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# Control of a Quadrotor

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Control of a Quadrotor

*Abstract*
The objective of this thesis is to investigate the use of commercial devices as user interfaces on a quadrotor and to investigate solutions to the problem of slung load control. A slung load is a uniform mass attached with a wire which is allowed to swing freely to the bottom of the quadrotor. The purpose of substituting the radio control (RC) controller with a commercial smartphone is that they are more easy to grasp and might therefore be easier to use for a novice than an RC controller. The existing radio control link does not exist on a smartphone so it was complemented by a wireless network connection via transmission control protocol (TCP) or user datagram protocol (UDP). The smartphone does not have the same interface as the RC controller either so the same functionalities were implemented by using the touch screen and the inertial measurement unit (IMU) of the smartphone. However, this requires altitude control since the lack of multitouch in Android does not allow several inputs at the same time, thus making it impossible to adjust the thrust as the pitch and roll is adjusted. Another commercial device that was investigated was a PlayStation 3R gamepad (PS3 gamepad), whose joysticks were very similar to the RC controller's but its shape was smaller and more ergonomic. It also communicated via TCP or UDP over a wireless network connection. The purpose of slung load control is to reduce the oscillations of the slung load and its effect on the quadrotors flight performance, thus enabling it to handle heavier loads. The slung load control consisted of several subproblems; model of a slung load, altitude control, filtering of noisy sensors and the slung load control itself. These were all solved but the last one where the slung load control was not implemented on the quadrotor due to lack of time. The model of the slung load was done by letting the dynamics of two traversed simple pendulums approximate the slung load's angular movement.
The altitude control consists of a PID controller extended with anti-windup and bumpless transfer which is combined with a feedforward control of the tilt angle. The controller acts upon a low-pass filtered pressure sensor as a measurement signal and receives its setpoint from one of the commercial devices mentioned above. The low-pass filter of the pressure sensor is a second order Butterworth filter, whose purpose is to reduce noise and the impact of spikes induced by events in the surroundings.

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# Abstract

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The purpose of substituting the radio control (RC) controller with a commercial smartphone is that they are more easy to grasp and might therefore be easier to use for a novice than an RC controller.

The existing radio control link does not exist on a smartphone so it was complemented by a wireless network connection via transmission control protocol (TCP) or user datagram protocol (UDP). The smartphone does not have the same interface as the RC controller either so the same functionalities were implemented by using the touch screen and the inertial measurement unit (IMU) of the smartphone. However, this requires altitude control since the lack of multitouch in Android does not allow several inputs at the same time, thus making it impossible to adjust the thrust as the pitch and roll is adjusted.

Another commercial device that was investigated was a PlayStation 3®gamepad (PS3 gamepad), whose joysticks were very similar to the RC controller's but its shape was smaller and more ergonomic. It also communicated via TCP or UDP over a wireless network connection.

The purpose of slung load control is to reduce the oscillations of the slung load and its effect on the quadrotors flight performance, thus enabling it to handle heavier loads.

The slung load control consisted of several subproblems; model of a slung load, altitude control, filtering of noisy sensors and the slung load control itself. These were all solved but the last one where the slung load control was not implemented on the quadrotor due to lack of time.

The model of the slung load was done by letting the dynamics of two traversed simple pendulums approximate the slung load's angular movement.

The altitude control consists of a PID controller extended with anti-windup and bumpless transfer which is combined with a feedforward control of the tilt angle. The controller acts upon a low-pass filtered pressure sensor as a measurement signal and receives its setpoint from one of the commercial devices mentioned above.

The low-pass filter of the pressure sensor is a second order Butterworth filter, whose purpose is to reduce noise and the impact of spikes induced by events in the surroundings.

# Preface

This has been a fun and challenging thesis and we would like to thank Karl-Erik Årzén and Patrick Doherty for offering it to us.

We would also like to give thanks to Piotr Rudol, Mariusz Wzorek and Jerker Nordh for being excellent mentors and to Fredrik Heintz for guiding us in the end of the thesis.

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We would like to thank Anders Robertsson for interesting discussions and for tipping us about the thesis.

We also like to give thanks to our girlfriends for their unwavering support and belief in us.

# Glossary

**attitude and heading reference system** The attitude and heading reference system of the LinkQuad.
**bill of material** A bill of materials is a list of the parts and the quantities of each needed to manufacture an end product.
**unmanned aerial vehicle** A powered, aerial vehicle that does not carry a human operator.
**Control MCU** The microcontroller unit (MCU) that is responsible for control inputs on the LinkBoard.
**human interface device** A device that provides direct interaction with humans.
**inertial measurement unit** An electronic device that measures and reports on a craft's velocity, orientation and gravitational forces.
**linear quadratic regulator** A state-feedback controller which optimizes its poles according to a quadratic cost function.
**least significant bit** In computing, the least significant bit is the bit position with the least significant value.
**most significant bit** In computing, the most significant bit is the bit position with the most significant value.
**proportional-integral-derivative controller** A generic and simple feedback controller..
**PlayStation 3®gamepad** Gamepad originally configured for Sony PlayStation 3®console. It is possible to connect the gamepad to a computer via Bluetooth.
**pulse-width modulation** A technique for controlling power to a motor.
**Simple DirectMedia Layer** A cross platform hardware API widely used in Linux games.
**Sensor MCU** The MCU that is responsible for sensor algorithms on the LinkBoard.

