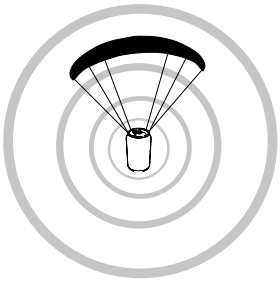
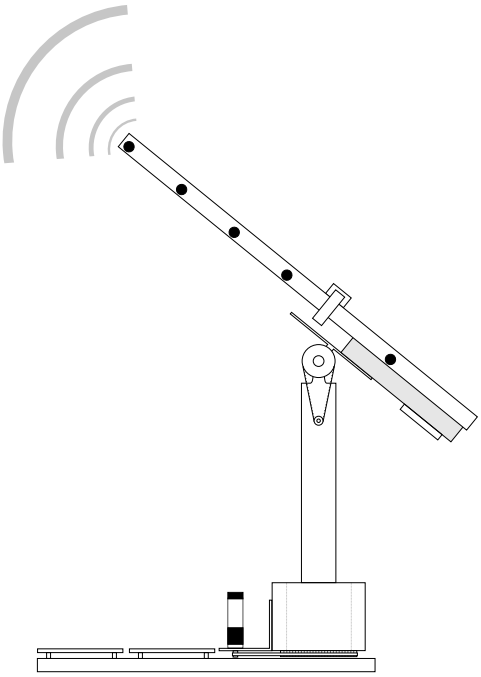
CanSat Ground Station





Electronics & IT
P5 Student Project
Autumn Semester 2010
Group 10gr503

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Title: CanSat Ground Station

Subject: Distributed embedded systems in cooperation with physical systems.

Project period:
P5, autumn semester 2010

Project group:
10gr503

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Number of copies: 8

Number of pages: 176 (last page is p. 168)

Attachments: 1 cd

Appendices: 7

Ended the 20/12 2010

Abstract:

Background
CanSat competetitions are held anually by several space organizations. This project regards the development of a ground station, that can support students participating in these competitions. The ground station must be able to track the CanSats and communicate with them wirelessly. Other projects have had the goal of designing and constructing such CanSats. The WARP radio protocol has been developed in coorperation between these projects, it allows the constructed ground station and CanSats to work togther.
Results
The system consists of a ground station and a remote user client. The ground station can communicate wirelessly with CanSat's. The remote user client and ground station can communicate through an Ethernet link, eg. over the internet.
The ground station is designed as an embedded system and connected to a pan & tilt platform with two PWM-powered DC-motors, and an Yagi-Uda type antenna attached. As the platform for the ground station software, a preemptive real-time operating system is designed and implemented on an ARM-based microcontoller.
The pan & tilt platform is modeled as two independent second order systems. Non-linear corrections are introduced, in order to compensate for the non-linear nature of the friction and gravity, affecting the platform. Feedback control is designed using frequency domain design methods.
The user interface to the system is the remote user client, developed as a Java based GUI application. This program allows the user to remotely control the ground station, and send commands to the CanSat. It also handles and saves incoming CanSat telemetry, relayed by the ground station.
Conclusion
The final system is able to accommodate most of the requirements. The antenna controller system has been shown to be able to follow a simulated launch of a CanSat. With further development, it is possible to make the ground station system feasable for use in CanSat competitions.

Preface

This report has been composed by group 503 at the faculty of engineering-, nature- and medical science at Aalborg University, in the period from 2-9-2010 to 20-12-2010. It is a 5. semester project at the Department of Electronic Systems - Electronics and IT, and has been created in cooperation with supervisor Jens Dalsgaard Nielsen. The general theme of the project is distributed embedded systems in cooperation with physical systems. In the project an antenna system for tracking a CanSat has been designed. The target group for this report is university students and teachers.

Because the project is made mainly for educational purposes, the final product is not to be thought of as having commercial value.

The report is divided into three main parts: "Project Specifications", "Design & Implementation" and "Assessment & Conclusion". Referenced sources are denoted by a number in square brackets, like: [1]. This number refers to the list of references, which can be found on page 127. If the report is read electronically it is possible to jump to chapters, sections, figures, tables and citations by "clicking" on their references. Different acronyms and terms are widely used throughout the report. In appendix A on page 130 a list of these can be seen. The reader is advised to read this carefully. In the report `functions()` and `variables` written in code, are emphasized by a different font.

Appendices are placed in the end of the report. These appendices contains test journals, protocols and other things that support the development of the product as well as the report. The appendices are denoted A, B, C and so on, while the test journals are numbered. In appendix G on page 146 a schematic of the entire system and a part list can be found. Along with the report a CD is enclosed, containing datasheets, developed software, test software, Matlab scripts and a PDF version of this report. On the CD, a folder with videos and pictures of the developed system can be found [1]. Throughout the report, there will be referenced to material on the CD in this way, the full path can be found as a footnote.

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[1] `/multimedia`

Contents

CHAPTER 1

Introduction

In August 2010 four students from Nørresundby Gymnasium participated in the European CanSat competition in Norway along with 10 other groups of students from upper secondary schools. The competition was hosted by the European Space Agency (ESA) in order to motivate young people to study science and technology[2], by having them build and launch a CanSat. A CanSat is a tiny satellite, built to fit inside a standard 330 mL soda can. It is deployed from a rocket in an altitude of approximately 1 km before parachuting back to Earth. During the travel the CanSat sends telemetry data to a ground station to be used for educational purpose e.g. to calculate the apex (highest point) of the flight.

The goal of the CanSat competitions is not to build real satellites, but rather to have students gain insight into the process of building a real satellite. Many space organisations have held CanSat competitions for students from upper secondary school or universities[3],[4],[5]. These competitions seek to inspire young scholars to follow careers within science and engineering. This way, the space organisations hope to ensure the future workforce of scientists and engineers for developing space programmes.

The Danish Agency for Science, Technology and Innovation are considering hosting a CanSat competition for students in danish upper secondary schools. Therefore, they have requested Aalborg University to develop a CanSat kit. The kit must be designed to be easy to use, low-cost, open source and based on off-the-shelf components. The kit will consist of:

- An onboard CanSat controller.
- A radio communication link on a license free band.
- A sensor sub platform (possibility to extend with custom sensors).
- A ground station for communication with CanSat during flight.

In the fall semester 2010, at the time of writing, four groups of students at the department of Electronic Systems at Aalborg University, are doing semester projects regarding the development of this kit. Three groups put their focus on the CanSat itself and one group focus on the ground station. The groups have cooperating, shared experiences, and a common radio communication protocol has been developed in order to ensure compatibility between CanSats and ground stations.

This report is the documentation of the work done by group 10gr503. The starting point of this particular project is the development of the ground station with an automatic

satellite tracking antenna. Acquisition and saving of the CanSat telemetry data is a crucial part of the CanSat project. Since the rocket propelled launch is a one time opportunity, the main mission of the ground station is to gather and save as much information about the flight as possible. To accomplish this task, precise tracking of the CanSat is necessary in order to minimize the amount of lost information.

Part I

Project Specification

CHAPTER 2

Preliminary Analysis

The purpose of this chapter is to clarify the background and requirements for this project. First the CanSat competition will be described in order to get an overview of what the ground station system is going to be used for. Then a system overview identifies the different components a ground station system consists of, and the technical aspects in designing and realising these units are discussed. A discussion of the design of the common radio protocol between ground stations and CanSats follows. The final outcome of the chapter is the foundation of the requirements specification.

2.1. CanSat Competition

The CanSat concept was introduced in the late 1990s by the American professor Robert Twiggs[6]. Since then, several CanSat competitions have been held in the USA, Japan and Europe with slightly different rules and requirements.

The CanSat competition, this project evolves around, is held by the European Space Agency, ESA. The competition is aimed at students in the upper secondary school. It was first held in 2010, where students from 11 different countries participated. In august 2010 the students launched their CanSats from the Andøya Rocket Range, an independent branch of the Norwegian Space Center.

Information about the CanSat competition in 2011 has not yet been published. Therefore this project is based on information for the 2010 competition [5]. Participating teams must consist of 3-10 high-school students. They must build CanSats that measure air temperature and air pressure. These data must then be transmitted to the ground station at least once every second after release and during descend. In addition to this primary mission, a secondary mission of free choice must be accomplished. The secondary mission can be anything, as long as it has some technological, investigative or innovative value. It could for example be:

- Advanced Telemetry: measurement of acceleration, GPS location or radiation levels.
- Telecommand: having the ground station send commands to the CanSat.
- Comeback: have the CanSat autonomously navigate to a target land point.
- Landing System: a safe landing system, such as a bespoke parachute or airbag.

- Planetary Probe: Simulate an exploration flight to a new planet, e.g. taking measurements on the ground after landing.

The rules for the competition are not directly targeted at the ground station, they specify requirements such as size and weight of the CanSat itself. The specific rules will thus not be mentioned here, but they can be found on the ESA website [5].

2.2. System Overview

The purpose of this project, is to design and build a ground station for CanSat satellites. This ground station must be able to receive data from and send data to the CanSats constructed by other groups.

2.2.1 Project Contents

In previous years, a directional antenna has been used to receive the radio signals from the CanSats. This is due to the fact, that the CanSats can only transmit a very weak radio signal, because they can only contain small antennas. Also, they run on small batteries and maximum transmission power is specified by government regulations. These government regulations are investigated further in section 7 on page 45. This directional antenna must thus be pointed in the direction of the CanSat at all times during flight. It has been chosen, that this ground station system must have the following functionalities:

- Ability to automatically point the antenna at the CanSat and track it as it moves.
- Ability to receive the wireless data from the CanSat, namely telemetry data measured from onboard sensors, and transmit them in realtime to a computer located elsewhere. This transmission is done via an internet connection. The receiving computer is henceforth referred to as the "remote user client", or just RUC.
- Facilitate control of the ground station from the remote user client.

An overview of the project content can be seen on figure 2.1.

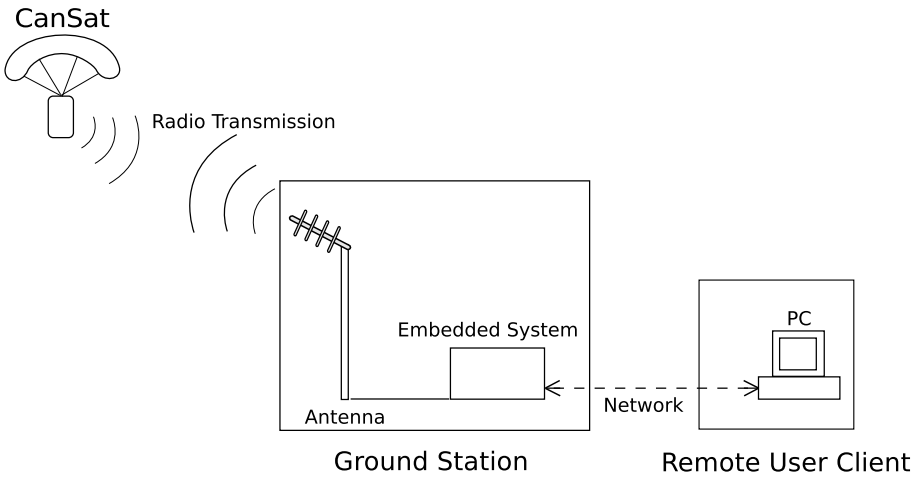


Figure 2.1: *This figure illustrates the CanSat, Ground Station and Remote User Client. The project is limited to the objects contained within the boxes.*

Note that the construction and design of the CanSat and the network between the ground station and the remote user client, is not part of this project. The premise for choosing

the elements that the project contains, has primarily been that, they should contain technical aspects, that the group would like to learn about:

- The automatic pointing of the antenna, requires the development of feedback control of the physical system consisting of the tilt and pan platform and antenna.
- The radio link to the CanSat, requires a data transfer protocol to be developed and implemented.
- By having the ground station and remote user client placed at different locations, a network connection must be established between them. Again, an application level network communication protocol is needed for this link.
- The ground station is going to be an embedded system with real time and multitasking requirements. A real time operating system is thus required.
- The application on the remote user client must be a GUI application, that can manage the GUI and service the network connection. To do this in a satisfactory way, multi programming techniques must be used.

2.2.2 Technical Aspects

The ground station is implemented as an embedded system, that takes care of receiving radio data from the CanSat, forwarding these to the remote user client and controlling the antenna direction. The remote user client needs to be capable of saving the received data and representing this to the user. Since a PC offers great conditions for data storage and representation, the remote user client is implemented as a GUI application running on such a system. The project thus consists of the following technical aspects, that are implemented in the product:

- **Automatic Antenna Direction Control**
  The antenna needs to be adjusted to point straight towards the CanSat at all times. To ensure this functionality, a pan and tilt platform, assisted by a controller, is utilized. The controller is designed and constructed by the project group, whereas a pre built pan and tilt platform will be used. In order to design the controller, it is necessary to design a mathematical model of how the motors on the pan and tilt platform affect the direction the antenna is pointing.

  In order to know which way to point the antenna, the ground station needs to know where the CanSat is. For this, it has been chosen to require the CanSat to be equipped with a GPS. These GPS coordinates will then be sent to the ground station over the radio link, which can then be used to calculate in which direction to point the antenna. CanSats that should be tracked automatically by the ground station, must thus be equipped with a GPS. For this to work, the ground station must know the GPS coordinates of its own location as well. Furthermore, it is desirable to be able to override this automatic antenna control and manually control the antenna. This can be used if the ground station is used with a CanSat that do not contain a GPS or if the ground station looses track of the CanSat and thus does not receive new GPS coordiantes anymore. The design and implementation of the antenna control is described in chapter 9 on page 65.
- **Radio Communication**
  The radio link from the CanSat to the ground station must be working on some license free frequency band, because it is undesirable to require the schools using the CanSat kit to acquire a license for the radio link. Pre built radio transceivers are used for the transmission. Since the project group would like to work with data protocols, it has been chosen that these radio transceivers should provide

nothing but a (possibly unreliable) byte- or bit stream transmission. The design, construction and implementation of the radio communication system is described in chapter 7 on page 45.

- **Network Based Connection**
  As illustrated on figure 2.1 on page 6, a network is used to connect the remote user client to the ground station. It has been chosen to use the TCP/IP network protocol suite on top of an Ethernet network. This way the network can be an Ethernet cable, an existing LAN network or the internet. This gives the user great flexibility in choosing how to connect the ground station and the remote user client. The actual implementation of these protocols is described in chapter 6 on page 37.

- **Remote User Client**
  The users that are going to utilize the CanSat kit and thus also the ground station and remote user client developed in this project, will be students from upper secondary schools. It is thus vital that the system can be used by non-technical people who haven't worked with electronics before. Therefore, the remote user client is developed as a GUI application on a PC. This GUI must be fairly intuitive and easy to use. It has been chosen to use Java as the programming environment for this application, since it provides an excellent cross-platform environment for developing GUI applications. Java also provides great network support and it's easy to create multi-threaded applications, since this is supported at the language level by Java. It should be noted however, that since the project group is receiving courses on Java this semester, it is the obvious choice. The design and development of the remote user client is described in chapter 10 on page 91.

- **Realtime operating system**
  The ground station must be able to handle the connection to the CanSat, handle the connection to the remote user client and perform the antenna pointing direction control. This must all be done in parallel and in a timely manner. It has been chosen to implement this on an embedded computer system running a real time operating system. The design and implementation of this real time operating system is a part of the project, because it presents some interesting technical challenges. It is further described in chapter 5 on page 31.

- **Telemetry Data Backup**
  One of the primary tasks of the ground station is to receive telemetry data from the CanSat. Under normal operation the received CanSat data will be transferred to the remote user client and saved as a file upon arrival there. The network link may break however, and other unforeseen events e.g. a computer crash, could lead to loss of incoming data. Therefore it is desired to save telemetry data to persistent memory on the ground station as well. This is referred to as the telemetry data backup. In case of link breakage or crash the data on the ground station would be available for later retrieval. It is worth considering keeping a similar backup aboard the CanSat, which could then be read after retrieving the CanSat after a flight, if the radio link is unreliable or completely lost during the flight. The construction of the CanSat is not part of this project though. Due to time constrains, the telemetry data backup has not been implemented in the system.

- **Event Log**
  It is desirable for the user to be able to analyze what happened during flight. Therefore, the remote user client maintains a log of recorded system and user activity. This includes user interaction with the GUI and information about received packets. This is called the event log. Implementation of this is described in the chapter descibing the RUC, chapter 10 on page 91.

2.3. WARP AAU Radio Protocol

In order to make it possible to use the ground station constructed in this project, with the CanSats being designed by other project groups, a common protocol for the transfer of data over the wireless link is to be defined. In this section, protocol requirements originating from this project are analysed. Then the protocol design choices are discussed.

The protocol specification has been developed in cooperation with the remaining groups working on CanSat kits at AAU in the autumn semester 2010. The final protocol specification can be found in appendix B. It precisely outlines the technical aspects of the protocol. Anyone should be able to implement the protocol by reading this specification, but will not necessarily understand why the protocol is designed the way it is. It has been chosen to name this protocol WARP, which is a recursive acronym for "WARP AAU Radio Protocol".

2.3.1 Protocol Requirements Set by This Project

Since the ground station needs GPS data from the CanSat in order to track it, it must be able point the antenna towards the CanSat at all times, including during the launch phase. This also enables collection of telemetry data during launch. The satellite will be accelerated to it's maximum speed very quickly, which requires the antenna control to be very responsive. As the position changes rapidly, the ground station has to receive the position frequently. Should the ground station completely loose track of the CanSat during launch, further tracking will be impossible as no updated GPS data will be received.

These circumstances set a requirement to how old the latest received position of the CanSat is allowed to be. This requirement is incorporated into the common radio protocol. The following calculations gives an estimation of the minimum sample rate and maximum latency of the CanSat GPS data, which are required for the ground station to be able to track the CanSat during launch. First the maximum angular velocity of the elevation angle is found. The timing requirements are then derived from this value.

Maximum angular velocity of tracking antenna

The purpose of the following calculations is to find the maximum angular velocity of the elevation, which is required for the ground station antenna to track the CanSat.

The ground station is placed in a horizontal distance r from the launch site and the altitude of the rocket is denoted h as shown in figure 2.2 on the next page. To calculate the maximum angular velocity $\omega_{\max}$ of the elevation of the ground station antenna, the following scenario is assumed:

- The angular velocity of the elevation reaches it's maximum value during the launch phase (until rocket releases its payload).
- The rocket only moves along the vertical axis. This scenario is assumed because the angular velocity required to track lateral movements of the rocket is expected to be much smaller.
- The distance $r = 400\,\mathrm{m}$.
- The maximum velocity of the rocket $v_{\max} = 600\,\frac{\mathrm{km}}{\mathrm{t}} = 166.7\,\frac{\mathrm{m}}{\mathrm{s}}$ is reached with a constant acceleration $a = 20 \cdot g = 20 \cdot 9.82\,\frac{\mathrm{m}}{\mathrm{s}^2} = 196.4\,\frac{\mathrm{m}}{\mathrm{s}^2}$ and the velocity is maintained during the rest of the launch phase. $v_{\max}$ is the highest expected rocket velocity. In comparison the maximum velocity for the rocket used in the ESA 2010 CanSat competition was $544\,\frac{\mathrm{km}}{\mathrm{t}}$[6]. The value of a comes from the maximum acceleration a CanSat should be able to withstand [5].

- The inaccuracy of the GPS data can be neglected, because it is small compared to the horizontal distance r to the rocket.

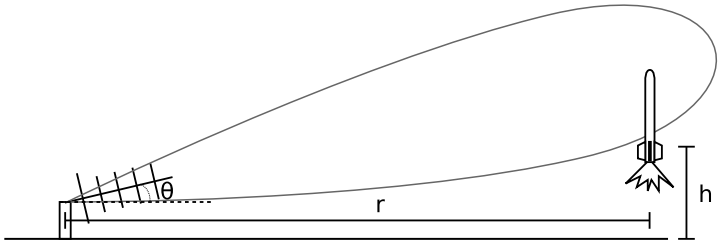


Figure 2.2: *Illustration of CanSat tracking during launch.*

From these assumptions the movement of the rocket can be divided into the two phases, constant acceleration and constant velocity. The angle between the ground plane and a straight line from the ground station to the rocket is the desired elevation angle $\theta = \arctan(\frac{h}{r})$. The altitude of the rocket h during the acceleration phase can be written as $h = \frac{1}{2} \cdot a \cdot t^2$, where t is the time from the beginning of the launch. The angular velocity of the elevation angle is the derivative of θ with respect to time. The angular velocity during the acceleration phase ω_1 is given by:

$$\omega_1(t) = \frac{d\theta}{dt} = \frac{d \arctan(\frac{\frac{1}{2} \cdot a \cdot t^2}{r})}{dt} \tag{2.1}$$

$$= \frac{art}{r^2 + \frac{1}{4}a^2t^4} \tag{2.2}$$

A similar expression is found for the constant velocity phase:

$$\omega_2(t) = \frac{d \arctan(\frac{h_1 + v_{\max}(t - t_1)}{r})}{dt} \tag{2.3}$$

$$= \frac{v_{\max}}{r + \frac{(h_1 + v_{\max}(t-t_1))^2}{r}} \tag{2.4}$$

where:

ω_1	is the angular velocity of the elevation during the constant acceleration phase	$[\mathrm{s}^{-1}]$
ω_2	is the angular velocity of the elevation during the constant velocity phase	$[\mathrm{s}^{-1}]$
a	is the acceleration during the constant acceleration phase	$[\frac{\mathrm{m}}{\mathrm{s}^2}]$
$v_{\max}$	is the maximum velocity of the rocket	$[\frac{\mathrm{m}}{\mathrm{s}}]$
r	is the horizontal distance between the ground station and the launch site	[m]
h_1	is the distance travelled by the rocket during the constant acceleration phase	[m]
t_1	is the duration of the constant acceleration phase	[s]
t	is the time since the beginning of the launch	[s]

With the assumed values for r, a and $v_{\max}$ the angular velocity of the elevation angle versus time can be plotted, as shown in figure 2.3 on the facing page. The angular velocity increases during the acceleration phase and the maximum velocity is reached in under 1 second. From the graph the maximum angular velocity $\omega_{\max}$ can be read as approximately 0.4 rad/s. Note that because of the assumptions made in the calculations, the angular velocity found is a rough estimation.

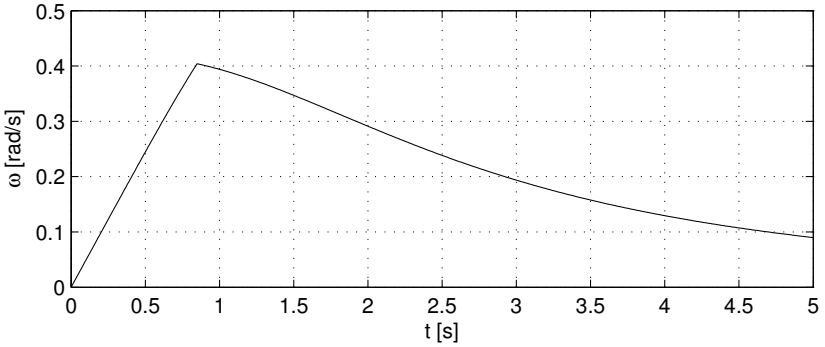


Figure 2.3: *Calculated angular velocity of the desired ground station elevation versus time during the launch*

GPS position update time

The maximum angular velocity of the antenna tracking platform has been calculated to approximately 0.4 rad/s. This value can now be used to get an idea of how often the GPS position must be updated in order to be able to track the CanSat with the antenna. It is assumed that the ground station will be able to track the CanSat if the latest elevation angle fed as reference position to the controller never deviates more than 10° from the real value. At an angular velocity of 0.4 rad/s a rotation of 10° takes 436 ms. If the GPS sample rate is set to 5 Hz, the sample period is 200 ms. This leaves 236 ms for the GPS data to be transmitted and fed into the controller. It is assumed that from the time the CanSat has completed transmitting a package with the GPS data, until the ground station has passed it to the controller, no more than 36 ms will pass. Therefore, it is a requirement to the CanSat, that no more than 200 ms may pass, from the time a GPS sample is taken until the package with the data has been transmitted.

However it is clear from the above that packet loss in the CanSat to ground station communication during the launch, can be fatal for the automatic antenna tracking system. Thus a panic action should be considered in case of a lost link. For example the current CanSat position could be extrapolated based on previously obtained GPS data.

2.3.2 Protocol Design Decisions

Before designing the protocol, it is worth considering what the protocol's job is, which features it should contain and so forth. This can be used as the basis of how the protocol should be designed. The protocol is to be used on top of a wireless radio data link. This link is a byte stream, i.e. a channel, where bytes are put into one end and taken out of the other. Since it's a wireless link, no assurances are made that the bytes are transfered undamaged. It is worth noting, that often the rockets will bring multiple (typically two) CanSats into the air at the same time. Measures must thus be taken to ensure the radio link will be working correctly, even if multiple CanSats, all using the WARP protocol, are airborne at the same time. There might also be multiple ground stations, all using WARP. It is desired however, that different CanSats - ground station pairs use different frequency bands for their communication, so interference between them is avoided.

Package Delimiting

A way to delimit each chunk of information is needed. It has been chosen to use a package oriented protocol. To delimit these packages, a start and a stop byte will be used. The advantage of using this scheme compared to fx. having a length field in the packages, is that it is known that if an (unescaped) start byte is received, then that is the start of

the next package. This will thus correct any errors in the transmission. If only a length field was used, errors in one of these length fields, would result in all following packages not being received correctly, since the package limits would be unknown. This requires all occurrences of the start and stop byte to be escaped, which will be done using byte stuffing.

Implementing devices that adhere to the protocol, is much easier, if a maximum package size has been specified. This way, it is known how much buffer space to allocate for received packages. This maximum package size will be specified as the package size before adding start- and stop bytes and escape characters, since it is expected that devices will be removing these bytes before saving them into a buffer. The maximum package size has been chosen to be 150 bytes.

Since errors may occur in the bytes transmitted over the wireless link, a way to ensure that the package was transferred without any errors is required. For this, a checksum field will be used.

Transfer of Telemetry Data

Obviously, it should be possible to transmit measured telemetry data from a CanSat to the ground station. The measurement will likely happen at a fixed time rate, e.g. 2 Hz. Each time such a measurement has been performed, it should be transmitted to the ground station. If there is bandwidth and computation power left over, it is better spent on increasing the rate at which measurements are taken and transmitted, than using them on some acknowledgement scheme that ensures arrival of every measurement taken. For this reason, an unacknowledged transmission scheme will be used for this type of data, where a CanSat just transmits a number of packages and the ground station receives as many of these as the circumstances allows it to.

Remote Control of CanSats

It has been chosen that the students should be offered the possibility to perform some sort of remote control of a CanSat, while they are airborne. The communication protocol, must thus be 2-way and allow commands to be sent from the ground station to a CanSat. What these commands do, is not to be specified by the protocol. To keep the protocol simple, it has been chosen that the command is sent as a "command number" that can then be used to execute the corresponding function on the CanSat. It will not be possible to send arguments along with the commands. It is required that only one ground station is communicating with each CanSat.

A transmission scheme similar to the one used for transfer of telemetry data, cannot be used for this. When the user has asked for a command to be executed, he needs to be assured that this command has actually been performed. Therefore a scheme where a CanSat has to send an acknowledgement after successfully receiving a command package will be used.

It is desired to ensure that the ground station, doesn't transmit a package, at the same time as the CanSat is transmitting a package. For this, a flag in the packages going from the CanSat to the ground station, is used to indicate if the ground station is allowed to transmit in a time interval following the reception of the package. This time interval has been chosen to be 50 ms. As it will be shown in chapter 11, sending a command package in the used setup will take 8 ms.

CHAPTER 3

Requirements Specification

The analysis in the previous chapter outlines some of the aspects that form the basis of this project. It described the basic composition of the project and the product to be designed. In the following chapter, use cases are used to describe the desired functionalities of the final product, seen from the users perspective. Next, a requirement specification outlines the technical requirements that the product should comply with. Based on this, an acceptance test specification is made. If the product can pass this test, it complies with the requirements specification. The use cases and the requirements specification are based on the previous analysis.

3.1. Use Cases

To establish an overview of what the product should contain seen from the users perspective, a use case diagram has been drawn up. The diagram is based on the preliminary analysis and the chosen areas of focus, described in chapter 2. Each use case describes a functionality that needs to be incorporated into the final product. These use cases set the scope for the product, but without eliminating the opportunity to add extra functionality. The use case diagram can be seen in figure 3.1 on the next page.

3.1.1 Actors

The system has the following two actors:

- **User**
  The user could be a student at an upper secondary school, who is participating in the CanSat competition.
- **CanSat**
  The CanSat is what needs to be tracked by the ground station. It provides the ground station with different kinds of data, such as telemetry data like temperature and pressure.

3.1.2 Description of Use Cases

The following lists the use cases and describes the goals, normalscenarios and in some cases exceptions of the use cases. The goal description of each use case explains the

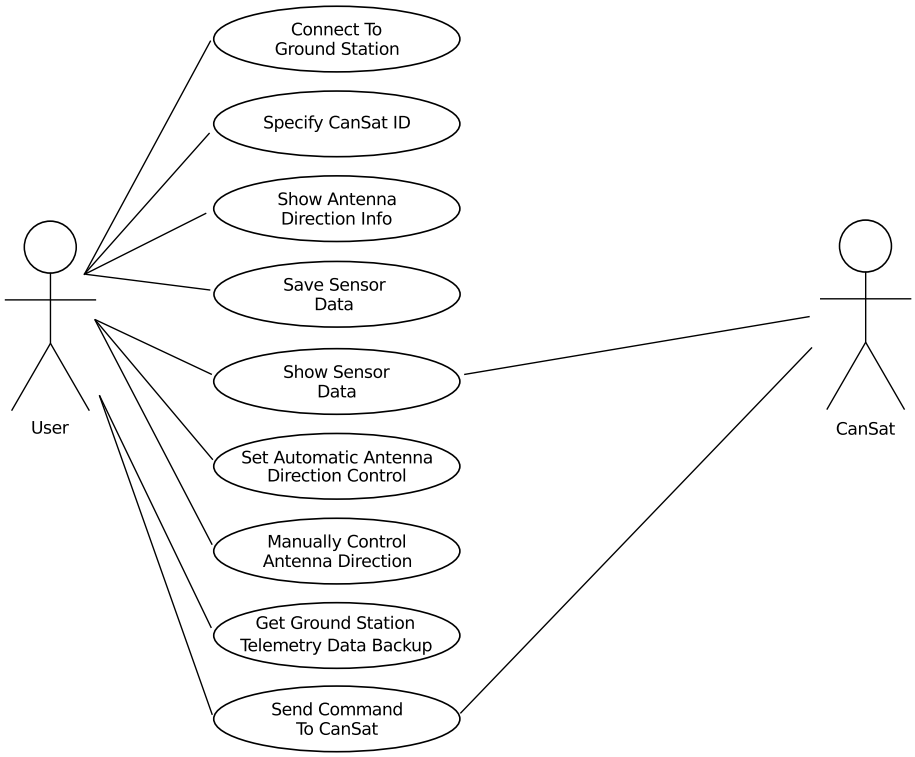


Figure 3.1: *This figure illustrates the products use case diagram.*

desired result from the action performed. The normalscenario describes the dialogue between user and system. The exceptions describes how the system should act if an error occurs.

1: **Connect to Ground Station**

Goal description: The user establishes a connection to the ground station.

Normal scenario:

1. *User:* Sends a connection request to the ground station.
2. *System:* Receives the request and establishes a connection.
3. *System:* Acknowledges that the connection has been established.

Exceptions:

- **No connection can be established**
  The user is informed that the connection could not be established, and is given the opportunity to try again.

2: **Show Antenna Direction Info**

Goal description: The current position of the antenna is shown to the user.

Normal scenario:

1. *User:* Queries the system for the current antenna position.
2. *System:* Receives the query and shows the current position.

Exceptions:

- **Current position cannot be determined**
  No antenna direction is shown.

3: Show Sensor Data

Goal description: Data from the user-specified sensors on board the CanSat, is shown to the user.

Normal scenario:

1. *User:* Queries the system for CanSat sensor data.
2. *System:* Receives the query and shows sensor data.

4: Enable Manual Antenna Direction Control

Goal description: The user can adjust the system's antenna.

Normal scenario:

1. *User:* Changes the antenna position configuration.
2. *System:* Receives new configuration and adjusts the antenna.

Exceptions:

- **The user specifies an invalid configuration**
  The system ignores the new configuration, and warns the user.

5: Enable Automatic Antenna Direction Control

Goal description: The system will take control of adjusting the antenna direction.

Normal scenario:

1. *User:* Queries the system to enable automatic antenna direction control.
2. *System:* Receives the query and takes control of the antenna.

Exceptions:

- **The system is set to conformance class 1, or no ground station location is set**
  The system ignores the user request.

6: **Specify CanSat ID**

Goal description: The system will store and use the specified CanSat ID.

Normal scenario:

1. *User:* Specifies the desired ID.
2. *System:* Receives the ID and stores it.

Exceptions:

- **The user specifies an invalid CanSat ID**
  The system ignores the user input, and warns the user.

7: **Save Sensor Data**

Goal description: The user specifies a destination for the saved data.

Normal scenario:

1. *System:* Queries the user to specify a file destination to store the data.
2. *User:* Specifies a destination.

Exceptions:

- **The user specifies an invalid file destination**
  The system ignores the file destination, and the user is given the opportunity to retry.

8: **Retrieve Ground Station Telemetry Data Backup**

Goal description: The user can send a request specifying that he/she wants to obtain the ground station telemetry data backup.

Normal scenario:

1. *User:* Queries the system to retrieve telemetry data backup from the ground station.
2. *System:* Receives the query and attempt to retrieve the backup.

Exceptions:

- **The ground station telemetry data backup is empty**
  The system reports that the requested backup is empty.

9: **Send Commands to CanSat**

Goal description: The user can send different commands from the system to the CanSat.

Normal scenario:

1. *User:* Queries the system to send commands to the CanSat.
2. *System:* Receives the query and sends the specified command to the CanSat.

Exceptions:

- **The requested command never reaches the CanSat**
  If the system doesn't receive an acknowledgement from the CanSat, the command will timeout. When the command times out, it will be re-sent. This procedure will be repeated until the system receives the acknowledgement.

3.2. Requirements Specification

The purpose of this chapter is to define and specify the requirements for the product. These requirements are based on the general goal of the project and the previous analysis of the system. The final product must comply with the following requirements:

Requirement 1. **Must implement and adhere to the WARP protocol.**
To be able to receive and process data from any CanSat, the ground station must implement the WARP protocol described in appendix B.

Requirement 2. **Must implement and adhere to TCP/IP and Ethernet protocols.**
The ground station will be connected to a network via an 8P8C-connector (also known as RJ45-connector). This network will be TCP/IP based and the connection to it will be

an Ethernet connection. The ground station and RUC must thus adhere to the TCP/IP protocol suite and the Ethernet protocol.

Requirement 3. **No more than** 200 ms **may pass from a package is received on the ground station's wireless link, until the processed package containing this information, is sent to the RUC, if this is connected through a direct Ethernet cable.** This requirement will ensure a certain response time for the user when using the system, by limiting the ground station's package processing time. It is assumed that the response time of the RUC is insignificant, compared to the processing time of the ground station. This assumption is based on the fact that the ground station is implemented on an embedded system, and the RUC is implemented on a PC.

Requirement 4. **The RUC must save all received data as a comma separated values file (CSV).**
This requirement stems from the need to save all recorded data in an easily handled format. CSV is cleartext with a simple format and is supported by many applications.

Requirement 5. **If the RUC crashes, any data that already has been received, must not be lost.**
In order to achieve this requirement, all data processed by the RUC should be saved to a file immediately after reception.

Requirement 6. **The ground station must keep a backup of the latest received telemetry data. This backup must contain data from the last 5 minutes or more, given a package rate of** 5 Hz **with each package being the maximum package size (**150 bytes**).**
If the connection to the RUC is lost prior to or during a flight, it is desirable to backup all received data. It noted that the rules for the competition state that a CanSat cannot be airborne for any more than 120 s [5]. It is estimated that a data recording won't last for any more than 5 minutes and the maximum package rate will not be more than 5 Hz. Please note the maximum package size includes some header fields, which can be omitted.

Requirement 7. **The connection between ground station and CanSat must be able to transmit** 60 byte **packages at a distance of** 1.5 km **with a maximum package loss of** 10 %**. This is assuming that the CanSat and ground station are placed in line of sight, the CanSat is within the antennas half-power beamwidth and the package transmission rate is** 5 Hz**.**
The 60 byte packages are used, to test the wireless connection at an expected normal work load. The distance of 1.5 km is the estimated distance between the ground station and the CanSat after launch. Notice that some package types are acknowledged in the WARP protocol, described in appendix B on page 131. As a result, the actual package loss will be less than the results of this test. Please note that this requirement depends on the CanSat, which is constructed by other groups.

Requirement 8. **The ground station must be able to control the antenna so that an object following the launch graph on figure 2.3 on page 11 can be tracked. The target must be within the half-power beamwidth of the antenna at all times.**
This requirement will ensure that a CanSat can be tracked during launch. It is assumed that the CanSat is easily tracked during its descend, if it can be tracked during the launch phase. The target must always be within the half-power beamwidth of the antenna, to ensure that the ground station and CanSat antennas can 'see' each other at any given moment. Notice the half-power beamwidth is determined by the utilized ground station antenna.

3.3. Acceptance Test Specification

The purpose of this section is to describe which tests needs to be performed on the designed system to ensure that it meets the system requirements. The requirements can be seen in section 3.2 on page 17. These tests are as follows, to see more details about how these tests are performed, see chapter 12 on page 117.

Test 1. **Covers Requirement 1 and 2**
Packages adhering the WARP protocol are sent to the ground station. On the RUC, an Ethernet connection is established, and a specific package format from a specific CanSat ID is to be expected. The packages send will be marked as originating from two different CanSat's by setting different CanSat ID's in the packages. These packages will be transmitted for at least five minutes. The packages with the matching CanSat ID must be transmitted at least five times per second.

In order to pass this test, the system must filter out the packages with the wrong CanSat ID. It also has to retrieve the data from all the correctly received packages with the matching ID, and display these on the RUC.

Test 2. **Covers Requirement 3**
A CanSat telemetry data package is sent to the ground station. Once this is received a timer will be started. The ground station will then prepare a package containing the received data for the RUC protocol and transmit it. The package payload will be 150 bytes. The ground station and RUC will be connected directly through an Ethernet cable. Once the package has been transmitted, the timer will be stopped. This is repeated for 1000 packages, and the worst-case time is extracted.

If the worst-case time is less than 200 ms, this test is passed.

Test 3. **Covers Requirement 4 and 5**
10,000 packages with known data are sent to the RUC, using the RUC protocol. The saved data is compared with the data received, to see if they were stored correctly. Afterwards, the test is repeated, but this time, the RUC is terminated by the OS, halfway through receiving the data.

In order to pass this test, all received packages must, in both cases, be stored correctly.

Test 4. **Covers Requirement 6**
The ground station is set to track a CanSat, with a specific CanSat ID. Packages adhering the WARP protocol with this specific ID, is send to the ground station, at a rate of 5 Hz *with each package being the maximum package size (*150 bytes*). The RUC is then disconnected from the ground station. After 5 minutes, the package transmission is stopped. The RUC is then reconnected to the ground station, and the stored data in the ground station data back up is requested.*

In order to pass this test, the ground station must be able to send the last 5 minutes of CanSat telemetry received, to the RUC.

Test 5. **Covers Requirement 7**
A ground station and a CanSat is placed in line of sight, at a distance of 1.5 km*. The RUC is then connected to the ground station, and the corresponding SatID is specified. The CanSat is fitted with a serial connection which writes the received data to a computer, and enables it to send packages on demand. At a certain time, a stopwatch is started, and the CanSat is set to transmit 60 byte packages, at a rate of* 5 Hz*. After 5 minutes, the CanSat stops transmitting, and the received packages are inspected. Afterwards, this is repeated in the opposite direction.*

In order to pass this test, no more than 10% package loss is permitted, in either direction. This is calculated from the expected number of packages, relative to the number of valid packages received.

Test 6. **Covers Requirement 8**
The ground station is set to move the antenna along a predetermined path, as described in requirement 8. Using saved information from the controller, such as where the antenna is moving towards, and where its currently located, the maximum deviation is determined.

To pass this test, the maximum deviation must remain within the half-power beamwidth of the antenna, at any given time.

Part II

Design & Implementation

CHAPTER 4

Modularization

After having completed the initial analysis of the system and having specified requirements for it, the design of the system can begin. In section 2.2.1 on page 6 an outline of the system components is shown. It can be seen that, the ground station has to be connected to the remote user client over a TCP/IP based network. In the following, the application level protocol for the communication over this network, will be defined. This protocol defines the interface between the two major subsystems: the ground station system and the remote user client. The ground station functionality can furthermore naturally be divided into a number of subtasks. This division into subtasks will be described, thus further modularizing the system. For this decomposition of ground station tasks, the Hard Real Time Hierarchic Object-Oriented Design method (HRT-HOOD) is used.

4.1. Utilized Hardware

Before going into further details with the breakdown of the systems into smaller parts, an overview of the system is given. This overview is shown in figure 4.1 on the next page. The figure emphasizes which hardware components are used in the system and how they are connected.

As the base for developing the ground station, a development board based on the ARM7TDMI [7] CPU core has been chosen. The Mini-Max/ARM-E development board from BiPOM Electronics [8], has an on board Ethernet controller chip, which makes it easier to develop the Ethernet support required for the ground station. The development board is based on the LPC2138 microcontroller from NXP [9],[10]. A summary of the NXP LPC2138 features:

- ARM7TDMI CPU core, that can be clocked at speeds up to 60 MHz.
- 32 KiB RAM
- 512 KiB flash ROM
- Usual microcontroller features: 6 x PWM, 2 x SPI, 2 x I2C, 2 x UART, ADC, DAC and Timer/Counter, all with various interrupt possibilities.
- Debugging and programming over JTAG.

For wireless communication with the CanSat, the RFM12B [11], [12] transceiver is used, more details can be found in chapter 7 on page 45.

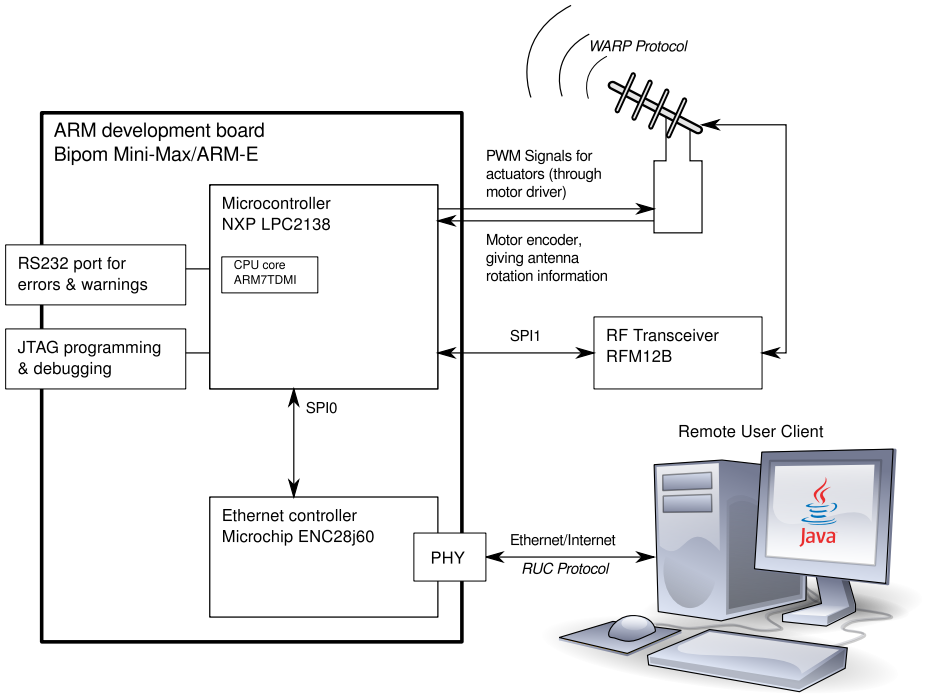


Figure 4.1: *Overview of the hardware used in the system*

A full list of utilized hardware, a total schematic and the physical construction of the system can be seen in appendix G on page 146.

4.2. Remote User Client Protocol

All user-interaction with the ground station is done through the remote user client. The communication between the ground station and the RUC, is done over a TCP/IP connection. On top of this TCP/IP connection, an application level protocol must be defined, this protocol will be referred to as the RUC protocol.

4.2.1 Information to be handled

The information going from the RUC to the ground station primarily consists of commands and configuration of what the ground station should do. This includes:

- Ask the ground station to calibrate the antenna direction control, see section 9.3.5 on page 82 for more details.
- Specify whether to use automatic (based on GPS information received from the CanSat) or manual control of antenna pointing direction.
- When using manual control, specify wanted azimuth and elevation of the antenna.
- Set GPS location of ground station, which is used to calculate the direction to point the antenna, when using automatic antenna direction control.
- Set ID of the CanSat that should be tracked. This corresponds to the SatID in the WARP protocol packets received from the CanSats.

- To illustrate the effect of different types of feedback control, it can be specified which type of feedback control should be used. See section 9.3.5 on page 82 for more details.
- Retrieve saved telemetry data from the telemetry data backup. Due to time constrains, this has not been implemented in the ground station, but it is included in the protocol.
- Ask the ground station to send a command to the CanSat.

The ground station will also be sending information to the RUC, which will primarily consist of data:

- Telemetry data received from CanSat. This must be displayed to the user and it must be possible for the user to save this data in a CSV file.
- Information about the antenna position. Two value sets are to be sent: Current (actually measured antenna position) and wanted position (position being fed into the controller). This information must be shown to the user, who can then decide if manual or automatic antenna control is to be used. By both supplying the wanted and current antenna position, it is possible for the user to see if the feedback control is able to follow the antenna position that is wanted. This information must be sent at a high rate, so that it can be used to test the feedback control as well. The RUC should save the received information about antenna position in a file, so that it can be analyzed when testing the feedback control of the pan & tilt platform.
- Acknowledgment of commands previously sent to the CanSat.

4.2.2 Underlying Protocol

TCP has been chosen, because it provides reliable connection oriented byte-stream transfer between two hosts, and it is widely supported by existing networks and hardware. This means that TCP guarantees that sent data will ultimately arrive in the order they were sent and without errors. The most obvious alternative to TCP is the UDP protocol. It is fundamentally different from TCP, since it's datagram oriented instead of connection oriented. UDP doesn't make any guarantees about data actually being delivered, data integrity on delivery or the order in which the data is delivered. The RUC to ground station connection requires all the reliability provided by TCP, if for example two commands to set the CanSat ID are sent quickly after each other, the order they arrive at the ground station determines which one will ultimately be effective. If UDP was used, basically all the reliability that TCP provides had to be reimplemented in the RUC protocol, therefore TCP has been chosen.

