.5U CubeSat. There's CubeSat that can achieve 40 Mbps data rates.

2.2 On-board computer

For this project, we try to implement Raspberry Pi as on-board data handling for this CubeSat. In recent years, Raspberry Pi has make step forward to send Raspberry Pi into space. A few researchers trying to send raspberry Pi into space, such as using Raspberry Pi with high altitude balloon to capture the image of earth.(Anand and Rajesh, 2016) Raspberry Pi also made a program to encourage students and researchers to send Raspberry Pi to International Space Station. The program called Astro Pi. This show their initiative to send Raspberry Pi to space (Honess and Quinlan, 2017). Raspberry Pi also has been used in NASA CubeSat, 1.2U Pi-Sat for capturing earth picture. NASA stats that Raspberry Pi could be very low-cost CubeSat platform. Raspberry Pi also popular with open source platform, that can minimize time in making the CubeSat. Arduino also popular with open source software. On the other hand, using open source hobbyist boards in CubeSats is a challenge itself. They will have to withstand the harsh environmental conditions during launch and in space, namely radiation, high vacuum, extreme temperatures, vibrations, etc. On top of that, power available on a CubeSat is sparse – a limitation that is usually not of much concern for terrestrial electronics (Scholz and Juang, 2015).

Raspberry Pi looks like a simple device and it is cheap. It is available in the market only for 35 dollars. Despite having low price, Raspberry Pi processor quite powerful to become microcontroller for CubeSat. Its flexibility also convenient for users. To build cheap CubeSat, Raspberry Pi was chosen to be the on-board data handling. Although, there is a lot cheaper microcontroller in a market such as Arduino.

Figure 2.1: Raspberry Pi board

Originally, Arduino is a microcontroller but in the same time, Arduino is not as fast as Raspberry Pi. It has 4 processor cores. Multiple cores allowed the system to handle multiple threads in a time. It also has promising clock speed which 1.4 GHz. For small board it considered to be good. Based on its powerful components, it is hard to turn down the possibility for Raspberry Pi to become leading on-board data handling for CubeSat. Raspberry Pi also easy to use even for people that does not know how to operate microcontroller before. After the power and HDMI has been plugged in this device can operate on the go. The installation of the software also is not hard. SD card is used to install the software, if someone wants to use multiple software, it can be changed by merely changing the SD card. Raspberry Pi consists of GPIO pins and ground pins. These pins will connect Raspberry Pi to the other subsystems such as electric power system (EPS), payload, transmitter and watchdog.

It has wide range of programming language that can be used with Raspberry Pi such as C, C++, and Python. The usual software for the Raspberry Pi is the Raspbian which can run C language and Python. It is not a limitation to stick with the Raspbian. There is a lot more software for Raspberry Pi that can be tried. Python language has top the charts in recent years over other programming languages such as C, C++ and Java and is widely used by the programmers in various applications. Many programmers nowadays use python because of its versatility features and produce fewer programming codes. There's many benefits of python that makes it popular now. Python also tried

As everyone knows, space has a harsh environment. It is hard to ensure the computer will operate reliably for certain period.

2.3 Impact of ionosphere

Ionosphere is the layer of the earth's atmosphere that is ionized by solar and cosmic radiation.(Zolesi and Cander, 2014) This ionization is becoming big problem when transmitting a radio wave and electronics part in the CubeSat. The ionization of the Ionosphere is divided by two categories, which is during the day and the night. During the day, the high energy from the sun and the cosmic rays, the atoms located in ionosphere have been stripped of one or more of its electrons, this phenomenon also called ionized. Because of the electron being stripped away from them, the atoms in ionosphere will be positively charged. The stripped or ionized electron will act as free particles.

This situation will make ionosphere have high energy. During the night, the absence of the Sun does not mean there is no ionization happen. Besides, ionosphere will be ionized by cosmic rays, but it will be not as strong as the energy of the Sun. Comic ray origin is from various sources throughout the galaxy and the universe such as neutron stars, supernova, radio galaxies, quasars and even black holes.

Although ionosphere has complicated situation, it also serves a significant role to the Earth which is protecting Earth from the most intense forms of space weather. (Zell, 2013) It also helps in radio propagation, by producing waveguide which the radio signals can bounce and make their way to the ground.(Kelley, 1989)

Another phenomenon produced by the sun is coronal mass ejection. This phenomenon is solar explosions propel burst of particles and electromagnetic fluctuations into Earth's atmosphere. The particles burst by coronal mass ejection can collide with electronics on-board and disrupt its system. In this case, coronal mass ejection does not directly affect the satellite in ionosphere, but it can increase the number of free electrons in ionosphere.(Fox, 2013)

Besides, cosmic radiation also can cause problem to the on-board of the CubeSat. First, cosmic radiation may interfere with transistors and will bit-flip the computer memory. Bit-flipping is algorithmic manipulation of binary digits. Bit-flipping also known as soft error. Bit-flip is a situation where the state of single binary bit has changed from 0 to 1 or 1 to 0. A negative environmental impact is one of the factors for bit-flip. Increasing hit, lowering the voltage and cosmic radiation can lead to bit-flip. Although, bit-flip sounds simple it can cause a huge problem to the CubeSat as a whole. It can corrupt saved data and causing instability in the whole system.(Myrland, 2013) It means, if bit-flip happen in on-board data handling the CubeSat may not perform well or becomes a failure.