**ad hoc network** A network connection without Dynamic Host Configuration Protocol (DHCP) between two devices.
**Android Client** The client application for connecting and controlling the LinkQuad from a Android smartphone.
**Android SDK** The software development kit for android smartphones.

**Computer Client** The client application for connecting and controlling the LinkQuad from a computer.

**LinkBoard** The LinkQuad hardware.
**LinkGS** Graphical User Interface used to configure, develop and operate the the LinkBoard..
**LinkQuad** A specific quadrotor used in the thesis as a test platform.

**Server** This is the server program that was made to take care of the outer loop control in the gumstix on the LinkQuad.
**simple pendulum** A simplification of a pendulum, which consists of a mass moving without friction on the circumference of a circle.
**spherical pendulum** A simplification of a pendulum, which consists of a mass moving without friction on a sphere.

# Acronyms

**AHRS** attitude and heading reference system.

**BOM** bill of material.

**CMCU** Control MCU.

**GPS** global positioning system.

**HID** human interface device.

**IMU** Inertial Measurement Unit.

**LQR** Linear Quadratic Regulator.
**LSB** least significant bit.
**LTI** linear time-invariant.

**MCU** microcontroller unit.
**MSB** most significant bit.

**PID controller** proportional-integral-derivative controller.
**PS3 gamepad** PlayStation 3®gamepad.
**PWM** pulse-width modulation.

**RC** radio control.

**SDL** Simple DirectMedia Layer.
**SMCU** Sensor MCU.

**TCP** transmission control protocol.

**UAV** unmanned aerial vehicle.
**UDP** user datagram protocol.

# Contents

# 1. Introduction

## 1.1 Quadrotors

A quadrotor, is a vertical take-off and landing aircraft that is propelled by four rotors instead of using two rotors as a helicopter. The advantages of a quadrotor in comparison to a helicopter is that quadrotors do not require to alter the angle of attack of the rotors to tilt the aircraft. It increases the thrust on one rotor and decreases the thrust on the opposite rotor to affect an angle. Mechanical linkages to vary the rotor blades' angles are therefore omitted and thereby simplifying the design and reducing maintenance time and cost.

The usage of four rotors allows each individual rotor to have a smaller diameter than an equivalent helicopter rotor to produce the same thrust, which lessens the kinetic energy that is produced. This reduces the damage the rotors would do if they hit an object and thus it is safer to use in close proximity to humans or delicate equipment.

These advantages make the quadrotor an excellent air vehicle to be used both indoors and outdoors. This is one common reason why quadrotors are used as both radio control (RC) quadrotor models and as unmanned aerial vehicles (UAVs).

**Flight Dynamics**

This section will give a general introduction to the dynamics of a quadrotor.

***Definitions*** The first coordinate system is called world coordinates $[X, Y, Z]$, where $X$ is horizontal, parallel to the equator and positive in a westbound direction. $Y$ is horizontal, perpendicular to the equator and positive in a northbound direction. $Z$ is vertical and positive towards the center of the Earth. It can be used to define the absolute position of a quadrotor.

The second coordinate system is called body coordinates $[X_B, Y_B, Z_B]$, where $X_B$ is parallel to the axis of the front and back rotors and positive towards the front rotor. $Y_B$ is parallel to the axis of the left and right rotors and positive towards the right rotor. $Z_B$ is parallel to the normal of the plane spanned by $X_B$ and $Y_B$ and positive in a downwards direction.

Euler angles of the body axes are $[\theta, \phi, \psi]$ with respect to the world axes and are referred to as pitch, roll and yaw in the given order.

The front and back rotors rotate clockwise and the left and right rotors rotate counter-clockwise.

***Dynamics*** The quadrotor's acceleration and attitude can be controlled by changing the rotation rate of each rotor and thus, the induced thrust of each rotor. A quadrotor is said to be hovering when there is no horizontal movement, each rotor induces the same thrust and their combined thrust equals the force induced by gravity. Each rotor's thrust at hovering is called hover thrust, $T_H = \frac{mg}{4}$, where $m$ is the mass.

The combined thrust of the rotors will control the acceleration in the Z-axis if the quadrotor is horizontal. To change the thrust of all rotors, the rotation rate of all

rotors shall be changed by an equal amount. This combined thrust can be seen as the throttle of quadrotor if its attitude is stabilized.

Attitude control is achieved by controlling each angle, {pitch, roll, yaw}, individually. Pitch can be controlled by creating a difference in thrust between the front and back rotor. If the front rotor's thrust is increased, it will raise the front rotor. The back rotor will be decreased with the same amount to maintain the total thrust. By increasing the back rotor's thrust and reducing the front rotor's, the front rotor will be lowered. The behaviour for pitch and roll are analogous, except that for roll, the left and right rotors are used.

The torque of a rotor is related to its rate of rotation and the torque can be reduced or increased by reducing or increasing the rate of rotation. Yaw is affected by the rotation created by the difference in total torque in between the rotors. This torque difference is usually cancelled out by having a pair of rotors rotating clockwise and another rotating counter-clockwise. By increasing a pair of rotors' rotation rate and decreasing the other's, a torque difference can be created and be used to control the yaw. As before, the increase of rotation rate on the clockwise rotating rotor pair requires a decrease on the other pair to maintain the total thrust.