4.2.3 Effect of Large Latencies

It must be considered how the system reacts to large latency times on the network. The network connection may go through the Internet, which is a very likely source of considerable latencies. These may for example be caused by large physical distances between hosts, congestion in the network, large data loss rates (which results in many retransmissions) and more. This will obviously only be the case when connecting to the ground station remotely. The effect of large latencies on the different types of data on the RUC to ground station connection is:

- **Telemetry data from ground station to RUC.**
  Latency here will result in the user experiencing that the data shown to him/her, is not the most current data. This is an acceptable effect, since the data will

ultimately arrive and the data most often will be saved for later analysis. It is useful for the user to know at which time the telemetry data was received from the CanSat (eg. to perform calculations of speed based on GPS position data). This information is not included in the WARP package. Since the latency from ground station to the RUC may vary, a timestamp specifying the arrival time of the telemetry data cannot be done on the RUC. The ground station must thus send a timestamp along with each package containing telemetry data, specifying the time the data was received from the CanSat. The timestamp is only used to calculate the relative time between packages, and has been chosen to be the time in milliseconds since any arbitrary reference time (likely the time the ground station was started).

- **Antenna position information from ground station to RUC and specification of azimuth and elevation when using manual antenna control.**
  If the user is trying to control the antenna position over a high-latency network, the latency will be very noticeable, since there will be a time delay from specifying a wanted antenna position until the antenna starts moving towards the specified position. Furthermore, there will be a delay until the new antenna position is shown in the RUC. This will give the user a feeling of unresponsiveness, but this issue cannot be avoided.

  As with the telemetry data, it is desirable to know at which relative times the antenna position data was captured and a timestamp must be sent along in this case as well.

- **Configuration setting commands from RUC to ground station.**
  This includes specifying CanSat ID, setting ground station GPS location, asking ground station to calibrate, specifying automatic/manual control, specifying feedback controller type and asking to receive telemetry data backup.

  Obviously latency here, will result in a delay from the time the user specifies a setting to the time it takes effect. This effect cannot be avoided. If the latency is large, it is possible that multiple configuration setting commands specifying different values for a setting, will be "stored" in the network. Since TCP guarantees correct reception order of the data, the last issued setting command will be the one that is received last, and thus also the setting that will be effective, which is the desired behaviour.

- **CanSat commands from RUC to ground station and acknowledgment thereof.**
  When sending commands to the CanSat, the WARP protocol specifies that the CanSat must acknowledge successful reception of the command. This information should be passed to the user. There might be a considerable delay from sending a CanSat command until it has actually been delivered. The command has to be transferred from the RUC to the ground station, then over the wireless link to the CanSat, which then acknowledges the reception of the command. Hereafter the ground station must forward the acknowledge to the RUC. The part that is transferred over the wireless link may require some retransmissions if the link is bad, which will further delay the delivery of the command.

  If the user doesn't receive an acknowledge that his command was send relatively fast, he might think the try was unsuccessful and try again. However the command or the acknowledge thereof may just be "stored" somewhere in the network and the user ends up having sent a number of commands, even though he only wanted to send one. Therefore it has been chosen, that once a CanSat command has been sent, another one cannot be sent until the first one has been acknowledged. This also simplifies the protocol, since the CanSat command acknowledge sent from the

ground station to the RUC, will always be an acknowledge of the last command sent.

These considerations have been part of the base, from which the protocol has been designed.

4.2.4 Protocol Outline

The RUC protocol uses one-way messages, ie. when sending a message there is no direct reply message. As described above, this is acceptable, also with large network latencies. TCP provides a byte-stream, ie. it does not preserve package boundaries, so the RUC protocol must provide a way to distinguish messages from each other in the byte stream. For this, each message is put into a package, and each package is started by a start byte and then followed by a length field, specifying the length of the package. Occurrences of the start byte in the package are escaped using byte stuffing. No checksum is used, since TCP guarantees data integrity. The details of the RUC protocol can be found in appendix C on page 135.

4.3. Ground Station Subtasks

To support the design of the ground station, Hard Real Time Hierarchical Object Oriented Design (HRT-HOOD) is used. The method is used as described by Burns and Wellings [13]. HRT-HOOD is a structured software design method for hard real time systems. The ground station contains both software and hardware parts, but the design of the ground station is done, by considering it solely as a software system. This is done because the interface between the different parts of the system lie in software.

HRT-HOOD is hierarchical and uses a top-down approach. It is object oriented, not in the C++/Java understanding of object orientation, but in the way that all tasks/modules are described as objects that provide interfaces for other objects to use. The objects express pieces of code to execute and not data structures (HRT-HOOD doesn't concern itself with the data structures of the software system at all). The design method is based on decomposing the complete system into a number of objects. These objects can then again be analyzed and decomposed into smaller objects. This hierarchical decomposition continue until a sufficient amount of subdivision is achieved. The concept of breaking down a system into smaller, more manageable, subsystems, is a common base for almost all system design methods. What is special about HRT-HOOD and the reason for choosing it, is that it provides a framework for graphically representing the objects and their relations.

4.3.1 Usage in This Project

The design life cycle of HRT-HOOD is shown in figure 4.2 on the next page. It starts out with the requirements specification, after which the logical architecture design is done. It is here, the decomposition into objects is done. The physical architecture design maps the designed system onto the platform (hardware and kernel) available. Schedulability analysis is performed to analyze if the platform is sufficiently powerful for the job. Detailed design and coding follows, implementing the software. At last HRT-HOOD specifies that testing should be done. As with all software design methods, a perfect design cannot be made the first time, so some iteration between the design stages is to be expected, as shown by the arrows to the left in figure 4.2 on the following page.

In this project, the HRT-HOOD design life cycle is not used as described above. The decomposition is started below to specify which subobjects should be constructed and the interface between them. Only a first level decomposition is performed here.

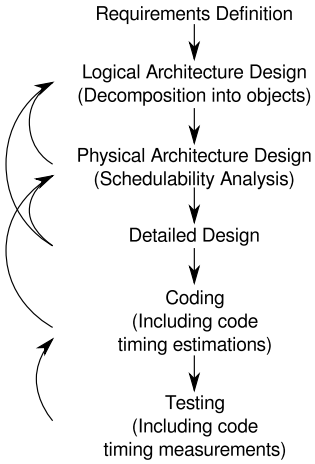


Figure 4.2: *Life cycle of the HRT-HOOD design method. [13]*

When designing and implementing the individual subobjects, the objects are further decomposed. After this, no physical architecture design is performed, instead detailed design and coding of the subobjects is done. Hereafter measurements of the execution time of the code, is used to perform an schedulability analysis, to ensure the system will satisfy the timing requirements set to it. Before constructing the subobjects, an operating system that implements the required multiprogramming facilities must be employed.

4.3.2 HRT-HOOD Objects

An object in HRT-HOOD is represented graphically as shown in figure 4.3 on the next page. Each object specifies it's name, type and the operations that they provide. The operations of an object make up the interface it provides to other objects. 5 types of objects exists, each describing when the code of the object is executed. These are as follows:

A - Active The most general type of object, it has no restrictions placed on them. May control when invocations of their operations are executed. Can be decomposed into a number of the remaining object types.

P - Passive When invoking an operation on a passive object, it is performed immediately. This effectively corresponds to a call to a method in fx. C, which is also the way these object types are implemented.

Pr - Protected Represents code or data that must be accessed under mutual exclusion.

C - Cyclic Periodic activities that execute irrespectively of whether there are any of it's operations that have been invoked.

S - Sporadic Objects that start executing at arbitrary time instances. These are often started by an interrupt. They have a minimum arrival time associated with them, specifying the maximum rate at which they occur.

Having mentioned the different object types, the relations between objects can be explained. There are many different types of "execution requests" in HRT-HOOD, each describing a way one object can invoke an operation of another object. Here, only these will be mentioned and used:

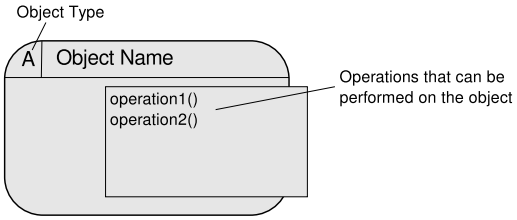


Figure 4.3: *Graphical way of representing a HRT-HOOD object. [13]*

ASER - Asynchronous Execution Request When an operation is invoked by an ASER, the caller is not blocked, but continues to execute. The execution request is noted and performed by the called object at some later time.

ASER_BY_IT - Asynchronous Execution Request from Interrupt Same as ASER, but is invoked by an interrupt, either via a synchronizing semaphore or directly as an interrupt handler.

HSER - Highly Synchronous Execution Request The calling object is blocked until the requested operation has been completed. Effectively a regular call to a method in C.

PSER - Protected Synchronous Execution Request The same as HSER but invoked on a protected object, which means the calling task will be additionally blocked if another object is using the object.

Data flow between objects is represented by an arrow (○→) labeled with a brief description of the data. There exists rules concerning which object types can include which objects and which relations can exist between each object type, for more info, see [13].

4.3.3 Decomposition of Ground Station Software into Objects

The ground station system basically has three natural objects:

- Control the position of the antenna, based on either GPS data from the CanSat or a manual specification of the position from the user.
- Handle the data received from the CanSat and send commands to it, based on the specifications in the WARP protocol.
- Handle the TCP/IP/Ethernet connection to the RUC, which basically means implementing a stack of handlers for the protocol layers used by the link:
  - Interface to the ENC28j60 Ethernet controller and handle Ethernet level packages.
  - Handle the TCP- & IP protocol layers.
  - Receive and send packages in compliance with the RUC protocol.

These 3 objects are shown in figure 4.3. They are all active objects, that thus can be broken down into a number of smaller objects. It can be seen that, sending a package on the RF CanSat link or to the RUC through Ethernet, is done as asynchronous execution requests, ie. the transmission of the package is queued and then performed whenever the link is ready for the transmission. Upon reception of a package in one of the two links, the package is decoded and the required action is performed immediately by performing synchronous calls to the antenna controller or ASER's to send package on the other link. For example, reception of telemetry data from the CanSat would result in an ASER to the Ethernet & RUC protocol object, asking it to forward the received data to the RUC.

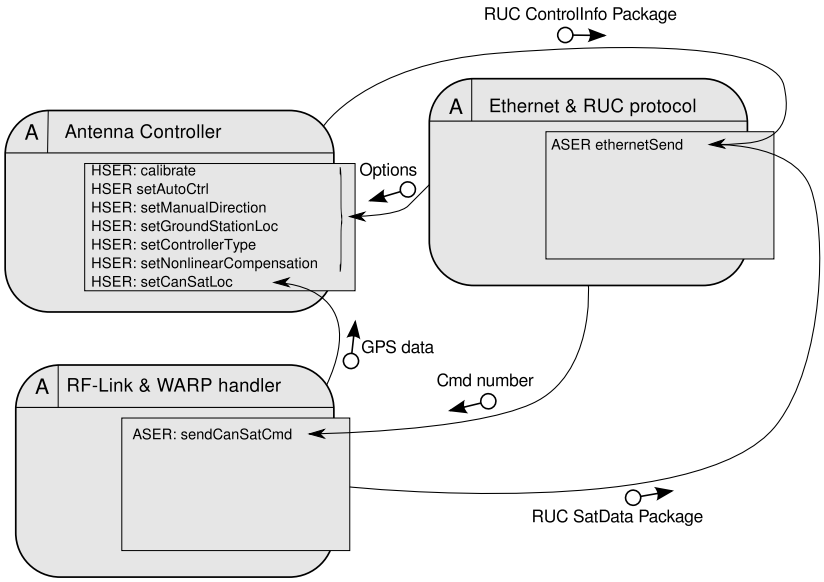


Figure 4.4: *RT-HOOD Logical Architecture Design of the Ground Station*

Summary

Above, the basic platform for constructing the ground station system has been chosen. Also, the overall structure of the software to be executed on the ground station has been designed. This allows for each ground station subsystem to be designed in detail and implemented independently. The interface between the RUC and ground station is the application level protocol used on the TCP/IP connection between them. This protocol has been specified as well, which allows for the RUC and ground station to be developed in parallel.

CHAPTER 5

Real Time Operating System

To implement the system described in chapter 4, a real-time multi-tasking operating system is required. Real-time means the ability to fulfill strict timing demands e.g. reacting to incoming events before a certain deadline. A multi-tasking environment introduces concurrent execution of different tasks from the programmer's point of view, which supports the HRT-HOOD design paradigm well. This chapter regards the design and implementation of the operating system tailored for this project. Overall the system must have the following features:

- *Concurrent (pseudo parallel) execution of several prioritized tasks.*
- *Synchronization and message passing between tasks.*
- *Scheduling and execution of periodic tasks.*

The operating system in this project is dubbed ARTOS, which is an acronym of ARM Real-Time Operating System. Throughout this chapter the design and inner workings of ARTOS will be discussed. The chapter ends with a verification test of the operating system's functionality.

5.1. System Calls

System calls (or syscalls) represents the interface between user programs and the operating system. In ARTOS there are 14 different system calls, which are shown in table 5.1 on the next page. These are supposed to give an overview of the different features of the OS. The prototypes for these functions are located in "os.h" in the ground station source code found on the CD [1]. See appendix E on page 139 for more details of the prototypes and their arguments. The implementation of the OS is found in "os.c" and some low-level routines are written in assembly and can be found in "os.S". Reference documentation for the ground station software is generated with the Doxygen documentation tool, and can be found on the CD [2].

In order to describe how system calls are processed, we need to look into the different execution or processor modes of the hardware platform. The ARM architecture supports seven different processor modes as shown in table 5.2 on the next page. All modes except user and system mode are exception modes, which means they are entered on

[1] `/groundstation`
[2] `/groundstation/doc/`

Number	Syscall name	May block
0	`osTaskCreate`	
1	`osTaskTerminate`	
2	`osWaitForDivisibleTick`	Yes
3	`osEnterCritical`	
4	`osLeaveCritical`	
-	`osSemInit`	
5	`osSemDown`	Yes
6	`osSemUp`	
-	`osSemUpFromIsr`	
-	`osQueueInit`	
7	`osQueueRead`	Yes
8	`osQueueWrite`	Yes
-	`osQueueReadFromIsr`	
-	`osQueueWriteFromIsr`	

Table 5.1: *Syscalls provided by ARTOS. A system call is issued by loading the number into R12 and generate a software interrupt. Some system calls does not require a transition to supervisor mode and have therefore no syscall number*

Processor mode	Description
User	Normal program execution mode
Supervisor	Protected mode for the operating system
FIQ	Fast Interrupt Request
IRQ	General-purpose interrupt request
Abort	Implements memory protection
Undefined	Supports software emulation of hardware coprocesssor
System	Runs privileged operating system tasks

Table 5.2: *ARM architecture processor modes [14]*

exceptions. All the exception modes have some banked registers, which means that some of the user/system mode registers are replaced with registers that are only accessible in the specific exception mode. User mode is the only unprivileged mode, which means some instructions are not available. When the user mode program issues a system call, the R12 register is loaded with the corresponding system call number, and then a software interrupt is generated. This puts the processor into supervisor mode, where interrupts are disabled. The operating systems performs the system call and may enter system mode to access all the user mode registers. Some system calls doesn't require a transition from user to supervisor mode. They are implemented as regular functions and therefore have no syscall number. Many system calls are implemented in assembly for performance reasons. It is important to spend as little time as possible in supervisor mode, in order to not miss any interrupt requests.

Notice that there are no system calls for dynamic allocation of memory. It is preferred to statically allocate buffers in the ground station system, because the tasks to be done are known in advance and it makes the system more deterministic.

The `osWaitForDivisibleTick` is the only way to create cyclic tasks within ARTOS. This syscall takes a 32 bit bitmask as argument. The syscall will block until the mask bitwise ANDed with the system tick counter is zero. As an example the mask is `0b11` and `OS_SYSTICK_TIME` is 8 ms, which mean the system tick counter is incremented by 1 for every 8 ms. The caller will be unblocked when the two least significant bits of the system tick counter is 0. This happens every $4 \cdot 8$ ms. The periodic task will

then look like this:

```
for(;;){
    osWaitForDivisibleTick(0b11);
    <Work that takes less than 32 ms>
}
```

The masked approach enables the implementation of periodic tasks to be efficient and precise. A conventional `sleep` function would not take into account the time it takes for the periodic code to execute or that it may take some time before the execution of the code is begun.

Many of the system calls will put the calling task into a blocking state. When returning from supervisor mode, the processor will then resume execution of another task in user mode. This leads to the following discussion of multi-tasking.

5.2. Multi-tasking

Multi-tasking is a way of sharing computational resources among different tasks, so they are executed concurrently from the programmers point of view. The operating system is the resource manager. The simplest form of multi-tasking comes with the introduction of hardware interrupts. It is then possible to react on interrupts quickly in the interrupt service routine (ISR) and pass on time consuming work to the main program. This concept is taken to the next step in a multi-tasking operating system, where the workload is passed between tasks in the main program as well. In modern operating systems, there is usually two types of tasks, divided into processes and threads. The main difference is most often that threads share their memory space and processes do not. In ARTOS there is only one memory space, since the hardware platform does not have a memory managing unit (MMU). Thus there is only one type of task in ARTOS. Each task is represented in memory by a task descriptor:

```
struct taskDescriptor {
    struct taskDescriptor *nextTask; /* Pointer to the next task */
    int32_t context[17];        /* Saved task context (R0..R14, SR, PC) */
    uint32_t priority;          /* Priority of the task */
    void * stackBase;           /* Lowest address in stack */
    uint16_t stackSize;         /* Stack size in bytes */
};
```

The task descriptors are allocated by the user mode programs, which means the OS supports an arbitrary number of tasks. Every task has its own stack space, which is also provided by the user mode program. The programmer must assure that a task never uses more stack space than is assigned to it or the whole system will have unpredicted behaviour. There is no stack overflow detection in ARTOS. Stack overflow detection in a MMU-less system could be implemented by putting a known value at the top of the stack and then do periodic checks to see if the value has been overwritten. This technique is used by the real-time operating system FreeRTOS[15].

A task can be in three different states as shown on figure 5.1 on the following page. Only one task can be in running state. When a task leaves the running state, all the current registers will be saved in the task descriptor's context array. When a task reenters the running state, the registers will be reloaded from the task descriptor. The transition to blocked state can only happen on syscalls e.g. performing a read request on an empty queue. When the resource becomes available, the task will go to the ready state and the scheduler will pick the task with the highest priority, which will become the running task.

Notice that there are no state information in the task descriptor struct and there are no "process tables" in the OS. The state of a task in ARTOS depends on which linked list the task is a node of. This is what the `nextTask` pointer is used for. A task can appear

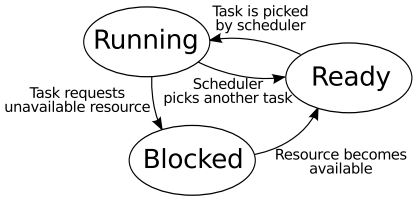


Figure 5.1: *Tasks can be in three different states. Transitions between the states are triggered by different events as shown.*

in only one single linked list at a time. There is a ready list for each priority in the system. Linked lists of blocked tasks occur in the semaphore and queue structs as well as the `divisibleTickList`, which consists of tasks waiting for a divisible tick. Furthermore the global variable currentTask points to the currently running task. Table 5.3 shows the different lists of task descriptors. An alternative to the decentralised linked list approach

List name	Task state	Note
currentTask	Running	Only one task
readyLists[OS_NUM_PRIORITIES]	Ready	Number of lists depends on number of priorities in OS
divisibleTickList	Blocked	Waiting for divisible tick
(struct queue).blockedTasks	Blocked	Blocked to read or write
(struct semaphore).blockedToDown	Blocked	Blocked to down a semaphore with value 0

Table 5.3: *In ARTOS the task descriptors always occur in linked lists. Each queue and semaphore contains a linked list of blocked task descriptors.*

could be to have a central fixed size process table within the OS. This solution makes good sense on hardware platforms with protected memory capabilities, so that user mode programs can't change the task descriptors. As protected memory is not available on the used hardware platform, the decentralised solution wins on its flexibility.

The operating system creates two tasks on startup. The priority 0 task is the idle routine, which is run when no other task wants to run. If the preprocessor variable `OS_SLEEP_ON_IDLE` is defined, the idle routine will put the CPU into idle mode, which removes the clock signal to the CPU core to save power, but keeps the peripherals of the LPC2138 powered. The CPU will wake up on interrupts. Sleep on idle is disabled by default, because it will turn off the JTAG debugging interface as well. It should be considered whether using idle mode increases the interrupt latency, but the LPC2138 user manual[10] provides no information on this issue. The operating system creates a priority 1 task as well, which will run the `main()` procedure. This is the starting point for user mode programs.

5.2.1 Inter-task Communication

When having several concurrently running tasks, they need a way to communicate. As all tasks are executing in the same memory space, the simplest form of communication is by reading and writing to the shared memory. This will lead to errors though, when two tasks are working on the same memory "simultaneously". In order to ensure only one task is working on a shared variable, one can use a critical region, basically by disabling interrupts, before working on the variable. This ensures that no other task gets to run until the task has left the critical region. ARTOS supports critical regions with the `osEnterCritical()` and `osLeaveCritical()` syscalls. The major drawback

of this solution is that interrupts may be missed if too much time is spend inside critical regions. Therefore more sophisticated inter-task communication techniques are needed.

In ARTOS there are two primitives for inter-task communication, which have already been mentioned: Semaphores and queues. Semaphores provides a more elegant solution to mutual exclusion than the disabling/reenabling of interrupts, though the overhead of semaphores is a bit higher. A semaphore used for mutual exclusion will be initialized with the value 1. A task will down the semaphore before entering a critical region, setting the semaphore to 0. When any other task tries to down the semaphore, it will be blocked and be added to the semaphore's `blockedToDownList`, until the running task leaves the critical region by upping the semaphore value. Another use of semaphores is synchronization between tasks. For example an interrupt service routine could up a semaphore to signal a task, that an I/O device has become ready. Queues have a bit more overhead than semaphores, so although they could be used for the same purposes as semaphores, they are especially designed for message passing. The queues in ARTOS are using the FIFO (first in, first out) scheme. All the inter-task communication primitives are used in the design of the Ethernet communication module, which will be discussed in chapter 6 on page 37.

5.3. Fixed Priority Scheduling

The operating system topics discussed until now, are applicable to any multi-tasking operating system. This section will look into the concept of a real-time operating system. A real-time system can be defined as a system, which maps a sequence of real-time events to another sequence of real-time events. A real-time operating system makes it feasible for the programmer to specify an appropriate response to a real-time input sequence[16]. A task in a real-time system is associated with a deadline, which is the instant in time where the task has to be finished executing. Tasks can be categorized as hard real-time if the deadline may never be missed, and soft real-time if the deadline is specified as a mean value, that the task can miss from time to time without fatal consequences, as long as the deadline is met when taking the average of completion times.

Scheduling is the discipline of sharing CPU time between a set of tasks. Scheduling algorithms have different goals depending on which type of systems they are designed for. For some systems maximizing job throughput may be the primary goal. For real-time systems the scheduler's primary goal is to pick tasks in such a way that all deadlines are met[17]. The scheduling scheme can be preemptive or non-preemptive. A non-preemptive scheduler won't pick a new task before the current task releases the CPU voluntarily. This approach is simpler compared to a preemptive scheduler, but it is not well suited for real-time systems with several aperiodic tasks.

Furthermore scheduling algorithms are categorized based on their execution time sharing scheme. The following well known categories exists[18]:

Fixed schedules The schedule is defined pre-runtime; simple, efficient but less flexible.

Round robin Each task is given an equal time slice; simple, flexible, but less efficient.

Fixed priorities Priorities are assigned pre-runtime. The highest priority ready task will run; simple and flexible, but medium efficiency.

Dynamic priorities Priorities are assigned based on runtime parameters e.g. earliest deadline first; complex, flexible and efficient.

Within the prioritized schemes, effort goes into assigning tasks the most optimum priority. This requires characterization and analysis of each task, which will be done in chapter 11. The scheduler scheme chosen for ARTOS is fixed priority, because of its

simplicity over dynamic priorities. This requires the scheduler to be able to do preemption. Preemption happens when a higher priority task becomes ready. Furthermore the scheduler can be configured on compile-time to do round robin scheduling between tasks of the same priority, by setting the preprocessor variable `OS_SYSTICK_RESCHEDULES`. This will make the timer interrupt handler reschedule on every tick. Otherwise switching between equal priority tasks will only happen when the task runs to completion. This way is preferred and used on the ground station, because it is wanted to let the current task run to completion, when no higher priority task wants to run, without doing unnecessary context switches. The number of priorities is set at compile-time.

5.4. Verification

As the operating system provides the base for the rest of the software, it is important that the programmer can rely on its functionality. The reliability is tested through verification tests. During development a lot of ad-hoc tests have been performed to test specific features. Furthermore four formal tests have been constructed:

1. Critical regions by disabling/enabling interrupts. Two equal priority tasks prints to the serial port in a critical region.
2. Mutual exclusion by the use of semaphores. Two equal priority tasks prints to the serial port in a critical region as in the last test, but this time the critical region is implemented by the use of semaphores.
3. The creation of periodic tasks and the use of semaphores for task synchronization. One task uses the `osWaitForDivisibleTick()` system call to run periodically. When executing it signals another task by the use of a semaphore. Both tasks prints to the serial port when executing.
4. The use of queues in a producer/consumer situation. One high priority producer task writes 10 values into a queue with the capacity of only 4 values. The consumer task continuously reads values out of the queue in order to make room for all the producer values. Each task prints the value read/written to the serial port.

Each test consists of a C-file that replaces the original main file. The files can be found on the cd [3]. Each file contains a brief description of the test and the expected result. Run the test by replacing "main.c" file in [4] by the test file and compile as described in the comment at the top of the file.

The operating system has passed all the tests and is thus considered to be working and fulfilling the originally defined requirements.

Summary

The preemptive operating system ARTOS has been designed and tested. It only provides the kernel of an operating system and is used as a platform for the further development of the ground station system software. The operating system's feature highlights are semaphores, message queues, periodic task execution and a fixed priority scheduler. The features of the system are utilized by the other software modules.

[3] `/tests/ostests/main.c.test<#>`
[4] `/groundstation/src`

CHAPTER 6

Wired Communication with Remote User Client

This chapter is about the design and implementation of the "Ethernet & RUC protocol" block shown in figure 4.4 on page 30. The following requirements from the requirements specification is directly related to this module:

- *Requirement 2. Must implement and adhere to TCP/IP and Ethernet protocols.*
- *Requirement 3. No more than* 200 ms *may pass from a package is received on the ground station's wireless link, until the processed package containing this information, is sent to the RUC, if this is connected through a direct Ethernet cable.*

First an overview of the used hardware and software is introduced. This is followed by a discussion of the implementation of the TCP/IP stack software. In the end of the chapter, the maximum data throughput of the network link is tested.

6.1. Overview

An additional requirement to the module is the minimum TCP data byte stream throughput, which is estimated from the following worst-case scenario:

- The longest RUC package that can occur is of the type pkgSatData, which contains telemetry data from the CanSat. The maximum package size is 158 bytes. In this scenario this package is sent at a rate of 10 Hz and is byte stuffed to 310 bytes.
- The controller info RUC package pkgControlInfo is sent at a rate of 125 Hz, contains 16 bytes but is byte stuffed to 32.

The total required throughput is thus 7100 $\frac{B}{s}$.

The TCP/IP protocol stack is shown in figure 6.1 on the following page with the layer names used in RFC1122[19] from the Internet Engineering Task Force (IETF). The application layer protocol is the RUC protocol specified in appendix C on page 135.

The hardware used by this module is the LPC2138 microcontroller, communicating with the Ethernet controller Microchip ENC28J60 through the SPI (Serial Peripheral Interface) bus. The Ethernet controller provides the physical layer and some parts of the link layer. The implementation of a full TCP/IP protocol stack is outside the scope

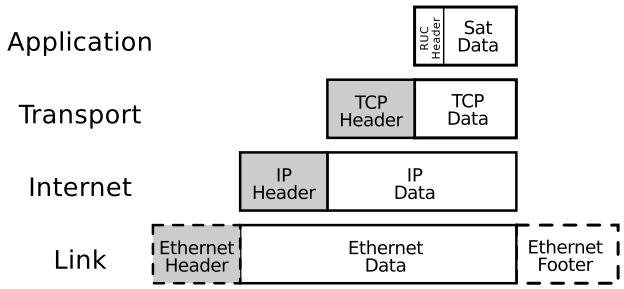


Figure 6.1: *TCP/IP Layer Model and the corresponding encapsulation of application data. The grey boxes are provided by the uIP library and the dashed boxes are provided by the Ethernet controller.*

of this project. Instead the open-source TCP/IP stack, called uIP, has been ported to the platform. The library supports IPv4 and ARP (Address Resolution Protocol) and is designed for embedded microcontrollers. See the author's homepage[20] for detailed documentation. This library provides the boxes marked with grey in figure 6.1. The Ethernet module software is structured into several tasks within ARTOS. In the following sections, the design considerations around the Ethernet communication module are discussed.

6.2. Ethernet Controller

The ENC28J60 Ethernet controller provides the MAC sublayer as well as a 10Base-T physical layer. Instead of going through all the technical internal details of the chip and the procedure for setting up the 128 internal registers, only the important features will be outlined here. The details can be found in the datasheet[21]. The most important features are:

- Supports full and half-duplex modes (configured for half-duplex).
- Automatic retransmit on collision and automatic rejection of erroneous packages.
- Automatic generation of preamble, CRC checksum and padding for Ethernet frames.
- SPI interface with clock speeds up to 20 MHz. Runs at maximum speed of LPC2138 (7.4 MHz).
- Programmable receive packet filtering based on Ethernet packet addresses.
- Configurable 8 kB transmit/receive FIFO buffer.
- One interrupt output pin (connected to EINT0 of LPC2138).
- Two configurable LED outputs for PHY chip status indication.

The Ethernet controller is configured to discard Ethernet frames with a different destination MAC address than the one assigned to the controller. An Ethernet frame is shown in figure 6.2 on the next page. The Ethernet controller will automatically generate the preamble and Start Of Frame byte as well as the padding and checksum. The address fields, length and data must be filled in by the software at higher layers. ENC28J60 contains three types of memory:

- Control Registers.
- Transmit/receive buffer.

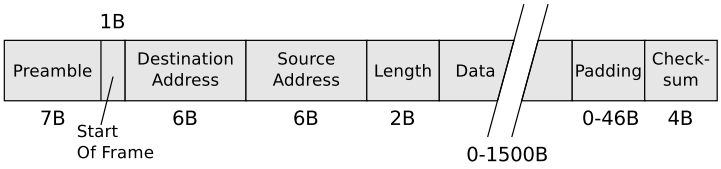


Figure 6.2: *IEEE 802.3 standardized Ethernet frame format[22]*

- PHY registers.

The PHY registers are accessed through the control registers and are used for configuring the PHY module. The transmit/receive buffer contains the actual data to be transmitted and the data received from the network. The buffer is divided into a configurable receive and transmit area. When the microcontroller has a packet ready, it is transferred via SPI to the transmit area of the buffer and some control registers are programmed with the start and end address of the packet. The transmission process is started by writing to another register.

The buffer's receive area works like a circular FIFO buffer. The chip is configured to assert the interrupt pin, whenever there are unprocessed packets in the buffer. The first two bytes of the packets, written to the receive buffer, is a pointer to the start of the next packet. In that way the Ethernet controller's receive buffer can contain several unprocessed packets structured as a linked list. If the receive buffer gets filled up, any incoming packages will be discarded. The microcontroller must free the receive buffer space, by setting a special read pointer within the receive area, and decrement the count of pending packages by writing to one of the control registers.

The device driver for the ENC28J60 Ethernet controller can be found on the CD [1] and has the following function prototypes:

```
void encInit(void);
uint16_t encReceivePacket(uint8_t *buf, uint32_t length);
void encTransmitPacket(const uint8_t *buf, uint32_t bufLen);
void encRegDump (void);
uint8_t encReadIrqFlags(void);
void encSetBank (uint8_t bank);
uint8_t encReadOp (uint8_t operation, uint8_t address);
```

6.3. Integrating the uIP TCP/IP Protocol Stack

The uIP TCP/IP protocol stack software implementation is designed to be compatible with tiny 8-bit microcontrollers without operating systems. In this section it is discussed how this library can be integrated into the ground stations operating system. As a reference, the uIP documentation provides an example main loop, which is polling uIP and the device driver continuously. See appendix D on page 137 for the example. The polling wastes a lot of CPU cycles. In this section a more efficient structure is found by utilising several tasks, but in order to do this a brief analysis of the uIP implementation is required.

Because uIP is targeted at small microcontrollers, some limitations exists in order to keep the memory footprint small. One statically allocated buffer (`uip_buf`) is used for all packets, which implies that only one Ethernet packet can be outstanding at any time. For example, uIP can't send a new TCP package until the last one has been acknowledged. The size of the buffer determines the maximum TCP segment size supported. This size is limited by the maximum size of IP packets sent over Ethernet, which is 1500 bytes as

[1] `/groundstation/chips/enc28j60.<c,h>`

stated in RFC894[23]. The ground station will act as a TCP server, and in order to keep things simple, only one TCP connection is supported, although uIP can be configures to support multiple connections.

6.3.1 Communicating with uIP

The communication between uIP and the layers around it, mainly goes through the global variables `uip_len` and `uip_buf`. The variable `uip_len` contains the number of currently valid bytes in the buffer. The device driver will never be called by uIP itself. Instead the value of `uip_len` will be set to a non-zero value after the invocations of some uIP functions, to indicate that data is ready to be sent to the Ethernet controller. On the contrary, uIP will call the user-defined function `appcall()`, when some event is relevant for the application layer. When the `appcall()` is invoked, uIP has set some global flags, which can be checked inside the `appcall()` in order to find out why the invocation happened e.g. `uip_connected()`, `uip_newdata()`, `uip_acked()`. For clarification, the following example goes through what typically happens in the main loop, shown in appendix D on page 137, when a new Ethernet frame arrives:

1. `encReceivePacket()` copies the frame from the Ethernet controller to `uip_buf` and `uip_len` is set to the number of bytes read.
2. The frame contains an IP packet, so `uip_input()` is called from the main loop.
3. The packet is processed by `uip_input()` and identified as a TCP data packet. The `newdata` flag is set by uIP and `appcall()` is invoked.
4. The application checks the `newdata` flag and reads out the data from `uip_buf`. In this example the data is a new elevation angle for the antenna controller, so the application sets a global variable in the controller and returns control to uIP.
5. Back in the `uip_input` function a TCP ACK packet is now written into `uip_buf` and `uip_len` is set to the length of the new package. uIP returns to the main loop.
6. The main loop checks the `uip_len` variable, which is non-zero, thus a call to `encTransmitPacket()` is made.
7. The TCP ACK packet is copied to the Ethernet controller and send.

The call graph for this particular example is shown in figure 6.3 on the facing page. Note however that an invocation of `uip_input()` not necessarily generates an invocation of the application function `appcall()` e.g. if the incoming IP packet was an ICMP (Internet Control Message Protocol) packet used for Pinging.

6.3.2 Structuring into Tasks

Instead of using the mainloop polling reference implementation just mentioned, the uIP processing is structured into three different tasks. The processing of incoming Ethernet frames from the Ethernet controller can be put into a task of its own. The task will be sporadic and triggered by the interrupt output of the Ethernet controller. The task is named `encIrqHandlerTask` and is shown in HRT-HOOD diagram in figure 6.4 on the next page. The task is synchronized with the interrupt service routine through a semaphore (`encIrqSyncSem`).

The main loop in the uIP example main loop has one more operation to do. It periodically calls `uip_periodic` every 0.5 s and `uip_arp_timer` every 10 s. This enables uIP to clean up it's ARP table from time to time and decide when to retransmit TCP

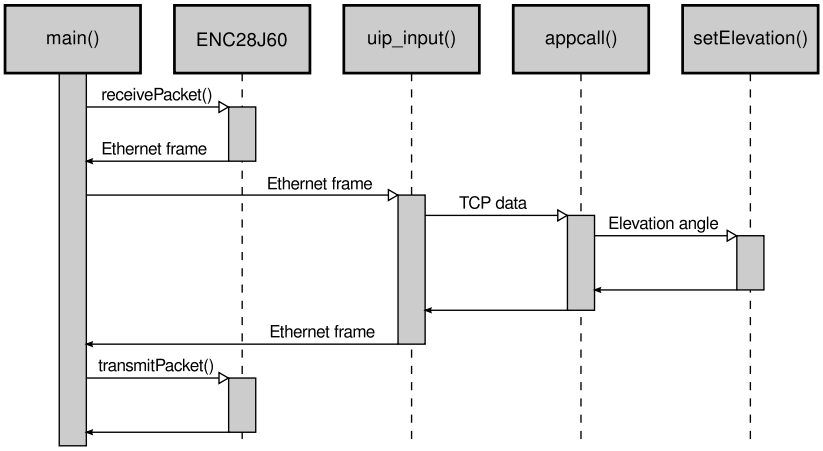


Figure 6.3: *Example uIP call graph on incoming Ethernet frame illustrated as an UML sequence diagram.*

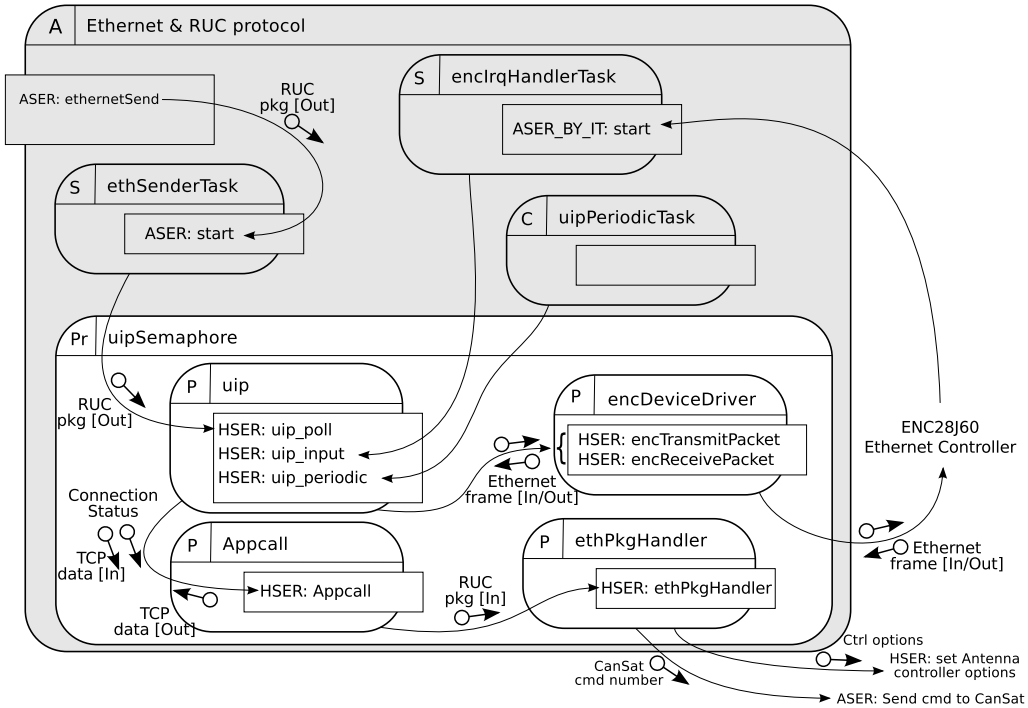


Figure 6.4: *HRT-HOOD logical architecture design of the Ethernet communication software module. Three tasks (the grey boxes) access the uIP data and functions protected by mutual exclusion with the* `uipSemaphore`*. The circles shows data flow, labelled with type of data and origin ([In] means the data is coming from the Ethernet, and [Out] means the data eventually will be sent through the Ethernet).*

packets. The functionality is structured into a periodic task called `uipPeriodicTask`, as shown in figure 6.4.

A third task is added to the Ethernet communication module, which is responsible for sending RUC packages to the remote user client. Because of the nature of uIP, applications are only allowed to send TCP stream data, when the `appcall()` is invoked with the correct flags set. In the used implementation, data is only sent when the `uip_poll` flag is set, which means that the connection has no outstanding packages. The `ethSenderTask` shown in figure 6.4 will actively call `uip_poll_conn()` whenever outgoing RUC packages are pending and the connection has no outstanding TCP packages. The task is notified by `encIrqHandlerTask` through a synchronization semaphore (`ethCtsSem`), when there are no outstanding TCP packages. The semaphore is not shown in the figure for simplicity. The outgoing RUC packages are transferred to the `ethSenderTask` via a queue, a system that will be described in further detail in the next section.

The three Ethernet tasks access the uIP library under mutual exclusion. For this purpose `uipSem` is used. To prevent deadlocks no blocking calls are made within the critical region protected by `uipSem`.

6.3.3 Queueing and Assembling of RUC Packages

The `ethernetSend()` operation request is an asynchronous execution request. This can be accomplished in practice by the use of a queue, that contains the outgoing packages. To avoid a lot of data copying, only pointers to the packages are written into the queue. This requires a memory allocation system, so that the Ethernet communication module can free the memory used by the packages, when the packages have been successfully sent. A simple memory allocation system has been implemented in the file "helper.c". 80 buffers with the fixed size of 158 bytes, which is the maximum length of a RUC package, has been statically allocated. A pointer to each buffer is put into a queue, `bufFreeQ`. A buffer is dynamically allocated by reading out a pointer from the queue, and freed by writing it back. This system is fast, simple and generates no memory fragmentation. The disadvantage is that it becomes memory inefficient when sending a lot of small packages. Note that the allocation system is only used for packages.

When the `ethSenderTask` shown in figure 6.4 manages to trigger an `appcall()`, several RUC protocol packages may be queued up in the Ethernet queue. Each RUC package can be small in size and it would be inefficient to send an Ethernet packet for each RUC packet. In the `appcall()` the RUC packages are byte stuffed as defined in the RUC application layer protocol and put together into a single TCP data section, before returning control to uIP. The buffers that contained the RUC packages will be freed as soon as the TCP segment has been acknowledged.

Receiving RUC Packages

The buffer system is not used for receiving packages from the remote user client. Since TCP provides a byte stream to the application layer, a single RUC package sent from the remote user client, may be split into several TCP segments. When the ground station is receiving the TCP data, it will remove the stuffing bytes and assemble the data into a single RUC package within the `appcall()`. When a whole application layer RUC package has been received, a call will be made to the function `ethPkgHandler()`, which interprets the content of the package and calls the other software modules, passing on the settings from the package. This is illustrated in figure 6.4 on the preceding page by the arrows leaving the Ethernet software module.

6.4. Maximum Throughput and Verification

The design of the Ethernet communication module has now been discussed. A verification test will determine if it fulfills the requirements specified. Initial tests have shown that TCP throughput decreases significantly when using large TCP segment sizes. This is due to the delayed acknowledgement (ACK) algorithm described in RFC1122[19], which is activated by the receiving PC when the TCP segment size is approaching the maximum segment size. The delayed ACK algorithm implemented by most TCP receivers means[24]:

1. ACK must be generated within 500 ms of the arrival of the first unacknowledged packet.
2. ACK should be generated for at least every second full-sized segment.
3. Since receiver and transmitter might not agree on the size of a full-sized segment, it is recommended that an ACK is generated for every second segment in order to avoid stretched ACKs.

The delayed ACK algorithm enables the receiving application to update the receive window and send an immediate reply without generating multiple TCP segments[19]. Since uIP can have only one outstanding Ethernet frame at a time, the ground station will wait for up to 500 ms plus the round-trip-time before sending a new TCP segment, when the delayed ACK algorithm is activated. Obviously a packet rate of 2 Hz and an Ethernet frame size of maximum 1500 B will cause a poor throughput rate.

The theoretical maximum throughput for uIP is:

$$r = \frac{S}{t_{\mathrm{rtt}} + t_{\mathrm{d}}} \tag{6.1}$$

where:

r	is the maximum throughput	$[\frac{\mathrm{B}}{\mathrm{s}}]$
S	is the segment size	[B]
t_{rtt}	is the round-trip-time of the network link	[s]
t_{d}	is the delay before an ACK is generated by the receiver	[s]

There are two solutions to the delayed ACK problem applicable to uIP. The first solution is to split maximum sized segments into two segments and wait for the acknowledgement. This solution is made available by the author of uIP by a module named "uIP TCP throughput booster hack." Since this solution adds more complexity and the required throughput is relatively low, a simpler solution has been chosen. The maximum TCP segment size has been set to 510 bytes, which prevents the delayed ACK algorithm from kicking in on the hosts tested. It should be noticed however, that the result may vary between different TCP implementations.

Equation 6.1 implies that the throughput of uIP will suffer greatly from delays in the network link. The estimated worst case throughput requirement outlined in the beginning of this chapter was 7100 $\frac{\mathrm{B}}{\mathrm{s}}$. Say the average segment size is 400 due to only an integral number of RUC packages will be assembled into a single segment, solving equation 6.1 for $t_{\mathrm{rtt}} + t_{\mathrm{td}}$ yields:

$$t_{\mathrm{rtt}} + t_{\mathrm{d}} = \frac{400}{7100} = 0.056\,\mathrm{s} \tag{6.2}$$

The maximum tolerated delay in the network is thus around 56 ms.

6.4.1 Throughput Test

A throughput test program has been created, which will continuously fill the outgoing Ethernet buffer with RUC packages with the size of 42 bytes (arbitarily chosen size to represent RUC package size under typical usage). The test program can be found on the cd[2]. The ground station is connected to the laboratory network of AAU (lab.es.aau.dk) and a PC is connected to the wired network of AAU. Ping packets give a round-trip-time of 2.2 ms in average. The PC establishes a TCP connection to the ground station through Telnet and the traffic on the Ethernet link is captured by the network analysis tool Wireshark. Data is captured for 200 s. The capture file can be found on the cd [3]. Figure 6.5 shows the throughput during the test and the ACK delay from the PC receives a TCP packet until an ACK is generated. Only bytes in the TCP data section is counted as throughput. Each packet sent contained 473 TCP data bytes. The figure

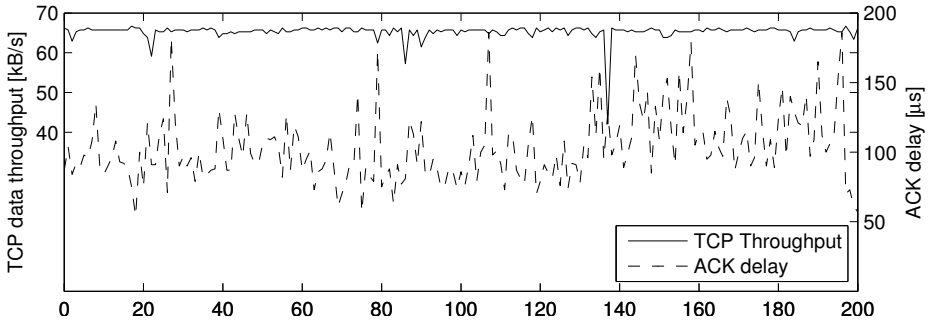


Figure 6.5: *Throughput and ACK delay for the communication between ground station and a PC*

shows an ACK delay of less than 200 μs, which won't be the bottleneck of the connection. A throughput of 65 $\frac{\text{kB}}{\text{s}}$ is achieved, which is sufficient to fulfill the requirement of 7.1 $\frac{\text{kB}}{\text{s}}$ derived in the beginning of this chapter.