Cosmic rays and solar flares also can cause a single event latch-up (SEL). Single event latch-up is a hard error. Single event latch-up happened when energetic particles causing single event upsets. Single event upset (SEU) is a change of state caused by one ionizing particle strike a sensitive node in a microelectronic device. Ionizing particle example is ions, electrons and photons. Single event latch-up results in an abnormal high-current state. These errors can be cleared by power toggling the device. If this action does not happen soon enough the device will suffer permanent damage.(Nashville, 2012)

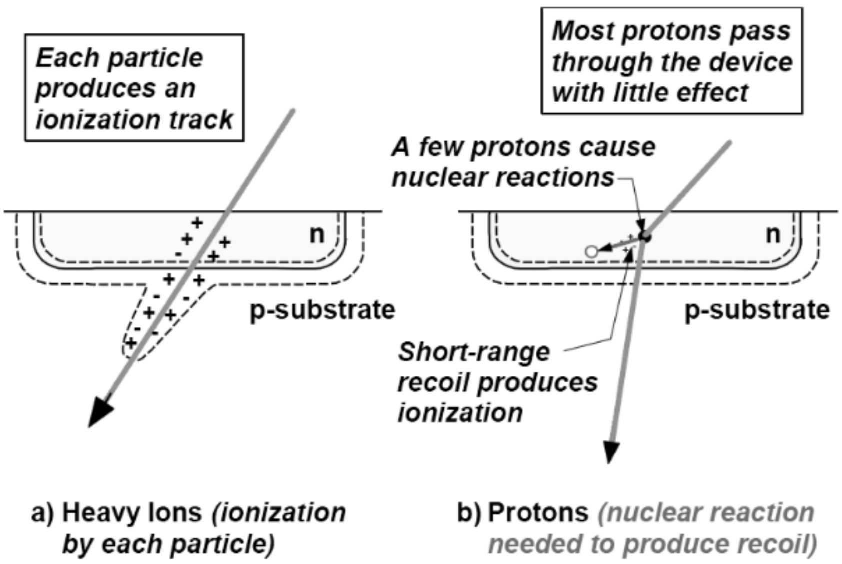

Figure 2.2: Mechanisms for Heavy Ion and Proton single event upset effects

As we know, the ionosphere is an area full of radiation or ionized particles. If the CubeSat components exposed to the surrounding, there is no guarantee that the CubeSat can operate anymore. The cosmic radiations in the ionosphere make things worse as it can affect the on-board computer of the CubeSat. There a few solutions to avoid ionized particles affect the CubeSat components. First, by using radiation-hardened electronic components, this problem can be solved easily.(Ødegaard and Skavhaug, 2013) However, for building CubeSat, budget limitations are much stricter than high reliability system. As this solution need a huge amount of money to be made, so there is a possibility that this solution is not good enough. To solve this problem by changing the board structure is also expensive.(Myrland, 2013) By using off-the-shelf CubeSat, this problem can be avoided as the structure is effective in reducing the radiation. This off-the-shelf CubeSat also one of the way to solve this problem cheaply. In this project the CubeSat was made in our own laboratory, hopefully it can withstand cosmic radiation and solar flare as well as off-the-shelf CubeSat.

Chapter 3

Methodology

3.1 Approach

The approach of writing an algorithm can be called a strategy. As lack of strategy may lead someone to write the algorithm that is not necessary for a mission or the objective of the project.

The project flowchart can be referred in figure 3.2. First, the mission, objective and requirement need to be well defined. The mission definition is the starting point of how to approach the project. As mission, objective and requirement are defined, the algorithm will be written simply to achieve the mission and objective alongside the requirement so there will be no mistake when writing the algorithm. The connection of the subsystem with on-board data handling showed in figure 3.1.