## 1.2 The LinkQuad

The LinkQuad is the quadrotor that has been used as a test platform in this thesis. It has the capability to act as a UAV, but in the normal case it is controlled from a RC that communicates to the LinkQuad through a radio link. An application for monitoring and configuration, LinkGS, is delivered together with the LinkQuad. This application can be used to change how the LinkQuad should be controlled and change how the LinkQuad internal control algorithms should behave.

The LinkQuad contains the high performance circuit board LinkBoard III that is built up by two Gumstix computer-on-module boards, two microcontrollers referred to as Sensor MCU (SMCU) and Control MCU (CMCU), sensors, camera and some other components. The LinkBoard contains the following sensors: One 3 axis accelerometer, three gyrosensors, a magnetometer, a GPS and a pressure sensor. The LinkQuad also has an external analog camera, whose video output is not accessible through the LinkQuad. However a computer on the ground can receive a videofeed from the analog camera through a framegrabber.

The SMCU handles all the communication with the sensors. For other components to use any sensor data, a request query to the SMCU must be sent. This request, containing identifiers for the data that is requested, is sent via a serial bus to the SMCU. The SMCU will respond by continously pushing the latest sensor values of the requested data. In the same way, if another component should set setpoints of the existing attitude control instead of steering with the RC, a serial connection has to be maintained and inputs sent through it to the CMCU, which handles the inner control loops and the pulse-width modulation (PWM) outputs to the motors. Through LinkGS, the inputs and the parameters of the inner control loops can be configured to assign the user specified inputs from the serial bus as setpoints instead.

The Gumstix boards have a WiFi circuit, which supports the 802.11 b/g protocol and allows a wireless connection from computers or other WiFi-supporting units to the LinkQuad. The Gumstixs can be used as the components that can request sensor data and send inputs to the motors via the CMCU and they are the hosts for all the

software developed for the LinkQuad in this thesis. A sketch of the different components and the connections in between them can be seen in Figure 1.2.The dimensions of the LinkQuad [AB11] can be seen in Figure 1.1.

**Existing Control**

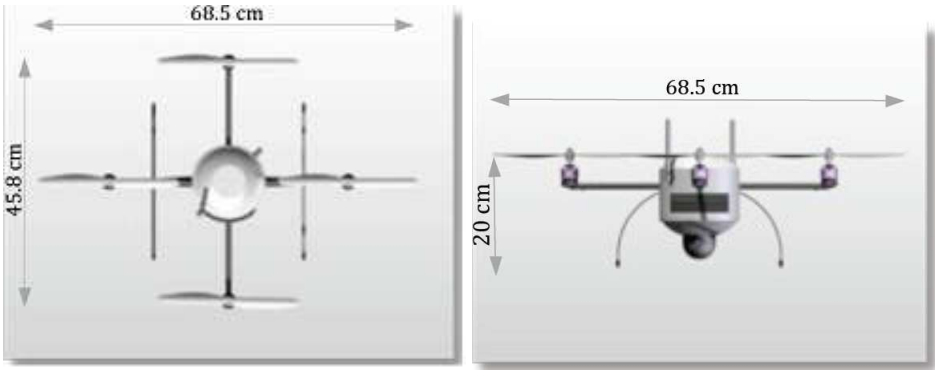
The existing control, previously mentioned as the inner control loops, consists of stabilization of attitude and an open loop control of the thrust. The nature of the dynamics allows pitch, roll, yaw and thrust to be controlled individually.

Each angle is stabilized with a PD controller and the thrust is not controlled but is forwarded directly to the motors through the mixer, see Figure 1.3.

Each PD controller use the corresponding input from the RC controller as a setpoint and the angle to be controlled and its corresponding angular velocity as measurement values. The output is the reduction or increase in thrust that should be put on each rotor, which is aligned with the angle.

Each controller is then connected to a mixer, which calculates each motor's control input. This is done by adding the thrust input to the output from the PD controllers of yaw and the angle which is parallel to the current motor. As an example, the back motor's input is the sum of the output from the thrust control, the output from the yaw control and the negated output from the pitch control. The output from the pitch control is negated to have the inverse effect on the back rotor compared to the front rotor.

Each angle and its angular velocity are derived from an attitude and heading reference system (AHRS).




(a) Top View (b) Front View

Figure 1.1: *Dimensions of the LinkQuad [AB11]*

## 1.3 Problem Description

Thesis extends the existing system in two ways:

1. User control via a commercial device, i.e. a smartphone or a PlayStation 3®gamepad (PS3 gamepad), will be introduced. the user should be able to steer the LinkQuad via this device without using the existing RC.
2. The LinkQuad should be able to function as a mobile crane with a slung load. A slung load is a uniform mass attached with a string to the bottom of the quadrotor and it is allowed to swing freely.