Summary

A functional lightweight TCP/IP stack has been designed and implemented using the uIP TCP/IP library and the ENC28J60 Ethernet controller. This provides the link, internet and transport layers on which the RUC application layer protocol is implemented. The execution of uIP has been structured into three tasks. The maximum throughput has been tested under good circumstances and was found to be 65 $\frac{\text{kB}}{\text{s}}$. The maximum total delay in the network under which this implementation is still able to deliver a throughput of 7100 $\frac{\text{B}}{\text{s}}$ (worst case estimate of required throughput) was found to be 56 ms. The weakness of uIP is the inability to cope with more than one unacknowledged Ethernet frame at a time. This makes the throughput prone to delays in the network.

The maximum delay requirement (requirement 3 from the requirement specification) has not been tested, because it heavily depends on the way the tasks are scheduled. The scheduling analysis is performed in chapter 11 on page 105 and the requirement is tested in the acceptance test in chapter 12 on page 117.

[2] `/tests/ethtest/main.c`
[3] `/tests/ethtest/wireshark.cap`

CHAPTER 7

RF Communication with CanSat

The ground station has to communicate with the CanSat over a wireless link. This link should be fairly reliable, even though some bit errors in the transmission can be accepted. The checksum present in packages sent over the link (WARP protocol packages) will enable detection of any errors and erroneous packages will be discarded. The design of the RF communication is done in cooperation with other groups who are creating CanSats, to enable the ground station to work with these CanSats later on. The requirement specification mentions the following, which has relevance for the connection link:

- *Requirement 1. Must implement and adhere to the WARP protocol.*
- *Requirement 3. No more than* 200 ms *may pass from a package is received on the ground station's wireless link, until the processed package containing this information, is sent to the RUC, if this is connected through a direct Ethernet cable.*
- *Requirement 7. The connection between ground station and CanSat must be able to transmit* 60 byte *packages at a distance of* 1.5 km *with a maximum package loss of* 10 %*. This is assuming that the CanSat and ground station are placed in line of sight, the CanSat is within the antennas half-power beamwidth and the package transmission rate is* 5 Hz*.*

In this chapter a radio transceiver and antenna for this will be chosen. The available range in this setup will be calculated, to see if it is sufficiently large. Hereafter, the software for the RF communication is designed.

7.1. Basic Setup

It has been chosen to use the RFM12B[11] (based on the RF12B chip[12]) RF transceiver from Hope RF, as the basic building block for the wireless link between the ground station and the CanSat. These modules are very cheap, which makes it affordable for the upper secondary schools that have to build their own CanSats. They are based on Frequency Shift Keying (FSK) and are available for 3 frequency bands: 433 MHz, 868 MHz and 915 MHz. In Denmark, the 868 MHz frequency band can be used without a license[25], so the 868 MHz version is used. Within this band, there are several frequencies, which the RFM12B can use. By selecting a different frequency, multiple pairs of RFM12B can be

connected without disturbing each other. The maximum allowed transmission output of the specified frequency span is limited to 25 mW effective radiated power [25] by danish government regulation. The RFM12B have a maximum output power of 7 dBm = 5 mW [12]. Since the effective radiated power cannot become larger than this, the law is thus obeyed. The RFM12B can be used at different bitrates, up to 125 kbit per second. The higher the bitrate, the higher demand is set to the quality of the link. On the basis of this, the bitrate has been chosen to 19.2 kbit/s. It is noted that, at 19.2 kbit/s, the longest possible WARP package of 302 bytes, including control characters (escape-, start- and stopbytes,) will take the following time to transmit:

$$t = \frac{302\,\text{byte} \cdot 8\,\text{bit/byte}}{19\,200\,\text{bit/s}} = 125.8\,\text{ms} \tag{7.1}$$

This allows for a whole package to be transmitted between the time a new package are ready for transmission, which is every 200 ms. There might be problems if multiple CanSats are airborne at the same time though. This can be solved by having each CanSat - ground station pair use a different frequency band within the 868 MHz band. For this project these specific frequency settings are used:

- Carrier frequency: 860.32 MHz
- FSK frequency variation (df_{fsk}): ±90 kHz

The groups who are building CanSats for use with the ground station, uses the same RF transceiver module. They have chosen to use a whip antenna, consisting of a piece of wire, a quarter wavelength long. As will be investigated below, a directional antenna is needed to be able to receive the signal from the CanSat, as this is fairly low power. For this, a Yagi-Uda style antenna with 6 elements is used[26],[27].

7.2. Link Budget

To determine the range available in this setup, a link budget is calculated. This link budget calculates the available range, by considering how much of the power emitted by the transmitting antenna, which can be collected by the receiving antenna. If the antenna is isotropic, it emits an electro-magnetic field (EM-field) that propagates spherically in all directions. Therefore, the EM-field power density available for an receiving antenna decreases by the square of the distance between the antennas. The danish radio engineer Harald T. Friis formulated this in what has become known as Friis transmission equation. The equation can be found in[28, pp. 95]. Assuming impedance and polarization matching and neglecting losses in antennas, it reduces to:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 \tag{7.2}$$

where:

P_r	is the power delivered to the load at the receiving antenna terminals	[W]
P_t	is the power delivered at the transmitting antenna terminals	[W]
G_t	is the gain of the transmitting antenna, compared to an isotropic antenna	[dBi]
G_r	is the gain of the receiving antenna, compared to an isotropic antenna	[dBi]
λ	is the wavelength	[m]
R	is the distance between the two antennas	[m]

The RFM12B chips can transmit a signal with 4 dBm power[11]. The whip antenna used on the CanSat is assumed to be isotropic, ie. $G_r = 1$ dBi. The antenna used on the ground station has a max gain of 11.5 dBi[26], but it will not always be pointed directly

at the CanSat, and the gain will thus be lower. It is assumed, that the CanSat is always within the half-power beamwidth area of the antenna, ie. $G_t = 11.5\,\text{dBi} - 3\,\text{dB} = 8.5\,\text{dBi}$. The half-power beamwidth is achieved at angles up to 25° to each side of maximum radiation[26]. At launch, the ground station is to be placed at least 400 m from the CanSat, and the CanSat is expected to be launched to a height of approximately 1000 m. Given these data, and noting that the CanSat is not launched and descending in a direct vertical line, the maximum distance is set at 1500 m. Given these data, calculating the power available at the receiving antenna terminals, gives:

$$P_r = \log 10 \left\{ 8.5 \cdot 1 \cdot \left(\frac{\frac{c}{868\,\text{MHz}}}{4\pi \cdot 1500\,\text{m}} \right)^2 \cdot 10^{\frac{4}{10}} \right\} \cdot 10 = -81.4\,\text{dBm} \tag{7.3}$$

where:

c is the speed of light $\approx 300 \cdot 10^6$ $[\frac{\text{m}}{\text{s}}]$

In the calculation, P_t is converted from a value in dBm to a value in mW, which is then converted back to dBm when calculating P_r. The calculation is valid both for sending from CanSat to ground station and for transmission from ground station to CanSat.

At 19.2 kbit/s, the RFM12B module has a sensitivity of −102 dBm, when a BER (Bit Error Rate) of 0.1 % is required[12]. This means that the input power to the RFM12B should be at least −102 dBm, if said BER is to be achieved. Therefore, it can be seen that there is $-81.4\,\text{dBm} - (-102\,\text{dBm}) = 20.6\,\text{dB}$ more power available at the receiver, than what is theoretically required. This value is referred to as the link margin. The above calculation, assumes the following:

- Perfect polarization matching in orientation of antennas. Both the transmitting and receiving antennas are mostly linearly polarized. The way the antenna on the ground station is mounted, makes it horizontally polarized. The orientation of the antenna on the CanSat, will vary during flight. If the two antennas orientation have their polarization orthogonal to each other, then no power will be transferred, while having them parallel to each other will give the result described above.
- Perfect impedance matching between RF transceiver and antenna on the ground station. The antenna used has an impedance of 50 Ω [26], while the transceiver has an impedance of $8.7 - \text{j}\,66\,\Omega$. This will result in some power lost due to the signal reflections in this connection.
- Perfect impedance matching between RF transceiver and antenna on the CanSat. Again, unmatched impedance will cause lower power transmission, due to reflections at the connection between the RF transceiver and antenna.
- No reflections of radio waves, possibly creating destructive interference, which can reduce the received power significantly.
- No loss of power in antennas, ie. 100 % antenna efficiency. Both the transmitting and receiving antenna has losses, which means that some of the power received or to be transmitted, will be lost as heat in the antenna.

All these effects cause the transmission to not always be as good as specified. As was seen above, a link margin of 20.6 dB between required and available transmission power is present, thus allowing for some of the mentioned losses to affect the transmission, and still achieve a usable link.

7.3. Software for RF Communication

The RFM12B RF transceiver can be operated in two modes: FIFO mode and raw mode. In FIFO mode, a byte is transferred to/from the chip over SPI and the RFM12B takes

care of transmitting/receiving the byte. In raw mode, every single bit is received/sent directly on a GPIO pin. It has been chosen to use the tranceiver in FIFO mode. It is possible to have the RFM12B look for a synchronization pattern in the received byte stream. Filling of the FIFO will be disabled until this pattern has been received. The pattern `0x2DD4` is used as this synchronization pattern. Before sending anything, the RFM12B requires a preamble to be sent. This preamble should contain many 0-1 and 1-0 transitions, as it's used to tune receiver frequencies. 3 preamble bytes with the value `0xAA` are sent prior to the synchronization bytes.

The RFM12B hardware FIFO is only 16 bit (2 byte), so when a byte has been transmitted or received, the microcontroller must have handled it before the next byte has completed transmission/reception, otherwise FIFO overflow or underflow will occur. At 19.2 kbit/s, the transmission of 1 byte takes:

$$t = \frac{8\,\text{bit}}{19\,200\,\text{bit/s}} = 416\,\mu\text{s} \tag{7.4}$$

As this is fairly often, it has been chosen to implement the handling of each byte directly in the interrupt service routine servicing the interrupt from the RFM12B chip. This is shown as the sporadic task `rfmIrqHandler` in figure 7.1. The RFM12B module is set to receive the majority of the time, because the WARP protocol specifies time constraints as to at what times the ground station are allowed to transmit. During receival, the ISR handles the removal of start-, stop- and escape characters and collects the received bytes into packages.

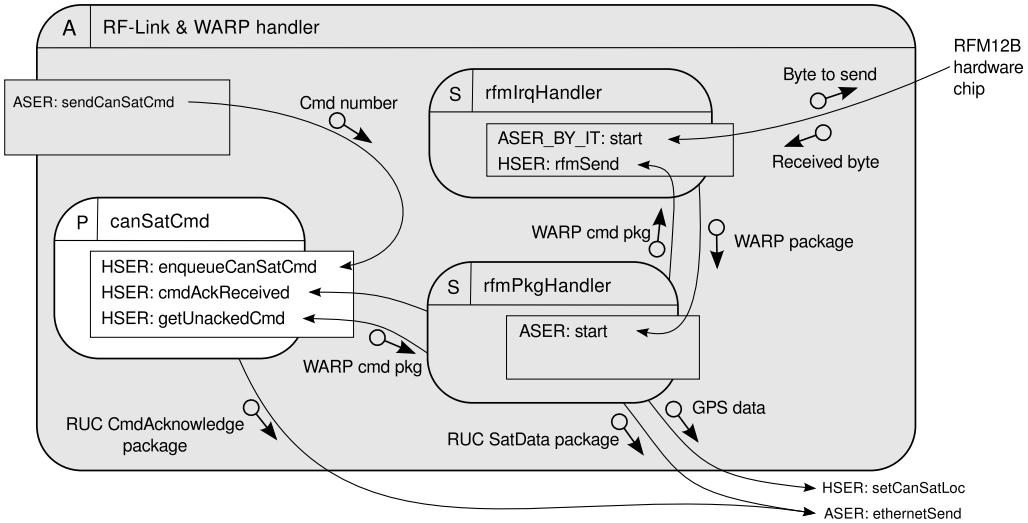


Figure 7.1: *HRT-HOOD analysis of RF and WARP handling software*

Packages that have been assembled by the `rfmIrqHandler`, are forwarded to the `rfmPkgHandler`, which decodes the package according to the WARP specification. If it is a type 0 package, the GPS coordinates are extracted and send to the controller, by `setCanSatLoc`. Hereafter a RUC `SatData` package is built and sent to the Ethernet object for transmission to the RUC. To avoid having to copy the WARP package when sending it between objects, the buffer system described in section 6.3.3 on page 42 is used. This also means that a queue is used for the ASER between `rfmIrqHandler` and `rfmPkgHandler`. Upon reception of the first byte of a package, the `rfmIrqHandler` retrieves a free buffer and fills the package into this. It is filled into the buffer at an offset, so that there is room to build an RUC package "around" it, when the buffer is forwarded to the `rfmPkgHandler` and this has to forward the received WARP package to the RUC.

Commands that are to be sent to the CanSat are saved by the canSatCmd object. Whenever a type 0 WARP package is received, it will contain a bit specifying if the ground station is allowed to transmit a package. If so, the `getUnackedCmd` is used to get the command that needs to be sent (if one such exists). The command is then immediately transferred to the CanSat by the `rfmIrqHandler`. When the command has been transmitted, `rfmIrqHandler` starts receiving bytes again. When receiving an acknowledge of a command sent to the CanSat, the canSatCmd object is informed. This one forwards this information to the RUC. Only one CanSat command can be enqueued for transmission at any given time, thus the RUC should not allow the user to issue multiple CanSat commands.

7.4. Verification

Having designed the wireless communication, it is now to be verified that this communication is working as desired. The transmission of data from the ground station to the CanSat (uplink) is working well, while transmission from the CanSat to the ground station (downlink) doesn't work very well. It has been tested how far uplink transmission is working, as described in journal 1 on page 150. It is seen that a distances up to 260 m, a reliable connection is always available, independent of the orientation of the CanSat antenna. When moving further away, at least some packages can be transmitted (depending on orientation of the CanSat,) until a distance of 400 m is reached. This is not as far as is required (1500 m), so a better antenna or more powerful transceiver module is required.

For downlink, it has not been possible to achieve a link that is usable in practice. In the test of the downlink, also described in journal 1, it was only possible to achieve an acceptable link at distances of up to 3 m, and then correct orientation of the CanSat antenna was required. The orientation where transmission is possible, is when the antenna is held horizontally, which is the orientation where the antennas are polarization matched.

These issues with reception on the ground station can not be explained at this time. It has been tried to use a wire whip antenna similar to the one used on the CanSat, but the reception quality is approximately the same. Another group (group 502, 5. semester EE at AAU, autumn 2010,) who uses the same radio transceivers also with wire whip antennas, doesn't have these issues with reception. It has been shown that the uplink connection is working fairly well, so it should be possible to achieve a similar link quality for downlink transmission.

Summary

In this chapter, the RF communication has been designed. The theoretical link range is high enough to satisfy the requirement of 1500 m. There are however situations where the link range is not sufficient, due to polarization mismatch and other assumptions in the calculation. In practice, for downlink it has not been possible to get close to the theoretical link range, but this is assumed to be caused by some error in the setup. For uplink, the measured range is also not as long as required, and it can thus be concluded that the RF communication link has to improved before it is used for an actual CanSat launch.

CHAPTER 8

Modelling of Pan & Tilt Platform

This chapter describes the process of setting up a model, that accurately describes the behavior, of the physical components of the system. The goal is to derive a transfer function that takes an applied voltage as input, and outputs the resulting position of the antenna, ie.

$$H(s) = \frac{\theta(s)}{V_i(s)}$$

Such a model is necessary in order to design an efficient control scheme for the system. The first section of this chapter gives an overview of all the components that are to be modelled. This includes a description of how each component is modelled, and what parameters are needed. The following section describes how the individual parts of the model are combined, and finally presents the transfer functions to be used for simulation of the physical components, and for the design of a feedback control system. Finally the output of the model is compared to the actual performance of the physical components for verification.

8.1. Model Overview

A sketch of the physical system to be modelled is shown in figure 8.1 on the following page. The antenna platform consists of two parts:

- A tower structure that holds the entire construction. The tower can be rotated 360° by a DC motor and determines the azimuth of the antenna.
- A small platform at the top of the tower, on which the antenna is mounted. The platform can be tilted back and forth by a DC motor and determines the elevation of the antenna. The rotation is physically limited by the tower.

The DC motors are connected to their load through gears. Each gear consists of two cogwheels and a belt that transfers torque from the motor to the part being rotated. Since both motors also have an internal gear, the following terms must be defined to avoid confusion:

Rotor refers to the internal part of the motor that is forced to rotate by the magnetic field and its angular velocity is denoted by ω_m.

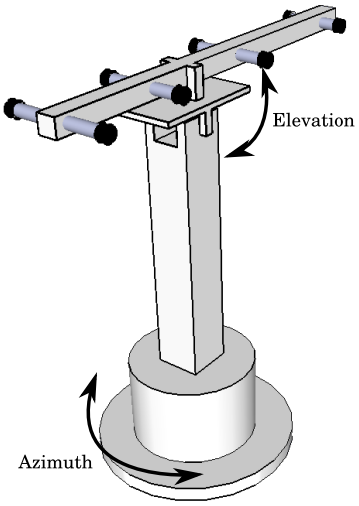


Figure 8.1: *A sketch of the antenna platform showing the rotation in the azimuth and elevation directions.*

Shaft is the part that sticks out of the motor. Its velocity is denoted by ω_s.

The shaft is connected to the rotor through the internal gear. The external gears connect the load to the shaft. The velocity at the load is denoted by ω_L. Since azimuth and elevation rotate independently, they can also be modeled as so. The two models are very similar though, and the differences lie solely in the parameters.

8.1.1 Assumptions

The following assumptions are made about the system being modelled:

- All moving parts including the belts are rigid.
- The DC motors behave linearly, except for dry friction.
- The effect of wind resistance is negligible.
- The platform is in level at all times.
- The effects of using a PWM signal instead of a constant voltage are negligible. [1]

8.1.2 DC motors

Figure 8.2 on the facing page shows an equivalent electrical diagram of a generic DC motor and figure 8.3 on the next page shows the moments of force that apply to the rotor. From the electrical diagram, the following equation can be written:

$$V_i = I_a(t) \cdot R_a + L_a \cdot \frac{\mathrm{d}}{\mathrm{d}t} I_a(t) - V_{\mathrm{emf}} \tag{8.1}$$

$$= I_a(t) \cdot R_a + L_a \cdot \frac{\mathrm{d}}{\mathrm{d}t} I_a(t) - K \cdot \omega_m(t) \tag{8.2}$$

[1] This assumption is valid because the duty cycle frequency of the signal has been chosen high enough, that the current is smoothed out by the motor coil. More details on this can be found in section 9.3.2 on page 76

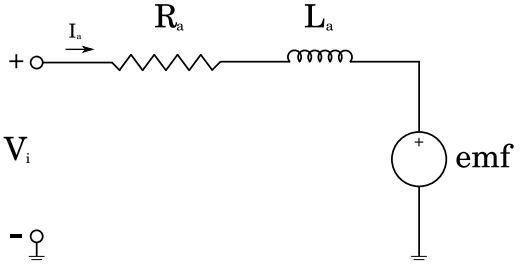


Figure 8.2: *Electrical equivalent diagram of a DC motor.*

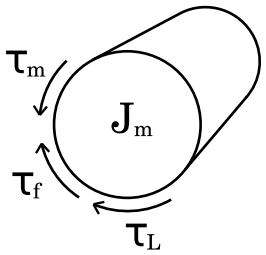


Figure 8.3: *Illustration of the torque that affects the motor rotor.*

where:

V_i	is the applied input voltage at the motor terminals.	[V]
I_a	is the current running through the motor coil.	[A]
R_a	is the terminal resistance of the motor.	[Ω]
L_a	is the terminal inductance of the motor.	[H]
V_{emf}	is the backwards electromotive force.	[V]
ω_m	is the angular velocity of the rotor.	[rad/sec]

From figure 8.3 we have the following. Note that the non-linear dry friction, τ_c, is ignored at this time.

$$J_{\text{m}}\frac{d}{dt}\omega_m(t) = \tau_m - \tau_{\text{L}} - \tau_{\text{f}} \tag{8.3}$$

$$= K \cdot I_a(t) - \tau_{\text{L}} - B \cdot \omega_m(t) \tag{8.4}$$

where:

J_m	is the inertia of the rotor.	$[\text{kg} \cdot \text{m}^2]$
τ_m	is the amount of torque delivered by the rotor.	[Nm]
τ_L	is the amount of torque applied to the rotor by an external load.	[Nm]
τ_f	is the amount of torque applied to the rotor by friction.	[Nm]
K	is the torque constant. Defines how current is converted into torque in the motor.	$[\frac{\text{Nm}}{\text{A}}]$
B	is the viscous friction coefficient for the entire system.	$[\frac{\text{Nm}}{\text{rad/sec}}]$

All of the aforementioned parameters must be known, in order to make a precise model of how the system behaves.

The DC motors used in the system setup are both A-Max 110949[29] with a built in planetary gear head (order nr. 144029[30]). Data sheet parameters for motors and gear are shown in table 8.1.

Property	**Symbol**	**Value**	**Unit**
Torque constant	K	$13.3 \cdot 10^{-3}$	$\frac{\text{Nm}}{\text{A}}$
Terminal resistance	R_a	3.65	Ω
Terminal inductance	L_a	$0.372 \cdot 10^{-3}$	H
Rotor inertia	J_m	$1.32 \cdot 10^{-6}$	$\text{kg} \cdot \text{m}^2$
Gearhead inertia	J_s	$5 \cdot 10^{-6}$	$\text{kg} \cdot \text{m}^2$
Gear ratio	N	14 : 1	-

Table 8.1: *Motor and gear parameters.*

8.1.3 Antenna platform

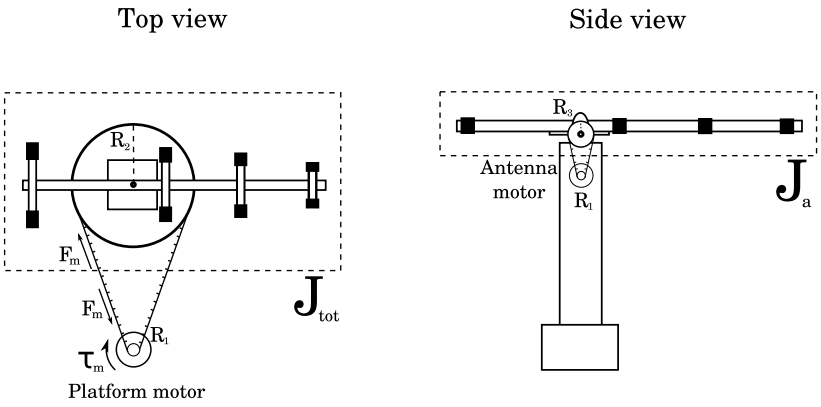


Figure 8.4: *A side- and top view of the antenna platform, showing what parts are rotated by the motors. F_m illustrates the force that affect the belt*

The antenna platform is essentially the load of the DC motors and thus determines the value of τ_L. Since the azimuth and elevation axis' are rotated independently, different parts of the platform will act as load for each motor. This is illustrated in figure 8.4. It can be seen that the relationship between the radii of the cogwheels, determines the gear ratio from shaft to load. The ratios for azimuth and elevation are given by:

$$N_{\text{az}} = \frac{R_2}{R_1} \tag{8.5}$$

$$N_{\text{el}} = \frac{R_3}{R_1} \tag{8.6}$$

The following is calculated for the external gears but the derived expression is general and can be applied to the internal gear as well. When torque is applied to the motor shaft, a force F_m affects the belt in both directions, due to Newtons third law of motion. Since torque is defined as $\tau = r \cdot F$ and ignoring friction for now, the following equations can be written:

$$J_s \cdot \frac{\mathrm{d}}{\mathrm{d}t}\omega_s = \tau_s - F_m \cdot r_1 \tag{8.7}$$

$$J_L \cdot \frac{\mathrm{d}}{\mathrm{d}t}\omega_L = F_m \cdot r_2 \tag{8.8}$$

where:

J_{s}	is the moment of inertia of the motor side of the gear	$[\text{kg} \cdot \text{m}^2]$
ω_s	is the angular velocity of the first cog wheel (motor side).	$[\frac{\text{rad}}{\text{sec}}]$
r_1	is the radius of the first cog wheel (motor side).	[m]
J_{L}	is the moment of inertia of side being driven through the gear.	$[\text{kg} \cdot \text{m}^2]$
ω_L	is the angular velocity of the second cog wheel.	$[\frac{\text{rad}}{\text{sec}}]$
r_2	is the radius of the second cog wheel.	[m]
τ_s	is the torque provided to the first cog wheel by the motor.	[Nm]
F_m	is the force that affects both cog wheel through the belt.	[N]

By isolating F_m, substituting $\omega_L = \frac{\omega_s}{N_{\text{ext}}}$ in (8.8) and inserting in (8.7) we have:

$$\tau_s = \left(J_s + \frac{J_L}{(N_{\text{ext}})^2} \right) \frac{\mathrm{d}}{\mathrm{d}t}\omega_s \tag{8.9}$$

Where N_{ext} is the external gear ratio given by $\frac{r_2}{r_1}$. Knowing the amount of torque transferred from load to shaft, the total load torque that affects the rotor is then given

by

$$\tau_L = \left(J_m + \frac{J_s + \frac{J_L}{(N_{\text{ext}})^2}}{(N_{\text{int}})^2} \right) \frac{\mathrm{d}}{\mathrm{d}t}\omega_m \tag{8.10}$$

Where N_{int} is the internal gear ratio. Since the moment of inertia of the motor shaft itself is small and furthermore is divided by $(N_{\text{int}})^2$, it can be neglected. The expression is thus reduced to:

$$\tau_L = \left(J_m + \frac{\frac{J_L}{(N_{\text{ext}})^2}}{(N_{\text{int}})^2} \right) \frac{\mathrm{d}}{\mathrm{d}t}\omega_m \tag{8.11}$$

$$= \left(J_m + \frac{J_L}{(N_{\text{ext}} \cdot N_{\text{int}})^2} \right) \frac{\mathrm{d}}{\mathrm{d}t}\omega_m \tag{8.12}$$

Equation (8.12) thus defines the torque that is applied to the rotor by the load (in this case, either the antenna or the entire tower) via the gears.

The physical parameters of the antenna platform have all been calculated from measurements made on the platform. All measurements and calculations can be found in Test 1 of journal 3 on page 155. The relevant parameters are shown in table 8.2.

Property	**Symbol**	**Value**	**Unit**
Antenna inertia	J_a	$11.3 \cdot 10^{-3}$	$\text{kg} \cdot \text{m}^2$
Elevation gear ratio	N_{el}	$4.6 : 1$	-
Total platform inertia	J_{tot}	$18.5 \cdot 10^{-3}$	$\text{kg} \cdot \text{m}^2$
Azimuth gear ratio	N_{az}	$8.9 : 1$	-

Table 8.2: *Antenna platform parameters.*

8.2. Combining the Model

In the following, a complete model that express the position of the antenna in terms of the motor input voltage is derived. The derivation is true in general and thus valid for both azimuth and elevation. The first step in combining the elements of the model is to Laplace transform the equations involved. This is done to both ease calculations and to eventually allow frequency domain analysis of the system. Transforming equations (8.2) and (8.4) yields:

$$V_i(s) = I_a(s) \cdot R_a + s \cdot L_a \cdot I_a(s) - K \cdot \omega_m(s) \tag{8.13}$$

$$s \cdot J_m \cdot \omega_m(s) = K \cdot I_a(s) - \tau_L - B \cdot \omega_m(s) \tag{8.14}$$

The effect of the inductance L_a can be examined by comparing the electrical and mechanical time constants. The mechanical is given by 27.1 msec[29] and will be even higher when the motors are loaded. The electrical time constant can be calculated by:

$$\tau = \frac{L_a}{R_a} = \frac{0.372 \cdot 10^{-3}}{3.65} = 102\,\mu\text{sec} \tag{8.15}$$

It can be seen that the mechanical time constant is much higher than the electrical, meaning that the frequency response at the lower frequencies of operation is dominated by the mechanical elements. It is therefore safe to ignore the effect of L_a and remove it from the equations. (8.13) is thus reduced to:

$$V_i(s) = I_a(s)R_a - K \cdot \omega_m(s) \tag{8.16}$$

By Laplace transforming eq. (8.12) and inserting in (8.14) we have:

$$sJ_m\omega_m(s) = KI_a(s) - \omega_m(s) \cdot s(J_m + \frac{J_L}{N^2}) - B\omega_m(s) \tag{8.17}$$

Where N is the product of internal and external gear ratios. By combining eq. (8.16) and (8.17) we get:

$$\frac{\omega_m(s)}{V_i(s)} = \frac{N^2K}{(R_aJ_mN^2 + R_aJ_L)s + (R_aBN^2 + K^2N^2)} \tag{8.18}$$

Which is a transfer function of angular velocity over input voltage. Since the goal is an expression that gives the position of the antenna, the velocity must be integrated and divided by the gear ratio:

$$H(s) = \frac{\theta(s)}{V_i(s)} = \left(\frac{1}{s \cdot N}\right) \frac{N^2K}{(R_aJ_mN^2 + R_aJ_L)s + (R_aBN^2 + K^2N^2)} \tag{8.19}$$

$$= \frac{NK}{(R_aJ_mN^2 + R_aJ_L)s^2 + (R_aBN^2 + K^2N^2)s} \tag{8.20}$$

And the desired transfer function has thus been found. Before it can be used, though, all the necessary parameters must be determined. Also, the effects of non-linear elements that affect the system must be taken into account.

8.3. Friction

The total friction τ_f in the rotating system can be decomposed into static friction (stiction, τ_s), dry friction (coloumb friction, τ_c) and viscous friction ($\omega_m \cdot B$). The different kinds of friction are illustrated on figure 8.5. Only the viscous friction is linearly depen-

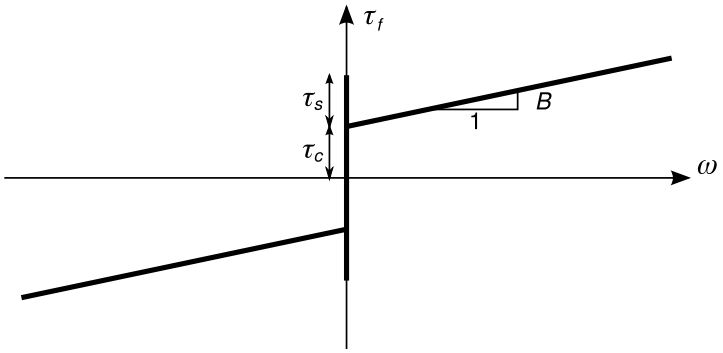


Figure 8.5: *Different types of friction in the ground station system.*

dant of ω_m. The other two types of friction introduces a non-linearity into the system. The stiction is only present, when ω_m is zero and it will not be taken into account in the modelling of the platform. The dry friction is constant and independent of the angular velocity and will be dealt with in the following.

Eq. (8.4) expresses the total torque on the motor shaft. Substituting the total friction torque τ_f by a viscous friction component given by $B \cdot \omega_m$ and a dry friction component τ_c gives:

$$J \cdot \frac{\mathrm{d}}{\mathrm{d}t}\omega_m = \tau_m - \tau_L - \tau_c - B \cdot \omega_m \tag{8.21}$$

where:

J	is the moment of inertia.	$[\mathrm{kg} \cdot \mathrm{m}^2]$
ω_m	is the angular velocity of the motor.	$[\frac{\mathrm{rad}}{\mathrm{sec}}]$
τ_m	is the torque applied by the motor.	[Nm]
τ_L	is the torque of the load.	[Nm]
τ_c	is the dry friction component.	[Nm]
B	is the viscous friction coefficient.	$[\frac{\mathrm{Nm} \cdot s}{\mathrm{rad}}]$

The dry friction parameter accounts for both actual friction but also voltage drops in the H-bridge used to supply the motors with power, since this is a similar non-linear effect. To counter the effects of dry friction, a voltage offset is added to all values applied to the motor. The offset value is calculated using the following equation, which calculates the voltage required for the motor to deliver a torque as large as τ_c. The expression is derived from eq. 8.4 on page 53, with $\frac{\mathrm{d}}{\mathrm{d}t} I_a(t) = 0$ (as the effect of L_a is neglected, as previously mentioned) and $\omega(t) = 0$ (as the offset voltage will not cause the motor to rotate.)

$$0 = K \cdot I_a - \tau_c \tag{8.22}$$

$$= K \cdot \frac{V_{\text{offset}}}{R_a} - \tau_c \tag{8.23}$$

$$\Downarrow$$

$$V_{\text{offset}} = \tau_c \cdot \frac{R_a}{K} \tag{8.24}$$

8.4. Non-linearity in Elevation Model

For elevation, the antenna rotates around a horizontal axis. Therefore, it would be ideal to have its center of mass lie exactly on the axis of rotation, whereby the gravitational force would be equal in both ends, effectively cancelling out regardless of orientation. Due to the design of the antenna though, it has been necessary to mount it so the center of mass lies approximately 5 cm above the axis. This means that gravity does affect the antenna differently, depending on how far to either side it's been rotated. This is not a problem for azimuth rotation.

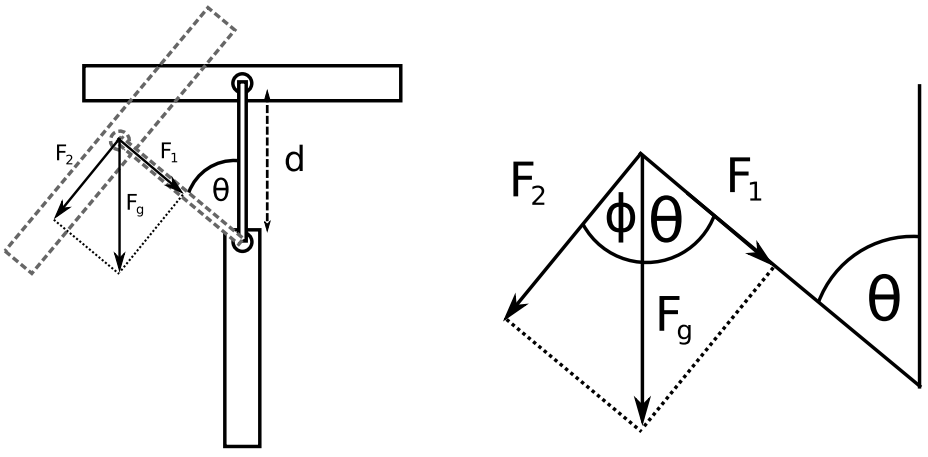


Figure 8.6: *An illustration showing how gravity affects the rotation of the antenna in the elevation direction.*

Figure 8.6 shows how gravity affects the system. The angle θ specifies the rotation of the antenna and F_g is the gravitational force (the product of the gravitational constant

(g) and the mass of the antenna (m)). To calculate the effect of gravity more specifically, the force F_g is resolved into two components F_1 and F_2 that are perpendicular to each other. F_1 will always point towards the axis so this force will never affect the rotation of the antenna. (It might affect friction, but this effect is neglected.) F_2 on the other hand will result in a torque on the rotation axis, and it's value must therefore be determined. This torque is non-linear and depends on the position of the antenna. By looking at the figure, the following expression can be written:

$$\cos(\phi) = \frac{F_2}{F_g} \quad \Rightarrow \quad F_2 = \cos(\phi) \cdot F_g \tag{8.25}$$

Since F_1 and F_2 are perpendicular it follows that $\phi = 90^\circ - \theta$ and exploiting that $\sin(\theta) = \cos(90^\circ - \theta)$, F_2 can be written as:

$$F_2 = \sin(\theta) \cdot F_g \tag{8.26}$$

The torque can be found by multiplying with the distance from center of mass to the axis. Because the torque is applied at the load, though, it must be divided by N (the combined gear ratio) to find the necessary motor torque:

$$\tau_g = \frac{F_2 \cdot d}{N} \tag{8.27}$$

Substituting all known values, the final expression is given by:

$$\tau_g = \sin(\theta) \cdot 0.388 \cdot 9.82 \cdot 0.05 \tag{8.28}$$

$$= \sin(\theta) \cdot 0.190 \tag{8.29}$$

This is thus a non-linear torque that will affect the model for elevation. Now that the value of the torque is known, it can be taken into account in the control system.

8.5. Parameter Determination and Model Verification

Since some parameters in the model, namely inertia and friction, are difficult to measure directly, it is necessary to determine these through tests done on the system. The inertia parameters have been roughly determined by direct measurements of the dimensions and weight of the moving parts, and so these values cannot be assumed accurate and must be verified first. The friction parameters can be determined by observing how the system performs when a constant voltage is applied. This has been done in a set of tests, all described in Test 2 and 3 of journal 3 on page 155.

Method for Determination of Parameters

The data that's been sampled is position data, so the velocity must be found by differentiation. By observing where the slope of the position curve is constant and selecting two consecutive values of position and the corresponding time, the angular velocity is found by:

$$\omega_L = \frac{p_2 - p_1}{t_2 - t_1} \tag{8.30}$$

where:

p_1	is the first position value	[rad]
p_2	is the second position value	[rad]
t_1	is the first time value	[s]
t_2	is the second time value	[s]

Note that ω_L is the angular velocity measured after the gear, and is thus $\frac{\omega_m}{N}$ where N is the ratio of the internal and external gears combined. To minimize quantization errors due to the limited resolution of the data, the values are chosen 5 samples apart from each other instead of 1.

If the velocity is constant, the acceleration is $0\,\mathrm{m/s^2}$ and the terms $\frac{\mathrm{d}}{\mathrm{d}t}\omega$ and τ_L vanish from eq. (8.21). It thus reduces to:

$$0 = \tau_m - \tau_f \tag{8.31}$$
$$= I_a \cdot K - B \cdot \omega_m - \tau_c \tag{8.32}$$

By looking at figure 8.2 on page 53 and acknowledging that the voltage across the motor coil is 0 V due to a constant current, I_a is given by:

$$I_a = \frac{V_i - V_{\mathrm{emf}}}{R_a} \tag{8.33}$$
$$= \frac{V_i - K \cdot \omega_m}{R_a} \tag{8.34}$$

Inserting the found expression into (8.32) we have:

$$0 = \frac{V_i - K \cdot \omega_L \cdot N}{R_a} \cdot K - B \cdot \omega_L \cdot N - \tau_c \tag{8.35}$$

In which the only unknowns are B and τ_c. By writing two equations using the sampled data, both friction parameters can be determined.

8.5.1 Azimuth Friction Parameters

Two tests have been performed to determine azimuth parameters, applying voltages of 4 and 6 V. For calculating the velocity at 4 V, the data points (0.8063 rad, 1.552 sec) and (0.8273 rad, 1.592 sec) have been chosen from the recorded CSV-files[2] where the position slope is constant. By using eq. (8.30) the angular velocity can be determined:

$$\omega_{4\mathrm{V}} = \frac{(0.8273 - 0.8063)}{(1.592 - 1.424)} = 0.524\,\frac{\mathrm{rad}}{\mathrm{sec}} \tag{8.36}$$

For the velocity at 6 V, the following data points have been chosen: (2.1450 rad,1.552 sec) and (2.2026 rad, 1.592 sec). The velocity is then:

$$\omega_{6\mathrm{V}} = \frac{(2.2026 - 2.1450)}{(1.592 - 1.552)} = 1.44\,\frac{\mathrm{rad}}{\mathrm{sec}} \tag{8.37}$$

All known values are now inserted in (8.35). Keeping in mind that the sampled angular position is for the antenna and not the motor, the velocities must be multiplied by the gear ratio:

$$0 = \frac{6 - 13.3 \cdot 10^{-3} \cdot 1.75 \cdot (14 \cdot 8.9)}{3.65} \cdot 13.3 \cdot 10^{-3} - B \cdot 0.524 \cdot (14 \cdot 8.9) - \tau_c \tag{8.38}$$
$$0 = \frac{8 - 13.3 \cdot 10^{-3} \cdot 2.88 \cdot (14 \cdot 8.9)}{3.65} \cdot 13.3 \cdot 10^{-3} - B \cdot 1.44 \cdot (14 \cdot 8.9) - \tau_c \tag{8.39}$$

By solving the two equations, the values of τ_c and B are found:

$$B = 15.4 \cdot 10^{-6} \tag{8.40}$$
$$\tau_c = 0.0104 \tag{8.41}$$

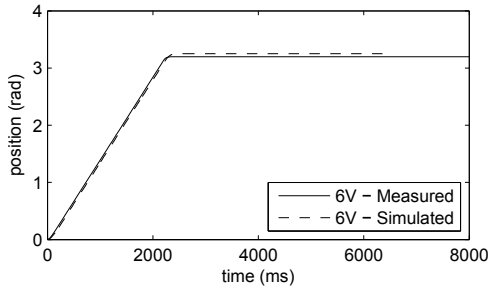


Figure 8.7: *A plot showing the sampled position data at 6 V as well as simulated values. A voltage offset of 2.86 V has been used.*

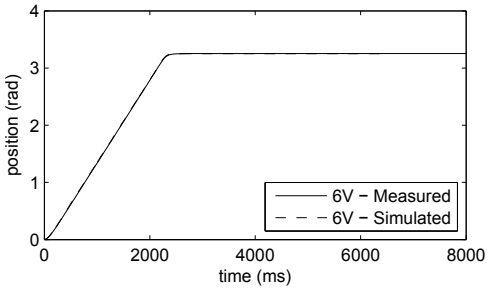


Figure 8.8: *Same as before but with an adjusted moment of inertia.*

8.5.2 Graphical Adjustments of Azimuth Parameters

The initial calculation of the moment of inertia has been based on simple measurements and assumptions, and thus the value found cannot be considered entirely accurate. The value can be refined by observing how the system performs in tests, and comparing this to the output of the model. By using Simulink to simulate the output of the transfer function, using the same input as in the actual tests, the two results can be compared directly. The simulation files can be found on the cd [3]. Figure 8.7 shows a plot of the sampled system performance with a constant input of 6 V along with a simulation using the model expression. The dry friction has been simulated by adding a voltage offset to the model input. This has been calculated using eq. (8.24):

$$V_{\text{offset}} = -0.0104 \cdot \frac{3.65}{13.3 \cdot 10^{-3}} = -2.86\,\text{V} \tag{8.42}$$

It can be seen that the curves coincide very well. By inspecting the plots closely though, it's apparent that the simulation curve settles faster than the measured curve. This indicates that the inertia parameter has been set too low. By gradually adjusting the value and observing the result, a new value of $0.0555\,\text{kg} \cdot \text{m}^2$ has been determined. Figure 8.8 plots the transfer function with the new inertia value.

Figure 8.9 on the facing page plots the measured and simulated values at various voltages. It can be seen that the curves coincide nicely at higher voltages but diverge at lower ones. The exact cause of this discrepancy is uncertain but it's likely to be friction phenomena, not addressed by the model used. Since friction beyond what can be described as coulomb and viscous is very difficult to address effectively, no further attempt has been made at this. The model describing the azimuth rotation is considered good enough to be used in designing a robust controller.

8.5.3 Elevation Parameters

Because of the non-linear torque component that's caused by the shifting center of mass, determining the friction parameters for the elevation is more complicated than for azimuth. For instance, it is not possible to maintain a constant angular velocity at a constant voltage and the method used for determining the parameters for azimuth is therefore not directly applicable. A way to work around this problem is to add compensation for the non-linear component based on the current angle of elevation. This can be done by calculating the torque from eq. 8.29 on page 58 and applying a voltage that

[2] The position has been converted to radians and the time is specified relative to the first sample.
[3] `/journals/parameter_determination/simulink/<#>`

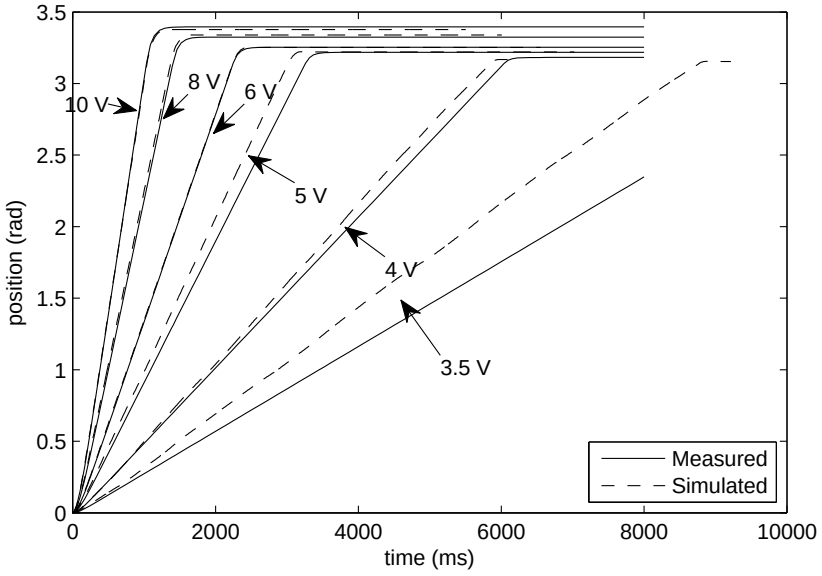


Figure 8.9: *A plot showing the sampled and simulated curves with the adjusted inertia value.*

cancels it out. Assuming steady state, the voltage is given by:

$$V_g = \frac{\tau_g}{N} \cdot \frac{R_a}{K} \tag{8.43}$$

$$= \sin(\theta) \cdot \frac{0.190}{64.4} \cdot \frac{3.65}{13.3 \cdot 10^{-3}} \tag{8.44}$$

$$= \sin(\theta) \cdot 0.812 \tag{8.45}$$

By doing this, the system should in theory behave like a linear system in steady state and allow the friction parameters to be determined. To be able to do this however, the non-linear compensation needs to be accurate, which must also be verified.