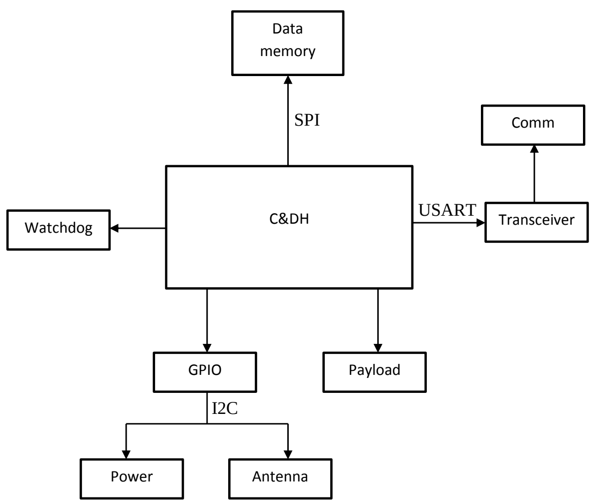

Figure 3.1: Block diagram of the CubeSat

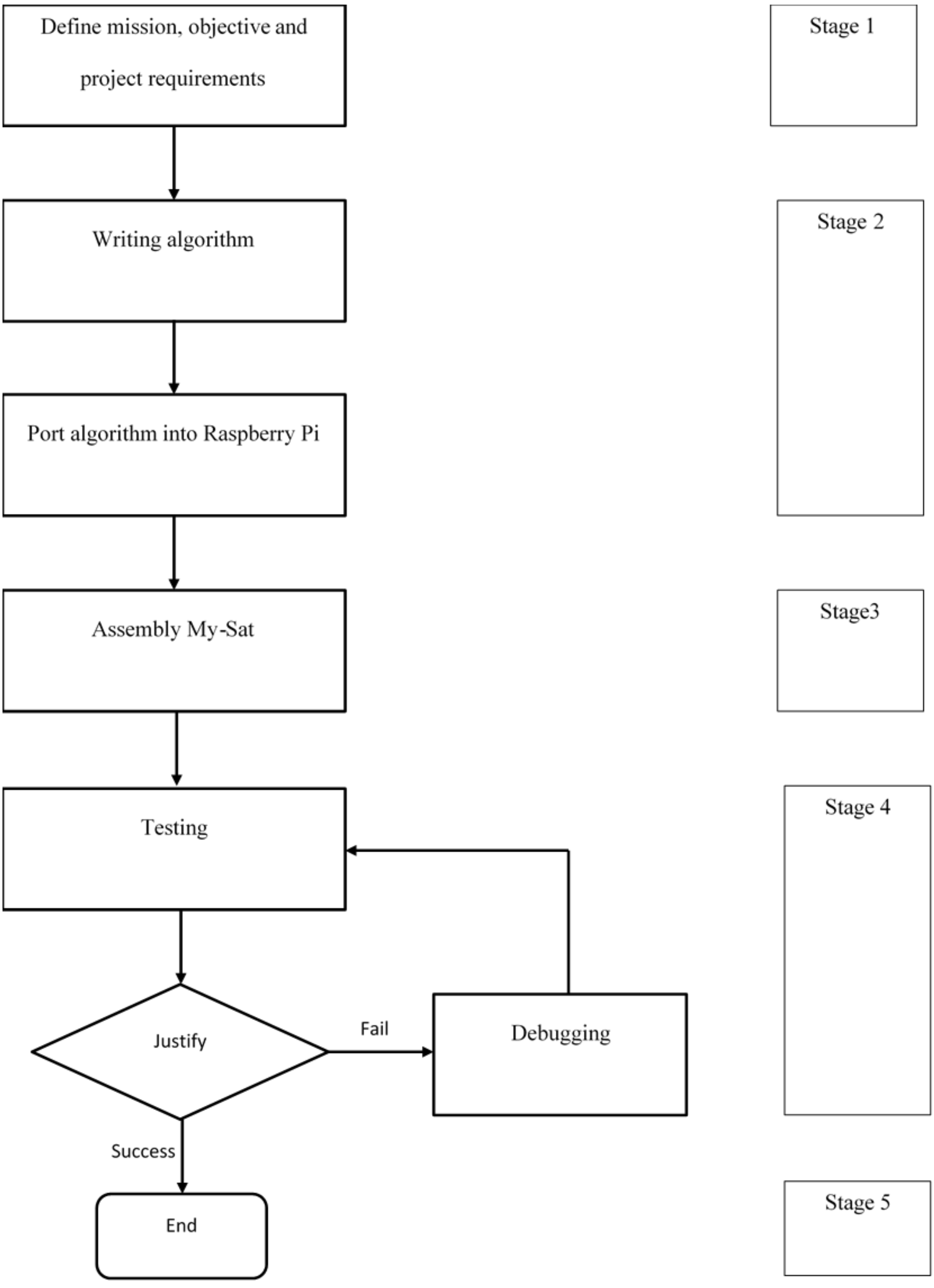

Figure 3.2: Project flowchart target