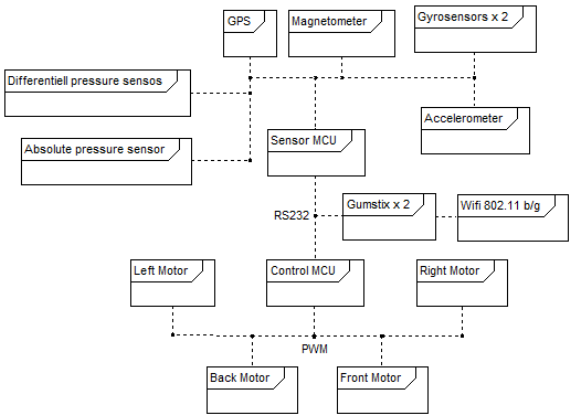



Figure 1.2: *This sketch shows the different components of the LinkBoard and the known protocols that are used between the components.*

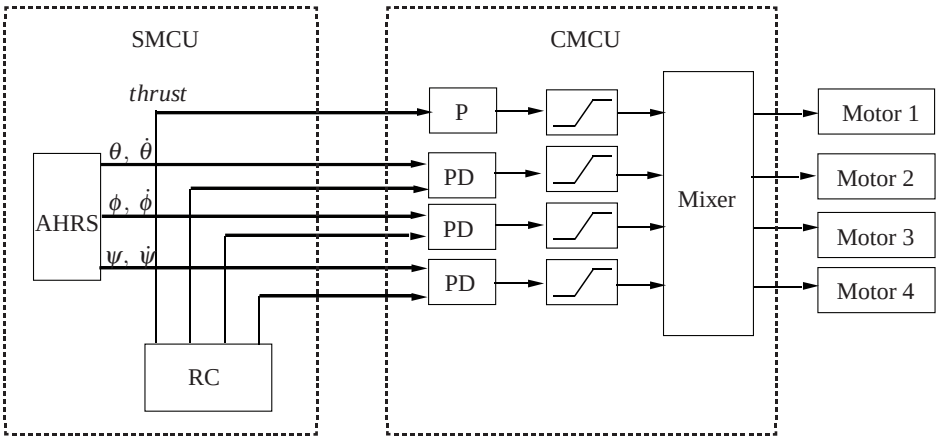



Figure 1.3: *The existing control: Setpoints are received from the RC receiver at the SMCU. The setpoints and the estimated angles from AHRS is sent to the CMCU. At the CMCU, the controllers' outputs are calculated, saturated, mixed into individual PWM outputs and sent to the motors.*

The first problem introduces the following subproblems:

- Choice of smartphone platform.
- Communication between the smartphone and the LinkQuad.
- A user friendly interface on the smartphone which enables most of the functionalities of the RC.

Since smartphones do not support the same radio links as the RC, another method of communication needs to be found. The Gumstix board on the LinkBoard has access to a Wifi connection which could be used instead. This implies that the communication is required to go through the Gumstixs instead of passing through the existing radio link that the RC use. This can be solved by creating a server application on the Gumstix which uses the serial communication to forward inputs and commands.

The second problem introduces oscillations from the slung load and will impair the

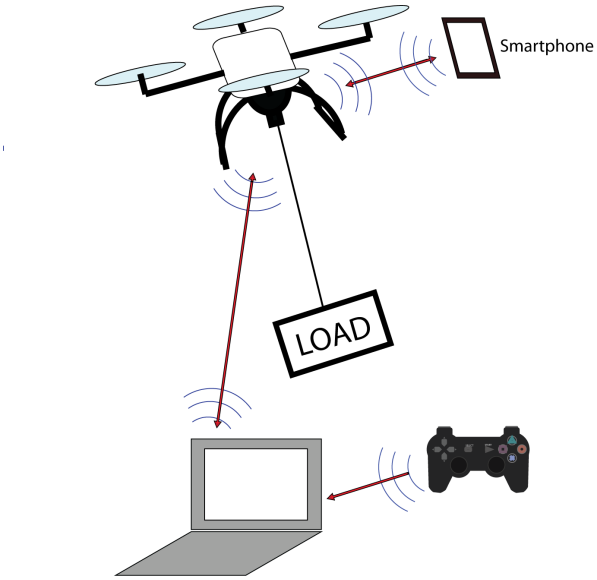



Figure 1.4: *Illustration of the system.*

flight capabilities. Therefore, control of the slung load must be introduced to reduce the pendulum effect of the load. The quadrotor should then be able to lift, fly, hover and land with a slung load and during the hover be able to reject disturbances, see Figure 1.4 for a sketch of the system in action.

The second task could not be completed fully, but the following subproblems were found and completed:

- Control of a slung load in the horizontal plane on an experimental rig.
- Investigation of the existing sensors to get an estimate of the altitude.
- Altitude control.

The control of the slung load could either lie on an external personal computer or in the server application on the Gumstix board. If the angles of the slung load would be derived by computer vision algorithms, it would have to lie on an external computer. However if local sensors could be used, it would be possible to have the solution on the Gumstix. Since a sensor solution from a present laboration rig is easier to use and it is available, it will be the first choice.

To apply the solutions to the slung load control and communication device, altitude control of the LinkQuad is required. This could be provided by the global positioning system (GPS) but only outdoors.

Due to this and to that the GPS was not fully implemented at the time of the thesis, it was disregarded but for future solutions it could be used to provide absolute positioning. Measurements of the altitude could still be derived from a pressure sensor.

## 1.4 Context and Purpose

The objective of this report is to investigate the use of commercial devices as user interfaces on a quadrotor and to investigate solutions to the problem of slung load

control.

The purpose of substituting the RC controller with a commercial smartphone is that they are more easy to grasp and might therefore be easier to use for a novice than an RC controller.

The purpose of slung load control is to reduce the oscillations of the slung load and its effect on the quadrotor's flight performance, thus enabling it to handle heavier loads.

ELLIIT is a collaboration between multiple universities within common fields, i.e. realtime systems and artificial intelligence, and the development of the LinkQuad quadrotor is one of its projects. This Master's thesis is a part of the ELLIIT collaboration.