An attempt to do this has been carried out by testing the system performance at constant voltages with the non-linear compensation first enabled and then disabled. In both cases, the antenna starts out pointing as far down as possible and moves up when the voltage is applied. Figure 8.10 on the following page shows the resulting position curves. In a linear system, the position curves would quickly accelerate and then form into straight lines. Because of the gradual shift in gravity though, this doesn't happen. The compensation improves the situation, but doesn't manage to make the curves entirely linear. It does make the acceleration faster though, and it stabilizes the velocity, especially at lower voltages. The result is considered enough of an improvement that the compensated curves can be used to determine friction parameters for elevation.

8.5.4 Elevation Friction Parameters

All elevation tests were performed with non-linear compensation enabled in the software. The tests were carried out by applying voltages of 4, 6 and 8 V. Points on the curves were chosen where the angular velocity is approximately constant and the values can be seen in table 8.3. The velocities have been found using eq. 8.30 on page 58.

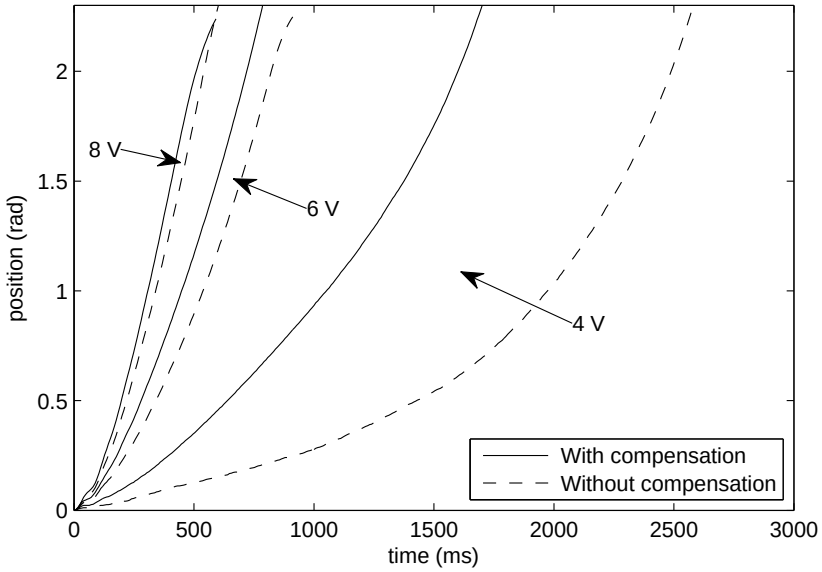


Figure 8.10: *A plot comparing the measured elevation performance with non-linear compensation enabled and disabled.*

V	t_1	t_2	p_1	p_2	ω_L
4	1.152	1.192	1.1380	1.1973	1.4835
6	0.512	0.552	1.2078	1.3456	3.4470
8	0.352	0.392	1.2182	1.4277	5.2360

Table 8.3: *Measured time and position values from elevation tests*

As these measurements are uncertain due to the non-linearity, the values of τ_c and B vary quite a bit depending on the (V,ω_L) data sets used. Therefore, the values have been calculated by linear regression of the three data sets using the MATLAB script found on the cd [4]. This yields the following values:

$$B = 12 \cdot 10^{-6} \tag{8.46}$$

$$\tau_c = 0.0087 \tag{8.47}$$

8.5.5 Verification of Elevation Parameters

Figure 8.11 on the facing page shows a plot of sampled position data at 4, 6 and 8 V along with simulated curves that have been offset by

$$V_{\text{offset}} = -0.0087 \cdot \frac{3.65}{13.3 \cdot 10^{-3}} = -2.39\,\text{V} \tag{8.48}$$

It can be seen that the model curves do not coincide with the measured ones, and at low voltages, there is a fair amount of deviation. Still, the model manages to approximate the actual elevation performance to an acceptable degree, and it is considered usable for designing the controller. Due to the discrepancies between the model and the actual performance, it has not been possible to correct the value for moment of inertia. The value found by measurements is therefore used.

[4] `/journals/parameter_determination/linear_regression.m`

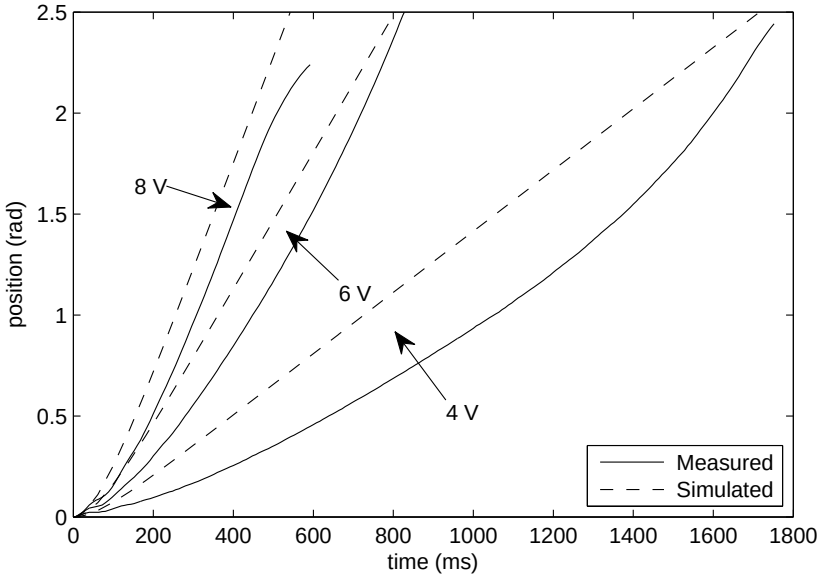


Figure 8.11: *A plot comparing measured and simulated results at various input voltages.*

8.6. Final Expression

By inserting all the values, the final transfer functions are as follows:

$$H_{\text{az}}(s) = \frac{1.657}{0.2775s^2 + 3.596s} \tag{8.49}$$

$$H_{\text{el}}(s) = \frac{0.8565}{0.06118s^2 + 0.9153s} \tag{8.50}$$

When the voltages to compensate for dry friction, were applied to the motors, it was found that the motors started to move. This is caused by too high offset voltages. To alleviate this effect, new values for the dry friction offset voltages have been determined, by gradually reducing these, until the motors did not start to move. The values determined this way are the ones used when designing the controller. The offset values are as follows, with the ones previously determined in parenthesis:

$$V_{\text{offset\_az}} = 2.4\,\text{V} (2.86\,\text{V}) \tag{8.51}$$

$$V_{\text{offset\_el}} = 2.2\,\text{V} (2.39\,\text{V}) \tag{8.52}$$

To compensate for gravity on the elevation axis, the following voltage offset is calculated dynamically and is subtracted from all elevation motor input, to counter the effect of gravity:

$$V_{\text{elev\_g}} = \sin(\theta) \cdot 0.812 \tag{8.53}$$

Summary

In this chapter, a complete model of the system has been built. This model combines the mathematical description of a DC motor with the dynamic motion of the moving parts, ie. the tower and the antenna. The result is transfer functions for both azimuth and elevation that produce the angular position from an input voltage. All necessary parameters have been determined, either by data sheets, or through testing. In the process of determining parameters, the model has been held up against the actual performance of the system.

It has been observed that the model describes movement on the azimuth axis with good accuracy. The elevation on the other hand is affected by a non-linear torque caused by gravity and the linear transfer function therefore doesn't describe the elevation accurately. To counter this, a non-linear voltage offset is added, to cancel out the gravitational torque. This has improved the accuracy of the model to a point where it is considered feasible for use in designing the elevation control.

CHAPTER 9

Feedback Control of Pan & Tilt Platform

In this chapter the design and implementation of the controller is described. The controllers function is to make it possible for the system to point the antenna in a wanted position and maintain this position. A motor driver has been constructed to make the ARM-board able to control the motors with regard to voltage and current levels. It is possible to control the antenna in manual mode or in automatic mode. In manual mode a user can control the antenna by inputting elevation- and azimuth positions of the antenna. In automatic mode the antenna position is adjusted automatically in response to incoming GPS data from a CanSat. The controller is designed on the basis of the model described in chapter 8 on page 51.

The requirements specification mentions the following, which is of relevance for the controller:

- *Requirement 8. The ground station must be able to control the antenna so that an object following the launch graph on figure 2.3 on page 11 can be tracked. The target must be within the half-power beamwidth of the antenna at all times.*

9.1. Interpretation of the Requirement

It is now desired to analyse the requirement given above, and turn it into requirements that are suitable for designing the controller. Time domain specification is used for this, which means specifying rise time (t_r) and overshoot (M_p) for the response of a unit-step input to the closed loop system. An illustration of how these are defined, is seen in figure 9.1 on the next page. Settling time is not very relevant, as the antenna position will continuously be adjusted during tracking, so it is not specified.

Elevation Requirements

From the WARP protocol described in appendix B on page 131 it is evident that new packages with GPS data will arrive every 200 ms. It is necessary for the controller to keep up and be able to adjust to the new position before a new package arrives. The rise time doesn't include the time it takes for the controller to accelerate until 10 % of the step, and the time for the deacceleration after 90 % of the step has been reached.

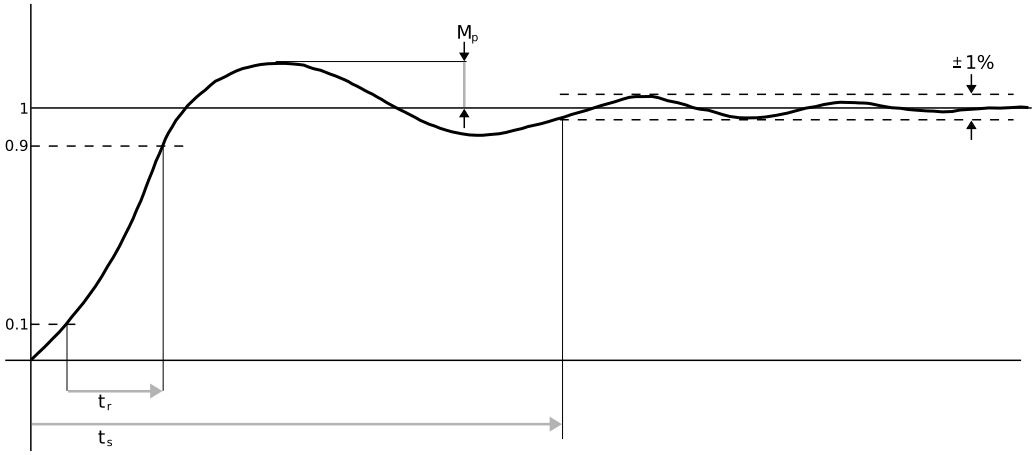


Figure 9.1: *This figure illustrates how t_r,t_s and M_p is defined.*

Therefore, the rise time is chosen to 100 ms, which provides an additional 100 ms for the mentioned acceleration and deacceleration.

In section 2.3.1 on page 9 the maximum deviation between the direction to the CanSat and the direction fed into the controller, is determined to be 10°. The half-power beamwidth of the antenna is 25°, which allows the controller to deviate up to 15° from the wanted direction. Assuming that the maximum velocity of the antenna, and thus the maximum overshoot, will occur at a step of 50°, this will allow an overshoot of $\frac{15^\circ}{50^\circ} \cdot 100\,\% = 30\,\%$. This is a fairly large overshoot, and the maximum overshoot is set to 10 % instead.

The above leads to requirements for the maximum overshoot M_p and the rise time t_r of the system:

- $M_p \leq 10\%$
- $t_r \leq 100\text{ms}$

Azimuth Requirements

The requirements outlined address the elevation controller and are therefore not applicable for the azimuth controller. The requirements for the azimuth controller are not as strict, since the CanSat will not move as fast in this direction. The requirements are set to:

- $M_p \leq 10\%$
- $t_r \leq 200\,\text{ms}$

9.2. Controller Design

The pan and tilt platform needs two separate controllers, one for the azimuth direction control and one for the elevation direction control. The models for each plant to control, are derived in chapter 8 on page 51. As seen, this gives two second order systems. The task is to design the controllers so they meet the requirements, set above.

9.2.1 Design Strategy

In figure 9.2 a general block diagram of a negative feedback loop can be seen. This block diagram gives cause to some general equations that are used when designing the controller:

$$\text{Direct term: } D(s) \cdot G(s) \tag{9.1}$$

$$\text{Open loop: } L(s) = D(s) \cdot G(s) \cdot H(s) \tag{9.2}$$

$$\text{Closed loop: } T(s) = \frac{Y(s)}{R(s)} = \frac{D(s) \cdot G(s)}{1 + D(s) \cdot G(s) \cdot H(s)} \tag{9.3}$$

$$\text{or: } T(s) = \frac{\text{Direct term}}{1 + \text{Open loop}} \tag{9.4}$$

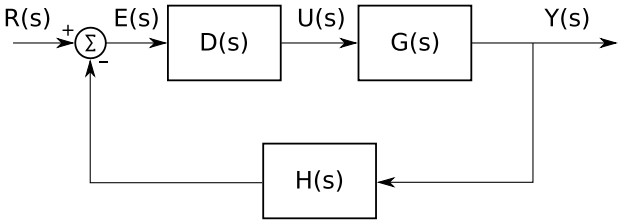


Figure 9.2: *This figure illustrates a general block diagram of a feedback loop. R(s) is the setpoint, E(s) is the error, D(s) is the controller, U(s) is the controller output, G(s) is the plant, H(s) is the feedback and Y(s) is the output of the system.*

In the special case where the closed loop T(s) is a 2. order system as the one seen in eq. (9.5), some clear design rules are specified for the time domain. Let the 2. order system be written in the standard form:

$$T(s) = \frac{\omega_n^2}{\mathrm{s}^2 + 2\zeta\omega_n s + \omega_n^2} \tag{9.5}$$

where:

ω_n	is the natural undamped frequency	[rad/s]
ζ	is the damping factor	[-]

Then, these design rules exists, as derived in [31]:

$$t_r \cong \frac{1.8}{\omega_n} \quad [\mathrm{s}] \tag{9.6}$$

$$M_p = \exp\left(\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}\right) \quad [\%] \tag{9.7}$$

$$t_s(x) = \frac{-\ln(x)}{\zeta\omega_n} \quad [\mathrm{s}] \tag{9.8}$$

where:

x is the percentage deviation when calculating settling time. For $\pm 1\%, x = 0.01$.

The above are design rules for the time domain, and thus it is also necessary to analyze the design in the frequency domain. Since the controller is implemented on a microcomputer, it is necessary to determine at what frequency the controller should be sampled at. To calculate the sampling frequency ω_s the following design rule is used:

$$40 \geq \frac{\omega_s}{\omega_{\mathrm{BW}}} \geq 20 \tag{9.9}$$

where:

ω_s	is the sampling frequency	[rad/s]
ω_{BW}	is the closed loop $-3\,\mathrm{dB}$ bandwidth of the system	[rad/s]

To ensure that the system is stable (in the sense of BIBO stability), it is important to choose a sufficient phase margin. When doing a stability analysis, the open loop $L(s)$ of the system is plotted in a bode plot. In order for the system to be stable, the phase at the crossover frequency ω_c isn't allowed to be $-180°$ or below. Please note that this stability criterion is not applicable to all systems in general[31, p. 337].

A rule of thumb is to choose the phase margin to be 45° or more. This insures stability in the system. With a proportional controller, the phase margin is typically increased by decreasing the gain, which in turn makes the system react slower to changes.

The design rules for the time- and frequency domain can now be employed when designing the controllers.

9.2.2 Azimuth Controller

To make the design of the azimuth controller as simple as possible, it has been chosen to design a proportional controller. This approach is assessed to be sufficient because of the simplicity of the model. If the designed proportional controller doesn't live up to the requirements a iteration of the design phase is necessary. A block diagram of the azimuth control loop can be seen in figure 9.3.

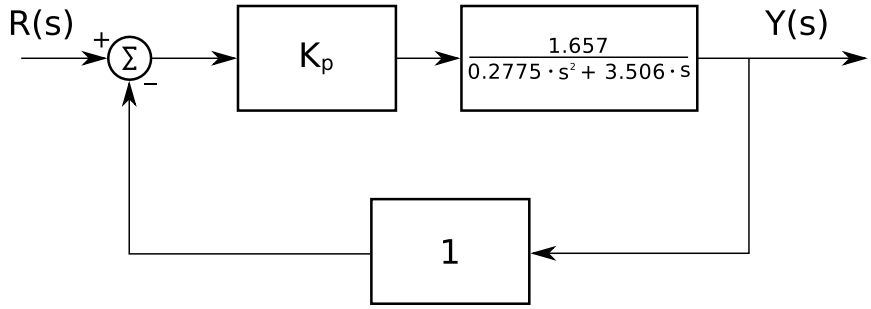


Figure 9.3: *This figure illustrates the block diagram of the azimuth control loop.*

Time Domain Design

The transfer function of the azimuth plant can be seen in equation 8.49 on page 63. If the controller D(s) is chosen only to be a proportional controller and the feedback H(s) is 1, then the closed loop expression is given by:

$$T(s) = \frac{K_p \cdot 5.971}{s^2 + 12.634 \cdot s + 5.971 \cdot K_p} \tag{9.10}$$

It is a 2. order expression of the general form seen in equation 9.5 on the preceding page and therefore the design rules described in section 9.2 on page 66 can be applied. From equation 9.10, ω_n and ζ can be defined, which then leads to equations for t_r, t_s and M_p.

$$\omega_n = \sqrt{5.971 \cdot K_p} \quad [\mathrm{rad/s}] \tag{9.11}$$

$$\zeta = \frac{12.634}{2 \cdot \sqrt{5.971 \cdot K_p}} \quad [-] \tag{9.12}$$

The expressions for ω_n and ζ can be put into the expressions for M_p and t_r and then solved, since the maximum value of M_p and the minimum value of t_r are known:

$$t_r < 0.2 \Rightarrow \frac{1.8}{\sqrt{5.971 \cdot K_p}} < 0.2 \qquad \Rightarrow K_p > 13.6 \tag{9.13}$$

$$M_p < 0.1 \Rightarrow \exp\left(\frac{-\pi \cdot \frac{12.634}{2\cdot\sqrt{5.971\cdot K_p}}}{\sqrt{1-\left(\frac{12.634}{2\cdot\sqrt{5.971\cdot K_p}}\right)^2}}\right) < 0.1 \qquad \Rightarrow K_p < 19.1 \tag{9.14}$$

From the equations above it is clear that if $13.6 < K_p < 19.1$ then the requirements for M_p and t_r are fulfilled. The settling time t_s if the threshold is set to $\pm 1\%$, can be calculated by eq. 9.8 on page 67, and becomes 0.729 s. The value of K_p has no effect on t_s because it is cancelled out in the equation.

Steady-State Error

In the special case where $H(s)$ is 1, the system type is the same as the number of poles in 0 of $D(s) \cdot G(s)$. By solving the denominator in $D(s) \cdot G(s)$ it becomes evident that the system has a pole in 0. This means that the system is a type 1 system, and therefore has no steady state error e_{ss}, if the input is a unit step. When the input is a unit ramp (ramp with slope 1) the e_{ss} is a constant, and when the input is a parabola, the e_{ss} will evolve towards infinity. The equations for finding steady state errors are derived in[31, p. 335]. If the input is a ramp, then e_{ss} can be calculated from:

$$e_{\text{ss ramp}} = \frac{1}{K_v} \quad \text{[rad]} \tag{9.15}$$

where:

$$K_v = \lim_{s\to 0} sD(s)G(s) \tag{9.16}$$

In this case:

$$K_v = \lim_{s\to 0} s \cdot K_p \cdot \frac{1.657}{0.2775s^2 + 3.506s} \Rightarrow K_v = 0.473 \cdot K_p \tag{9.17}$$

Which means $e_{\text{ss ramp}}$ is given by:

$$e_{\text{ss ramp}} = \frac{2.116}{K_p} \tag{9.18}$$

Frequency Analysis

In order to choose a value for K_p, a stability analysis needs to be performed. This takes place in the frequency domain. In figure 9.4 on the following page a bode plot of $L(s)$, where K_p is the highest allowable value, can be seen.

It is evident from figure 9.4 on the next page, that when $13.6 < K_p < 19.1$ the system is stable. The minimum phase margin is approximately 60°. If K_p is chosen to the largest possible value, then ω_{BW} is given by:

$$|T(s)| = -3\,\text{dB} \Rightarrow \omega \approx 12.5\,\text{rad/s} \tag{9.19}$$

This means that $\omega_s \geq 20 \cdot 12.5\,\text{rad/s}$ which equals $f_s \geq 40\,\text{Hz}$. The sample frequency can then be lowered, by lowering the value of K_p. By lowering the value of K_p, the phase margin and t_r will increase, while M_p will decrease. Choosing a value for K_p will be a compromise between M_p and t_r.

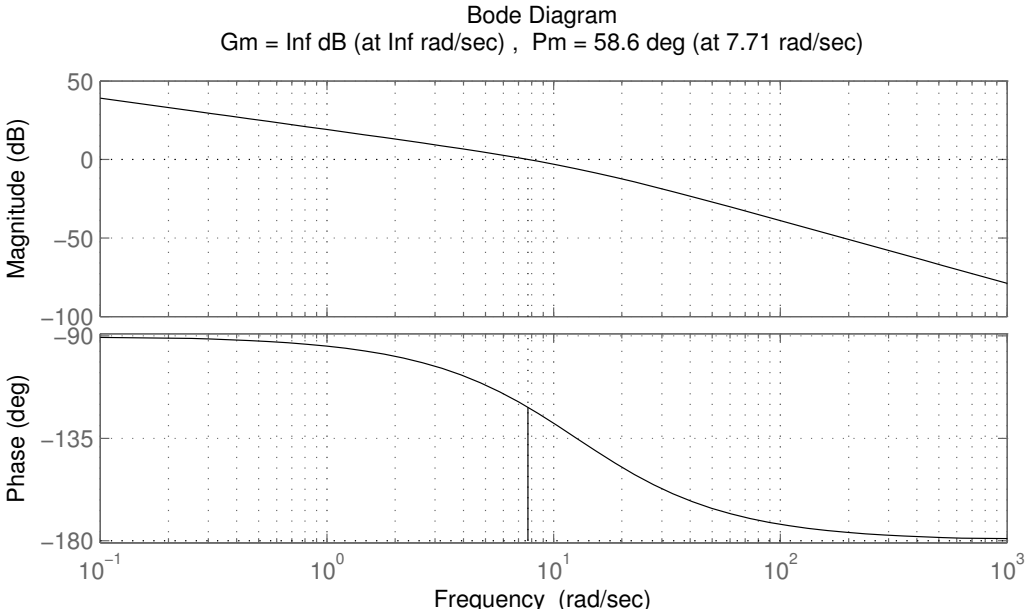


Figure 9.4: *Bode plot of the open loop system where K_p is 19.1.*

Choice of Parameters

In figure 9.5 a plot of M_p and t_r as a function of K_p can be seen. The figure shows that the controller meets the requirements as long as K_p is between 13.6 and 19.1.

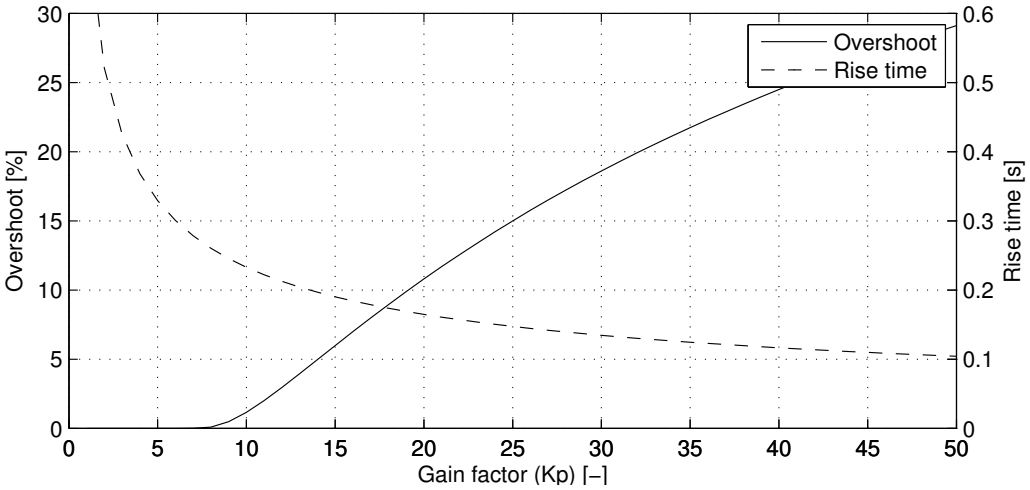


Figure 9.5: *This figure illustrates M_p and t_r as a function of K_p.*

In figure 9.6 on the next page a simulation of the systems response to a step function can be seen. The dotted curve is when the value of K_p is the highest possible value and the solid curve is for K_p equal to the lowest possible value. The value of K_p has been chosen to the highest value, 19.1, which means a quick response (small rise time) has been chosen, at the cost of a higher overshoot. This gives a steady state error of 6.35° when the input is a ramp. The final value of K_p can always be altered under testing, to tune the controller. It might be necessary to tune the controller, since an ideal model of the system can't be realized.

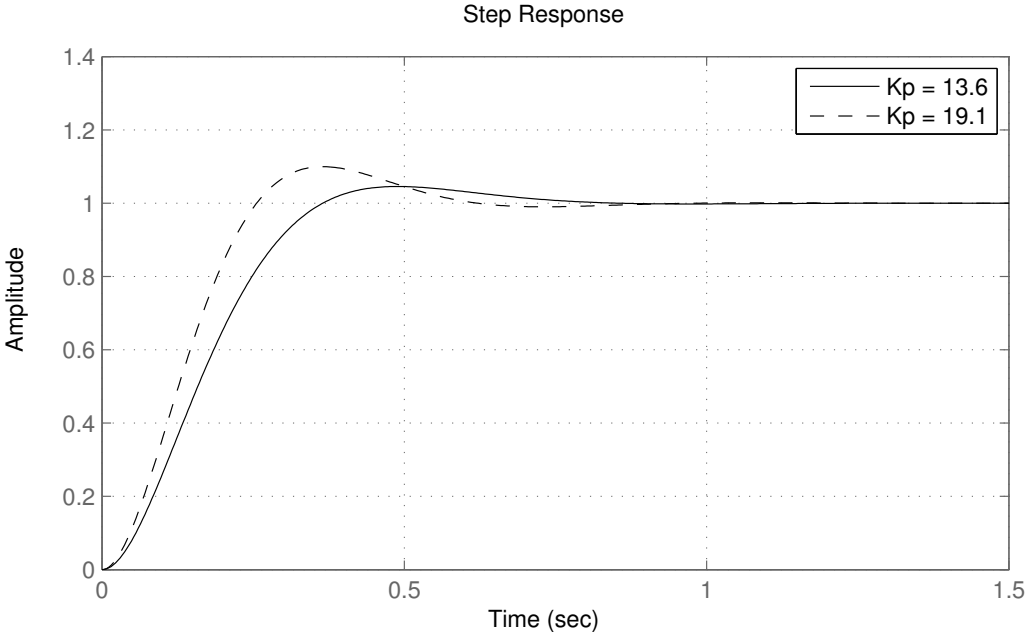


Figure 9.6: *This figure illustrates the systems response to a step input. Simulated values.*

9.2.3 Elevation Controller

The elevation direction controller is designed the same way, as the azimuth direction controller. The only difference between these, is a non-linear element in the elevation plant. The non-linear element appears because the antenna is balancing on a point of gravity that shifts when the antenna is changing direction. An illustration of the non-linear element can be seen in figure 8.6 on page 57.

Non-linearity Correction

From equation 8.45 on page 61 it is seen, that the only element that aren't a constant is θ. Since θ is known at all times, because of feedback from the motor encoders described in section 9.3.1 on page 76, it is possible to calculate the voltage that needs to be subtracted from the controller output, to counter the effect of the non-linearity. Please note that the sign changes depending on the angle, and thus the result can both increase or decrease the voltage output of the controller.

Design

The design of the controller follows the description outlined in section 9.2 on page 66. A transfer function for the elevation plant can be seen in equation 8.50 on page 63, and a block diagram of the control loop can be seen in figure 9.7 on the next page.

Time Domain Design

If the controller D(s) is chosen, like the azimuth controller, to be a proportional controller, and the feedback H(s) is 1, then the closed loop expression is given by:

$$T(s) = \frac{K_p \cdot 13.99}{s^2 + 14.96 \cdot s + 13.99 \cdot K_p} \tag{9.20}$$

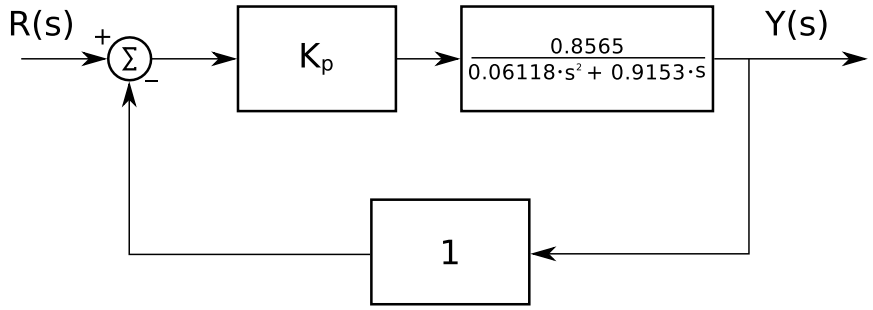


Figure 9.7: *This figure illustrates the block diagram of the elevation control loop.*

As in the case of the azimuth system, T(s) is a second order expression of the general form. Therefore the same design rules are applied. From equation (9.20 on the preceding page) ω_n and ζ can be defined.

$$\omega_n = \sqrt{13.99 \cdot K_p} \quad \text{[rad/s]} \tag{9.21}$$

$$\zeta = \frac{14.96}{2 \cdot \sqrt{13.99 \cdot K_p}} \quad \text{[-]} \tag{9.22}$$

The expressions for ω_n and ζ can be put into the expressions for M_p and t_r and solved, since the maximum value of M_p and the minimum value of t_r are known:

$$t_r < 0.1 \Rightarrow \frac{1.8}{\sqrt{13.99 \cdot K_p}} < 0.1 \Rightarrow K_p > 23.2 \tag{9.23}$$

$$M_p < 0.1 \Rightarrow \exp\left(\frac{-\pi \cdot \frac{14.96}{2 \cdot \sqrt{13.99 \cdot K_p}}}{\sqrt{1 - \left(\frac{14.96}{2 \cdot \sqrt{13.99 \cdot K_p}}\right)^2}}\right) < 0.1 \Rightarrow K_p < 11.43 \tag{9.24}$$

The equations above clarifies that the requirements for the elevation controller, can't be met with a proportional controller. In order to compensate for this, a lead network is incorporated into the controller. In the following, it is desired to have a proportional controller to compare to this lead controller. For this proportional controller, K_p is chosen to be the value between the two above, ie. $K_p = 17.3$.

Design of Lead Compensation

The general expression for a lead network can be seen in equation (9.25). A lead network enables a controller to decrease the rise time, while the overshoot remains the same. This is done by raising the phase margin with a zero followed by a pole. This increased phase margin then allows for an increase of the crossover frequency, until the phase margin again is lowered to the original values. The increased crossover frequency results in increased system bandwidth and thus lower rise time.

$$\text{LEAD}(s) = \frac{1}{\beta} \cdot \frac{s \cdot \frac{\beta}{\omega_c} + 1}{s \cdot \frac{1}{\omega_c \cdot \beta} + 1} \tag{9.25}$$

where:

ω_c is the crossover frequency [rad/s]

The value of β can be calculated with equation 9.26.

$$\beta = \tan(\Phi_L) + \sqrt{(\tan(\Phi_L))^2 + 1} \tag{9.26}$$

where:

Φ_L is the phase lead [rad]

The design of a lead compensation takes place in the frequency domain. Knowing the minimum value of K_p, the crossover frequency ω_c is found. The value of K_p should be higher then 23.2 and are therefore chosen to 25. In figure 9.8 the phase margin and ω_c of the system can be seen. The phase margin of the system can then be changed to

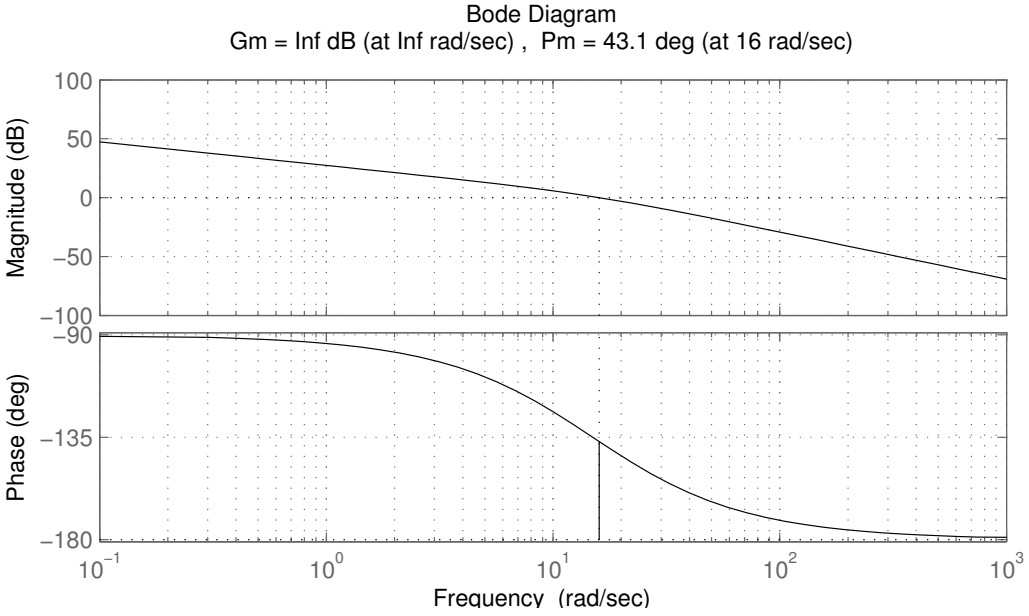


Figure 9.8: *This figure illustrates the phase margin of the open loop system without lead compensation.*

minimize the overshoot. From figure 9.9 on the following page it is seen that in order for M_p to be 10 % or less, the phase margin should be 60° or higher. Knowing that the phase margin of the system is 43.1° and needs to be 60°, the phase lead Φ_L can be calculated. This is done by subtracting the PM at ω_c from the wanted PM. The value of Φ_L then becomes 16.9°, this can be put into equation 9.26 on the preceding page:

$$\beta = \tan\left(\frac{16.9 \cdot \pi}{180}\right) + \sqrt{\left(\tan\left(\frac{16.9 \cdot \pi}{180}\right)\right)^2 + 1} \Rightarrow \beta = 1.35 \tag{9.27}$$

With the values of β and ω_c known, the lead network can be found from equation (9.25 on the facing page):

$$\text{LEAD}(s) = \frac{1}{1.35} \cdot \frac{s \cdot \frac{1.35}{16} + 1}{s \cdot \frac{1}{16 \cdot 1.35} + 1} \tag{9.28}$$

$$= \frac{0.063 \cdot s + 0.741}{0.046 \cdot s + 1} \tag{9.29}$$

The phase margin of the system with the lead network incorporated, can be seen in figure 9.10 on the next page. The stability criterion is met due to a phase margin of 60°, and thus no further frequency analysis of the elevation controller is necessary.

Effect of Design

By designing the controller with a lead network, no parameters are left to be chosen. The effect of sample frequency, steady state error and so on is calculated.

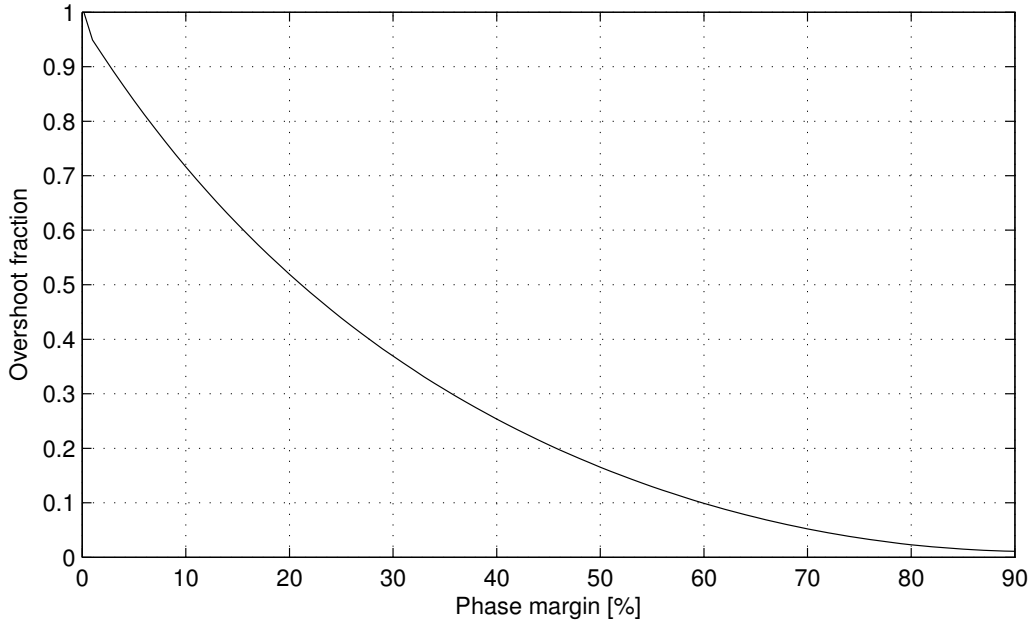


Figure 9.9: *This figure illustrates overshoot M_p as a function of phase margin PM. It is calculated on basis of equation (9.7 on page 67)*

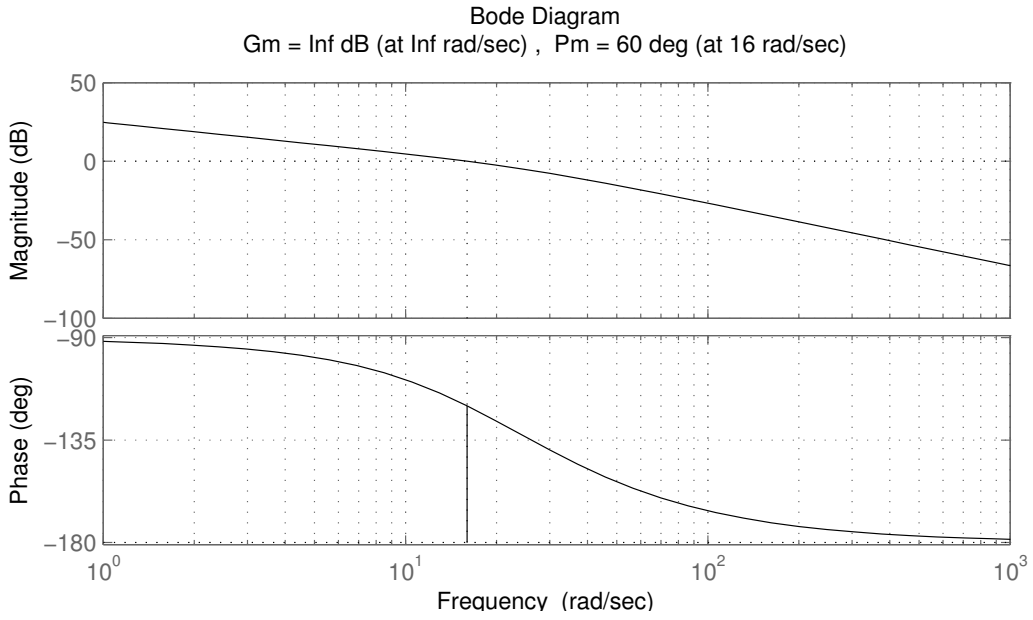


Figure 9.10: *This figure illustrates the phase margin of the open loop system with lead compensation.*

The steady state error of the system can be calculated in the same way, as for the azimuth controller. The elevation controller with lead compensation is also a type 1 system, which means that the steady state error of a ramp input is given by:

$$e_{\text{ss ramp}} = \frac{1}{K_v} \quad \text{[rad]} \tag{9.30}$$

where:

$$K_v = \lim_{s \to 0} sD(s)G(s) \tag{9.31}$$

In this case:

$$K_v = \lim_{s \to 0} s \cdot \frac{1.34 \cdot s + 15.87}{0.003 \cdot s^3 + 0.104 \cdot s^2 + 0.915 \cdot s} \Rightarrow K_v = 17.33 \tag{9.32}$$

Which means $e_{\text{ss ramp}}$ is given as:

$$e_{\text{ss ramp}} = \frac{1}{17.33} = 0.058\,\text{rad} = 3.32^\circ \tag{9.33}$$

In order to find the sample frequency ω_s, the bandwidth ω_{BW} of the closed loop can be found from a bode plot to be 25.4 rad/s. With known ω_{BW} the sample frequency is given as:

$$f_s \geq \frac{20 \cdot \omega_{\text{BW}}}{2 \cdot \pi} \Rightarrow f_s \geq 81\,\text{Hz} \tag{9.34}$$

In figure 9.11 the system with, and without the designed lead compensation can be seen. It is evident that the controller wouldn't be able to meet the requirements, without the lead compensation.

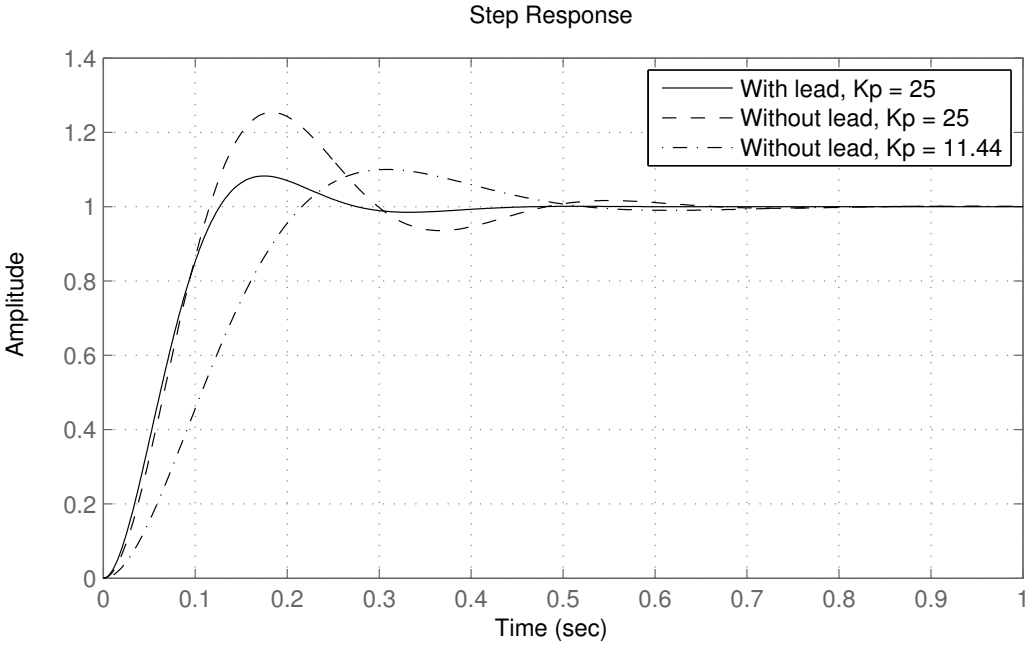


Figure 9.11: *This figure illustrates the effect of the lead network. Simulated values.*

9.3. Implementation

Both the azimuth and elevation controller are implemented on the ARM-board. The azimuth controller is only implemented as a proportional controller. The elevation controller is implemented as a proportional controller and as a lead controller. For the lead

controller all values are known, so the implementation lies in converting the continuous controller designed, to a discrete format that can be implemented on the ARM-board. The controllers implemented are as follows:

Azimuth

- A proportional controller: $D(s) = 19.1$

Elevation

- A proportional controller: $D(s) = 17.3$
- A proportional controller with lead compensation: $D(s) = \frac{0.063 \cdot s + 0.741}{0.046 \cdot s + 1}$

Before implementing the controllers on the ARM-board, some overall tasks have to be solved:

- The encoder signals need to be interpreted and converted into radians or degrees.
- A PWM frequency needs to be chosen.
- The GPS coordinates need to be converted to azimuth and elevation coordinates.
- A physical link between the ARM-board and the motors/encoders needs to be implemented.

9.3.1 Encoders

The encoders mounted on the azimuth and elevation motors are of the type 225771[32] from maxon motors. It is a rotary encoder that gives 128 counts per turn or a count for every 2.8°. There are two signals from each encoder to the ARM-board, consisting of an A signal and a B signal. The B signal is 90° delayed compared to signal A. The A signal from each encoder, are attached to an interrupt pin on the ARM-board. When an A signal goes from low to high, an interrupt routine is run. This interrupt routine checks if signal B is high too. If so, the motor must be turning in one direction, otherwise the motor must be turning in the opposite direction. In this manner, the motor rotation can be measured.

If both A and B are high the interrupt routine increments the encoder value, if not it decrements the value. An illustration of how signal A and B from the encoders work, can be seen in figure 9.12 on the next page. The encoder value are converted by dividing the encoder value with the value of an entire revolution, and then multiplying with 2π for radians, or 360 for degrees. How the interrupt routines are implemented in the software, can be seen in figure 9.18 on page 83. In order for the interrupt routine to work as described the value of B must be read before the dotted line in figure 9.12 on the next page. If this is not the case the software will not be able to know when to decrement the encoder value.

9.3.2 PWM Signal

It has been chosen to control the speed of the motors with a PWM signal but there are some pros and cons when choosing which PWM frequency the system should use[33]:

- Choosing a too high frequency, may interfere with the radio link. This is caused by the increased number of rising/falling edges on the PWM signal.

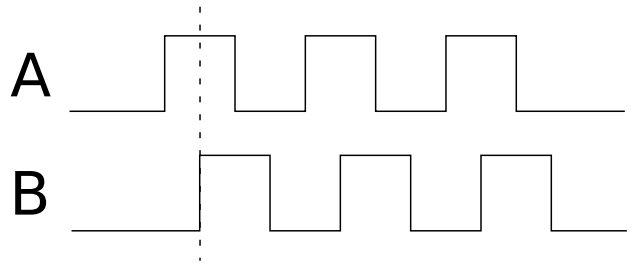


Figure 9.12: *The figure illustrates the relationship between signal A and B on the encoders.*

- Each switching between on and off of the PWM signal will result in little power loss in the MOSFET's inside the motor driver. Therefore the more time spent switching, the more power is wasted.
- The higher the switching frequency, the more stable is the current waveform in the motors. At high frequencies the inductance of the motor will smooth out the current wave, to an average DC current.

One way to choose a PWM frequency is to look at the motor parameters. By choosing a maximum deviation in current from the average current, the expression in equation 9.35 can be derived[1]. The expression is derived from the worst case, where the on and off periods in the PWM signal are equal.

$$f = \frac{R}{-2L \cdot \ln\left(1 - \frac{P}{100}\right)} \tag{9.35}$$

where:

f	is the PWM frequency.	[Hz]
R	is the motors internal resistance.	[Ω]
L	is the motors internal inductance.	[H]
P	is the maximum current deviation.	[%]

The values for the motor parameters R and L are known from section 8.1.2 on page 52. Because the resistance in the MOSFETS driving the motors are much smaller than the resistances inside the motors, these can be neglected. The frequency can then be calculated by choosing a value for P. A plot of allowable deviation and PWM frequency, can be seen in figure 9.13. A table with selected P values can be seen in table 9.3.2 on the next page.

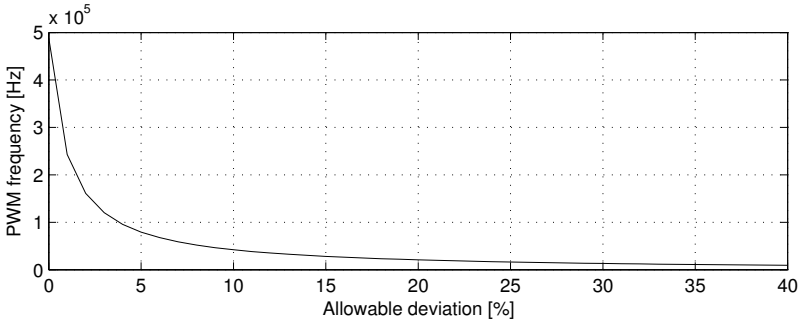


Figure 9.13: *The figure illustrates PWM frequency as a function of current deviation in percentage.*

The PWM frequency has been chosen to 120 kHz which gives a deviation of 4 %.

[1] It is chosen not to derive the expression in the rapport, but refer to [33] instead.

Percentage	PWM frequency
1	488.1 kHz
5	95.6 kHz
10	46.6 kHz
20	21.9 kHz
40	9.6 kHz
60	5.4 kHz
80	3.0 kHz

Table 9.1: *Current deviation in percentage at different PWM frequencies.*

9.3.3 Conversion of GPS data

When the ground station successfully receives a package containing a set of GPS coordinates, it must be able to translate this into a direction and thus point the antenna in that direction. In order to do so, the GPS coordinates must first be converted to a corresponding azimuth and elevation. To do this, the coordinates are extracted and by using them along with the coordinates of the ground station, the wanted azimuth and elevation can be calculated, using trigonometry. This section describes how this conversion is done.

Format of GPS Coordinates

According to the WARP specification, specified in appendix B on page 131, the GPS coordinates consist of 3 elements. These are longitude, latitude and altitude. The coordinates are spherical and specifies the position of an object on the surface of the Earth, with respect to sea level. Longitude is specified by degrees (0° - 180°), minutes (0.000 - 59.9999) and a letter specifying if the object is on the western (W) or eastern (E) hemisphere. Latitude is specified in the same way by degrees (0° - 90°), minutes (0.000 - 59.9999) and a letter (N or S). The altitude is specified in meters above the sea level.

Coordinate conversion

The most accurate and correct approach to handle the coordinates, is to first convert them from the spherical to a Cartesian coordinate system, and then perform the necessary trigonometry to calculate azimuth and elevation. This way, the curvature of the Earth is taken into account, and the system will be operational on a global scale. However this method is computationally intensive to use. Since the ground station and the satellite must be within radio communications range, the distance between them will always be relatively small. Therefore, the azimuth and elevation can be calculated through a simpler albeit approximated method.

By using the approximated method, the curvature of the Earth is assumed to be negligible within the area of interest, and the GPS coordinates are treated as if they were Cartesian. The procedure is as follows:

1. Degrees and minutes are combined as a floating point degree value for both latitude and longitude.
2. A conversion factor for the current latitude is calculated. The longitude factor is assumed constant for all coordinates.
3. The conversion factors are applied to latitude and longitude to convert the degrees to meters.

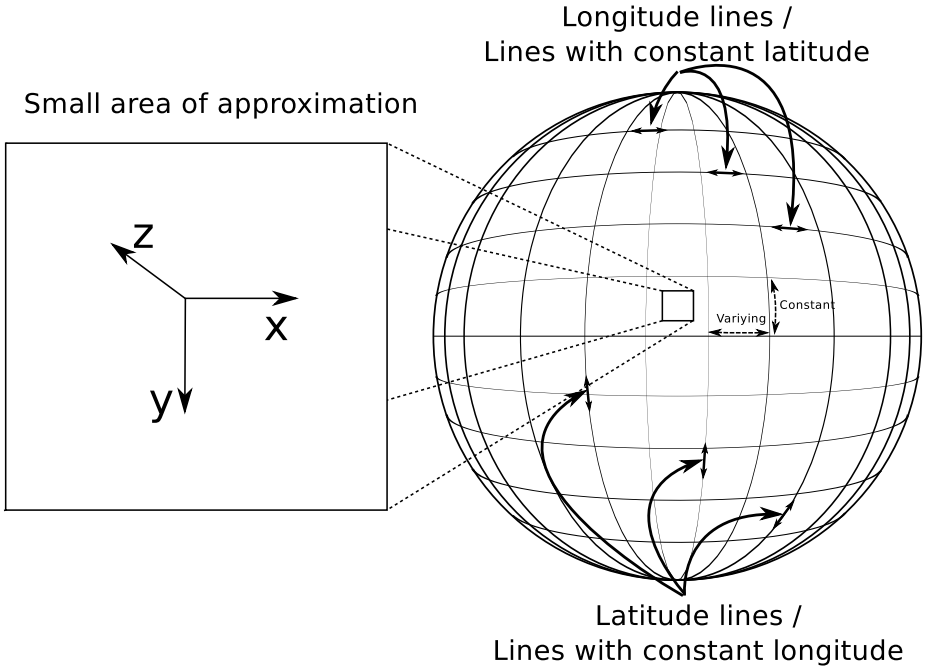


Figure 9.14: *An illustration of latitude and longitude coordinates, and the approximation used.*

4. The ground station position is subtracted from the satellite's and the ground station is placed at the origin of the coordinate system.

The conversion factors are used to convert the longitude and latitude coordinates to meters. In doing this, it is assumed that the Earth is a perfect sphere[2] whereby the distance between two consecutive degrees of latitude is the same everywhere. Thus, the conversion factor for latitude is constant. By knowing that the circumference of the Earth, going through the poles, is 40 008 km[34] the conversion factor can be calculated:

$$d_{\text{lat}} = \frac{40008}{360} = 111.134\,\text{km} \tag{9.36}$$

The conversion factor for degrees of longitude is not constant though, as the distance between two degrees will depend entirely on the latitude, as illustrated on figure 9.14. Again, by assuming that the Earth is a perfect sphere, the distance between two consecutive degrees of longitude can be calculated using the following expression:

$$d_{\text{long}} = \cos(\Phi) \cdot A \tag{9.37}$$

where:

d_{long}	is the distance between two consecutive degrees of longitude.	[m]
Φ	is the current latitude.	[°]
A	is the distance between two degrees at the equator.	[m]

The circumference of the Earth along the equator is 40075.16 km[34] and the value of A is given by:

$$A = \frac{40075.16}{360} = 111.320\,\text{km} \tag{9.38}$$

[2]Note that this is assumed only for individual calculations as different values for circumference are used for latitude and longitude.

Calculating Azimuth and Elevation

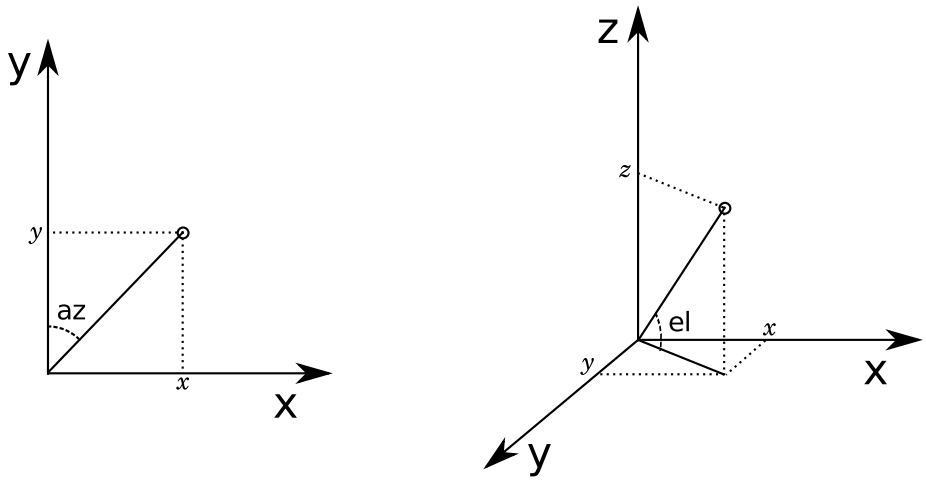


Figure 9.15: *An illustration of the angles that define azimuth and elevation.*

With latitude and longitude converted into meters, calculating azimuth and elevation is done by using trigonometry. To ease the notation, latitude, longtitude and altitude are henceforth denoted by x,y and z respectively. Since azimuth can be defined as the angle between the ground station and the satellite on the horizontal plane, as seen on 9.15, it can be calculated by:

$$\text{az} = \arccos\left(\frac{y}{\sqrt{x^2+y^2}}\right) \tag{9.39}$$

Elevation can be defined as the angle between the ground station and the satellite on a vertical plane, that contains both points. The angle can be calculated by:

$$\text{el} = \arcsin\left(\frac{z}{\sqrt{x^2+y^2+z^2}}\right) \tag{9.40}$$

Calculation Example

The following example shows how a conversion is done using real coordinates. The ground station and satellite positions are given by the following GPS coordinates, and the goal is to calculate the azimuth and elevation that points the antenna at the satellite.
Ground station
latitude: 56° 59.9243’ N
longitude: 9° 57.0225’ E
altitude: 0
CanSat
latitude: 57° 0.1404’ N
longitude: 9° 56.8074’ E
altitude: 400 m

The first step is to combine degrees and minutes:

$$\text{gs}_{\text{lat}} = 56 + \frac{59.9243}{60} = 56.998738^\circ \tag{9.41}$$

$$\text{gs}_{\text{long}} = 9 + \frac{57.0225}{60} = 9.950375^\circ \tag{9.42}$$

$$\text{sat}_{\text{lat}} = 57 + \frac{0.1404}{60} = 57.002340^\circ \tag{9.43}$$

$$\text{sat}_{\text{long}} = 9 + \frac{56.8074}{60} = 9.946790^\circ \tag{9.44}$$

Next, the conversion factor for longitude is found using eq. (9.37). The ground station is used as reference:

$$d_{\text{long}} = \cos(56.998738) \cdot 111320 = 60\,630\,\text{m} \tag{9.45}$$

The degrees can now be converted to meters:

$$\text{gs}_{\text{lat}} = 56.998738 \cdot 111134 = 6\,334\,497\,\text{m} \tag{9.46}$$

$$\text{gs}_{\text{long}} = 9.950375 \cdot 60630 = 603\,291\,\text{m} \tag{9.47}$$

$$\text{sat}_{\text{lat}} = 57.002340 \cdot 111134 = 6\,334\,898\,\text{m} \tag{9.48}$$

$$\text{sat}_{\text{long}} = 9.946790 \cdot 60630 = 603\,074\,\text{m} \tag{9.49}$$

The ground station position is now subtracted from the satellites

$$x = 603074 - 603291 = -217\,\text{m} \tag{9.50}$$

$$y = 6334898 - 6334497 = 401\,\text{m} \tag{9.51}$$

$$z = 400 - 0 = 400\,\text{m} \tag{9.52}$$

The values for azimuth and elevation can now be found using eq. (9.39) and (9.40):

$$\text{az} = \arccos\left(\frac{401}{\sqrt{(-217)^2 + 401^2}}\right) = 28.4^\circ \tag{9.53}$$

$$\text{el} = \arcsin\left(\frac{400}{\sqrt{(-217)^2 + 401^2 + 400^2}}\right) = 41.3^\circ \tag{9.54}$$

9.3.4 Motor Driver

In order for the system to be able to control the pan and tilt platform, a motor driver has been constructed. The motor drivers function is to provide the motors with the correct voltage level (12 V), and make it possible for the motors to consume the needed amount of current (1.03 A nominal). In other words, the motor driver takes care of the electrical link between the ground stations ARM-board, and the platform. An outline of how the motor driver, motors and ARM-board are linked together can be seen in figure 9.16 on the next page.

To control the speed of the motors, it has been chosen to use PWM signals from the ARM-board, as mentioned earlier. For direction control it has been chosen to use an output pin for clockwise(CW)- and one for counterclockwise(CCW) rotation of each motor. A schematic of the constructed motor driver can be seen in figure 9.17 on the following page.

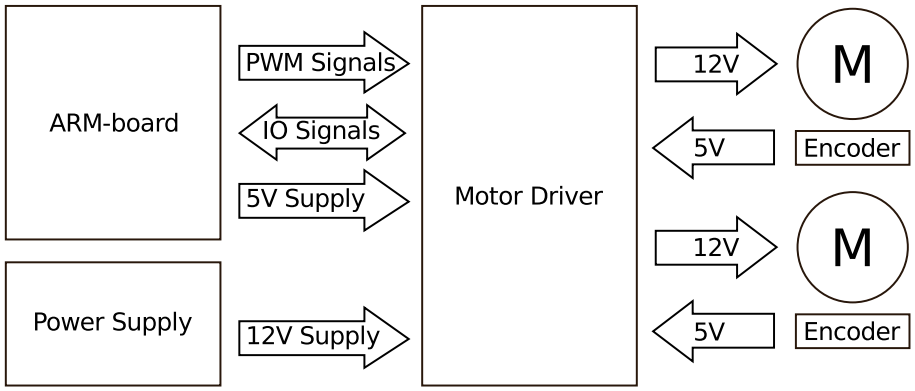


Figure 9.16: *This figure illustrates how the motor driver is linked together with the ARM-board and the motors.*

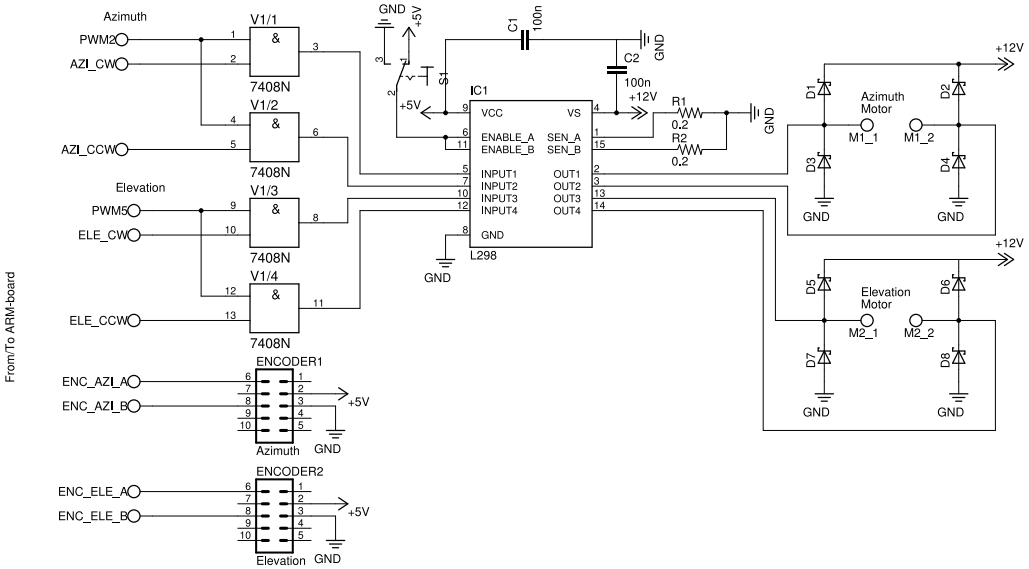


Figure 9.17: *This figure illustrates the schematic of the motor driver.*

The L298 IC[35] is a dual full-bridge driver, designed to drive inductive loads such as DC-motors. From the L298 datasheet[35] a standard application for driving a DC-motor has been chosen. The diodes function are to take care of the voltage inducted by the motors. The sense output can be used to provide overcurrent protection or just measuring the motor current. The AND gates are added because the PWM signal for driving a motor CW, is the same as driving it CCW. Output signals from the encoders are connected directly to input pins on the ARM-board.

9.3.5 Software Implementation

From the design of the controllers it is clear that they need to be sampled at different frequencies, and therefore should be run in separate cyclic tasks. For simplicity, it has been chosen to run the two controllers in the same task, though. A HRT-HOOD diagram of the controller software can be seen in figure 9.18 on the next page.

As mentioned, the controller can work both in manual mode and in automatic mode. To toggle between them, a package is sent from the RUC to the ground station. Routines handling the Ethernet link then calls the function `setAutoCtrl` with either a 0 or a 1

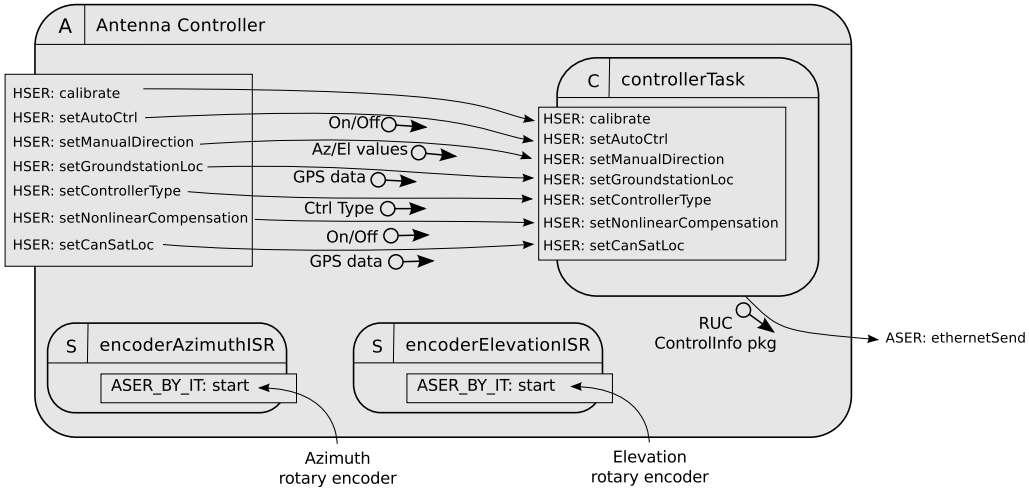


Figure 9.18: *HRT-HOOD analysis of the antenna controller software.*

as argument, where 1 will set it to automatic mode.

The controller pointing position depends on coordinates given as azimuth and elevation. In order for the controller to know these coordinates, it needs to know where it is pointing compared to north, and what its elevation position is compared to level. A calibrate function `calibrate`, which is called from the Ethernet handling routine, when a button on the RUC is pushed. The calibrate function clears the value of `currentAzimuth` and `currentElevation`. It is up to the operator of the systems task to make sure that the antennas pointing direction is north and that the elevation position is horizontal, when the system is calibrated.

In order for the controller to work, it needs an input in the form of a reference angle. The reference can be inputted either in manual mode or in automatic mode. In manual mode a package with azimuth and elevation position of the antenna is sent from the RUC to the ground station. When the ground station receives the package it calls the function `setManualDirection` which sets the global variables `desiredAzimuth` and `desiredElevation`, to the values inputted on the RUC.

Before the ground station can track a CanSat, it needs its own GPS position as a reference point. The location of the ground station can be specified in the RUC and sent over the Ethernet link. The Ethernet software then calls `setGroundStationLoc` with a pointer to the package containing the GPS data. The data is split in to altitude, latitude and longitude by the function `convertGPSstrToCoord`. The controller can now use these values as reference points to the GPS data, sent from the CanSat.

It is possible to choose between a proportional- and a lead controller. The idea is to observe and demonstrate what the difference in performance of the controller will be. A package can be sent from the RUC to the ground station with a number. This number indicates which controller type that should be used. The Ethernet software can then call to different functions depending on the number. The function `setControllerType` sets controller to run with or without the lead compensation. The function `setNonlinearCompensation` indicates if the non-linearity correction should be on or off in the controller. It should be noted that it is only possible to alter the elevation controller.

When the wireless link receives a CanSat package with GPS data, the wireless software, seen in figure 7.1 on page 48, calls the function `setCanSatLoc` with the GPS data. The data is first split into altitude, latitude and longitude. Afterwards the function `updateAzimuthElevation` is called, if the controller is in auto mode. This

function interprets the CanSat and ground station coordinates, in the way described in section 9.3.3 on page 78. The function then sets the azimuth and elevation values used as reference by the controller.

Azimuth Controller

The first thing to be done in the azimuth controller algorithm is to calculate the value of `output`. `output` is calculated by taking the global variable `desiredAzimuth` and subtracting the value of `encoderAzimuth`. The result is then multiplied by the chosen K_p. The value of `output` can be both positive and negative depending on which direction the antenna should turn. The output from the ARM-board is a PWM signal which is always positive. Thus, in order to make the antenna turn in both directions, the value of `lastVal_azi_out` is compared to the new `output` value, and logic pins are asserted or cleared. Finally the PWM duty cycle is set, and the value of `output` is saved to `lastVal_azi_out`. This algorithm can be put in a point form:

- Calculate `output` with: `output` $= K_p \cdot$(`desiredAzimuth`$-$`encoderAzimuth`).
- If `lastVal_azi_out` is ≥ 0 and the value of `output` is < 0, turn the antenna CW.
- Else if `lastVal_azi_out` is ≤ 0 and the value of `output` is > 0 turn the antenna CCW.
- Set the PWM duty cycle from the absolute value of `output`.
- Save the value of `output` to `lastVal_azi_out`.

Because of dry friction the offset found in section 8.5.2 on page 60 is added to the value of `output` when setting the PWM duty cycle.

Elevation Controller

The software implementation of the elevation controller differs from the azimuth controller in several ways. It isn't just a proportional controller, so the continuous equation needs to be converted into a discrete form that can be implemented in the software. It has also been chosen that the user should be able to switch between different types of controllers. The 4 different types that can be chosen are:

- Proportional controller.
- Proportional controller with non-linearity correction.
- Proportional controller with lead compensation.
- Proportional controller with lead compensation and non-linearity correction.

Continuous to Discrete Conversion

Because the lead elevation controller is designed in continuous time, it needs to be converted to discrete time, in order to be implemented on the ARM-board. In equation 9.55 the expression for the continuous controller can be seen. Figure 9.19 on the facing page shows a block diagram of how the continuous controller is converted to a digital controller.

$$D(s) = 25 \cdot \frac{0.063 \cdot s + 0.741}{0.046 \cdot s + 1} \tag{9.55}$$

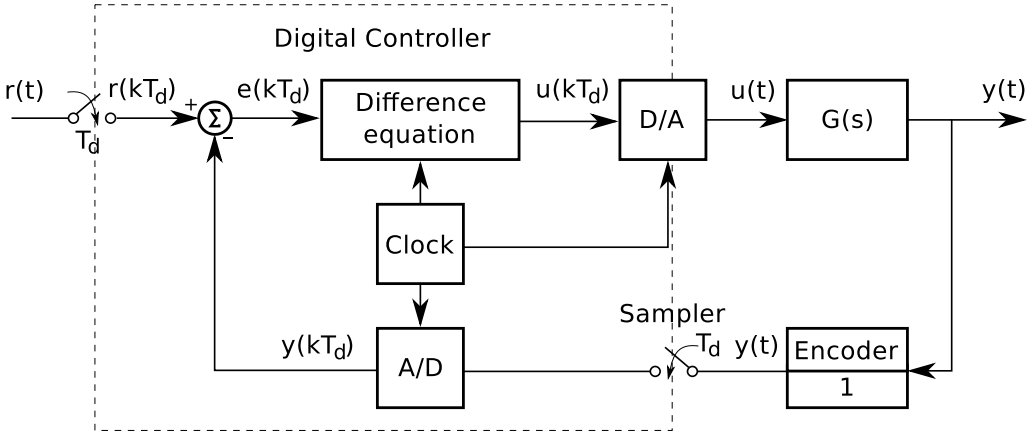


Figure 9.19: *Block diagram of a discrete controller. The difference equation is found from the continuous equation of the controller. T_d is the sample time.*

To convert the controller from continuous to discrete time, the bilinear transformation is used. The bilinear transformation is a first order approximation of the natural logarithm function. It maps the left half of the complex s-plane, to the interior of the unit circle in the z-plane. If the controller designed in continuous time is stable, it will also be stable when converted to discrete time with the bilinear transformation. The converting factor can be seen in equation 9.56.

$$s = \frac{2}{T_d} \cdot \frac{z-1}{z+1} \tag{9.56}$$

where:

T_d is the sampling time [s]

The required sampling frequency f_s for the controllers are 40 Hz and 81 Hz for azimuth and elevation respectively. These are minimum requirements. It is not possible to run the controller software with a sampling frequency of 81 Hz because of the way ARTOS handles cyclic tasks, more information about this can be found in chapter 5 on page 31. The only possible sampling frequency that meets the requirements is 125 Hz, so the sampling time becomes 8 ms. With the sample time known, the result of the bilinear transformation is:

$$D(z) = 25 \cdot \frac{0.063 \cdot \left(\frac{2}{0.008} \cdot \frac{z-1}{z+1}\right) + 0.741}{0.046 \cdot \left(\frac{2}{0.008} \cdot \frac{z-1}{z+1}\right) + 1} \tag{9.57}$$

$$= \frac{32.52 \cdot z - 29.57}{z - 0.84} \tag{9.58}$$

To implement the discrete controller into the software, an inverse Z-transformation needs to be done. To make the system causal, equation 9.58 is multiplied by z^{-1}. The expression for $D(z)$ then becomes:

$$D(z) = \frac{U(z)}{E(z)} = \frac{32.52 - 29.57 \cdot z^{-1}}{1 - 0.84 \cdot z^{-1}} \tag{9.59}$$

The difference equation can then be found by inspecting equation 9.59, to get:

$$u[k] = 0.84 \cdot u[k-1] + 32.52 \cdot e[k] - 29.57 \cdot e[k-1] \tag{9.60}$$

The expression in equation 9.60 can now easily be incorporated into an algorithm, that can be programmed. As it is seen In figure 9.20 on the following page, a simulation of

the continuous- and discrete controller coincide well. There are though a slightly higher overshoot on the discrete controller. This can be solved by raising the phase margin in the lead design. It is assessed that the overshoot doesn't pose a significant problem for the system. The simulink simulation of the continuous and discrete controllers can be found on the CD [3].

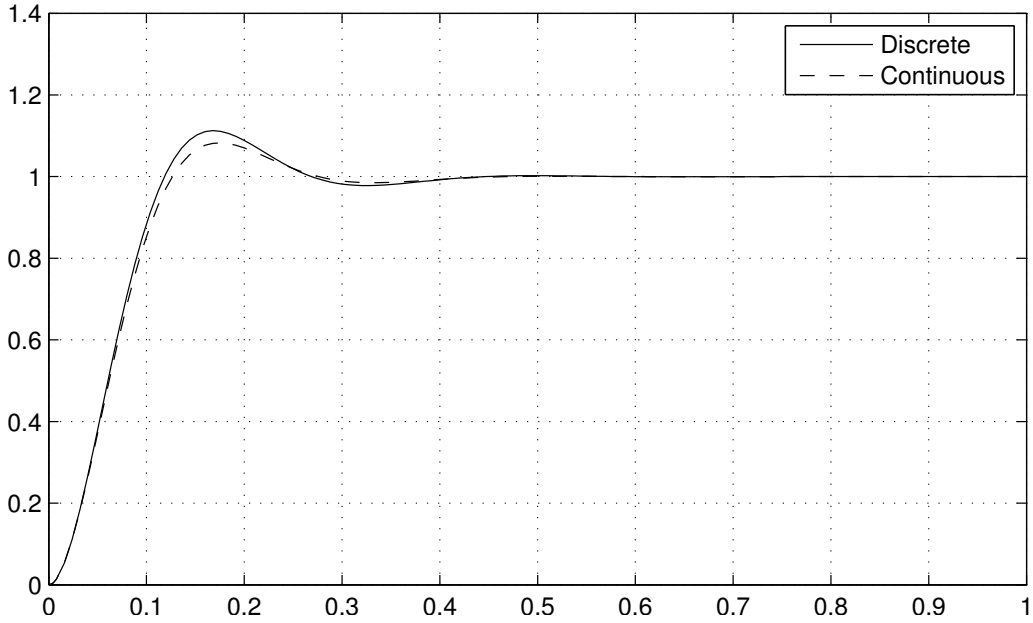


Figure 9.20: *Simulation of the continuous controller compared to the discrete controller.*

The type of controller that should be utilized, is selected on the RUC. The controller algorithm then needs to incorporate the selected controller. In the beginning of the algorithm, the selected controller calculates the output. Afterwards the algorithm is the same as for the azimuth controller. The calculations of output are as follows:

Proportional Controller The calculation of `output` is the same as for the azimuth controller.

Proportional Controller With Non-linearity Correction The calculation of `output` is almost the same as for the proportional controller. The only difference is that the non-linearity correction is added to the value of `output`.

Proportional Controller with Lead Compensation To calculate the value of `output`, equation 9.60 on the previous page is used. As it is seen, the expression needs both the previous input- and output values. The previous output- and input value are saved in the end of the algorithm.

Proportional Controller with Lead- and Non-linearity Correction The calculation is done the same way as for the 'Proportional Controller with Lead Compensation'. Non-linearity correction is added to the value of `output`.

9.4. Verification of Controllers

In this section the designed controllers are tested, to see if they perform as intended. The setup of the azimuth and elevation controller, most suited for a CanSat tracking, is then

[3] `/simulink/con_dis_controller.mdl`

tested according to acceptance test 6, to investigate if the system meets requirement 8 specified in the requirement specification.

A unit step is applied to each controller, to test these. This allows the theoretically calculated unit step response to be compared with the actually occurring unit step response. Since two different controllers have been designed for elevation, multiple tests are performed on this controller. The measurements are further documented in journal 4 on page 160. All graphs shown in the following are produced with the Matlab script [4].

9.4.1 Step Responses

Figures 9.21, 9.22 and 9.23 on the next page show measured and simulated response for a step input to the azimuth, elevation with proportional controller and elevation with lead controller respectively. The step is applied at time $t = 0.1\,\text{s}$. A step of 20° has been chosen, as a compromise between a small step which would result in large influence by non-linearities for small voltages and a large step which result in the voltage fed to the motor to reach saturation. For the elevation control, the measurements have been carried out with and without the non-linearity correction. The steps for elevation have been performed from an antenna location of 20° tilt to a 40° tilt, in order for the non-linearity problem to be present. Here follows a discussion of the results:

Azimuth

For azimuth, only a proportional controller has been designed. Measured and simulated response to an input step of 20° is shown in figure 9.21 on the following page. It can be seen that the simulated and measured response are almost identical. By inspecting the graph it is also seen that the requirements set to t_r and M_p, which respectively are 200 ms and 10 %, almost are met precisely. There is a slight steady-state error for the measured response, which theoretically should not be present, because the system is of type 1. This steady-state error is most likely caused by some non-linearities for the system at low motor input voltages. The dry friction has a relatively large torque compared to the torque delivered by the motor in this case. This could for example be caused by a slight deviation in the value of τ_c, which was determined in section 8.5.2 on page 60. The steady-state error is 0.5° (determined by inspecting the raw measurement results [5]). This is a very small value and is considered an acceptable steady-state offset.

Elevation

For elevation, 4 measurements have been performed. They are seen in figures 9.22 and 9.23 on the following page. The measurements for the proportional controller and for the lead controller show the same characteristics and deviations from the simulated responses. Therefore, they will be discussed collectively in the following.

The measured and simulated results doesn't follow as well as for azimuth. The measurements have a considerable higher overshoot. This is probably caused by some deviation between the model and reality, either some non-linearity or inaccurate model parameter values. It is here noted that the elevation model mainly differentiates from the azimuth model in two ways:

- The elevation is affected by gravity differently at different locations. This non-linearity has been tried cancelled by adding a non-linearity correction. It can be seen in the figures, that the responses with non-linearity correction enabled have

[4] /journals/controller/processing.m
[5] /journals/controller/measurements/stepaziRegInfo.csv

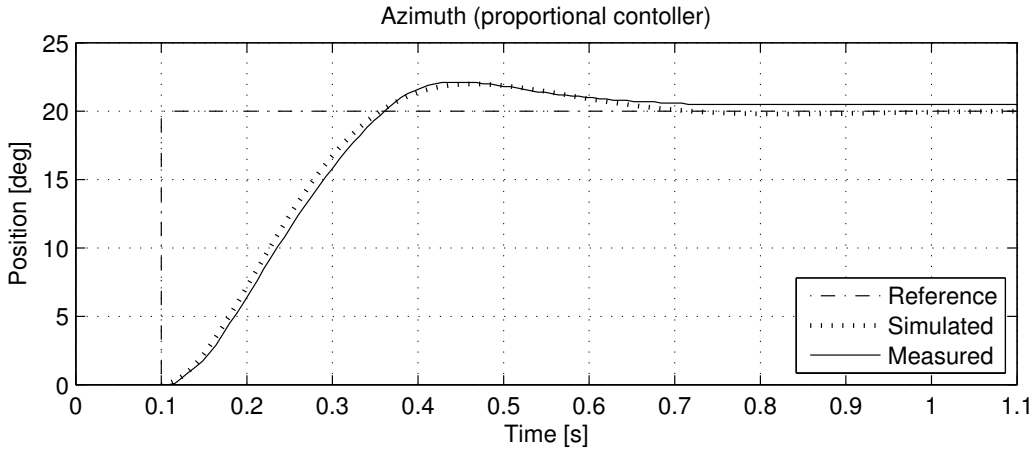


Figure 9.21: *Simulated and measured response to a 20° step for azimuth.*

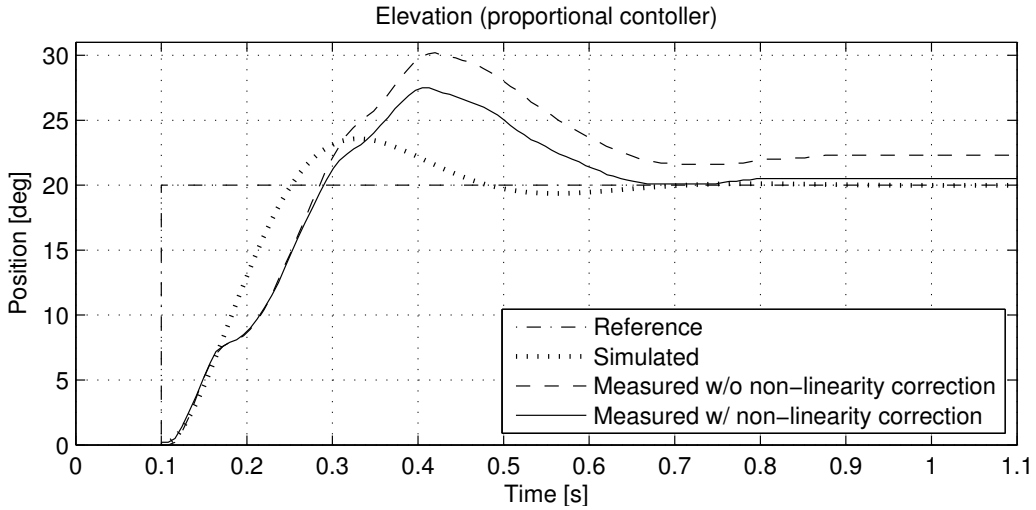


Figure 9.22: *Simulated and measured response to a 20° step for elevation with proportional control.*

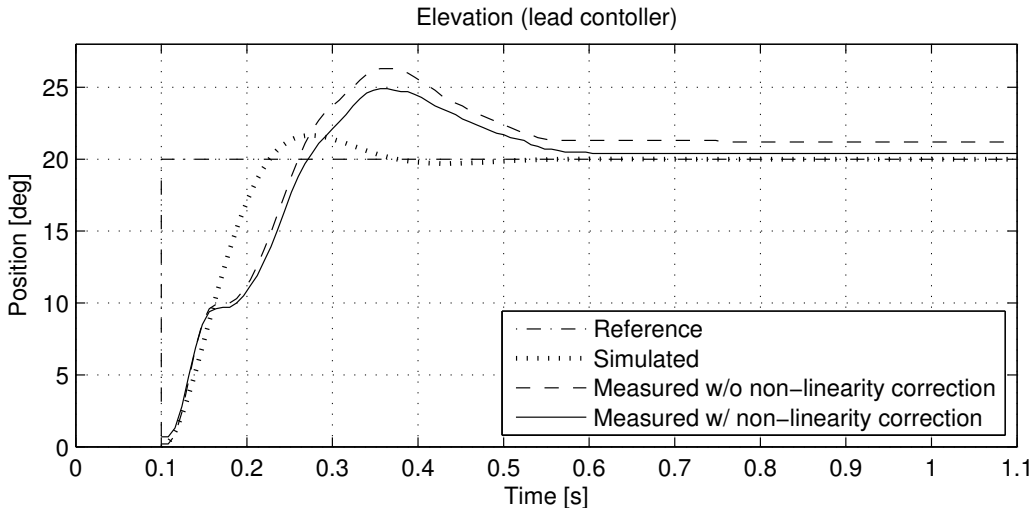


Figure 9.23: *Simulated and measured response to a 20° step for elevation with lead control.*

a better response with less overshoot and less steady-state error. The correction thus seem to be able to at least decrease the effect of this non-linearity.

- For elevation the motor only has to move the antenna, whereas for azimuth the motor must rotate the whole pan- & tilt platform. This results in the elevation model to be more sensitive to unforeseen forces, as these will be relatively higher compared to the forces that are modelled in the system. This is also seen in the figures, as the measured results for azimuth are more "smooth" than for elevation.

It thus cannot be concluded if the deviation from the simulated values is caused by deviations in the model parameters or that it is caused by non-linearities.

All the measured responses follow the simulated responses well, until a position of about 10°. At this point, the angular velocity decreases very fast, for the lead controller it almost decreases to 0. Within 50 ms, the antenna movement continues again. This is a very strange behaviour, that at first cannot be explained by non-linearities or model parameter values. It has not been possible to determine what causes this effect.

Because of the above mentioned it has not been possible to meet the requirements for t_r and M_p which respectively are 100 ms and 10 %. It is acceptable that these are not met, as they were simply design criteria used as a reference when designing the controller.

Chosen Controller

It can be seen that the controller that has the best response to the step input is the lead controller with non-linearity correction enabled. This controller has the smallest overshoot and almost no steady-state error. It can furthermore be seen that after 200 ms, the response never deviates more than 5° from the reference, which is less than the maximum allowed deviation of 15°.

9.4.2 CanSat Launch Simulation

This test is performed according to acceptance test 6, to test if it fulfills requirement 8 of the requirement specification. The test procedure is described in test 6 of journal 4 on page 160.

To test the performance of the tracking during launch of a CanSat, the result from section 2.3.1 on page 9 is used to find the angular position of the CanSat during a launch. This angle is applied as an input to the system. This is a simulation of the elevation position that would be fed to the controller during launch. The requirement of the controller is that it may never deviate more than 15° from the input reference value. The input reference values are discretized to a sampling time of 200 ms, as this is the sampling time for the GPS device in the CanSats.

Figure 9.24 on the next page shows the measured result to this input. By inspecting the raw measurement data [6] , the maximum deviation between the reference and measured value is found to be 4.5°. This is below the required 15° and requirement 8 from the requirement specification has thus been fulfilled. This simulation is based on the ground station being located 400 m from the launch site. It is assessed that because the maximum deviation is allowed to be 15° it wouldn't be a problem having the antenna platform placed closer to the launch site, even though this would result in a faster rising curve.

By inspecting figure 9.24 on the following page in detail it can be seen that the movement of the antenna is jerky. This happens because the controller is so fast, that it is almost able to follow the stair-case curve fed as input. (This may be more obvious

[6] `/journals/controller/measurements/curvetraceLeadnonRegInfo.csv`

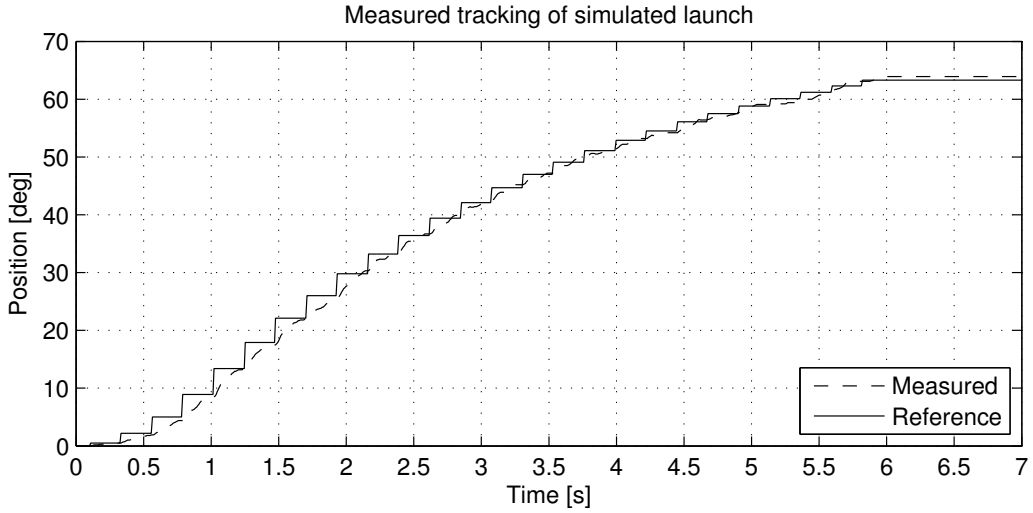


Figure 9.24: *Measured response to an input reference simulating the launch of a CanSat. Lead controller with non-linearity correction enabled.*

by looking at the graph in matlab, where it is possible to zoom in, see [7].) This may damage the motors over time because of the peaks in current, from stopping and starting the motors rapidly. It could thus be an idea to extrapolate the input data to give a more smooth curve for the controller to follow and thereby avoid the stair-case input shape.

Summary

In this chapter the controllers for the antenna positioning system have been designed. For azimuth, a single proportional controller has been designed. For elevation, a proportional and a lead controller has been designed. By comparing these, both in simulations and measurements, it has been determined that the lead controller is the one that is best suited for tracking the CanSat. By simulating a CanSat launch and feeding this into the designed controller, it has been shown that the system is able to track the CanSat in a satisfactory way.

[7] `/journals/controller/processing.m`

CHAPTER 10

Remote User Client

In this chapter, the design and construction of the remote user client (RUC) is described. The RUC needs to enable a remote user to adjust and control the ground station antenna, and send commands to the CanSat and ground station itself. It must also enable the user to easily gain access to CanSat telemetry data both during and after a CanSat flight, and log all relevant activities. In order to accomplish these functionalities, a Java based graphical user interfaced (GUI) program has been designed. To ensure a reliable communication between the ground station and the remote user client, an Ethernet link has been utilized. Therefore, the RUC needs to support this kind of connection. The packages sent over this connection will follow the RUC protocol described in appendix C on page 135. Consequently the RUC must adhere to this protocol. The code designed in this chapter is located here: [1] .

The following demands from the requirement specification, described in section 3.2 on page 17 are crucial for the RUC, to ensure the wanted product behavior.

- *Requirement 2. Must implement and adhere to TCP/IP and Ethernet protocols.*
- *Requirement 4. The RUC must save all received data as a comma separated values file (CSV).*
- *Requirement 5. If the RUC crashes, any data that already has been received, must not be lost.*

Note that the requirements are numbered according to the requirement specification. These requirements are tested for this module at the end of this chapter.

10.1. Overview and design

In this section the basic structure of the RUC will be explained. In order to gain a better understanding of the RUC, a use case diagram of its functionalities is made. This use case diagram is based on such features as the ability to send/receive packages, establish an Ethernet connection, save information in CSV files, interpret received telemetry data, display information and interact with the user through a GUI. The use case diagram of the RUC can be seen in figure 10.1 on the next page.

[1] `/ruc`

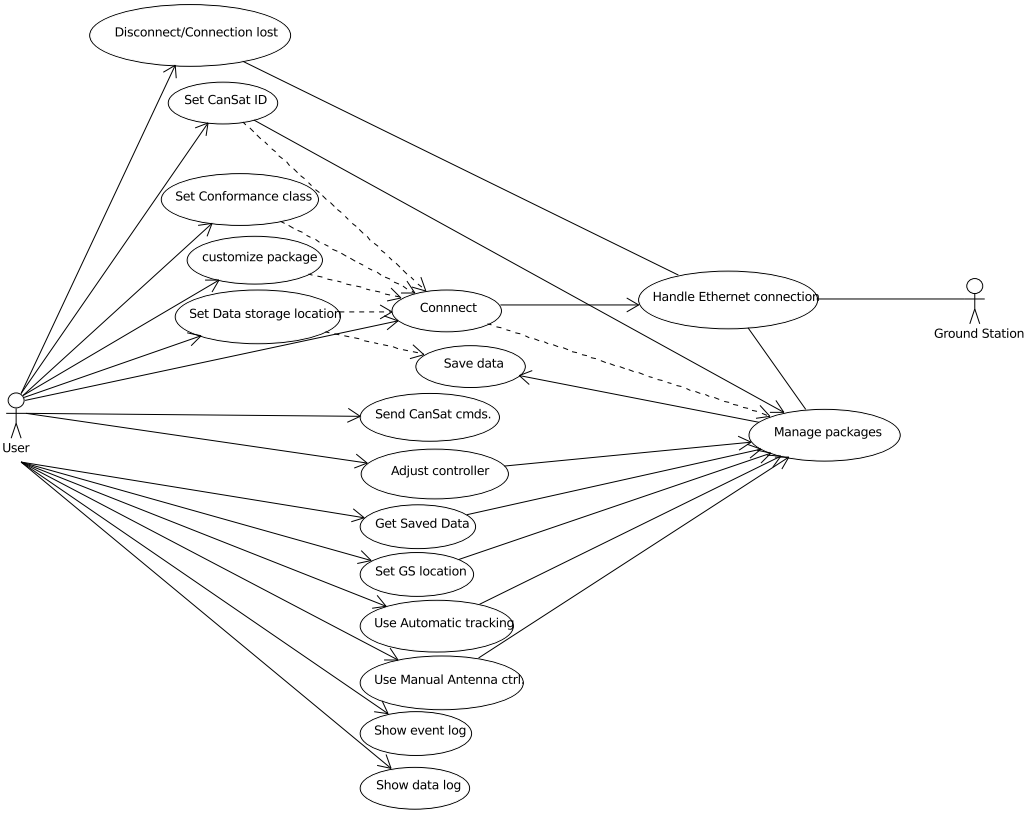


Figure 10.1: *Use case diagram for the RUC. The punctured arrows are dependencies. The normal arrows shows the flow of events in the RUC.*

The RUC will have a graphical interface. As a result, the GUI needs to support a number of user inputs, as shown on figure 10.1. Additional information about the design of the GUI can be found in section 10.2 on the next page.