## 1.5 Delimitations

The thesis considers only two types of smartphones, those with Android OS or Apple iOS. It was not relevant to do an evaluation of all smartphone operative systems, since it was more important that the smartphone fulfilled the requirements of the thesis and that the development could start early.

The load is considered to be attached or disattached and that no release or attachment mechanism exists. This implies that no effects of releasing or attaching the load will be controlled.

## 1.6 Method

The thesis started with an investigation of what possibilities and challenges it contained. This was done by using a ”Divide and Conquer” approach where the thesis was split into smaller subproblems and then a workflow was created from these subproblems, see Figure 1.5.

When the thesis had been broken down into workable challenges, the development started. The thesis was done in a more dynamic way by focusing on the most present and doable problem, instead of having different phases designated for i.e. development or testing. The planning was therefore done by using a bottom up traversal of the workflow so that all dependencies would be met before a new task was initiated.

It was also decided that the two authors should focus on their own area of expertise even if that was occasionally disregarded and both cooperated to solve a problem. Even though different areas of focus existed, both students worked to keep an understanding in each other's areas. Testing was done together since the LinkQuad requires both a pilot and an operator of LinkGS.

The tests were designed in different ways depending on what sort of functionality was to be tested. If it was a pure software function that required no actuation of the process, the functionality could be tested on the real platforms with the motors turned off. However, if the function required flying or some other live interaction with the LinkQuad, it was always simulated first using models or scripts in MATLAB and then tested on the real quadrotor.

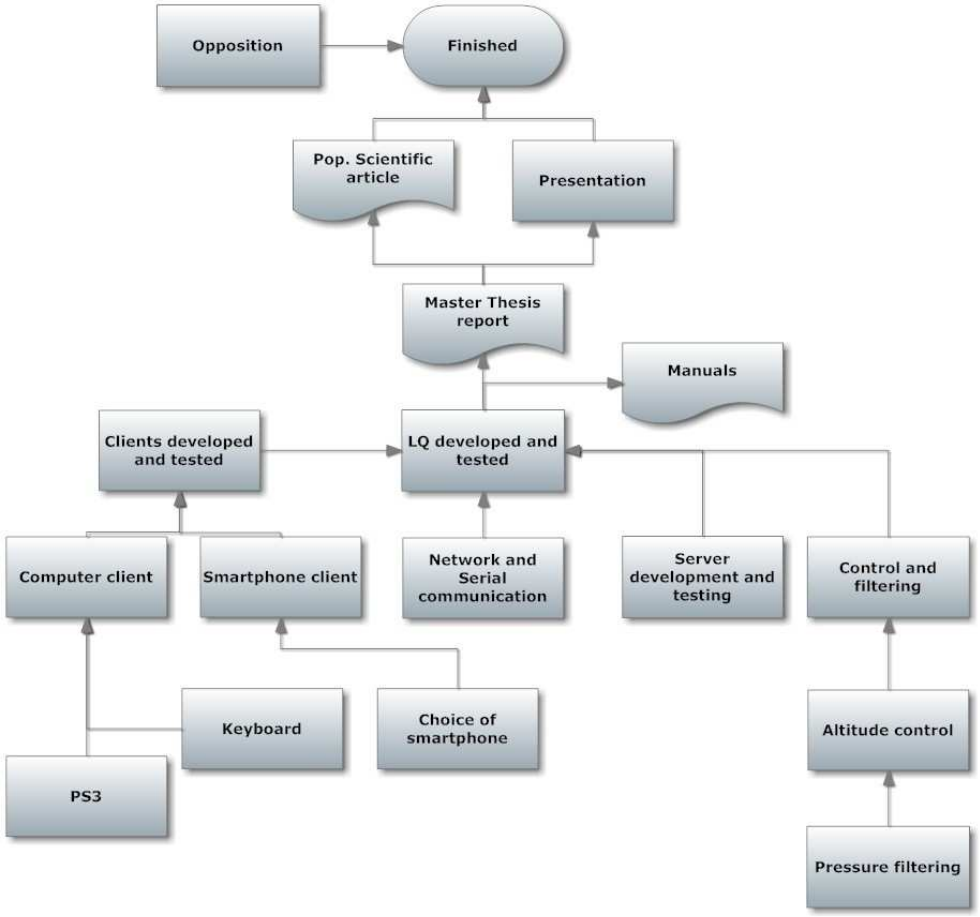



Figure 1.5: *Workflow chart.*

Documentation have been made continously to ensure that no knowledge was lost during the development and that the information was as precise as possible.

**Distribution of work**

| Mikael Rudner | Niklas Hansson | Common |
|---|---|---|
| Keyboard Controller | PlayStation 3® gamepad | Serial Communication |
| Network Protocol | Control | Server |
| Android Client | Gantry Crane | Computer Client |
| Testing | Simulations | Low-pass Filter |

Table 1.1: *The distribution of work between the two Master's Thesis students.*

In the beginning it was planned that Niklas Hansson would focus on the control problems of the LinkQuad while Mikael Rudner would focus on the programming problems. However, the dependencies of the subproblems implied that some areas of focus was intermixed. The distribution of the work can be seen in Table 1.1.

## 1.7 Related work

The interest in quadrotors has expanded over the latest few years since its simple design and control makes it an attractive solution for UAVs and, if properly configured, as radio controlled toys.

The research within steering quadrotors with smartphone is not so extensive but there are two significant projects, where the first is the commercial AR.drone, which is steered with either an iPhone or an Android smartphone. It can also be extended by creating a custom client for a computer and connecting a human interface device (HID) to the computer for inputs.

An second solution was investigated by Lichtenstern, Angermann and Frassl at German Aerospace Center (DLR) where an Android smartphone is used to control a swarm of quadrotors to film outdoor events. [LAF11]

The area of slung loads is host to a wide array of research projects for both large and small single-rotor helicopters. An example of such a project is the work of Bisgaard, Bendtsen and la Cour-Harbo, whom has investigated modelling of a slung load system on a small-scale helicopter. [BBlCH06] As for control of a slung load on quadrotor, it was not so extensive. Two videos were found from a project at the Aerospace Controls Laboratory (ACL) at Massachusetts Institue of Technology (MIT) in which a quadrotor successfully rejected disturbances on a slung load. However, no official papers or web page could be found.

## 1.8 Outline of the report

The report is divided into the following chapters. Each chapter contains a number of sections that are described below.

- **Introduction:** This chapter presents background information, problem description, context of the problem, methodology and related work.
- **System Overview:** This chapter describes the system as a whole, platforms, the main software of the server, network communication, serial communication, logging and how tests and verification was executed.
- **User Control of a Quadrotor:** This chapter describes the solution of the user control of the LinkQuad.
- **Slung Load Control on a Quadrotor** This chapter describes the gantry experiment, sensors, the altitude control and the progress of the control of the slung load.
- **Conclusions:** This chapter describes the conclusions of the thesis and recommendations for future work.
- **Appendices:** Documents that describe how to use the applications that has been developed and other aspects that help to set up the system.

# 2. System Overview

This chapter will discuss how the system as a whole is composed and how the different components interact.

The chapter first presents an overview over the system and then continues to the platforms of the system and the related development tools. Third, the server design and its implementation will be introduced. Fourth, the network communication will be described. The fifth section contains the implementation of the serial communication between the different microcontroller units. After that, the logging is presented and finally, the testing and verification of the system will be described.

## 2.1 Overview

The system can be distributed on three platforms; an arbitrary computer with support for wireless network and Bluetooth, a Android smartphone with root access (rooted), which is configured to support ad hoc networks, and the LinkQuad itself. The computer and the smartphone make up the client side of the system, where either enables the user to steer the LinkQuad. The LinkQuad hosts a server for a client on a Gumstix board and a client can connect to it via the ad hoc network. The user will need a PlayStation 3®gamepad (PS3 gamepad) to fly with the application on the computer, which is connected via Bluetooth and registered as a joystick on the computer. An illustration of the system can be seen in Figure 2.1.

From here on, the clients will be referred to as Computer Client and Android Client and the server as Server.

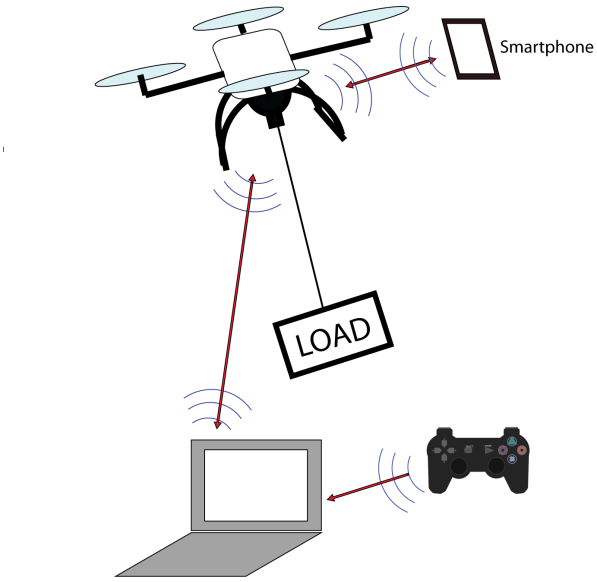



Figure 2.1: *Illustration of the system.*

## 2.2 Platforms

Each part of the system, e.g. clients for user control, has to reside on a platform and the development tools and design choices rely on these platforms' hardware design. In this section, the different platforms will be presented and the main focus will be on the smartphone since the hardware options are diverse but might introduce restrictions, such as programming language and input possibilities.

**Smartphone Client**

The Master's Thesis specification contained the assignment to develop a smartphone application that could be used to steer the LinkQuad. Some questions existed from the beginning such as if the target platform should be Android or Iphone.

***The Choice between Android and Iphone*** The first challenge to complete was the choice between Android smartphones and Iphone with iOS. Both had their advantages and disadvantages. The initial study of Android and iOS are shown in Table 2.1.

| | Android | IPhone |
|---|---|---|
| Java | + | |
| Objective C | | - |
| Apple Store | | - |
| Development License | | - |
| Accustomedness | + | |
| Open Source | + | |

Table 2.1: *Initial study of advantages and disadvantages of Android smartphones and Iphones. Plus sign (+) denotes a positive feature. Minus sign (-) denotes a negative feature.*

Android uses the Java programming language with the Android SDK and to develop an Android application no licenses are needed. Android itself is also open source which in the authors experience gives some assurance that it has some degree of code quality. [Goo11]

To develop for the Iphone, it is required to have a development license and a Mac computer, where the development license costs 99$ per year. The programming language for Iphone iOS is Objective C, which is a modified version of C and C++.