Since the Java language is object oriented in nature, the program will be divided into classes. To initiate the GUI upon program launch, a class called `GroundstationApp` is created. For establishing/disconnecting the Ethernet connection, receive and send data through the Ethernet connection and to handle the RUC protocol, as described in appendix C on page 135, a class named `GroundstationConnection` is created. To extract data from type 0 packages, interpret these according to the user-specified data types and write the CSV files, a class named `GroundstationData` is created. For drawing the GUI, respond to user inputs and update the GUI, a class called `GroundstationView` is created. A class diagram of this can be seen in figure 10.3 on page 94.

In order for the `GroundstationData`-class to interpret the received data, an interface named `Type` is used. This interface allows access to eight different classes, capable of interpreting data into several types, and storing them. The following classes implements the interface: `FloatType`, `SignedByte`, `SignedShort`, `SignedInt`, `StringType`, `UnsignedByte`, `UnsignedShort` and `UnsignedInt`. After the interpretation, data is stored in an array list. The `Type` interface is able to extract information from this array list as well. Notice that the user-specified names for each data type is stored within each instance of the data types. The names can also be extracted through the `Type` interface. The structure of the interface can be seen illustrated through the use of a class diagram on figure 10.2 on the facing page.

A class diagram of the RUC can be seen on figure 10.3 on page 94. For simplification, some attributes and methods are not included in the diagram and some encapsulates

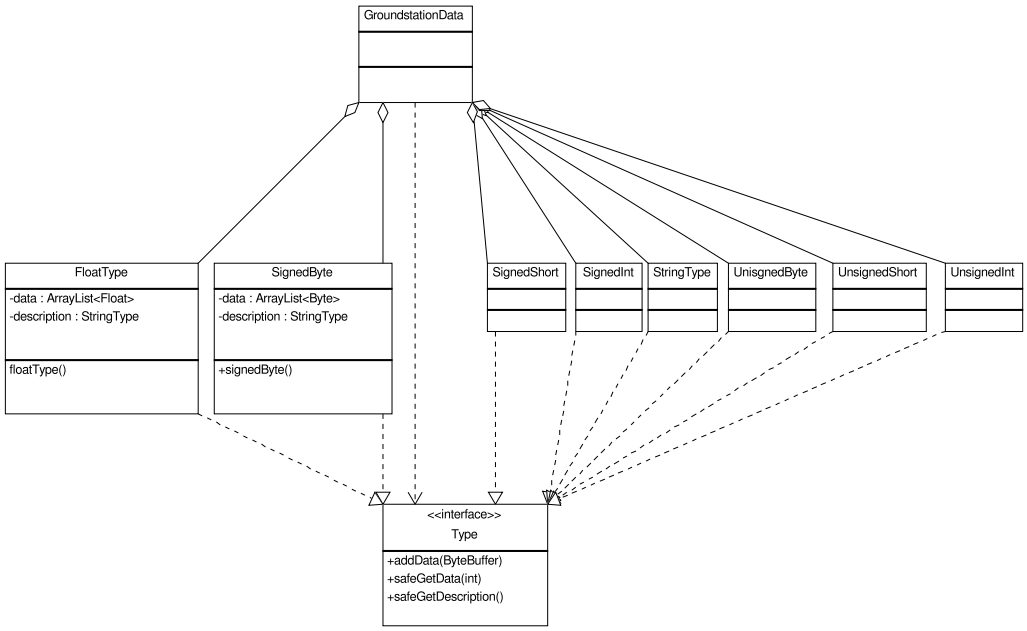


Figure 10.2: *Class diagram showing the interface named* `Type`*. Notice that most of the classes in the interface have been simplified or left blank, in order to maintain the overview.*

several of the methods/attributes that are actually used in the code. Therefore, public/private indicators have been removed.

10.2. User Interface and Functionalities

In order to allow the remote user easy access to the ground station, a GUI for the RUC is designed. The interface is divided into 4 tabs:

- Configuration
- Ground Station Control
- Event Log
- Data Log

The content of these tabs is discussed in the following.

10.2.1 Initial Connection

When the GUI is first presented to the user, a number of choices are available. In section 10.2.2 on page 95, a description of the selectable datatypes is given, which needs to be specified before connecting to the ground station. Furthermore, the user needs to specify whether the ground station will be using Conformance Class 1, or Conformance Class 2. This specifies whether automatic CanSat tracking is available, as described in appendix B on page 131. The PC-Ground Station panel can be seen on figure 10.4 on the following page. In order to connect to the ground station, the user needs to know the IP-Address of the ground station, which will be using TCP port 8. Also, the user needs to type in the CanSat ID. By clicking the 'Connect' button, a connection will be established, after the user has specified a filename for the CSV file.

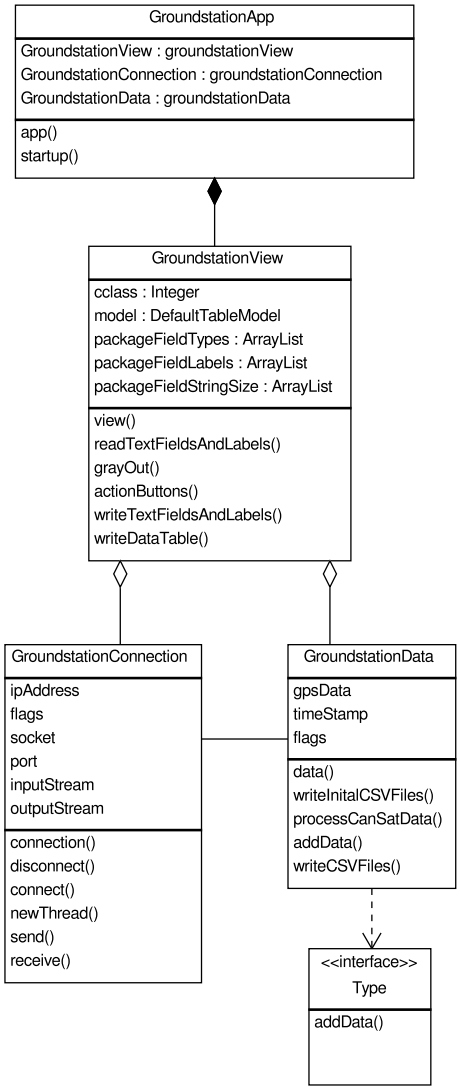


Figure 10.3: *Class diagram showing the structure of the RUC. Notice the class attributes and methods have been simplified and renamed, in order to maintain the overview. The public and private indicators, have been removed from the attributes and methods.*

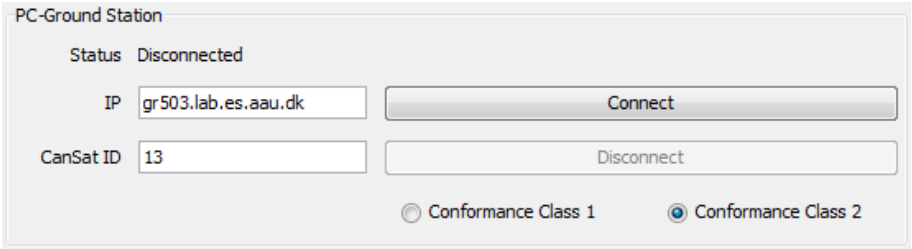


Figure 10.4: *The PC-Ground Station panel, as seen in the RUC.*

Upon making the initial connection, the RUC specifies the current settings, by sending a number of packages to the ground station. These are seen in the eventlog in figure 10.16 on page 100. The default packages are as follows.

- SetSatID package 129 with ID: 13
- GSCmds package 131 Operation 4 'Manual Antenna Control'
- GSCmds package 131 Operation 5 'Use P-Controller'
- GSCmds package 131 Operation 9 'Disable non-linearity correction'

By sending these initial packages, the ground station will know what settings to use. The above settings specifies that the CanSat ID should be '13', the antenna should be controlled manually from the GUI, and a P-Controller should be used to control the antenna, with the non-linearity correction disabled.

If the user disconnects, the CSV-files will be closed properly, and the connection will be closed. Similarly, closing the RUC will perform the same action before exiting the program.

10.2.2 User Selected Data

In the RUC protocol specification in appendix C on page 135 it can be seen that the CanSat package inside package type 0 contains a custom part, called the payload. In order for the RUC to interpret this data correctly, it is necessary for the user to specify, which data should be expected. The panel in which this is implemented, can be seen on figure 10.5.

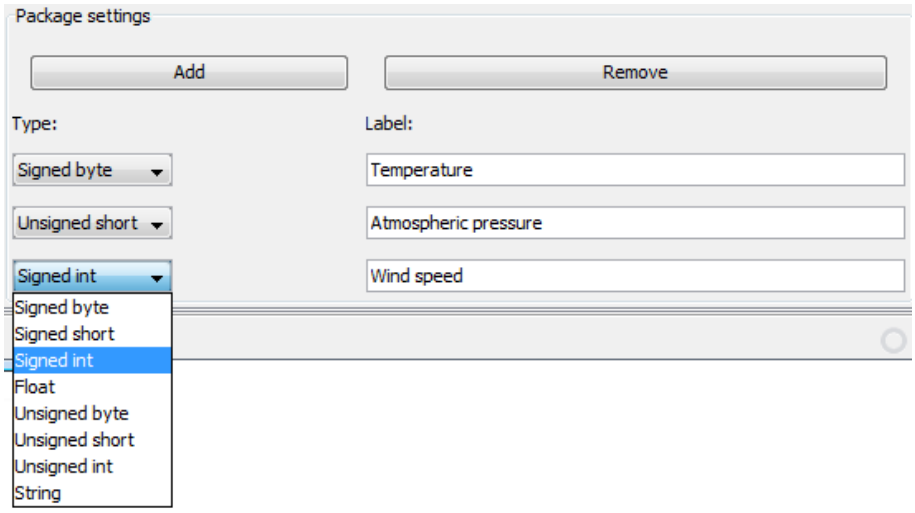
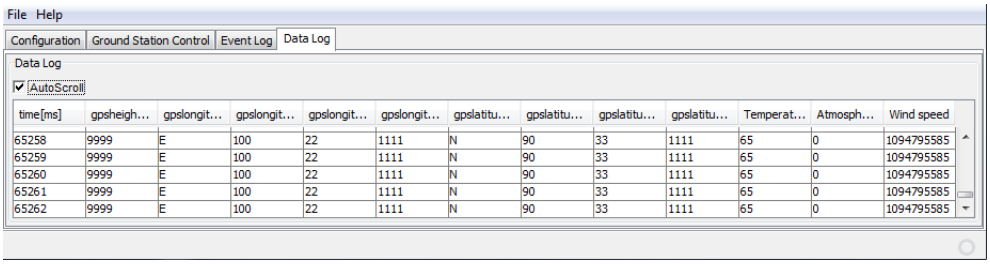


Figure 10.5: *Package settings panel in the GUI. Expected data is set to the following: Signed Byte labelled Temperature, Unsigned Short labelled Atmospheric pressure and a Signed Integer labelled Wind speed.*

The drop down boxes seen in figure 10.5 allows the user to choose between several data types. The text fields allows the user to label the data. The add button adds another data box, and the remove button removes the most recently added data box. Once a connection is established, the buttons and text fields seen in picture 10.5 will be grayed out. Once the data is received it will be written to the data log. Here the names of each data type will match the names given by the user, as seen in figure 10.6 on the following page.



time[ms]	gpsheigh...	gpslongit...	gpslongit...	gpslongit...	gpslongit...	gpslatitu...	gpslatitu...	gpslatitu...	gpslatitu...	Temperat...	Atmosph...	Wind speed
65258	9999	E	100	22	1111	N	90	33	1111	65	0	1094795585
65259	9999	E	100	22	1111	N	90	33	1111	65	0	1094795585
65260	9999	E	100	22	1111	N	90	33	1111	65	0	1094795585
65261	9999	E	100	22	1111	N	90	33	1111	65	0	1094795585
65262	9999	E	100	22	1111	N	90	33	1111	65	0	1094795585

Figure 10.6: *Illustration of the data log in the GUI. Expected data is set to the following: Signed Byte labelled Temperature, Unsigned Short labelled Atmospheric pressure and a Signed Integer labelled Wind speed. Notice this data log is specified as conformance class 2. As a result, GPS data is added.*

The check box seen on figure 10.6 enables auto scroll. This enables automatic scrolling to the most recent data in the table, whenever new telemetry data is received.

The received data is also written to a CSV file. This includes the GPS data if conformance class 2 is specified. New information will be written to the CSV file whenever a package type 0 is received. Doing so, ensures the data is saved, if the RUC should crash, and also allows easy data extraction, as CSV is a well established format. Inside the CSV file the data types will be labelled as to match the labels written in the GUI. The location of this CSV file is chosen by the user in a dialog box, before a connection is established. An example of such a CSV file can be seen in figure 10.7.

```
Temperature,Atmospheric pressure, Wind speed
65,0,1094795585
65,0,1094795585
65,0,1094795585
65,0,1094795585
65,0,1094795585
```

Figure 10.7: *Snapshot of a data CSV file example. Expected data is set to the following: Signed Byte labelled Temperature, Unsigned Short labelled Atmospheric pressure and a Signed Integer labelled Wind speed.*

A CSV file containing the Azimuth and Elevation information described in section 10.13 on page 98, will also be created, together with the data CSV file. This CSV file will be placed in the same directory as the data CSV file, with the text RegInfo added to its filename. Information written to this CSV file will be extracted from received type 1 packages in the RUC protocol, which can be seen in appendix C on page 135. An example of such a CSV file can be seen in figure 10.8.

```
CurrentAzimuth,CurrentElevation,WantedAzimuth,WantedElevation,regtimestamp
-1,-1,-241,-241,4279238415
-1,-1,-241,-241,4279238415
-1,-1,-241,-241,4279238415
-1,-1,-241,-241,4279238415
-1,-1,-241,-241,4279238415
-1,-1,-241,-241,4279238415
-1,-1,-241,-241,4279238415
```

Figure 10.8: *Snapshot of a control CSV file example. The data types contained within this CSV file are fixed.*

The CSV file illustrated in figure 10.8 will allow the user easy access to controller data about the antenna tracking, and thus provide useful information during debugging and testing of the controller. This CSV file will always contain the information within the ControlInfo packages.

10.2.3 Ground Station Location

In order to use automatic tracking, the ground station must know its own location. Because of this, the RUC must implement a way for the user to enter this information. Such an implementation can be seen on figure 10.9.

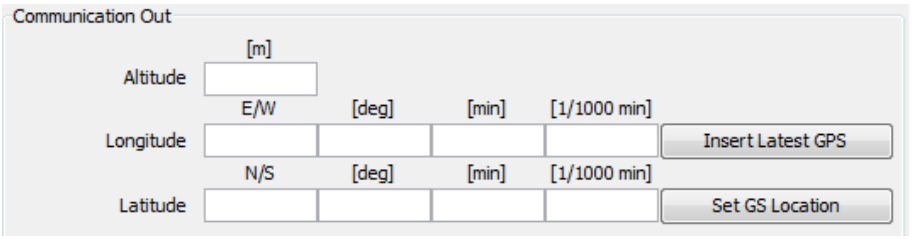


Figure 10.9: *Communication Out panel in the RUC. The text fields and buttons are used to set the ground station location. If no ground station location is set, the automatic antenna tracking button is grayed out.*

Notice this functionality is used for conformance class 2 only. If no ground station location have been set, the automatic antenna tracking button will be grayed out, until it is.

The location is specified in GPS coordinates, and thus entered in the same syntax, as the GPS coordinates transmitted by the CanSat. This is done to allow easier implementation on the ground station. The Set GS Location button seen in figure 10.9, sends a package of type 130 to the ground station, as specified in the RUC protocol, see appendix C on page 135. This package will contain the information typed into the 9 text fields. To ensure that a valid GPS location have been entered in these text fields, input validation is performed on all these text fields before transmission. The Insert Latest GPS button, seen on illustration 10.9, will auto fill the text fields with the latest GPS location, received by the ground station from the CanSat. This functionality will allow the user to quickly set the ground station location, by simply holding the CanSat next to the ground station and clicking the insert latest GPS button, followed by a click on the Set GS Location button.

10.2.4 CanSat Commands

The user must be able to send commands to the CanSat, by typing them into the GUI. The selected conformance class plays no role in this operation. The CanSat commands consists of a number between 0 and 255. Since the function of each CanSat command is unspecified in the RUC protocol layer, see appendix C on page 135, and thus interpreted individually by each CanSat, these commands will simply be typed into a text field. To send a CanSat Command, the user must click the send button.

Upon clicking this button, a package type 131 containing the CanSat command, is sent. As a way to keep the user from sending CanSat Commands before a connection to the ground station is established, the text field and send button will be grayed out as long as the RUC remains disconnected. Because CanSat commands must be acknowledged by the CanSat, the send button and text field are also grayed out until an acknowledge package (RUC protocol package type 2) is received, as specified in the RUC protocol. This is done to ensure that all CanSat commands are received, and to keep the user from flooding the radio link from the ground station to the CanSat. Furthermore, a status label is placed above the text box to inform the user of the current acknowledge status. An illustration of these functionalities can be seen on figures 10.10 on the following page, 10.11 on the next page and 10.12 on the following page.

Figure 10.10: *No Ethernet connection established. Send button and text field grayed out.*

Figure 10.11: *Ethernet connection established. Send button and text field enabled.*

Figure 10.12: *Ethernet connection established, but awaiting acknowledge. Send button and text field grayed out.*

Since the commands are limited to values between 0 and 255, input validation is performed when the user clicks the send button. If the CanSat command is invalid, the package will be dropped, and the user will be redirected to the event log. The send button, status label and text field are placed in the communication out panel.

10.2.5 Antenna Control

In order to control the antenna when tracking is set to manual, the GUI interface seen on figure 10.13 is implemented in the RUC.

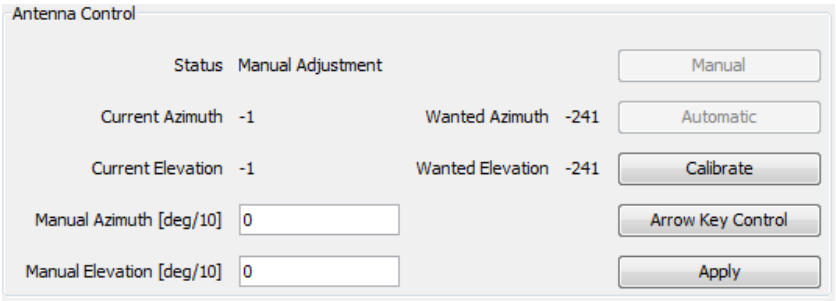


Figure 10.13: *The Antenna Control panel found in the RUC GUI. For incoming information about the antenna, package type 1 in the RUC protocol is received. For outgoing, package type 128 is used.*

Note that the status label, as well as the Manual, Calibrate and Automatic buttons seen in figure 10.13 are described in section 10.2.6 on the next page.

The Current Azimuth and Current Elevation labels seen in figure 10.13, informs the user about the current position of the antenna on the ground station. The Wanted Azimuth and Wanted Elevation indicates what position the antenna is moving towards. This information is useful for both remote controlling of the antenna, and for debugging the designed controller for the antenna. For debugging reasons, both current and wanted azimuth and elevation are saved into a CSV file called RegInfo, as further described in section 10.2.2 on page 95. The angles written in these labels are specified with the unit one tenth of a degree. Incidentally, 47 degrees would be written as 470. This information is retrieved through package type 1 in the RUC protocol.

The input fields Manual Azimuth and Manual Elevation seen on figure 10.13, are for typing in a specific direction, in which the antenna is to point. To apply the new setting, the user would have to click the apply button, which would send a package type 128 to the ground station with the new setting. The angle entered here is in the same format

as the status labels. The Azimuth is limited to values between +1800 and -1800, and the Elevation is limited to values between +700 and -400. These Azimuth and Elevation limits are set to prevent the antenna from damaging itself.

The button called Arrow Key Control, in figure 10.13 on the preceding page, allows the user to use the keyboard arrow keys for controlling the antenna, as long as the Arrow Key Control button is in focus. Each time a keypressed event from one of the arrow keys is captured, the angle is changed 3 degrees, or to the limits, and a package type 128 is send with the new values.

10.2.6 Ground Station Commands

In order to send commands from the RUC to the ground station, a package type 131 is specified in the RUC protocol in appendix C on page 135. It can be seen from the RUC protocol, that each ground station command has a valid range between 0 and 255, even though most of the numbers aren't used. Since each command number serves a specific function, their functionality is implemented with buttons. All these buttons are grayed out until a connection to the ground station is established. Command 5,6,7,8 and 9 are implemented with the buttons, seen on figure 10.14.

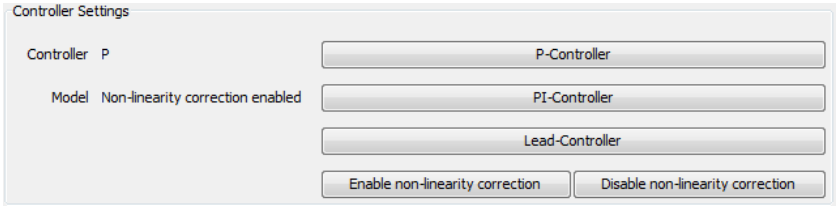


Figure 10.14: *Controller panel in the RUC. The buttons are used to set the controller options on the ground station.*

These buttons manages which controller and model the ground station uses for controlling the antenna. The labels seen on figure 10.14 indicates which model and controller is currently selected.

Clicking the Get Saved Data button, as seen on figure 10.15, will send a ground station command package 3.

Notice the PI-Controller and data storage for the Get Saved Data feature, was never implemented in the ground station. Clicking these buttons will send the correct packages, although no corresponding action will be performed by the ground station.

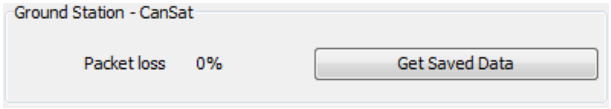


Figure 10.15: *Ground Station - CanSat panel. The Button Get Saved Data is used to send the ground station command 3. The status label 'Packet loss' informs the user about the packet loss rate on type 0 packages.*

The label 'Packet loss' seen on figure 10.15, informs the user of the packet loss. This packet loss is calculated from the package number set by the CanSat on all type 0 packages. The CanSat increments this number by 1 each time a new package is send. If the RUC receives packages skipping some numbers, this will indicate the packet loss.

Command number 0, 1 and 4 are used to specify whether the ground station should track manually, automatically or calibrate the antenna, respectably. These are implemented in the Antenna Control panel with the buttons Manual, Automatic and Calibrate seen on picture 10.13 on the preceding page.

When using conformance class 1, the user will only be able to use the manual antenna control, and the calibrate button. If the RUC is in conformance class 2, the user can enable automatic antenna tracking by specifying the ground station location. Until then, the Automatic command is grayed out. This is done, because the automatic CanSat tracking can't function until the ground station is aware of its own location. Notice a status label is placed in the Antenna Control panel, see figure 10.13 on page 98, to inform the user of the current tracking being used.

10.2.7 Event Log

In order to keep track of current and past events, a log is implemented into a tab in the GUI. As the RUC progresses, information is printed into the event log. This enables the user to easily monitor different information such as when certain packages are received, sent and whether errors occured. In the case of the latter, the focus will be shifted to the event log, as to alert the user of errors or other critical information. The following is a list of some of the events, that can occur during RUC operation:

- Connection information: IP, Port, connection status and more.
- Input errors: Invalid values in text-fields.
- Package information: Received and sent packages.

After a short time, the log will get quite long. This can be a problem as the user cannot see all the lines at once, and normally, only the oldest events are visible. Therefore, an optional autoscroll feature is implemented, that will scroll down to the most recent events. A typical example of the eventlog in action can be seen in figure 10.16.

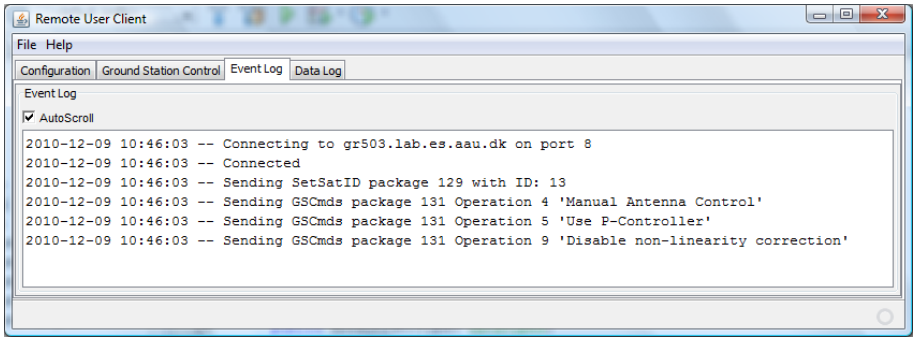


Figure 10.16: *A typical example of the event log. The RUC is connected to a server, and has established the initial settings, by sending several packages to the ground station.*

10.3. Threads

In order for the RUC to receive data on the Ethernet connection, keep the GUI running smoothly and be able to send packages, two threads are needed, as the receive loop will be blocking between received bytes. One for receiving and handling the incoming packages, and one to draw the GUI and send outgoing packages. Until the user clicks the connect button, the Java program is executed in one thread only. This thread is the event dispatcher thread, which is part of, and started by, the Swing GUI library [36]. This thread is denoted as the view thread in the code comments. When a connection needs to be established, a new thread is started to execute the needed code for maintaining the connection and receive the data on the Ethernet link. This thread is denoted the connection thread. An illustration of this can be seen on figure 10.17 on the facing page.

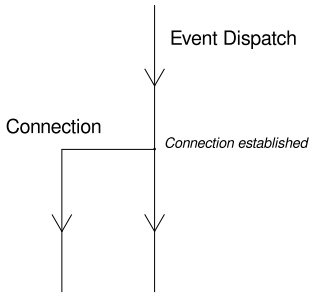


Figure 10.17: *The event dispatch thread starts the connection thread when a connection needs to be established.*

One reason for dividing the execution of the program into separate threads, is because the GUI should be executed smoothly. As a consequence, the event dispatch thread should never execute time consuming tasks[36]. Such tasks could be listening for new packages on the Ethernet connection, process these and write the processed data to CSV files. If a large quantity of incoming packages needed to be processed, the GUI could potentially lock up for a period of time, if everything was executed by a single thread.

The use of two threads in the RUC has some implications that needs to be addressed. For instance, all the used Swing objects for drawing the GUI aren't thread safe [36]. As a result, the Swing objects must only be accessed by the event dispatch thread. If several threads were to read/write to a certain non-thread-safe object at the same time, errors would occur.

When the connection thread needs to update parts of the GUI, such as text fields of labels, the `SwingUtilities.invokeLater` is utilized[37]. The connection thread will then put a `Runnable` object in a queue for execution by the event dispatcher thread. Once the event dispatch thread is ready to execute a new task, the task added to its queue will be executed. This is the main method used throughout the RUC, to ensure correct program execution. Methods using `SwingUtilities.invokeLater` will be denoted with the name "safe" in front. An example of such a method could be `safeSetConnectionStatusLabel`.

In some cases, the event dispatch thread might use the `SwingUtilities.invokeLater` method on itself. This is acceptable as this will simply add the task to the end of the event dispatch threads queue[37].

As mentioned briefly, the two threads are each responsible for different tasks. The connection thread establishes the Ethernet connection, handles incoming packages, processes these and writes them to the CSV files. The event dispatch thread updates and responds to the GUI, creates the CSV files, writes the initial information in the CSV files, handles outgoing packages and starts and stops the connection thread when needed. The connection thread is started and stopped when a connection is established and closed. Dividing the work like so, allows the GUI to stay responsive during the operation of the RUC.

10.4. Receive and Send Methods

One of the basic and important features of the RUC, is the processing of packages from the Ethernet network. These packages hold valuable information regarding the CanSat, and GS alike. Because the RUC protocol is a level above the TCP protocol, the first order of business is to interface to the ground station through the TCP protocol. As the RUC is written in Java, a TCP implementation is available in the standard library. Using this, the Ethernet connection is presented as a socket, that operates on separate

bytestreams. One stream for each direction. This offers an easy-to-use interface, where individual bytes are written and received in an output stream and an input stream. The socket is first created, by simply passing the IP and port number to the `Socket` constructor.

10.4.1 Send Method

When packages are to be sent, they need to be assembled in accordance with the RUC protocol, specified in appendix C on page 135. In most cases, packages are sent when the user clicks various buttons inside the GUI. This will call a method, which in turn forms the package, and writes it to the output stream. The method of operation is as follows.

1. A switch-statement decides what to do, based on the package type.
2. Bytes are retreived from elsewhere, such as text fields and arguments, and input validation is performed.
3. These bytes, and more info such as length and package type, are added to a Java `ByteBuffer` in accordance with specifications.
4. The `ByteBuffer` is added to a final `ByteBuffer`, where start byte and escape characters are added where needed.
5. The final `ByteBuffer` is written to the output stream.

Using the above method, packages can be sent from anywhere within the program, by doing a simple function call. However this has to be done with respect to thread safety, as described in section 10.2.5 on page 98.

10.4.2 Receive Method

In order to get the data from an incoming package, it needs to be disassembled. This is to be done in accordance with the RUC protocol. Each byte from the input stream is copied into a `ByteBuffer`, and in the end, the entire package is available for disassembling. The approach chosen, is as follows.

1. Determine if the byte is escaped or not, if so, set the 'escaped' flag. This is used to remove all escape characters as they are received.
2. If an unescaped start byte is found, start decoding the package, by writing unescaped bytes into a buffer.
3. After two bytes, the length is saved, and can be used to allocate a buffer long enough for the entire package.
4. At byte 3, the package type is saved.
5. The following bytes are saved in the allocated `ByteBuffer`. When the entire package is saved in the buffer, a switch-statement decides what to do with the package, based on the package type. For example, if it is a package type 0, the `ByteBuffer` contains a CanSat package, and is thus passed to the `processSatDataPacket` method for disassembling.

This way, relevant information can be stripped from the packages, and written to the right places for later use. Such information is written to labels and text areas inside the GUI, and to CSV files.

Within the `processSatDataPacket` method, the type 0 package is disassembled. This is done separately, as the type 0 package contains a payload field with telemetry data, that is directly affected by the user-chosen datatypes. The bytes in the payload field are then interpreted as one or more datatypes, based on user choices, and saved in both the data log and the data CSV file.

10.5. Verification

In the following section, the requirements specified for the RUC will be tested. These can be seen in the introduction to this chapter on page 91. These test results will be used to determine whether the RUC satisfies the specified requirements.

10.5.1 Requirement 2 test results

As the TCP/IP protocol is implemented into the RUC, using the standard Java implementation, this requirement is met.

10.5.2 Requirement 4 and 5 test results

These requirements are tested in test journal 2 on page 153, in test 1, with respect to the acceptance test specifications in test 3 on page 19. Evidently, the RUC can save both CanSat Telemetry and control data in CSV files, correctly. Also, it is shown that even though the RUC crashes while receiving data, that data is still available in the CSV files. Hereby the RUC passes requirement 4 and 5, from the requirement specification.

10.5.3 Conclusion

Given the previously mentioned test results, it can be concluded that the RUC module is fully functional. Also, it can be seen that requirement 4 and 5 from the requirement specification are met, since test 3 on page 19 from the acceptance test specification is passed.

10.6. Further Development

Some features have been left out of the RUC, due to time- and resource limitations. These would have been added if further development was to be done, and are as follows:

- 2D and 3D graphs to illustrate received CanSat telemetry, in order to allow the user of the RUC to gain a better understanding of the data. These graphs should be updated whenever new telemetry is available, to allow live interpretation by the user.
- A tool would be made to allow user customization of the graphs.
- Extended save/load options would be implemented, so that the user could simulate the flight of a CanSat from captured data.

Summary

In this chapter the RUC was designed, as a multi-threaded Java-based GUI program. The finished RUC is capable of establishing a TCP/IP based connection to a server, adhering to the RUC-protocol, retrieve and send data using this connection, displaying

retrieved data and saving these to CSV files. From this, it is concluded that the RUC meets all RUC-specific requirements.

CHAPTER 11

Scheduling of Ground Station Software

Design and implementation of all the modules identified in the modularization chapter has been discussed. This chapter looks into how these modules are put together. The main concern is the integration of the ground station software, since these modules are coupled together through their software interfaces, and share the same execution environment. This chapter provides an overview of the software modules put together, followed by a scheduling analysis to ensure that the hardware platform is shared in such a way, that every task gets its job done in time.

11.1. Software modules

The interfaces between the software modules have already been defined in the modularization chapter. Connecting the software modules, each designed and developed in their respective chapter, yields figure 11.1 on page 107. Overall, the ground station software can be decomposed into 5 tasks and 4 interrupt service routines. A summary of their functionality is given in the following list.

`encoderElevationISR` & `encoerdAzimuthISR` ISRs that count the ticks from the rotary encoders of each motor on the tilt and pan platform.

`rfmIrqHandler` ISR that is invoked by the RFM12B radio communication module, every time a byte has been send or received.

`encIrqHandler` ISR that signals `encIrqHandlerTask` by upping a semaphore, which makes the task run. The interrupt is triggered when the ENC28J60 Ethernet controller has a pending interrupt request, most often caused by a received Ethernet frame.

`controllerTask` Cyclic task that controls a PWM output voltage to each of the DC motors of the pan and tilt platform. The behaviour of the controller depends on the options set by its associated functions.

`rfmPkgHandlerTask` Sporadic task that is invoked through a queue by the `rfmIrqHandler` when a whole package has been received. The checksum of the package is verified, then information from the package is extracted and passed on to the two other modules.

uipPeriodicTask Cyclic task which updates the internal timers of the uIP library, and is responsible for retransmitting TCP packages. Takes the uIP semaphore (`uipSem`) before executing.

encIrqHandlerTask Sporadic task that processes the interrupt request from the Ethernet controller. Most often, it will interpret incoming Ethernet frames and react on its contents. If the incoming package contained a TCP ACK or a new TCP connection has been established, the clear to send semaphore (`ethCtsSem`) will be upped. Takes the uIP semaphore (`uipSem`) before executing.

ethSenderTask Sporadic task that is executed, when there is pending outgoing application layer packages in the outgoing Ethernet queue, and the networking system is clear to send. Thus the `ethSenderTask` can be blocked in three different ways: The outgoing Ethernet queue (`ethOutQ`) is empty, the clear to send semaphore (`ethCtsSem`) is 0 or the uIP mutual exclusion semaphore (`uipSem`) has been acquired by another task.

There furthermore exists the interrupt generated by the system tick in the ARTOS operating system. This is though neglected in the following analysis, as it should be executed very fast and only for every 8 ms. Having all the tasks of the ground station system defined, it now becomes possible to analyze if they will meet their deadlines, when everything is put together.

11.2. Scheduling

A multi-tasking operating system has been implemented and discussed in chapter 5. The implemented preemptive scheduler is using a fixed priority scheme, and has been configured to not preempt between tasks at equal priority, i.e. no preemption on system ticks. What characterizes scheduling in real-time systems, is that it has hard deadlines that has to be met. In the following, all the tasks of the ground station system will be analyzed in order to find deadlines, ready time etc. The goal of this analysis is to determine the priority assignment to tasks and if the system is schedulable, i.e. if the system can meet the specified deadlines.

First of all some scheduling definitions and terms need to be introduced. A task is a piece of work to be executed by the CPU. Each task can be characterized in time with the following attributes:

Ready time is the instant in time, where a task becomes ready for execution.

Interarrival time is the difference between two consecutive ready times. If the interarrival time is constant, the task is cyclic. Otherwise it is sporadic. These terms maintains consistency with the equivalent HRT-HOOD type of objects. Sporadic tasks can have a mean and/or minimum interarrival time associated to it. In this analysis only minimum interarrival times $T_{\min}$ are used. Sporadic tasks are thus analysed as if they were cyclic.

Computation time c is the total execution time of the task under the assumption that it is the only task running.

Starting time is the instant in time where the task first gets to run.

Completion time is the instant in time where the task is done executing.

Deadline is the instant in time where the task has to be finished. Relative deadlines t_{d} are assigned to tasks, which is the difference between the ready time and the deadline.

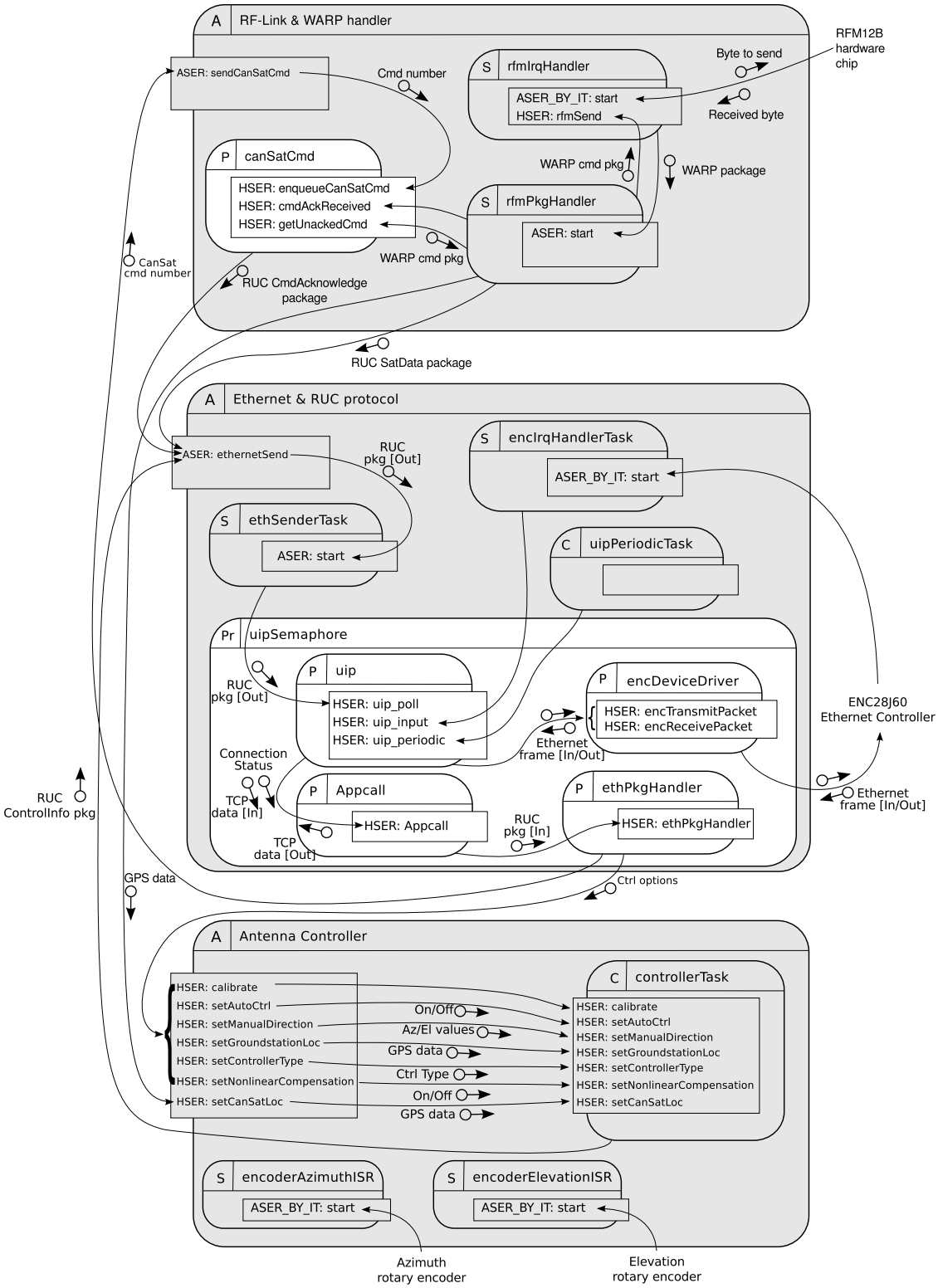


Figure 11.1: *HRT-HOOD logical architecture design of the final ground station software. The white boxes represents passive objects, that doesn't have their own tasks or ISRs allocated to them. The circles with arrows indicates the data flow.*

A task is deterministic if all it's ready times are known at time 0. Tasks are categorized as hard real-time if the deadlines must never be missed and soft real time if the deadlines are specified on a mean value basis and can be missed from time to time. In this chapter all tasks will be regarded as hard real-time.

11.2.1 Ethernet tasks

There are three tasks in the ground station system dealing with Ethernet handling as described in chapter 6. The tasks are listed in table 11.1, and the reason for the assignment of priorities will be described in this section. The three tasks are highly dependent

Priority	Task name	Type
3	`uipPeriodicTask`	Cyclic
2	`encIrqHandlerTask`	Sporadic
1	`ethSenderTask`	Sporadic

Table 11.1: *The three tasks of the Ethernet communication software. Higher priority number means higher priority.*

on one another, and are coupled through the use of semaphores for mutual exclusion and synchronization. Furthermore, the interarrival time of the sporadic tasks depends on the time given to these tasks by the CPU as well as the round trip time of the Ethernet link. For example the `ethSenderTask` can send up to 510 TCP data bytes when it is invoked, but if less data is available in the Ethernet out queue, it will be sent immediately. Sending the RUC packages in small TCP segments requires more computation time per amount of sent data, because of the encapsulation overhead of sending TCP data. If the system is under heavy load, the outgoing packages will be buffered up, and the `ethSenderTask` will send maximum sized TCP segments. Thus in the worst case scenario (high load), the `ethSenderTask` will converge towards the highest throughput sending scheme (maximum sized segments).

Sending more and smaller TCP segments will generate more TCP ACK packets, which decreases the interarrival time of the `encIrqHandlerTask`. The interarrival time of the `encIrqHandlerTask` can be close to zero, since the Ethernet controller will buffer up incoming packets, and keep on generating interrupt requests as long as there are unprocessed packets in the buffer. Furthermore the amount of traffic on the Ethernet caused by ARP (Address Resolution Protocol), ICMP (Internet Control Message Protocol) etc. are unknown. Because of the nondeterministic behavior of the Ethernet module, it is preferred to assign its tasks low priorities, to ensure the rest of the ground station system is working independently of the behavior of the Ethernet tasks.

All three Ethernet tasks are acquiring the uIP semaphore as long as they are executing. This will make the tasks wait for each other's completion. In addition the `ethSenderTask` will be blocked, waiting for the `encIrqHandlerTask` to up the `ethCtsSem` (Clear to Send semaphore), which happens on a new connection and on the arrival of TCP ACKs. Priority inversion may occur because no priority inheritance mechanism exists in the operating system. Priority inversion can be avoided by assigning the 3 Ethernet tasks 3 consecutive priorities, so only one of them can execute at any given time and they thus can be considered as a single priority in this regard.

Priority Assignment

When a TCP ACK package has been received, the following events occur:

1. `encIrqHandlerTask` is signalled by an ISR and takes the uIP semaphore, as it enters the uIP critical region.

2. It processes the ACK package and ups the `ethCtsSem`, on which the `ethSenderTask` is blocked in order to signal that a new TCP package can be sent.
3. The `encIrqHandler` leaves the critical region and thereby ups the uIP semaphore. It then blocks, waiting for more input from the Ethernet controller.
4. The `ethSenderTask` downs the `ethCtsSem` and then the uIP semaphore. After doing its job, the uIP semaphore is again upped.

The `ethSenderTask` is set to a lower priority than `encIrqHandlerTask` in order to avoid three unnecessary context switches triggered by the events just stated. If the `ethSenderTask` was higher priority, context switches would occur when the `ethCtsSem` is upped by the `encIrqHandler`. Then `ethSenderTask` would block on the uIP semaphore, causing another context switch to `encIrqHandler`, which won't do much more than upping the semaphore, causing another context switch. When `ethSenderTask` completes it's job, it would generate another context switch to the `encIrqHandler`, which then would block, waiting for new Ethernet input.

The priority of the `uipPeriodicTask` has been chosen to be the highest of the Ethernet tasks, as it is responsible for retransmission upon ACK reception timeout, and since it is desirable to retransmit as soon as possible, in order to minimize the effect of lost packages.

Interarrival- & Deadline Times

In order to deal with the Ethernet tasks in the schedulability analysis, they will first be regarded as a number of independent tasks to include their direct computation time. Afterwards the effect of them being executed under mutual exclusion will be analysed. In order to assign timing attributes to the tasks, they will be analysed in the case of highest possible throughput requirement, in which the following statements apply:

- `ethSenderTask` will converge towards the most effective sending scheme as described above, ie. each TCP package will be filled.
- `ethSenderTask` will only start executing, when `encIrqHandlerTask` has received a TCP ACK. `ethSenderTask` can thus never starvate `encIrqHandlerTask`.
- The time for computation time for the `encIrqHandlerTask` receiving a single ACK and signalling the `ethSenderTask` is not included in the computation time of the `ethSenderTask` and is considered negligible compared to the worst case execution time of the `ethSenderTask`.
- The I/O buffers of the `ethSenderTask` and `encIrqHandlerTask` are assumed to be sufficiently large to never overflow.

In order to find the interarrival time of the `ethSenderTask` in the worst case scenario, a result from section 6.4 is used: In order to achieve the throughput of 7100 $\frac{\mathrm{B}}{\mathrm{s}}$, which is a worst case estimate, the maximum allowed total delay in the network link is 56 ms. Still assuming 100 % CPU load, the interarrival time $T_{\min}$ for the `ethSenderTask` (for highest possible throughput requirement) is thus 56 ms. Giving 20 ms to the round trip time and the processing of the TCP packet by the RUC, the deadline of the `ethSenderTask` is 36 ms.

When neglecting the ACK processing time of the `encIrqHandlerTask`, its interarrival time is determined by the amount of requests sent from the remote user client. All requests from the RUC are issued by the user. It is assumed that the user is not able to issue requests faster than 100 ms, thus the interarrival time is 100 ms in worst case. The deadline of this task is set to 50 ms.

The last task, `uipPeriodicTask` is controlled by the `osWaitForDivisbleTick()` function of the operating system and is invoked every 500 ms. Its main job is to update internal timers within uIP and do retransmission if required. It is assumed that setting a deadline of 50 ms is sufficiently small to make uIP fully functional.

11.2.2 Timing Attributes

Worst case execution time, c, has to be determined for all tasks in the system. It can be found using static code analysis or by measurements. It has been chosen to use measurements. The execution time is measured for one single task at a time, by having it toggle a digital I/O pin upon start and stop of execution of the task. Pin 0.27 is used for this purpose. The measurement is described in journal 5 on page 163.