When an application has been developed, it has to be added to Apple's App Store to able distribution to more Iphones then the one it was developed on. This is required since Apple does not tolerate unmonitored third party applications and requires all applications are reviewed by them. This related to public distribution and details regarding any other options that might be available was not investigated. [App11]

Since Android smartphones were cheaper and that neither of the thesis students had any experience with Objective C, it was quickly decided that Android was the preferred choice.

After the development had started, it was noticed that the initial study missed some important parts, i.e. multitouch. A second study took place and is presented in Table 2.2.

| | Android | IPhone |
|---|---|---|
| Java | + | |
| Open Source | + | |
| Accustomedness | + | - |
| Multitouch | - | + |
| Ad Hoc | - | + |
| Reliability | | + |
| Objective C | | - |
| App Store | | - |
| Development License | | - |
| Different Platforms | - | |

Table 2.2: *Secondary Study of pros and cons. Plus sign (+) denotes a positive feature. Minus sign (-) denotes a negative feature.*

Iphone has a more accurate multitouch than Android smartphones, which has less accurate multitouch. This was noticed during the development of the joystick for the Android application. A second problem for Android is the hardware dependecy and the open source customability. Manufacturers may develop different implementations of the Android which may require porting of software. Since the different manufactures are using their own hardware, it may result in that a Android smartphone does not fullfil the hardware requirements.

Iphone smartphones are on the other hand restricted and they have all the similar hardware and are therefore more reliable. The Iphone, compared to the Android smartphone, also supported ad hoc networks which is a crucial feature since the Gumstix boards on the LinkQuad had no DHCP server configured in its present version. These problems limits the possibilities of which platforms can be used for an Android client.

Android was still considered to be the best choice, since the ad hoc network problem could be solved by changing the wpa_supplicant, the network software client, and since lack of multitouch was not a major drawback.

The problem of different platform specifications still remains and this system was tested on a LG P500 Optimus One, from here on referenced to as *the test phone* or *the test platform*.

***Multitouch or Singletouch*** When the development first started, it was planned to use the inertial measurement unit (IMU) to set pitch and roll and to use a virtual joystick to set thrust or altitude and yaw setpoints simultaneously.

The virtual joystick and a button to activate the capturing of IMU values were first implemented using the multitouch ability of the test phone. The multitouch would enable the simultaneous use of the IMU and the virtual joystick, but its performance was poor.

The specific implementation of multitouch mixes up the finger inputs and sometimes even loses track of a finger. This was unacceptable since the application could then send wrong control values, resulting in a crash. Multitouch was therefore

considered to be inadequate and a singletouch approach was used instead implying that thrust and yaw could not be controlled in parallel with pitch and roll.

***Ad Hoc Network*** One of the bigger challenges was that the Android smartphone did not support connections to ad hoc network. An initial assumption was that it could be avoided by configuring the Gumstix board to act as an DHCP server for the network it created but its operative system did not have support for it. The solution to the problem was found by using a rooted Android smartphone and a rebuilt wpa_supplicant file. [bla10]

The guide contained a prebuild on the wpa_supplicant, which changes the network filter's behavior to show and accept ad hoc networks. An ad hoc network is shown in the same place as other networks but has a prefix of an asterisk (*).

***Threads*** After the initial study of smartphones, one of the arguments for using Android was the Java programming language, which the students has experienced with. However, the Android SDK had made some changes which led to a more challenging development than was expected. The challenges and their solutions are listed below:

An Android application consists mainly of activities which are executed as the user interact with the screen. This is not suffice since the application will have to maintain a constant network connection and read continously from the IMU. It should thereby not be possible to have the application running when the smartphone is sleeping or the application is not in focus. This could be solved by extending the application with either a Java service or a Java thread to handle these tasks in the background. It was decided to use the latter since it was considered to be easier to implement.

The challenge of closing the thread and exiting the application on lost focus was solved by killing the application as soon as the actitivy, which the thread belonged to, was paused or exited.

Together with a non-blocking read operation in the network connection, it could be said that the Android Client is a single-threaded application with activities attached to it.

### Computer Client

The Computer Client application will reside on computer systems and since C++ was chosen as one of the programming languages for the thesis, see below, the problem of machine and operative system dependencies came forth. For example, a Windows machine does not support Posix threads (pthreads) per default and *nix systems does not support Windows threads.

The thesis students had access to computers with Windows, Unix and OS X as operative systems so it was decided that the applications should be portable to all three operative systems. This could be achieved by using the Boost C++ libraries that are portable to all of the operative systems in question. Boost supports everything from threads and math to network communication and file handling, which makes it ideal to use in a multiplatform application. [BD11]

**Server**

Since the Server is supposed to be executed exclusively on the Ångström based Linux distribution, it was decided to use the standard C++ libraries.

**Development Tools**

The main issue was the decision of which language to implement Server and Computer Client in. There was a probability in the beginning that the Computer Client would be integrated into the LinkGS. Thereby, the same programming language, C++, was chosen for Computer Client.

Since Server was to be put on the Gumstix board without any dependices, the list of possible languages was longer. However, since the Gumstix board uses the Ångström operative system, which supports gcc, and the Computer Client was to be implemented in C++, the choice fell upon C++ for the Server as well.

Since the smartphone was based on Android, it was to be developed in Java.

MATLAB was used together with Simulink to derive and simulate different control and filter algorithms.