Priority	**Task name**	**Type**	$T_{\min}$	c	T_{d}
FIQ	`encoderElevationISR`	Sporadic	60 μs	2.8 μs	15 μs
IRQ0	`encoderAzimuthISR`	Sporadic	60 μs	3.7 μs	15 μs
IRQ4	`rfmIrqHandler`	Sporadic	417 μs	110 μs	417 μs
IRQ5	`encIrqHandler`	Sporadic	100 ms	22.1 μs	1 ms
5	`controllerTask`	Cyclic	8 ms	1.1 ms	2 ms
4	`rfmPkgHandlerTask`	Sporadic	100 ms	712 μs	36 ms
3	`uipPeriodicTask`	Cyclic	500 ms	4.6 ms	50 ms
2	`encIrqHandlerTask`	Sporadic	100 ms	2.6 ms	50 ms
1	`ethSenderTask`	Sporadic	56 ms	5.5 ms	36 ms

Table 11.2: *Timing attributes associated with the different tasks in the ground station system.*

Table 11.2 shows the tasks in the ground station system and the associated timing attributes. The computation times have been measured for different states of the software, but only the longest computation times are used. For the Ethernet tasks, $T_{\min}$ and T_{d} have been determined above. In the following, the timing attributes for the remaining tasks will be discussed.

`encoderElevationISR` & `encoderAzimuthISR` The encoder interrupt service routines, are invoked every time a rising edge occurs on the output pin on the motor encoders. This happens for every 3° rotation on the motor axis. The maximum speed of the used motors[32] are 8300 rpm (138.33 $\frac{\text{round}}{\text{sec}}$) [29], which gives the following minimum time between interrupts:

$$\left(138.33\,\frac{\text{round}}{\text{sec}}\cdot\frac{360\,\frac{\text{degree}}{\text{round}}}{3\frac{\text{interrupt}}{\text{degree}}}\right)^{-1} = 60\,\frac{\mu\text{s}}{\text{interrupt}} \tag{11.1}$$

This is thus the interarrival time for the interrupts. As can be seen in figure 9.12 on page 77, the deadline for the interrupts are $\frac{1}{4}$ of the time between the interrupts. Thus the deadline are 15 μs.

`rfmIrqHandler` The task must handle the reception and transmission of bytes on the RF connection to the CanSat. This connection is run at a rate of 19 200 bit/sec. The time between each byte is thus:

$$T_{\min} = \left(\frac{19\,200\,\frac{\text{bit}}{\text{s}}}{8\,\frac{\text{bit}}{\text{byte}}}\right)^{-1} = 417\,\mu\text{s} \tag{11.2}$$

This is both the interarrival time and the deadline for the `rfmIrqHandler`.

encIrqHandler This ISR performs one job: an `osSemUpFromIsr()` on a semaphore which the `encIrqHandlerTask` has `osSemDown()`'ed. It thus has the same interarrival time as the `encIrqHandlerTask`. The deadline has been set to 1 ms.

controllerTask The controller task is run every 8 ms (see section 9.3.5 on page 82), which means that this is the interarrival time for this task. A strict deadline of 2 ms has been set to ensure that the time between controller updates is as constant as possible.

rfmPkgHandlerTask To determine the interarrival time for this task, the rate at which packages are received on the wireless link must be known. It is assumed that one CanSat is connected, and it is sending packages at a rate of 10 Hz. This gives an interarrival time of 100 ms. There are two requirements to the deadline for this task:

- The time it takes to initiate transmission of CanSat commands when packages with the clear to send bit set is received.
- The time it takes to process reception of GPS coordinates and feed these into the controller.

When receiving a package from the CanSat, it will contain a bit specifying whether the ground station is allowed to send commands to the CanSat in the following 50 ms. The packages that are to be sent to the CanSat can be up to 12 bytes long (including start-, stop- and escape bytes.) A package of this size, takes the following time to send, including a preamble and synchronization pattern of 7 bytes:

$$t = \left(\frac{(12\ + 7)\,\text{bytes} \cdot 19\,200\,\frac{\text{bit}}{\text{s}}}{8\,\frac{\text{bit}}{\text{byte}}} \right)^{-1} = 7.9\,\text{ms} \tag{11.3}$$

When receiving a package specifying that the ground station is allowed to send, it has 50 ms to send the package. The processing of the package is thus allowed to take $50\,\text{ms} - 7.9\,\text{ms} = 42.1\,\text{ms}$.

From receiving a set of GPS coordinates to these have been fed into the controller, a maximum of 36 ms may pass (see section 2.3.1 on page 9). This is the most stringent deadline and the tasks deadline is thus 36 ms.

The deadline of the `rmfPkgHandlerTask` ensures that the telemetry data from the CanSat will be in the Ethernet out queue within 36 ms after reception. The interarrival time of the `ethSenderTask` ensures that the Ethernet out queue will be emptied every 56 ms. In worst case the just received telemetry data will suffer a delay consisting of: The deadline of `rfmPkgHandlerTask`, plus two times the interarrival time of the `ethSenderTask` plus the deadline of the `ethSenderTask`. This gives a total delay of $36 + 2 \cdot 56 + 36 = 184\,\text{ms}$, which is sufficient to fulfill the requirement of maximum 200 ms from requirement 3 in the requirements specification.

11.2.3 Schedulability Analysis

As mentioned previously, the scheduling is based on a fixed priority scheduler. For the assignment of priorities, deadline monotonic assignment is used, except for the Ethernet tasks, which are given the priorities mentioned above. This gives the prioritization of tasks that is shown in table 11.2 on the facing page. The utilization of the CPU, i.e. the percentage of time where the CPU is busy, can be calculated using this formula:

$$U = \sum_{i=1}^{N} \frac{c_i}{T_{\min_i}} \tag{11.4}$$

where:

N	is the number of tasks	[-]
c_i	is the computation time of task i	[s]
$T_{\min_i}$	is the interarrival time of task i	[s]

Calculating this for the tasks given in table 11.2 on page 110 gives an utilization of 65 %. This does not state that all deadline will be met, only that there is in upper bound on the amount of work queued for the CPU to do.

Interrupt Service Routines

The tasks marked as FIQ or IRQ denote interrupt service routines. These are not regular tasks, as they are not prioritized in the same way and have very short computation times. The FIQ task have higher priority than IRQ's and can preempt these. The IRQ's are also prioritized, but cannot preempt each other. The lower the IRQ number, the higher priority.

`encoderElevationISR` is guaranteed to meet it's deadline, as it has the highest priority and can preempt other tasks. The remaining IRQ's cannot preempt each other and may have to wait for any of the other interrupts to complete, before it can execute. Table 11.3 shows the ISRs and their worst case completion time relative to their ready time. The `encoderAzimuthISR` may not meet its deadline, because it may wait for up to 112.8 μs before executing, if the `rfmIrqHandler` and `encoderElevationISR` are triggered at the same time. This problem could have been solved by having it run as a FIQ as well, sharing this status with `encoderElevationISR`. This has not been possible due to some problems implementing both ISRs as FIQ's in the vectorized interrupt controller (VIC) of the LPC2138 microcontroller. It is noted that the interarrival time for the encoder interrupts are a theoretical worst case value, based on the angular velocity for the motors when no load is applied to them. This is not the case in practice and the interarrival time will thus be higher in reality, even if the antenna is rotating at full speed. Also, the computation time for the `rfmIrqHandler` is a worst case value that only appears when a stop byte is received. Upon reception or transmission of a regular byte in a package, computation time is maximally 38 μs, as shown in journal 5. This decreases the severity of the IRQ problem, but it should be noted that the measured azimuth position in theory may drift because of the risk of missing interrupts.

ISR/Delayed by in worst case	**Completion time** [μs]	$T_\mathbf{d}[\mu s]$
`encoderElevationISR`:		
None	2.8	15
`encoderAzimuthISR`:		
`rfmIrqHandler` `+encoderElevationISR`	$110 + 2.8 + 3.7 = 116.5$	15
`rfmIrqHandler`:		
`encIrqHandler` $+ 2 \cdot$ `encoderElevationISR` $+$ `encoderAzimuthISR`	$22.1 + 2 \cdot 2.8 + 3.7 + 110 = 141.4$	417
`encIrqHandler`:		
`rfmIrqHandler` $+ 2 \cdot$ `encoderElevationISR` $+ 2 \cdot$ `encoderAzimuthISR`	$2 \cdot 2.8 + 2 \cdot 3.7 + 110 + 22.1 = 145.1$	1000

Table 11.3: *Worst case completion time for each ISR relative to its ready time. The completion time is composed of the total computation of the blocking ISRs plus the computation time of the ISR itself.*

Having shown that the scheduling of interrupts is acceptable (except for

encoderAzimuthISR), the interrupts can be excluded from the scheduling analysis. To do this, all the remaining tasks computation times are multiplied by a factor to account for the time the CPU will spend servicing the interrupts. This can be done because the interrupts occur very often compared to the remaining tasks (except for encIrqHandler, but this fact is neglected in this analysis as it's computation time is very low compared to the remaining tasks). The CPU utilization by the interrupts alone calculated from eq. (11.4) is 37.2 %. The computation time of the remaining tasks are thus to be multiplied by 1.372.

Regular Tasks

Taking into account that the computation times are increased by 37.2 %, the fixed priority scheduler will give the result in figure 11.2, if all tasks have their ready times at time $t = 0$. In the figure, deadlines are shown as a small vertical line, e.g. it can be seen that uipPeriodicTask and encIrqHandlerTask tasks have their deadlines at 50 ms. Execution of a tasks is shown as a fat black line. The CPU is able to handle the load and completes execution of all tasks before their deadline. As it is the worst case scenario that all tasks have their ready time at the same time instant, it has thus been shown that the chosen prioritization of tasks is feasible and all deadlines will be met.

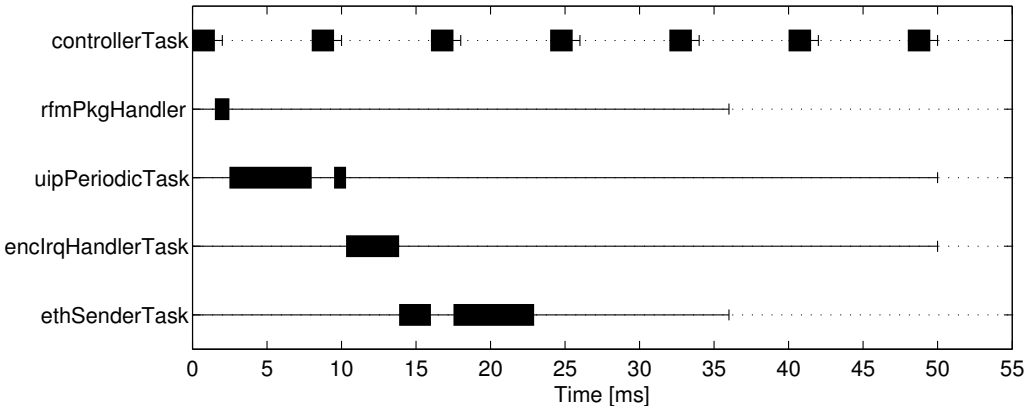


Figure 11.2: *Scheduling of tasks with deadline-monotonic assignment.*

Effect of uIP Mutex

The above analysis does not take into account the effect of the 3 Ethernet tasks executing under mutual exclusion. This effectively means that they can be forced to wait for each other, before they are scheduled. The ethSenderTask are the lowest priority and it has thus already been forced to wait for the remaining tasks. It can be seen in figure 11.2, that no matter which order the Ethernet tasks are executed in, they will all meet their deadline. It can thus be concluded that the scheduling is feasible, also when taking the mutual exclusion into account.

Summary

A scheduling analysis has been performed on the ground station system software and the conclusion is that the fixed priority scheduling chosen is feasible. The ISR of the azimuth rotary encoder may not meet its deadline though, due to problems implementing it as an FIQ on the hardware platform. The total worst case CPU utilization is 65 %.

The tasks related to the Ethernet module has been analyzed as hard real-time tasks in a worst case (high load) scenario. If the Ethernet module is given more CPU time, smaller TCP segments will be sent, and the Ethernet module will consume a slightly larger amount of CPU time.

In order to make the analysis, some assumptions about the network connection has been made. It is noted however, that the network traffic is highly nondeterministic and the network tasks have therefore been given the lowest priorities. In that way, the rest of the ground station system is independent of the Ethernet module's behaviour.

Part III

Assessment & Conclusion

CHAPTER 12

Acceptance Test

In this chapter, the system will be tested according to the acceptance test specification, found in section 3.3 on page 19. The purpose of this test is to investigate if the designed system meets the requirement specification written in section 3.2 on page 17. At the end of the chapter, the results of the tests will be summarized. These results can be seen in table 12.1 on page 119.

12.1. Tests

The tests performed on the designed system in this section, originates from the acceptance test specification, found in section 3.3 on page 19. The procedure for each test, can be seen in the respective test journals.

12.1.1 Test 1. Covers Requirement 1 and 2

- *Must implement and adhere to the WARP protocol.*
- *Must implement and adhere to TCP/IP and Ethernet protocols.*

This test is performed in test journal 6 on page 166. In this journal it is observed, that the ground station and RUC had received the same number of packages with matching CanSat ID's after approximately 12 minutes. It is seen that the data in the CSV file are stored correctly. The number of CanSat packages sent to the ground station from the CanSat in this test, exceeds the number of received packages on the RUC as all the CanSat packages with a different CanSat ID are filtered out. From these results it can be seen that all packages were processed and relayed over the Ethernet connection, correctly.

It can be concluded that the system has passed test 1, and therefore requirement 1 and 2 are satisfied.

12.1.2 Test 2. Covers Requirement 3

- *No more than* 200 ms *may pass from a package is received on the ground station's wireless link, until the processed package containing this information, is sent to the RUC, if this is connected through a direct Ethernet cable.*

This test is performed in test journal 7 on page 167. In test 1, the system is experiencing a light system-load, and in test 2 a heavy system-load, causing a package processing time of 7 ms and 54 ms, respectively. As a stress-test can be difficult to simulate, the worst-case processing time might be higher than the indicated 54 ms. However, this result is significantly lower than the 200 ms specified by the requirement, which leaves a fairly large margin for errors in the result. Therefore this test is considered to be passed, and thus requirement 3 is satisfied by the system.

12.1.3 Test 3. Covers Requirement 4 and 5

- *The RUC must save all received data as a comma separated values file (CSV).*
- *If the RUC crashes, any data that already has been received, must not be lost.*

The RUC is tested against an Ethernet server adhering the RUC-protocol, as done in test journal 2 on page 153. The test was conducted according to the acceptance test specifications, and will thus not be repeated. Instead the results from the part test in section 10.5 on page 103 is re-used. These results show that the designed system satisfies requirement 4 and 5.

12.1.4 Test 4. Covers Requirement 6

- *The ground station must keep a backup of the latest received telemetry data. This backup must contain data from the last 5 minutes or more, given a package rate of* 5 Hz *with each package being the maximum package size (*150 bytes*).*

Due to time limitations, the ground station data backup was never implemented into the designed system. Testing this functionality is therefore pointless, and the test is considered not to be passed. Evidently, requirement 6 isn't satisfied.

12.1.5 Test 5. Covers Requirement 7

- *The connection between ground station and CanSat must be able to transmit* 60 byte *packages at a distance of* 1.5 km *with a maximum package loss of* 10 %*. This is assuming that the CanSat and ground station are placed in line of sight, the CanSat is within the antennas half-power beamwidth and the package transmission rate is* 5 Hz*.*

Based on the test results from measurement journal 1 on page 150, it has been decided not to test this requirement. This is because the journal shows that all packages were corrupted at 400 m for uplink transmissions, and after 3 m for downlink transmissions. The journal used 21 byte packages, at a transmission rate of 1 Hz. The acceptance test specifies a distance of 1.5 km in either direction, for 60 byte packages at a transmission rate of 5 Hz. Because the demands set by the acceptance test are much stricter, such a test wouldn't be reasonable to conduct. Therefore, requirement 7 isn't satisfied.

12.1.6 Test 6. Covers Requirement 8

- *The ground station must be able to control the antenna so that an object following the launch graph on figure 2.3 on page 11 can be tracked. The target must be within the half-power beamwidth of the antenna at all times.*

The test performed in section 9.4.2 on page 89 was done according to the acceptance test specification for test 6. As so, this test isn't repeated. In section 9.4.2 it was found, that the controllers for the antenna, are capable of adjusting the antenna, so that a CanSat can be tracked during launch. Since this was done, without the CanSat ever leaving the half-power beamwidth of the antenna, acceptance test 6 is passed, and thus requirement 8 is satisfied by the system.

Summary

In this chapter it was found, that the system satisfies requirement 1,2,3,4,5 and 8 but not requirement 6 and 7, specified in the requirements specification in section 3.2 on page 17. This was done by performing the tests specified in the acceptance test specification in section 3.3 on page 19. An overview of the results can be seen in table 12.1.

System Requirement	Acceptance test	Passed
1	1	✓
2	1	✓
3	2	✓
4	3	✓
5	3	✓
6	4	✗
7	5	✗
8	6	✓

Table 12.1: *This table shows the system requirements, the test performed to investigate if the requirements are passed or not, and finally the results of these tests.*

CHAPTER 13

Conclusion

The starting point for this project has been the development of an open-source kit for constructing CanSats. This kit is supposed to make it easy for students in upper secondary schools to participate in CanSat competitions. Due to technical interests, it has been chosen to build a ground station that can track these CanSats. It can be argued that it is not realistic that competition participants build a replica of the ground station themselves, as the construction of a CanSat is a large enough challenge in itself. The ground station may be considered by organisers of CanSat competitions as an extra service to the participants.

Approach

The developed system consists of an embedded system, that receives data from a CanSat and controls a pan & tilt platform with an attached Yagi-Uda type antenna, to point in the direction of the CanSat. A PC-based remote user client (RUC) is connected to the ground station through an Ethernet connection. Received telemetry data is forwarded to the RUC and saved there.

The requirements for the platform have been found through analysis of former CanSat competitions. In contrast to tracking real satellites, the CanSat tracking system must respond more quickly, to be able to receive telemetry data during the rocket propelled launch. Furthermore, position data must be updated frequently. It has thus been specified by this project, that the CanSats must send GPS position data with an update rate of 5 Hz if automatic antenna control is used.

To support the design of the ground station software, a subset of the Hard Real Time Hierarchical Object Oriented Design (HRT-HOOD) method has been used. The method has especially been useful in visualizing both execution path and data flow in an unified, clear diagram. This has provided the group members with an equal comprehension of the overall software structure in the early design phase, thus helping to avoid misunderstandings.

Technical Results

The ARM Real-Time Operating System (ARTOS) has been developed to gain insight into the inner workings of operating systems. This operating system is preemptive and provides multiple ways of inter process communication. On top of this an Ethernet link has been implemented using a dedicated Ethernet controller and the uIP TCP/IP protocol stack. The throughput of the link is sufficient to fulfill the requirements of the

project, but it is noted that the uIP TCP implementation is very prone to delays in the network, for example caused by the delayed acknowledgement algorithm used by most network interfaces. Higher throughput may be achieved by using UDP instead, which is also supported by uIP. The reliability features of TCP must then be implemented by the application layer when needed though.

The wireless link between CanSat and ground station has been implemented using the RFM12B radio model, utilizing the license free 868 Mhz frequency band. For a bit error rate of 0.1 % and a required range of 1500 m, the link has a theoretical gain margin of 20.6 dB with the used antennas. In practice a transmission range of up to 400 m has been achieved. It has been suggested that the link could be improved by looking into impedance and polarity mismatch of the antennas, and increasing the transmission power. The downlink performance is poor even at very short distances, which most likely is an error in the setup. It is thereby concluded that the low-level radio modules are not straight-forward to configure and interface to.

Modelling of the pan & tilt platform has been performed in order to design an efficient controller. A linear second-order transfer function has been derived for each of the two axes. The transfer function maps an input voltage to an output angle. In order to allow the platform to be modelled as linear systems, compensation for non-linear phenomena has been introduced. Both axes are affected by dry friction, which is easily outweighed by applying a constant offset voltage to the motors. More difficulty has been caused by the disturbance torque applied to the elevation, because of the center of gravity is moved when the antenna is rotating. A non-linear correction has reduced the impact of this problem. The model is considered accurate enough to design an efficient controller.

A feedback controller has been designed for each of the two axes of rotation. The controllers have been designed using time domain specifications and frequency domain design methods e.g. Bode plots. For rotation on the azimuth axis, a proportional controller has been found sufficient. For elevation, a lead-controller has been introduced in order to achieve the desired overshoot and rise time. Verification of the controller, has been performed by simulating a CanSat launch. These tests have shown that the antenne position never deviates more than 5° from the virtual CanSat position. A deviation of 15° is allowed.

The remote user client (RUC), developed in Java, provides the user interface to the ground station. This allows the user to easily control the system and save telemetry data. Besides providing the user interface, the RUC has eased the process of controller design, with the ability to save antenna position data to CSV files.

A schedulability analysis of the ground station software has been performed. The fixed priority scheduling scheme implemented in ARTOS has been found feasible. The deadline of one of the rotary encoder's interrupt service routine may not be met though, due to some problems configuring the microcontroller to use more than one FIQ (Fast Interrupt Request). This only seems to be a theoretical problem, when considering the absolute worst case.

Fulfillment of Requirements

Of the features specified in the requirements specification, that has been implemented in the project, only one requirement has not been met. It has not been possible to achieve the required range on the wireless link.

The group considers the project a success, as most features and requirements are fulfilled. The concept of tracking a CanSat by means of wirelessly transmitted GPS coordinates has not been tested directly, but a simulation of a launch shows that the antenna control system has no issues with tracking a CanSat.

CHAPTER 14

Perspectives

This chapter deals with ideas for improvement and further development of the designed system, intended for a possible continuation of the project. This includes examples of hardware components that could have been chosen differently, and how different methods could have been used, to implement certain features. It is also described how the system could be used in CanSat competitions, and which additional features could be useful in this regard.

14.1. Improvements

As noted in the previous chapter, it hasn't been possible to satisfy all the stated requirements. Most notably is the inability to retrieve radio packets from a CanSat module, beyond very short distances. As the exact cause of this problem is unknown, a solution is also uncertain. A possible way to solve this problem is further debugging of the current setup. Another would be to choose different radio transceiver modules, possibly with higher transmission power. Different modules would hopefully interact better with the system, while higher transmission power would increase the transmission range, and thus meet the requirement.

Beyond this, another area of improvement could be impedance matching and choice of antenna. As an airborne CanSat descending by parachute will naturally wobble back and forth, so will its antenna. This causes the polarization of the EM-field to vary, and thus decreases the amount of power received by the antenna. Using a circularly polarized antenna would remedy this problem somewhat, although the antenna gain would generally be lower.

Another requirement not satisfied, is the ability to log and save CanSat data on the ground station itself, for later retrieval through the RUC. This feature has been left out due to time constraints, but could be implemented by saving the received data in the flash-memory already present on the Mini-Max board. In this case, the maximum number of write cycles that exists for flash memory should be considered however, as logging requires many writes over a long period of time.

Beyond the requirements, many features could improve the system performance. For instance, it would be desirable for the ground station, to be able to handle the loss of radio signal from the CanSat in a better way. This could be done by guessing the satellite position by extrapolating from recent coordinates received. If unsuccessful, a random tracking pattern could be initiated and carried out, until new packets were received.

To enhance the controller a different approach to the problem of non-linearity caused by gravity can be considered. This can for example be solved by adding a counterweight to the antenna, in such a way, that the center of gravity is moved to the axis of rotation.

Other possible features could include:

- Built in GPS module to determine the ground station position.
- Built in compass for automatic calibration of the antenna.
- Communication with more than one CanSat at a time.
- Programming of the ARM-board via the network link.

14.2. Usage in CanSat Competitions

Since the product has been made with the CanSat competition in mind, it would be natural to look further into accommodating this purpose.

To do so, the system should be placed in a casing capable of protecting it from the weather, since the ground station is meant to be placed outside. Also the user interface of the system should be reviewed, to make it more intuitive to users, with no or minor technical background.

Testing with actual CanSats would have to be done, under various conditions, to ensure protocol compliance. Perhaps most importantly, the user safety of the system would have to be ensured and verified extensively. Additional measures to prevent the system from damaging itself should also be incorporated.

The idea behind CanSat competitions are for the students to build the CanSat systems on their own. For this, other groups have designed CanSat kits, which try to lower the level of technical skills required to construct these CanSats. These kits are open source and only provides schematics, guides and software that can be used as the basis for constructing the CanSats. It is up to the competition participants to build the CanSats on their own. The ground station is made to be used with these CanSats, but it is unreasonable to ask students to build the ground stations on their own. Mass production is not likely, as only few ground stations are required and the price would not be acceptable compared to the value added to the CanSat competitions. Therefore, it could be considered that the organizations arranging the competitions could be interested in building a few ground stations and then providing these to the participants. It is also possible that on ground station could be set up by the arranging organization to retrieve telemetry data from all CanSats that are in the air at the same time. This would require modifying the ground station system to be able to receive data from multiple CanSats at the same time.

Another direction of development could be to retrofit the ground station, to serve different purposes. For instance, instead of only CanSats, it could be reconfigured to track any moving source. This could even include real satellites in orbit.

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Appendices

Appendix A: Word List

This appendix contains a list of abbreviations and terms used throughout the report. The list is made to help the reader gain a better understanding of the report content, and should therefore be carefully read before reading the report itself.

Abbreviations

WARP	WARP is a recursive acronym for "WARP AAU Radio Protocol". WARP is the protocol used for radio communications between ground stations and CanSats.
RUC	Remote User Client, see list of terms.
GS	Ground Station, see list of terms.
ARTOS	ARM Real Time Operating System, the operating system developed as part of this project.

Terms

upper secondary school	Also known as grammar school or senior high school. The danish name for this school is "gymnasium".
ground station	The embedded system performing the antenna control, CanSat radio communication and network communication to the remote user client.
remote user client	The PC executing the java based GUI program, which are interfacing with the ground station.
telemetry data	Sensor data transmitted from the CanSat to the ground station.
event log	A log on the remote user client, containing a full list of all activities performed.
telemetry data backup	A data storage on the ground station capable of storing 5 minutes of CanSat telemetry data.
elevation	Used together with azimuth to specify the direction the antenna is pointing. Specifies the angle between a horizontal plane and the antenna.
azimuth	Used together with elevation to specify the direction the antenna is pointing. Specifies the angle between north and the direction the antenna is pointing in the horizontal plane.

Appendix B: WARP Protocol Specification

WARP (short for WARP AAU Radio Protocol) is a package oriented data transmission protocol. It is designed for transmitting packages over a highly unreliable wireless link, that is working as a byte stream.

There are two conformance classes for the protocol. Conformance class 1 is the simplest and facilitates transmission of measured telemetry data from the CanSat to a ground station. Conformance class 2 is a superset of the specifications for class 1. Class 2 devices facilitates the use of a ground station that automatically can track the CanSat with it's antenna, using GPS coordinates. Class 2 thus defines a way to include GPS coordinates in the data being sent from the CanSat to the ground station. Furthermore, there are some timing restrictions, to ensure that the ground station have adequate recent GPS coordinates at all times.

The protocol defines 2 package types, that each accomplish a different task. Not all devices has to implement all package types, they can choose to ignore package types that provide features that are not wanted in that application. The protocol gives the possibility to create 14 custom package types, that can be utilised as desired. The following are basic specifications set by the protocol:

- All multi-byte values are sent as little endian.
- All signed numbers are in the two's complement format.
- The protocol uses `0xBE` as a start byte and `0xEF` as a stop byte to delimit packages. Any occurrences of these two bytes in the package (header or payload) must thus be escaped using byte stuffing. As escape character, `0x42` has been arbitrarily chosen. Occurrences of this byte, must thus also be escaped by preceding it with itself.
- Any package sent must not be longer than 150 bytes, excluding start- and stop bytes and escape characters. That means the maximum package size after adding start and stop bytes and escape characters will be 302 bytes, which is reached when all characters in the package must be escaped.

B.1 General Package Layout

Figure B.1 shows the general package layout, shared by all package types.

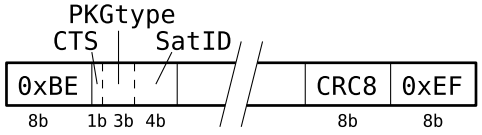


Figure B.1: *General package layout, shared by all package types.*

The fields in the package are as follows:

- **`0xBE` and `0xEF`**
  These are start and stop bytes, used to delimit each package.
- **`CTS`**
  Clear To Send, only in packages going from the CanSat to the ground station. If this is 1, the ground station is allowed to send a package to the CanSat after receiving the current package. 50 ms after the complete receival of a package with CTS set to one, the ground station must be done sending it's package.

- **PKGtype**
  The package type, which is a number between 0 and 7, thus allowing for 8 package types.
- **SatID**
  Satellite ID, which is used to distinguish the packages transmitted from and sent to different satellites, if multiple satellites are airborne at the same time. It is a number between 0 and 15, so up to 16 satellites can be airborne at the same time.
- **CRC8**
  This field contains a CRC8 checksum of the package. The checksum is calculated from the complete package, excluding the start- and stop bytes, the checksum field itself and without any byte stuffing (i.e. without any escape characters inserted).

B.2 Type 0 Packages

Type 0 packages are unacknowledged packages going from the CanSat to the ground station. They will be sent with a fixed or variable time interval and contain the telemetry data measured on the CanSat as their payload. The protocol makes it possible to detect if a package is lost in transit or contains errors on arrival. Lost or erroneous packages are simply lost and cannot be reconstructed or requested re-sent. If adequate bandwidth is available, the same package can be transmitted multiple times to increase the chance of a successful transfer. Figure B.2 shows the layout of a type 0 package.

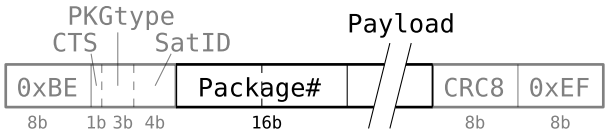


Figure B.2: *Layout of a type 0 package.*

The fields in the package that are added to the general package layout are the following:

- **Package#**
  The package number is used to make sure that the same package is not received twice and to detect if a package has been lost in transit. The first package being transmitted will be package number 0, and the package number is then incremented by one for each new package sent. If the same package is transmitted multiple times, the package number should not be incremented. If the package number reaches it's maximum value, it should continue from 0.
- **Payload**
  The payload is the telemetry data measured by the CanSat. The contents of this field consists of a number of measured data values. The layout of this payload is not specified in this protocol, but the basic datatypes that can be used to build this field are. The list of allowed datatypes can be found below. This way the user is able to construct a payload field that suits the types and number measurements the CanSat is taking, and then feed these into both the ground station and the CanSat. The ground station will then know how the layout of the payload field is and thus it can extract the values and present them to the user.

The 8 datatypes that can be used in the `Payload` field are the following:

- signed/unsigned char (8-bit integer)
- signed/unsigned short (16-bit integer)

- signed/unsigned int (32-bit integer)
- float (32-bit IEEE 754 binary32 floating-point number)
- text string

The text string is a fixed length array of char's, the length of this string is to be specified as part of the specification of the payload field layout. It is recommended that ISO-8859-1 is used as the charset for these text strings, but this is not required.

B.3 Conformance Class 2 Requirements

Conformance class 2 devices are required to send GPS location data in each type 0 package that is transmitted. This GPS location data is transmitted at the beginning of the payload field as a 23 character text string. The format is a slightly modified version of the GGA field in NMEA 0183, the standard used by most GPS receivers. The following format is to be used for transmitting the GPS data to the ground station:

```
char[4] height;                 /* Height in meters, can be negative by
                                 * prefixing with the '-' char. Valid range
                                 * is thus -999 to 9999 m */
char[1] longitude_east_west;    /* Either 'E' or 'W' */
char[3] longitude_degrees;      /* Longitude degrees */
char[2] longitude_minutes;      /* Whole longitude minutes */
char[4] longitude_minutes_frac; /* Longitude 1/1000's of a minute */
char[1] latitude_north_south;   /* Either 'N' or 'S' */
char[2] latitude_degrees;       /* Latitude degrees */
char[2] latitude_minutes;       /* Whole latitude minutes */
char[4] latitude_minutes_frac;  /* Longitude 1/1000's of a minute */
```

Furthermore, there are some timing requirements to ensure that the ground station always has an adequately recent GPS coordinate available. It is required, that a new type 0 package containing new GPS coordinates are transmitted at a fixed rate of 5 Hz. The GPS coordinates contained in each of these packages must not be any older than 200 ms when they are transmitted.

B.4 Type 1 Packages

Type 1 packages facilitates sending commands from the ground station to the CanSat. These commands will then correspond to an action to be performed on the CanSat. It is noted that, it is not possible to send any arguments along with these commands. An acknowledgement system is used to ensure that each type 1 package is successfully received, even if lost in transit. Also, it is guaranteed that the command in the package is only executed once. It is noted that ground stations should take measures to ensure that type 1 packages will only be sent to CanSats that support type 1 packages. Otherwise the ground station will never receive an acknowledgement and will thus continue to retransmit the packages forever. Figure B.3 shows the layout of a type 1 package.

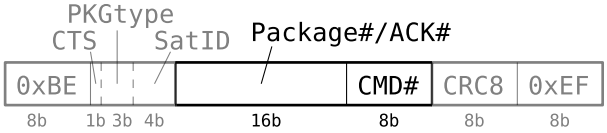


Figure B.3: *Layout of a type 1 package.*

The `CMD#` field contains a number from 0 - 255, identifying the command to be executed. For packages sent from the ground station to the CanSat the `Package#/ACK#` field contains a package number, that is incremented by one for each new command sent. This

package number is independent of the package numbers in type 0 packages. When the CanSat successfully receives a type 1 package, it should transmit a type 1 package back to the ground station, where the `Package#/ACK#` field contains the package number of the package just received successfully. In these packages, the `CMD#` field is optional, it's contents is to be ignored. The ground station must only send one type 1 package at a time, the next command cannot be sent until the current one has been acknowledged.

If the packages going from the ground station to the CanSat are lost or contains errors (detected by examining the checksum) and an acknowledgement package thus is not returned, the ground station must re-send this package after some timeout period. It is noted that if an acknowledge package is lost or erroneous on arrival, the ground station will retransmit the original command package after the timeout time. The CanSat must thus keep track of which package numbers it already received successfully and the only action to take when a repeated package arrives, is to retransmit the acknowledge of it.

B.5 Remaining Package Types

The remaining package types (from type 2-7) can be utilised as desired. Obviously, they must follow the general package layout. Devices must ignore all packages of unknown package type that are received.

Appendix C: RUC Protocol Specification

The RUC protocol is an application level protocol to be used on top of a TCP/IP connection between the remote user client and the ground station. These conventions apply:

- Each package is started by the start byte character: `0xBE`.
- Any occurrences of the start byte in the package content, must be escaped using byte stuffing with the escape byte character: `0xEF`. Occurrences of the escape character itself must also be escaped the same way.
- The communication is to be performed on a TCP/IP based network, on TCP port 8.

The basic package structure looks like this:

```
struct pkgRuc {
    uint16_t length;
    uint8_t pkgType;
    char pkgContents[];
};
```

The contents of the `pkgContents` field is determined by the `pkgType`. Table C.1 lists the possible package types available in the RUC protocol. Package 0 - 127 go from the ground station to the RUC, while packages with numbers higher than 127 go from the RUC to the ground station. Having specified the different types of packages, the contents

pkgType	Describing struct	Description
0	pkgSatData	Contains telemetry data received from the CanSats.
1	pkgControlInfo	Information about current and wanted azimuth and elevation of the antenna.
2	pkgAcknowledge	Informs the RUC that a command previously send to the CanSat, has been successfully received by the CanSat. Consists of the basic package structure only.
128	pkgManualAntennaCtrl	Specifies wanted azimuth and elevation for antenna, when using manual antenna control.
129	pkgSetSatId	Specifies the CanSat ID to use.
130	pkgSetManualLocation	Specifies the GPS location of the ground station, which is used for automatic CanSat tracking.
131	pkgGSCmd	Miscellaneous commands from the RUC to the ground station, that doesn't require any arguments.
132	pkgCanSatCmd	Request the ground station to send a command to the CanSat.

Table C.1: *List of package types in the RUC protocol*

of each package must be specified. This information is seen below, where comments are used to give further description. The packages that go from the ground station to the RUC are listed below, the structs describe the contents in the `pkgContents[]`-field.

```
struct pkgSatData {
    uint32_t timestamp;         /* Milliseconds since some arbitrary reference
                                 * time */
    uint8_t flags;              /* Bit0: 1 if CRC mismatch, 0 otherwise */
    struct pkgWarp warp;        /* A type0 WARP package, excluding start-, stop
                                 * and escape bytes */
};

struct pkgControlInfo {
    int16_t currentAzimuth;     /* 1/10 degree, 0 is north */
    int16_t currentElevation;   /* 1/10 degree, 0 is vertical */
    int16_t wantedAzimuth;      /* 1/10 degree, 0 is north */
    int16_t wantedElevation;    /* 1/10 degree, 0 i vertical */
    uint32_t timestamp;         /* Milliseconds since some arbitrary reference
                                 * time */
};
```

The packages that go from the RUC to the ground station are:

```
struct pkgManualAntennaCtrl {
    int16_t azimuth;            /* 1/10 degree, 0 i vertical */
    int16_t elevation;          /* 1/10 degree, 0 is north */
};

struct pkgSetSatId {
    uint8_t satId;              /* CanSat ID of CanSat to use */
};

struct pkgSetManualLocation {
    struct gpsData gps;         /* GPS data giving location of ground station.
                                 * This is a string with the same format as
                                 * GPS data in the WARP protocol. */
};

/* Ground station commands (sent from PC) */
#define CMD_CALIBRATE                   0
#define CMD_AUTO_CONTROL                1
#define CMD_GET_SAVED_DATA              3
#define CMD_MANUAL_CONTROL              4
#define CMD_USE_P_CTRL                  5
#define CMD_USE_PI_CTRL                 6
#define CMD_USE_LEAD_CTRL               7
#define CMD_ENABLE_LINEAR_CORRECTION    8
#define CMD_DISABLE_LINEAR_CORRECTION   9
struct pkgGSCmd {
    uint8_t command;            /* Command to ground station, as specified
                                 * in the above defines */
};

struct pkgCanSatCmd {
    uint8_t command;            /* Command number to send to the CanSat */
};
```

Appendix D: uIP Example Mainloop with ARP

The following C source code is example code for using uIP with ARP. The code is from the uIP documentation[20]. All the functions and variables prefixed with uIP are already implemented by uIP. The rest of the functions must be defined by the user of the library. In the example code, the function calls to the generic network device has been replaced by equivalent functions of the device driver for the ENC28J60 Ethernet controller.

```
#include "uip.h"
#include "uip_arp.h"
#include "chips/enc28j60.h" /*#include "network-device.h"*/
#include "httpd.h"
#include "timer.h"

#define BUF ((struct uip_eth_hdr *)&uip_buf[0])

/*---------------------------------------------------------------------------*/
int
main(void)
{
  int i;
  uip_ipaddr_t ipaddr;
  struct timer periodic_timer, arp_timer;

  timer_set(&periodic_timer, CLOCK_SECOND / 2);
  timer_set(&arp_timer, CLOCK_SECOND * 10);

  encInit(); /*network_device_init();*/
  uip_init();

  uip_ipaddr(ipaddr, 192,168,0,2);
  uip_sethostaddr(ipaddr);

  httpd_init();

  while(1) {
    uip_len = encReceivePacket(uip_buf, UIP_BUFSIZE) /*network_device_read();*/
    if(uip_len > 0) {
      if(BUF->type == htons(UIP_ETHTYPE_IP)) {
    uip_arp_ipin();
    uip_input();
    /* If the above function invocation resulted in data that
       should be sent out on the network, the global variable
       uip_len is set to a value > 0. */
    if(uip_len > 0) {
      uip_arp_out();
      encTransmitPacket(uip_buf, uip_len) /*network_device_send();*/
    }
      } else if(BUF->type == htons(UIP_ETHTYPE_ARP)) {
    uip_arp_arpin();
    /* If the above function invocation resulted in data that
       should be sent out on the network, the global variable
       uip_len is set to a value > 0. */
    if(uip_len > 0) {
      encTransmitPacket(uip_buf, uip_len) /*network_device_send();*/
    }
      }

    } else if(timer_expired(&periodic_timer)) {
      timer_reset(&periodic_timer);
      for(i = 0; i < UIP_CONNS; i++) {
    uip_periodic(i);
    /* If the above function invocation resulted in data that
       should be sent out on the network, the global variable
       uip_len is set to a value > 0. */
    if(uip_len > 0) {
      uip_arp_out();
```

```
      encTransmitPacket(uip_buf, uip_len) /*network_device_send();*/
    }
      }

      /* Call the ARP timer function every 10 seconds. */
      if(timer_expired(&arp_timer)) {
    timer_reset(&arp_timer);
    uip_arp_timer();
      }
    }
  }
  return 0;
}
/*---------------------------------------------------------------------------*/
```

Appendix E: ARTOS Function Prototypes

Function Documentation

uint32_t osGetTime (void)

Returns the time since system startup in ms, calculated from systickCnt and the timer used to increment this.

Do NOT use in an ISR.

Definition at line **182** of file **os.c**.

uint32_t osGetTimeFromIsr (void)

Returns the time since system startup in ms, calculated from systickCnt and the timer used to increment this.

To be used in an ISR.

Definition at line **190** of file **os.c**.

```
void osQueueInit ( struct queue *  queue,
                   uint32_t        length,
                   uint32_t        elementSize,
                   void *          buffer
                 )
```

Initializes a queue struct.

Must be called before any operation is performed on the queue.

Parameters:

queue	A pointer to the queue struct to be initialized.
length	Length of the queue in bytes.
elementSize	Size of each element in the queue.
buffer	Pointer to free memory of at least length bytes to contain the values of the queue.

Note:

osQueueInit does not allocate any memory for the queue. Memory for the queue and buffer must be allocated by the user.

Definition at line **264** of file **os.c**.

```
uint32_t osQueueRead ( struct queue *          queue,
                       void *                  dataDest,
                       enum allowBlockArg      allowBlock
                     )
```

Reads one value from a queue in a FIFO manner.

Parameters:

queue	A pointer to the queue to read from.
dataDest	A pointer to the destination where the read out value will be written to.
allowBlock	If the queue is empty and this argument is BLOCK, the caller will be blocked until another task writes to the queue, and then the data will be written to dataDest. If this argument is NOBLOCK the call will return immediately and the caller must determine from the return value if the read was successful.

Returns:

0 if read was successful and a value has been written to dataDest, nonzero if the queue was empty and no read operation has been performed.

uint32_t osQueueReadFromIsr (struct queue * queue,
void * dataDest
)

Read one value from a queue in a FIFO manner.

May be used from an ISR.

Parameters:

queue	A pointer to the queue to read from.
dataDest	A pointer to the destination where the read out value will be written to.

Returns:

0 if action was performed successfully, no rescheduling is required, 1 if rescheduling is required (i.e. a task with higher priority than currentTask was unblocked), 2 if action could not be performed, since queue was empty.

Definition at line **368** of file **os.c**.

uint32_t osQueueWrite (struct queue * queue,
void * dataSource,
enum allowBlockArg allowBlock
)

Writes one value to a queue in a FIFO manner.

Parameters:

queue	A pointer to the queue to write to.
dataSource	A pointer to the memory where the value to be written is read from.
allowBlock	If the queue is full and this argument is BLOCK, the caller will be blocked until another task reads from the queue, and then the data will be written to the queue. If this argument is NOBLOCK the call will return immediately and the caller must determine from the return value if the write was successful.

Returns:

0 if write was successful and a value has been written to the queue, nonzero if the queue was full and no write operation has been performed.

uint32_t osQueueWriteFromIsr (struct queue * queue,
void * dataSource

)

Writes one value to a queue in a FIFO manner.

Parameters:

queue A pointer to the queue to write to.

dataSource A pointer to the memory where the value to be written is read from.

Returns:

0 if action was performed successfully, no rescheduling is required, 1 if rescheduling is required (i.e. a task with higher priority than currentTask was unblocked), 2 if action could not be performed, since queue was full.

Definition at line **376** of file **os.c**.

void osSemDown (struct semaphore * sem)

Decreases the semaphore value by one.

Blocks the caller if the semaphore is already zero.

Parameters:

sem A pointer to the semaphore to be downed.

void osSemInit (struct semaphore * sem,
uint32_t initialValue
)

Initializes a semaphore struct with the given value.

Parameters:

sem A pointer to the semaphore struct to be initialized.

initialValue The starting value of the semaphore.

Definition at line **226** of file **os.c**.

void osSemUp (struct semaphore * sem)

Increase the semaphore value by one.

If a higher priority task is currently blocked by the semaphore, rescheduling will occur and the higher priority task will resume it's execution.

Parameters:

sem A pointer to the semaphore to be upped.

uint32_t osSemUpFromIsr (struct semaphore * sem)

Increase semaphore value by one.

This function may be called from an ISR.

Parameters:

sem A pointer to the semaphore to be upped.

Returns:

non-zero if rescheduling is required (i.e. a task with higher priority than the currentTask was unblocked)

Definition at line **238** of file **os.c**.

void osTaskCreate (struct taskDescriptor * td,
void * stackBase,
unsigned short stackSize,
unsigned char priority,
void(*)(void *) func,
void * arg
)

Creates a new tasks and adds it to the readylist with the specified priority.

The task will run immediately if no higher priority task is currently running.

Parameters:

td	A pointer to an empty **taskDescriptor** struct, which will contain the reresentation of the task itself.
stackBase	A pointer to the lowest adress of the stack.
stackSize	The size of the stack in bytes.
priority	The priority of the task in the range [1:OS_NUM_PRIORITIES -1], where OS_NUM_PRIORITIES - 1 is the highest priority.
func	A pointer to the function that will be run in the task. If the task returns, the task will be terminated.
arg	A pointer argument, that the func will be called with.

Note:

The osTaskCreate does not allocate any memory for the stack or the **taskDescriptor**. The required memory must be statically allocated by the user. Furthermore the user must ensure that the allocated stack size is sufficient to prevent stack overflow.

void osTaskTerminate ( )

Terminates the currently running task.

Has the same effect as returning from the task.

void osWaitForDivisibleTick (uint32_t mask)

Blocks the caller until the system tick count (systickCnt) ANDed with the mask is zero.

E.g. if OS_SYSTICK_TIME is 8 [ms] and the mask is 0b11, the caller will be unblocked when the two least significant bits of the systickCnt is 0, which happens every 8*4 [ms] (OS_SYSTICK_TIME * mask + 1). This masking system makes the implementation of osWaitForDivisibleTick efficient. This system call can be used to create periodic tasks.

Parameters:

mask 32 bit number to be ANDed with the systickCnt.

Variable Documentation

volatile uint32_t systickCnt

The system time measured in system ticks.

This variable shall be considered readonly from user programs.

Definition at line **24** of file **os.c**.

Referenced by **osGetTime()**, and **osGetTimeFromIsr()**.

Appendix F: CanSat Test Stand-in

In order to perform tests of the system, a device acting as a CanSat is needed. For this, an Arduino Mini Pro[38] with an RFM12B[11] radio transceiver is used. As the antenna for the CanSat stand-in, an 8.63 cm wire is used, ie. a quarter wave length whip antenna. This setup has been largely copied from the CanSat designed by group 502, autumn semester 2010, 5. semester EE at AAU.

The Arduino Mini Pro is programmed through the "FTDI Basic Break - 3.3 V" programmer. This also provides a connection to the serial rs232 port used in some of the tests. The connection of the RFM12B RF transceiver to the Arduino Mini Pro is done according to table F.1.

RFM12B pin (see [11, pp. 2])	**Arduino Mini Pro pin (see [38])**
nIRQ	2
nSEL	10
SDI	11
SDO	12
SCK	13
FSK/DATA/nFFS	VCC through 10 kΩ resistor
VDD	VCC
GND (2 pins)	GND

Table F.1: *Connecting the RFM12B to the Arduino Mini Pro. Unmentioned pins are not connected.*

Software

To perform the tests, various pieces of test code has to be executed on the Arduino. This testing code is build on top of the kernel and support software developed by group 502. To get this code compiled into the binary image uploaded by the Arduino tool, the "core" that includes this kernel, must be added to arduino. The core is found at [15]. To tell Arduino where the "core" is located, add the following to the `boards.txt` file found in the Arduino installation folder. On Linux, this is most likely the folder `/usr/share/arduino/hardware/arduino/boards.txt`.

```
aau_pro328.name=Arduino Pro or Pro Mini (3.3V, 8 MHz) w/ ATmega328 and AAUduino
aau_pro328.upload.protocol=stk500
aau_pro328.upload.maximum_size=30720
aau_pro328.upload.speed=57600
aau_pro328.bootloader.low_fuses=0xFF
aau_pro328.bootloader.high_fuses=0xDA
aau_pro328.bootloader.extended_fuses=0x05
aau_pro328.bootloader.path=atmega
aau_pro328.bootloader.file=ATmegaBOOT_168_atmega328_pro_8MHz.hex
aau_pro328.bootloader.unlock_bits=0x3F
aau_pro328.bootloader.lock_bits=0x0F
aau_pro328.build.mcu=atmega328p
aau_pro328.build.f_cpu=8000000L
aau_pro328.build.core=../../../../../../media/cd/cansat_standin/core
```

The last line has to be the relative path from the folder with the boards.txt file to the "core" folder provided. Now, open the .pde files provided as test code in arduino and it will use the "Arduino Pro or Pro Mini (3.3V, 8 MHz) w/ ATmega328 and AAUduino" board/core just added.

[15] `/cansat_standin/core/`

Appendix G: Schematic, Part-list and Physical Construction

The following is a complete list of all the hardware, that makes up the developed ground station.

- The Mini-Max/ARM-E development board from BiPOM Electronics[8], which consists of the following items:

  LPC2138[9] - Microcontroller

  ARM7TDMI[7] - CPU core

  ENC28J60[21] - Ethernet Controller

- RFM12B[11] - Wireless module

- Motor driver

  L298 IC[35] - Dual full-bridge driver

  Amax 26[29] - Motor

  ENC-MR-128imp-225771[32] - Encoder

The physical contruction can be seen on figure G.1, and on the cd[16]. A schematic of the designed system can be seen on figure G.2 on the next page. This can also be found on the cd[17].

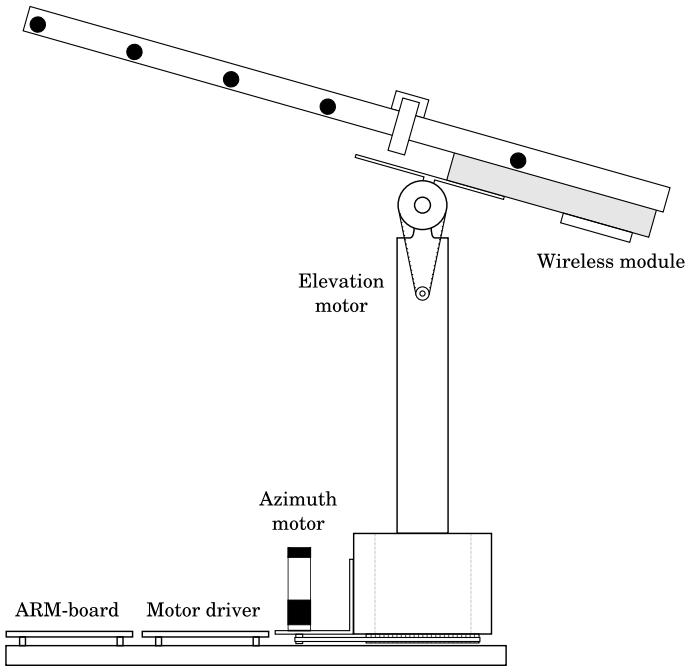
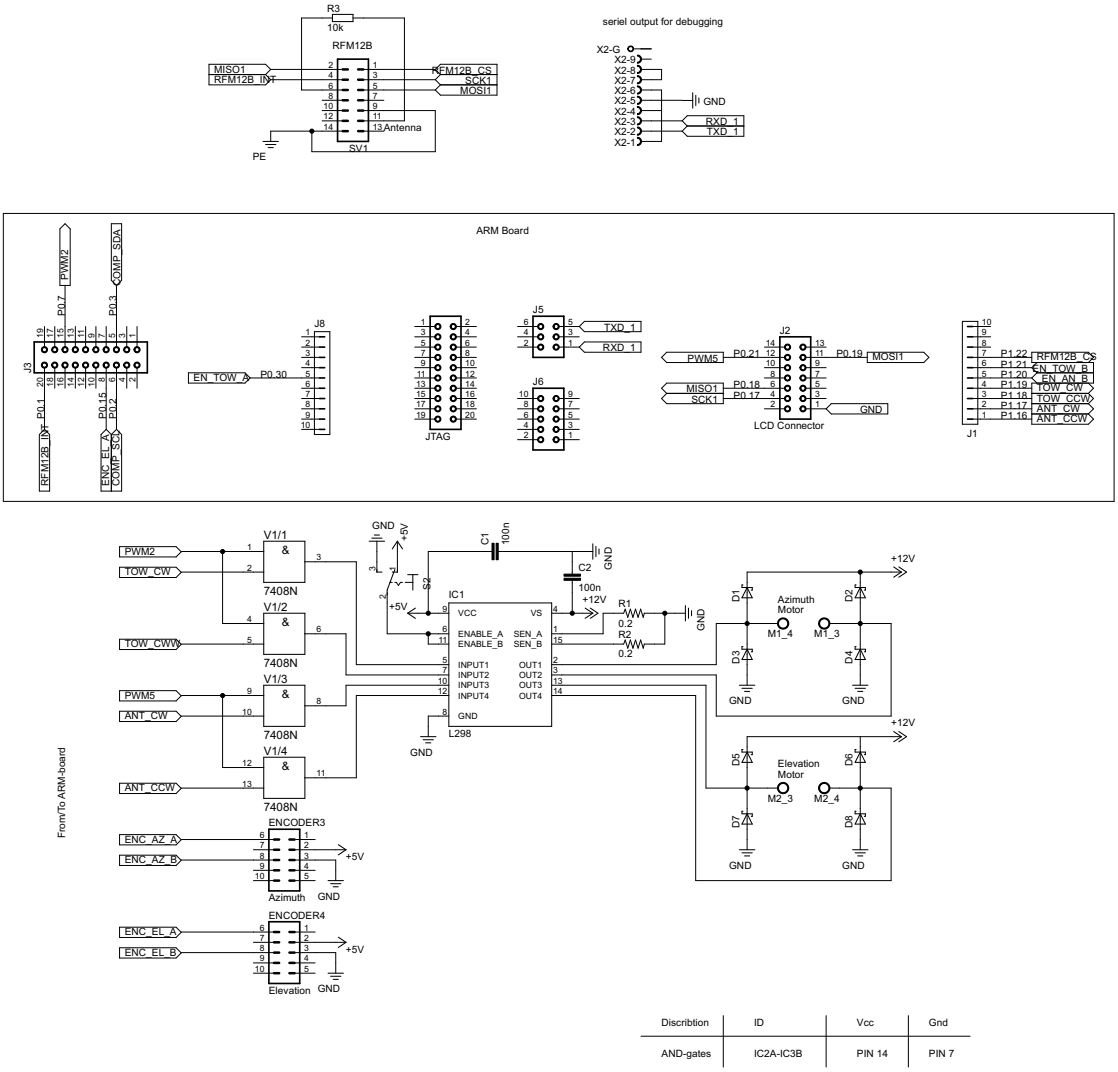


Figure G.1: *The physical contruction of the ground station.*

[16] /physical_contruction/construction.pdf
[17] /schematics/arm_total.<sch,pdf>



Discribtion	ID	Vcc	Gnd
AND-gates	IC2A-IC3B	PIN 14	PIN 7

Figure G.2: *Schematic of the designed system. Note that many labels refer to labels within the ARM Board schematic[8].*

Test & Measurement Journals

Journal 1: Range Test of RF Communication

1.1 Purpose

The purpose of the test, is to examine the radio communication used between the ground station and the CanSat. The maximum range where a communication link can be established, is to be determined. Both uplink (ground station to CanSat) and downlink (CanSat to ground station) communication is examined.

1.2 Test Object

The test object is the ARM development board with the RFM12B RF transceiver connected. The Yagi antenna is used.

A device transmitting respectively receiving the signal to/from the ground station is needed during the tests. As this, device acting as the CanSat, an arduino mini pro is used. This is connected to another RFM12B transceiver, with a quarter wavelength (8.63 cm) wire connected as it's antenna. The software running on this arduino, is based on the kernel and RFM12B driver code developed by group 502.

Used Equipment

Instrument	AAU-No	Make and type
CanSat stand-in		Arduino Mini Pro w/ RFM12B and 8.63 cm wire whip antenna. See appendix F on page 145.

Table 1.1: *Equipment used in the test.*

1.3 Approach

A different approach is used for the uplink and the downlink tests, because these act very differently in practice. The transmission link quality is sensitive to the orientation of the transmitter and receiver. For the uplink, two distances are determined:

- The maximum distance, where an error free link is available, independent of the orientation of receiver/transmitter.
- The maximum distance, where it is not possible to successfully transmit even a single package.

This test doesn't make much sense for the downlink connection, as reception on the ground station is very bad. Therefore, it is here examined how the connection quality varies at different distances and orientations. This is done by taking measurements of how large a percentage of packages can be successfully transferred at different distances and orientations.

The measurement of the distances, are not required to be of high accuracy, since the range cannot be precisely determined. It is highly dependent on the surroundings where the measurements are taken. Therefore, measurement of the distance is done by noting landmarks during the measurement, and then using Google Maps to measure the distance.

1.4 Uplink Test

The uplink test is performed in the way described below. An acceptable connection is understood to be a connection where 10 consecutive packages are transferred without errors.

1. The ground station is programmed with the software found at [18] with the patch [19] applied. This software transmits this package once every second:

```
static uint8_t buf[] = {0x0d, 0x00, 0x00, 0xab, 0xcd, 0xef, 0xab,
        0x00, 0x12, 0x34, 0x56, 0x78, 0x9a, 0xbc, 0xde, 0xff,
        0xed, 0xcb, 0xa9, 0x87, 0xeb};
```

2. The arduino mini pro is programmed with the software found at [20]. This software echoes all received packages on it's serial port at baud 115200. The package contents printed on this serial port is compared to the package specified above, to verify if it's contents is correct.
3. Let the ground stations antenna point in a direction where it is possible to walk far, while still keeping a clear line of sight to the ground station.
4. With a laptop connected to the arduino's serial port, walk away from the ground station. Keep a clear line of sight to the ground station. Walk further away, until an error free package is not received.
5. Walk closer to the ground station, until it is not possible to rotate the RFM12B antenna in such a way that the connection is not acceptable anymore, see definition above.
6. Note some landmark nearby, for later length measurement on Google Maps.
7. Continue walking further away, until it is not possible to hold the antenna in a position, where even a single package can be received without errors.
8. Again, note some landmark.
9. Measure the range lengths, by use of Google Maps.

The results from the test can be seen in table 1.2.

Test	**Result [m]**
Always acceptable connection	260
No error free packages received	400

Table 1.2: *Measurement result for uplink test*

1.5 Downlink Test

For the downlink test, the following steps are performed. The test is done in both a vertical and horizontal orientation, to examine the effect of wrong polarization between the antennas. The antennas are polarization matched, when holding the CanSat antenna in a horizontal position.

[18] `/groundstation`
[19] `/journals/rf_comm/uplink/test.diff`
[20] `/journals/rf_comm/uplink/arduino`

1. The arduino mini pro is programmed with the software found at [21]. This software transmits a package similar to the one in the uplink test, every second. Note that the package has a valid CRC8 character in the end. Also, the letter 'r' is printed on the arduino's serial port, when a package has been transmitted.
2. The ground station is programmed with the software found at [22] with the patch [23] applied. This software echoes all received packages to the serial port.
3. The ground station antenna should point directly towards the CanSat antenna at all times during the test.
4. With a laptop connected to the arduino's serial port, hold the CanSat antenna 1 m from the ground station antenna.
5. Hold the antenna in a horizontal position. Hold down the reset button on the arduino, release it and wait for it to have transmitted 10 packages. Now look at the ground station serial output, and note how many packages were received successfully respectively received with CRC errors.
6. Repeat step 5, while holding the antenna in a vertical position (i.e. rotated 90 deg in a plane normal to the direction the antenna is pointing.)
7. Repeat step 4 - 6, increasing the length 1 m, until nothing has been received for 3 m.

The results from the test can be seen in table 1.3.

Distance	**Orientation**	**Packages OK**	**Packages w/ CRC mismatch**	**Lost packages**
2 m	Horizontal	10	-	-
2 m	Vertical	-	-	10
3 m	Horizontal	10	-	-
3 m	Vertical	-	-	10
4 m	Horizontal	-	10	-
4 m	Vertical	-	-	10
5 m	Horizontal	-	-	10
5 m	Vertical	-	-	10
6 m	Horizontal	-	-	10
6 m	Vertical	-	-	10
7 m	Horizontal	-	-	10
7 m	Vertical	-	-	10
10 m	Horizontal	-	-	10
10 m	Vertical	-	-	10

Table 1.3: *Test results of downlink test*

1.6 Measurement Uncertainties

The environment where the measurements are taken, can have a significant implication on the results, as reflections and absorption of the RF signal occur. The measurement has been taken as free line of sight directly above the earth. When flying the CanSat, it will be in the air and thus further away from any reflection sources, such as the earth.

[21] /journals/rf_comm/downlink/arduino
[22] /groundstation
[23] /journals/rf_comm/downlink/test.diff

Journal 2: Test of RUC CSV File Saving

2.1 Purpose

The purpose of this test journal, is to test requirement 4 and 5 specified in section 3.2 on page 17, for the RUC. This test is performed with respect to the acceptance test specification in test 3 on page 19. The RUC is explained in further detail, in chapter 10 on page 91. The ability to save the ControlInfo CSV file is tested as well.

2.2 Test Object

The test object is the RUC.

Used Equipment

Instrument	AAU-No	Make and type
OS		Microsoft Windows XP
IDE		Eclipse SDK Version: 3.4.2
IDE		NetBeans IDE 6.9.1

Table 2.1: *Equipment used to test the RUC.*

The code for the server used in test 1, can be found on the CD [24], for both SatData and RegData.

2.3 Approach

The RUC will be connected to a server running inside the Eclipse IDE, adhering to the RUC protocol. This server will be sending packages to the RUC. Depending on which packages are sent, either the data CSV file, or the ControlInfo CSV file is being written to. To test if the data is saved correctly, the saved data is compared with the received data. Afterwards, the RUC will be terminated by the OS, and the CSV files will be checked for data loss.

2.4 Test 1

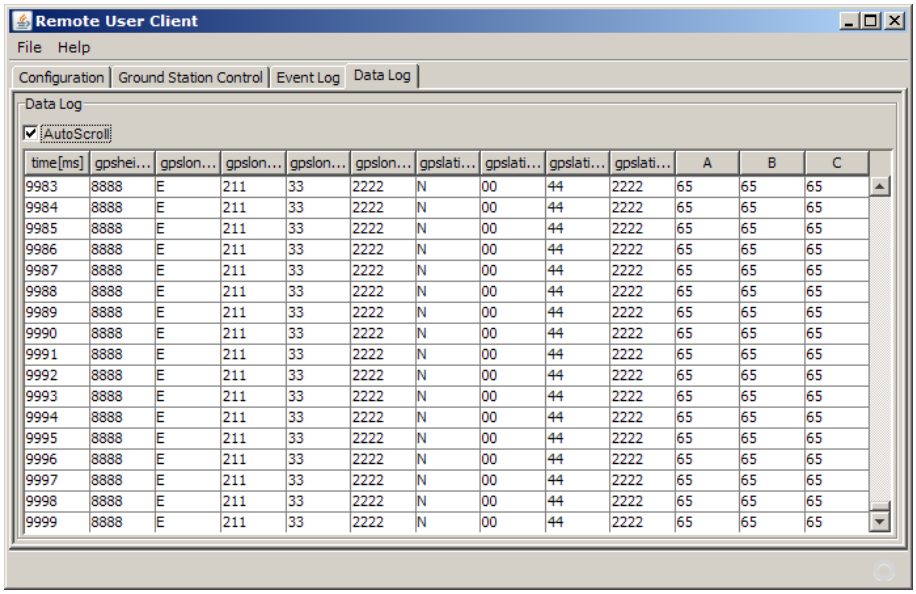
The RUC is connected to a server that is sending 10,000 SatData packages, where the timestamp field is incremented by one, for every package. Before connecting, the CSV filename has been set to "CSVfile". A snapshot of the received data is shown in figure 2.1 on the following page, and a snapshot of the saved data is shown in figure 2.2 on the next page. It is seen that the saved data matches the received data.

The test is now repeated, only this time the RUC is terminated by the OS after 5055 packages are received. A snapshot of the contents of the CSV file can be seen in figure 2.3 on the following page. It is seen that the CSV file contains 5055 valid packages. A similar test was done for the ControlInfo data, with similar results.

2.5 Measurement Uncertainties

One uncertainty is the platform, as a RUC crash might be treated differently, depending on the OS. It is assessed, that no other measurement uncertainties played any significant role.

[24] `/journals/ruc_csv/`



time[ms]	gpshei...	gpslon...	gpslon...	gpslon...	gpslon...	gpslati...	gpslati...	gpslati...	gpslati...	A	B	C
9983	8888	E	211	33	2222	N	00	44	2222	65	65	65
9984	8888	E	211	33	2222	N	00	44	2222	65	65	65
9985	8888	E	211	33	2222	N	00	44	2222	65	65	65
9986	8888	E	211	33	2222	N	00	44	2222	65	65	65
9987	8888	E	211	33	2222	N	00	44	2222	65	65	65
9988	8888	E	211	33	2222	N	00	44	2222	65	65	65
9989	8888	E	211	33	2222	N	00	44	2222	65	65	65
9990	8888	E	211	33	2222	N	00	44	2222	65	65	65
9991	8888	E	211	33	2222	N	00	44	2222	65	65	65
9992	8888	E	211	33	2222	N	00	44	2222	65	65	65
9993	8888	E	211	33	2222	N	00	44	2222	65	65	65
9994	8888	E	211	33	2222	N	00	44	2222	65	65	65
9995	8888	E	211	33	2222	N	00	44	2222	65	65	65
9996	8888	E	211	33	2222	N	00	44	2222	65	65	65
9997	8888	E	211	33	2222	N	00	44	2222	65	65	65
9998	8888	E	211	33	2222	N	00	44	2222	65	65	65
9999	8888	E	211	33	2222	N	00	44	2222	65	65	65

Figure 2.1: *The contents of the data log from test 1, after 10,000 packages.*

	A	B	C	D	E	F	G	H	I	J	K	L	M
9985	9983	8888	E	211	33	2222	N	0	44	2222	65	65	65
9986	9984	8888	E	211	33	2222	N	0	44	2222	65	65	65
9987	9985	8888	E	211	33	2222	N	0	44	2222	65	65	65
9988	9986	8888	E	211	33	2222	N	0	44	2222	65	65	65
9989	9987	8888	E	211	33	2222	N	0	44	2222	65	65	65
9990	9988	8888	E	211	33	2222	N	0	44	2222	65	65	65
9991	9989	8888	E	211	33	2222	N	0	44	2222	65	65	65
9992	9990	8888	E	211	33	2222	N	0	44	2222	65	65	65
9993	9991	8888	E	211	33	2222	N	0	44	2222	65	65	65
9994	9992	8888	E	211	33	2222	N	0	44	2222	65	65	65
9995	9993	8888	E	211	33	2222	N	0	44	2222	65	65	65
9996	9994	8888	E	211	33	2222	N	0	44	2222	65	65	65
9997	9995	8888	E	211	33	2222	N	0	44	2222	65	65	65
9998	9996	8888	E	211	33	2222	N	0	44	2222	65	65	65
9999	9997	8888	E	211	33	2222	N	0	44	2222	65	65	65
10000	9998	8888	E	211	33	2222	N	0	44	2222	65	65	65
10001	9999	8888	E	211	33	2222	N	0	44	2222	65	65	65

Figure 2.2: *The contents of the "CSVfile" from test 1, after 10,000 packages.*

	A	B	C	D	E	F	G	H	I	J	K	L	M
5043	5041	8888	E	211	33	2222	N	0	44	2222	65	65	65
5044	5042	8888	E	211	33	2222	N	0	44	2222	65	65	65
5045	5043	8888	E	211	33	2222	N	0	44	2222	65	65	65
5046	5044	8888	E	211	33	2222	N	0	44	2222	65	65	65
5047	5045	8888	E	211	33	2222	N	0	44	2222	65	65	65
5048	5046	8888	E	211	33	2222	N	0	44	2222	65	65	65
5049	5047	8888	E	211	33	2222	N	0	44	2222	65	65	65
5050	5048	8888	E	211	33	2222	N	0	44	2222	65	65	65
5051	5049	8888	E	211	33	2222	N	0	44	2222	65	65	65
5052	5050	8888	E	211	33	2222	N	0	44	2222	65	65	65
5053	5051	8888	E	211	33	2222	N	0	44	2222	65	65	65
5054	5052	8888	E	211	33	2222	N	0	44	2222	65	65	65
5055	5053	8888	E	211	33	2222	N	0	44	2222	65	65	65
5056	5054	8888	E	211	33	2222	N	0	44	2222	65	65	65
5057	5055	8888	E	211	33	2222	N	0	44	2222	65	65	65
5058													
5059													

Figure 2.3: *The crashed CSV used in test 1.*

Journal 3: Model Parameter Determination

This journal describes how the uncertain parameters for both the azimuth and elevation model have been determined through tests. The journal includes a list of all the equipment used, testing procedures and the results of each test.

3.1 Purpose

The purpose of these tests is to derive the model parameters that are unknown or uncertain, namely moments of inertia of the moving parts in the system, friction and gear ratios. All of these parameters are physical properties of the system, and they must therefore be determined experimentally or through direct measurements.

3.2 Test Object

Figure 3.1 shows the test object and dimensions to be measured.

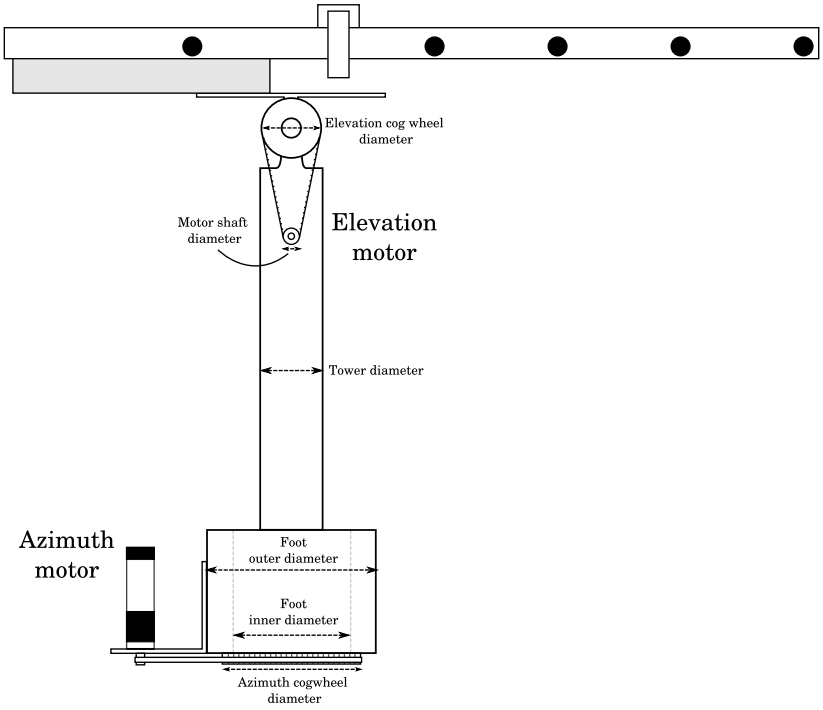


Figure 3.1: *The platform being tested*

3.3 Equipment list

The following equipment has been used:

Instrument	AAU-No	Make and type
PC		Linux OS
Voltage supply	61398	Hameg triple power supply HM7042-5
Scale	08432	Mettler PJ
Ruler		

Table 3.1: *Equipment used to test the ground station antenna platform.*

The following software has been used for data collection and processing:

- The RUC software
- Matlab
- OpenOffice Calc

3.4 List of Tests

The following tests have been performed:

1. Determination of gear ratios and moments of inertia.
2. Sampling system performance - Azimuth.
3. Sampling system performance - Elevation.

3.5 Test 1: Determination of Gear Ratios & Moments of Inertia

In this test a set of measurements are made on the dimensions of cog wheels and moving parts. The weight of the moving parts is also measured, making it possible to determine the moments of inertia.

Testing Procedure

1. Using the ruler, the diameter of each cog wheel is measured. The measurements are noted.
2. The antenna platform is split into the following parts: The foot, the tower and the antenna.
3. The diameter of the foot and the width of the tower is measured and noted.
4. The length of the antenna is measured and noted.
5. Using the scale, all the elements are weighed. The weights are noted.

Formulas Used

For calculating gear ratios the following formula has been used:

$$N = \frac{R_2}{R_1} \tag{3.1}$$

where:

N	is the gear ratio	[-]
R_1	Is the radius of the cog wheel where torque is applied directly	[m]
R_2	Is the radius of the cog wheel being driven by the gear	[m]

For calculating moments of inertia, three different formulas have been used for the tower, the foot and the antenna.

Antenna inertia: To simplify calculations, the antenna is assumed to have the same inertia as a rod with a given length and mass. With this assumption, the moment of inertia is given by[39]:

$$J_a = \frac{1}{12} \cdot M \cdot l^2 \tag{3.2}$$

Tower inertia: The tower is assumed to have the same moment of inertia as a hollow cylinder with a radius corresponding to the width of the tower. The moment of inertia is then given by[39]:

$$J_t = M \cdot r^2 \tag{3.3}$$

Foot inertia: Since the foot of the platform is also hollow but with thicker walls, it's moment of inertia is given by[39]:

$$J_f = \frac{1}{2} \cdot M(r_1^2 + r_2^2) \tag{3.4}$$

Results

The measured values are shown in table 3.2.

Property	Value	Unit
Motor shaft diameter	$5 \cdot 10^{-3}$	m
Azimuth cog wheel diameter	$44.5 \cdot 10^{-3}$	m
Elevation cog wheel diameter	$23 \cdot 10^{-3}$	m
Tower diameter	$25 \cdot 10^{-3}$	m
Tower mass	1.668	kg
Foot outer diameter	$65 \cdot 10^{-3}$	m
Foot inner diameter	$50 \cdot 10^{-3}$	m
Foot mass	$2 \cdot 10^{-3}$	kg
Antenna length	$605 \cdot 10^{-3}$	m
Antenna mass	0.388	kg

Table 3.2: *Values measured on the antenna platform.*

By using the formulas from section 3.5 on the preceding page the gear ratios and moments of inertia have been calculated. The values are shown in table 3.3.

Property	Value	Unit
Tower inertia	$0.52 \cdot 10^{-3}$	$\text{kg} \cdot \text{m}^2$
Foot inertia	$6.7 \cdot 10^{-3}$	$\text{kg} \cdot \text{m}^2$
Antenna inertia	$11.3 \cdot 10^{-3}$	$\text{kg} \cdot \text{m}^2$
Azimuth gear ratio	8.6 : 1	-
Elevation gear ratio	4.6 : 1	-

Table 3.3: *Parameters calculated from the measured values.*

3.6 Test 2: Sampling System Performance - Azimuth

The goal of this test is to determine the parameters for dry and viscous friction for rotation on the azimuth axis.

Testing Procedure

1. In the ground station software, the PWM duty cycle is set to 100%. And a rotation limit of 180° where the power will be cut off is specified. The software is then loaded onto the ARM board.

2. With power output disabled, the voltage supply is set to supply the motors with 3.5 V.
3. On the PC, the RUC is connected to the ground station. A unique filename is chosen for the collected data.
4. The antenna is manually adjusted to level. The angle sensors are then reset using the "Calibrate" button on the RUC.
5. Power output is enabled and the rotation starts.
6. When the rotation stops due to the 180° limit, the RUC is disconnected and the power output is disabled.
7. The procedure is repeated from step 2 for voltage with voltage values of 4, 5, 6, 8 and 10 V.

Results

CSV-files containing the collected data can be found on the CD [25] . The data set consists of the angular position in degrees, multiplied by a factor 10 and a timestamp measured in milliseconds. The dataset has been trimmed by removing all data points up until the point where voltage is applied.

3.7 Test 3: Sampling System Performance - Elevation

The goal of this test is to determine the parameters for dry and viscous friction for rotation on the elevation axis.

Testing Procedure

1. In the ground station software, the PWM duty cycle is set to match an output voltage of 4 V. Non-linearity correction is enabled and a rotation limit of 90° where the power will be cut off is specified. The software is then loaded onto the ARM board.
2. With power output disabled, the voltage supply is set to supply the motors with 12 V.
3. On the PC, the RUC is connected to the ground station. A unique filename is chosen for the collected data.
4. The antenna is manually adjusted to level. The angle sensors are then reset using the "Calibrate" button on the RUC.
5. Power output is enabled and the rotation starts.
6. When the rotation stops due to the 90° limit, the RUC is disconnected and the power output is disabled.
7. The procedure is repeated with a voltage value of 6 and 8 V.
8. The non-linearity correction is disabled in the software.
9. The same procedure is repeated again.

[25] `/journals/parameter_determination/data/measured/<#>`

Results

CSV-files containing the collected data can be found on the CD [26] . The dataset consists of the angular position in degrees, multiplied by a factor 10, and a timestamp measured in milliseconds. The dataset has been trimmed by removing all data points up until the point where voltage is applied.

[26] `/journals/parameter_determination/data/measured/<#>`

Journal 4: Controller Verification

4.1 Purpose

The purpose of this test, is to determine if the controllers designed in chapter 9 on page 65 functions as intended, and whether the system meets requirement 8 in the requirement specification, seen in section 3.2 on page 17. For this purpose, several tests will be done.

4.2 Test Object

The test object is the fully implemented system, described in chapter 4 on page 23.

Used Equipment

Instrument	AAU-No	Make and type
Alternative RUC		Added Curvetracer function

Table 4.1: *Equipment used in the test.*

In this journal, an alternative RUC is used. This version has a button added, that makes the ground station trace the curve on figure 2.3 on page 11. This way a CanSat launch is simulated.

4.3 Approach

The RUC establishes a connection to the ground station, and an arbitrary CanSat ID is entered. In test 1 through 4, a controller type will be selected, and the wanted elevation position will be changed 20° instantly. The 20° are chosen because it gives a more realistic situation of how a input step under a CanSat launch will be. A to large step will also saturate the output of the motor driver and the controller will no longer be linear. In test 5, the same step will be performed, for the azimuth controller. In test 6, the 'best' elevation controller is selected, as specified in section 9.4 on page 86, and the CanSat launch is simulated, with respect to acceptance test 6, seen in section 3.3 on page 19.

4.4 Test 1 - Elevation P-Controller Without Non-linearity Correction

In this test, the elevation position is set to 20° initially. This is done to test what the effect of running the controller with the non-linearity correction disabled. The elevation position is then changed to 40° instantly. The test results can be found here: [27]. A plot of the test can be seen in section 9.4 on page 86.

4.5 Test 2 - Elevation Lead-Controller Without Non-linearity Correction

In this test, the elevation position is set to 20° initially, for the same reason as in test 1. The elevation position is then changed to 40° instantly. The test results can be found here: [28]. A plot of the test can be seen in section 9.4 on page 86.

[27] `journals/controller/measurements/stepelevPRegInfo.csv`
[28] `journals/controller/measurements/stepelevLeadRegInfo.csv`

4.6 Test 3 - Elevation P-Controller With Non-linearity Correction

In this test, the elevation position is set to 20° initially. This is done to test the effect of running the controller with the non-linearity correction enabled. The elevation position is then changed to 40° instantly. The test results can be found here: [29]. A plot of the test can be seen in section 9.4 on page 86.

4.7 Test 4 - Elevation Lead-Controller With Non-linearity Correction

In this test, the elevation position is set to 20° initially, for the same reason as in test 3. The elevation position is then changed to 40° instantly. The test results can be found here: [30]. A plot of the test can be seen in section 9.4 on page 86.

4.8 Test 5 - Azimuth P-Controller

In this test, the azimuth position is set to 0° initially. The azimuth is then changed to 20° instantly. The test results can be found here: [31]. A plot of the test can be seen in section 9.4 on page 86.

4.9 Test 6 - Acceptance test 6

Only the elevation controller will be a part of this test because it is assessed that when the CanSat is launched the antenna is pointing at it, and the rocket containing the CanSat will fly straight op in the air. It can be seen from the plots in section 9.4 on page 86 that the elevation controller with the "best" step response, and therefor the one chosen for the test, is the lead controller with the non-linearity correction enabled.

The elevation position is initially set to 0°. A CanSat launch is then simulated by feeding position values according to the following formula into the controller. The formula has been derived by integrating eq. (2.2) and (2.4) which were described in section 2.3.1 on page 9.

$$\omega(t) = \begin{cases} \arctan\left(\frac{\frac{1}{2}\cdot a\cdot t^2}{r}\right) & : 0 \quad \leq t \quad \leq t_1 \\ \arctan\left(\frac{h_1 + v_{\max}(t-t_1)}{r}\right) & : t_1 \quad < t \end{cases}$$

where:

a	is the acceleration during the constant acceleration phase ($9.82\,\frac{\mathrm{m}}{\mathrm{s}^2}\cdot 20 = 196.4\,\frac{\mathrm{m}}{\mathrm{s}^2}$)	$[\frac{\mathrm{m}}{\mathrm{s}^2}]$
$v_{\max}$	is the maximum velocity of the rocket ($600\frac{\mathrm{km}}{\mathrm{h}} = 166.67\frac{\mathrm{m}}{\mathrm{s}}$)	$[\frac{\mathrm{m}}{\mathrm{s}}]$
r	is the horizontal distance between the ground station and the launch site (400 m)	[m]
h_1	is the distance travelled by the rocket during the constant acceleration phase (70.7 m)	[m]
t_1	is the duration of the constant acceleration phase (0.849 s)	[s]
t	is the time since the beginning of the launch	[s]

A new angle is calculated and fed into the system every 200 ms to simulate the effect of a GPS update rate of 5 Hz. Feeding the values into the controller is done from a modified

[29] journals/controller/measurements/stepelevPnonRegInfo.csv
[30] journals/controller/measurements/stepelevLeadnonRegInfo.csv
[31] journals/controller/measurements/stepaziRegInfo.csv

version of the RUC, which can be found on the CD [32]. The test results can be found on the CD [33] and a plot of the test can be seen in figure 9.24 on page 90.

4.10 Measurement Uncertainties

No significant measurement uncertainties are present for these tests.

[32] journals/controller/gscurvetracer
[33] journals/controller/measurements/curvetraceLeadnonRegInfo.csv

Journal 5: Measurement of Worst Case Execution Times

5.1 Purpose

The purpose of this test is to determine the worst case execution time of each task and interrupt service routine of the ground station. When tasks depend on each other, only the execution time of the task itself is to be measured.

5.2 Test Object

The test object is the complete ground station system hardware. The ground station software is altered to test one task at a time. The tasks and interrupt service routines (ISR) shown in table 5.1 are measured in the test. The used equipment is shown in table 5.2. The CanSat stand-in used is documented in appendix F on page 145.

Name	Type
ethSenderTask	Task
uipPeriodicTask	Task
encIrqHandlerTask	Task
rfmPkgHandler	Task
controllerTask	Task
encIrqHandler	ISR
rfmIrqHandler	ISR
encoderAzimuthIRQ	ISR
encoderElevationFIQ	ISR

Table 5.1: *Tasks under test.*

Used Equipment

Instrument	AAU-No	Make and type
CanSat stand-in		Arduino Mini Pro w/ RFM12B and 8.63 cm wire whip antenna
Oscilloscope	52772	Agilent Mixed Signal Oscilloscope 54621D
Laptop		Lenovo R61

Table 5.2: *Equipment used in the test.*

5.3 Procedure

The oscilloscope is connected to pin 0.27 of the LPC2138 microcontroller. This pin is high (3.3 V) when the task under test is running and low (0 V) otherwise. The time when the pin is high is measured on the oscilloscope. For each task tested, the ground station software is patched in order to stimulate it to the worst case execution time for the specific task. A patch for each test can be found on the CD. The tests are performed with printf debugging disabled i.e. compiled with the command `DFLAGS="-DDISABLE_PRINTF" make --environment-overrides`. Each task/ISR is tested as described in the following. The patch for each test is shown as a cd reference:

ethSenderTask The `ethSenderTask` is upped to highest priority in order to avoid preemption by other tasks. A task is added, which fills up the Ethernet outgoing Queue with RUC packages of 8 byte in size, thus a lot of RUC package assembling

is required. The IO pin is set to high as long as the `ethSenderTask` is running. The laptop connects to the ground station through Ethernet and the width of the widest pulse is read out on the oscilloscope. [34]

uipPeriodicTask The same scenario as for the ethSenderTask is used. The `uipPeriodicTask` is changed to highest priority and the IO toggling is assigned to this task. When the laptop has established the connection, the Ethernet cable is unplugged, which causes the `uipPeriodicTask` to issue a retransmission. The time spent by the retransmission is read out on the oscilloscope. [35]

encIrqHandlerTask The encIrqHandlerTask is upped to highest priority and IO toggling is assigned to this task. A PC program is created (`rucspam.c`), which connects to the ground station and sends a RUC package of the type `pkgSetManualLocation`, which is the RUC package requiring most processing, because of the conversion of GPS coordinates. The execution is read out on the oscilloscope. [36]

controllerTask The `controllerTask` is upped to the highest priority and IO toggling is assigned to this periodic task. The remote user client connects to the ground station and applies the lead controller and the non-linearity correction feature, which requires most execution time for the `controllerTask`. [37]

rfmPkgHandler The rfmPkgHandler task is upped to the highest priority and IO toggling is assigned to this task. The Arduino based CanSat stand-in is programmed with the software found on the cd [38] . This program sends maximum sized (150 bytes) WARP packages to the ground station with fake telemetry data. The time processing time spent by the `rfmPkgHandler` is read out on the oscilloscope. [39]

rfmIrqHandler The Arduino based CanSat stand-in is used as in the test of `rfmPkgHandler`. The IO toggling is added in the `rfmIrqHandler`. The handler receives bytes from the CanSat. There is an execution time difference between receiving the normal bytes of a package and receiving the last byte. The last byte requires more processing because the package must be passed on to the `rfmPkgHandler` via a queue. Both execution times are noted. [40] Another test is made by setting the `rfmIrqHandler` into transmit mode by adding a call to `rfmSend()` to the `main()` task. The time used by the `rfmIrqHandler` in transmit mode is also read out on the oscilloscope. [41]

encIrqHandler The IO toggling is added to the interrupt service routine for the ENC28J60 Ethernet chip. The RUC connects to the ground station and the time spent in the ISR is read out on the oscilloscope. [42]

encoderAzimuthIRQ The IO toggling is added to the interrupt service routine for the azimuth rotary encoder. The platform is rotated in the azimuth axis by hand, and the time spent inside the ISR is read out on the oscilloscope. [43]

encoderElevationFIQ The IO toggling is added to the interrupt service routine for the elevation rotary encoder. The platform is rotated in the elevation axis by hand and the time spent inside the ISR is read out on the oscilloscope. [44]

[34] `/journals/wcet_determination/ethsendertask.diff`
[35] `/journals/wcet_determination/uipperiodictask.diff`
[36] `/journals/wcet_determination/encirqhandlertask.diff`
[37] `/journals/wcet_determination/controllerhandler.diff`
[38] `/journals/wcet_determination/arduino/`
[39] `/journals/wcet_determination/rfmpkghandler.diff`
[40] `/journals/wcet_determination/rfmirqhandler.diff`
[41] `/journals/wcet_determination/rfmirqhandlertransmit.diff`
[42] `/journals/wcet_determination/encirqhandler.diff`
[43] `/journals/wcet_determination/encoderAzimuthIRQ.diff`
[44] `/journals/wcet_determination/encoderElevationFIQ.diff`

5.4 Results

Task/ISR	Case	time
ethSenderTask		5.5 ms
uipPeriodicTask		4.56 ms
encIrqHandlerTask	510 byte RUC data	26.6 ms
	27 byte RUC data	2.6 ms
rfmPkgHandler		712 μs
controllerTask		1.076 ms
encIrqHandler		22.2 μs
rfmIrqHandler	Receive last byte	110 μs
	Receive normal byte	36.0 μs
	Transmit normal byte	38.0 μs
	Transmit last byte	66.8 μs
encoderAzimuthIRQ		3.71 μs
encoderElevationFIQ		2.81 μs

Table 5.3: *Measured worst case execution time for the tasks and ISRs of the ground station software.*

5.5 Measurement Uncertainties

There is a limitation in how accurate the execution time of each task can be measured. In the measurements of the ISRs, the time used for reading the interrupt vector from the interrupt controller of the LPC2138 is not included in the measurements as well as the time used for saving and restoring two registers. In order to compensate for this an extra execution time of approximately 50 clock cycles (1 μs) can be added to the ISRs of the IRQs and 20 clock cycles (0.3 μs) to the ISRs of the FIQ. These values are however rough estimates. Larger values can be added to the execution time of the tasks in order to compensate for the overhead of context switching.

Journal 6: Acceptance Test 1

6.1 Purpose

The purpose of this test, is to determine if the designed system meets requirement 1 and 2 in the requirement specification, seen in section 3.2 on page 17. This test will be performed with respect to acceptance test 1, seen in section 1 on page 19.

6.2 Test Object

The test object is the fully implemented system, described in chapter 4 on page 23.

Used Equipment

Instrument	AAU-No	Make and type
CanSat stand-in		Arduino Mini Pro w/ RFM12B and 8.63 cm wire whip antenna

Table 6.1: *Equipment used in the test.*

The software running on the CanSat stand-in, is based on the kernel and RFM12B driver code developed by group 502. The CanSat stand in is described further in appendix F.

6.3 Approach

A connection is established from the RUC to the ground station, and a specific CanSat ID is specified. The ground station code is modified, so that all correctly received CanSat packages with the corresponding ID increments a package counter. A CanSat stand-in is then set up to transmit packages with a matching and a different CanSat ID, periodically. After 50 ms a CanSat package with a matching ID is transmitted, 100 ms later a CanSat package with a different CanSat ID is sent. In this manner, a package with the correct CanSat ID, is transmitted approximately every 150 ms, for at least 5 minutes. Afterwards the counter on the ground station, and the number of received packages on the RUC is compared.

6.4 Test 1

For this test, the code found at [45] was used on the CanSat stand-in. The test was running for approximately 12 minutes. The packages received on the RUC, can be seen in the generated CSV file [46]. All packages in this CSV file have been received correctly. The counter on the ground station was able to count 4514 packages received from the CanSat stand-in with the matching ID. This corresponds to an estimated package rate of 6.3 Hz. As seen in the previously mentioned CSV file, 4514 packages was received on the RUC. It is observed that these two numbers are matching one another.

6.5 Measurement Uncertainties

No obvious measurement errors was found during this test.

[45] `/journals/accept_test1/arduino`
[46] `/journals/accept_test1/measurement.csv`

Journal 7: Acceptance Test 2

7.1 Purpose

The purpose of this test, is to determine if the system meets requirement 3 in the requirement specification, seen in section 3.2 on page 17. This test will be performed with respect to acceptance test 2, seen in section 3.3 on page 19.

7.2 Test Object

The test object is the fully implemented system, described in chapter 4 on page 23.

Used Equipment

Instrument	AAU-No	Make and type
CanSat stand-in		Arduino Mini Pro w/ RFM12B and 8.63 cm wire whip antenna

Table 7.1: *Equipment used in the test.*

The software running on the CanSat stand in, is based on the kernel and RFM12B driver code developed by group 502. It can be found here [47] . The CanSat stand in is described further in appendix F on page 145. The software running on the ground station is patched with the patch found at [48] .

7.3 Approach

The RUC establishes a connection to the ground station, and a specific CanSat ID is entered. The CanSat stand in is then set to transmit packages with the previously mentioned ID. On the ground station a timer is started each time a CanSat package is received, and stopped when the package is transmitted to the RUC. This time is then saved. This is repeated for 1000 packages. If the value in the timer exceeds the value stored, the saved value is overwritten with the new value. In this manner, the saved time will represent the worst-case package processing time for the ground station. The test will be done with light, and heavy system-load, in test 1 and 2 respectively.

7.4 Test 1

In this test the ground station is only receiving CanSat telemetry packages, and transmitting these to the RUC. This simulates a light system-load. After 1000 packages, the worst-case processing time is found to be 7 ms.

7.5 Test 2

In this test the ground station is receiving both CanSat telemetry packages from the CanSat Stand-in, and ManuelAntennaCrtl packages from the RUC, while still transmitting the CanSat telemetry packages to the RUC. By using the arrow key controls inside the RUC, a stream of ManuelAntennaCrtl packages are send at a high rate. Based on these packages, the ground station must constantly adjust the antenna accordingly, which simulates a heavy system-load. After 1000 packages, the worst-case processing time is found to be 54 ms.

[47] `/journals/wcet_determination/arduino/`
[48] `/journals/accept_test2/test.diff`

7.6 Measurement Uncertainties

The worst-case system-load might be higher than indicated, as stress-testing can be difficult. However, it is assessed that measurement uncertainties in this test can be neglected.