## 2.3 Server

In this section the general implementation of the Server and design patterns will be discussed. Detailed implementations of specific parts of the Server are discussed in the following sections; Serial Communication (Section 2.5), Network Communication (Section 2.4), Sensors (Section 4.2), Control (Section 4.3) and Logging (Section 2.6).

The Server consists of three major parts; `Master`, `Connection` and `SerialCommunicator`. `Master` and its implementations contain a state machine and a control loop. `Connection` and its implementations handle the network communication. `SerialCommunicator` consists of two parts, an interface of functions for `Master` to use for the serial communication with the Control MCU (CMCU) and the second part is a thread which handles the serial communication with Sensor MCU (SMCU). Several patterns were used to structure and implement the Server, both to lower the code complexity and to make it easier to modify in the future.

`Master`, `Connection` and `SerialCommunicator` are separated with either a monitor or a mailbox to ensure mutual exclusion on shared data.

The heart of the Server is the abstract class `Master` and its two implementations, `LoadedMaster` and `FreeMaster`, that are two different state machines whose behaviour depend on whether a load is attached or not. The state machine functionality exists in `Master` where the current state is periodically invoked and the specific state's behaviour is defined and executed in the implementing class.

The current state is kept in `ReferenceMonitor` and state transitions can be made from either `Master` or `Connection`. This enables a transition to be triggered by commands from the network communication and thereby the user. The state machines and the control are discussed further in Section 4.3.

The `Master` classes' communicate with `Connection` through two mediators, `MailBox` and `ReferenceMonitor`, which were created using the Mediator

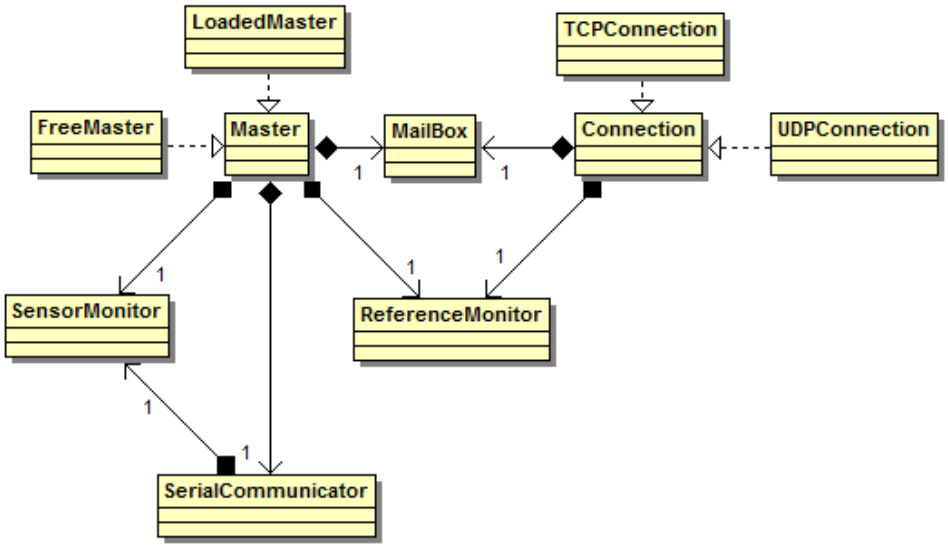



Figure 2.2: *The class diagram of the Server. The `Connection` are implemented according to the Template Method pattern. The `MailBox`, `ReferenceMonitor` and `SensorMonitor` are implemented according to the Mediator pattern.*

pattern.[Gam96, p.273-p.282] `Mailbox` can contain a message that should be sent to the connected client and `ReferenceMonitor` holds the current state and the setpoints of the control loop. The Mediator pattern implies that the `Master` classes need only to know that the message is only required to be put in `MailBox` to be sent. In the same way, it implies that the `Master` classes are only required to use `ReferenceMonitor` to get current setpoints. Both `MailBox` and `ReferenceMonitor` act as mediators, limiting the interaction between the two classes, thus making the two parties implementation independent of each other and easier to modify. Both `MailBox` and `ReferenceMonitor` have mutual exclusive entry to all functions to ensure thread safety.

The network implementation for the Server were implemented using the behavioral design pattern *Template Method*. The Template Method pattern allows a superclass `Connection` set a template of execution and deferring some steps to subclasses to implement.[Gam96] This enables future users to extend with their specific implementations of network communication. For further details, see Section 2.4.

`SerialCommunicator` consists of two parts, an interface for sending data to the CMCU and a thread which handles all communication with the CMCU. This is to enable fast access for the `Master` classes to send data and to reduce the computational delay for the control loop by removing the responsibility of receiving data.

The thread of `SerialCommunicator` is separated from `Master` with `SensorMonitor`. `SensorMonitor` is also implemented according to the Mediator pattern and is protected by mutual exclusion. Its main purpose is to supply the `Master` classes with the latest available sensor data. `SerialCommunicator` is thread-safe since all shared data is protected in `SensorMonitor` and the interface to CMCU does not share any data with the thread in `SerialCommunicator`.

## 2.4 Network Communication

The clients need a uniform way to communicate with Server as they are implemented on different platforms. Their inputs need to be forwarded to the Server and interpreted without consideration of which client the inputs originate from. A protocol was therefore developed for the communication between the clients and the control loop in the Server, see Section 2.4 for a detailed description of the protocol. Messages are packed according to this protocol and then sent to Server via a transmission control protocol (TCP) or user datagram protocol (UDP) connection. The choice of underlying protocols is also motivated in this section.

As can be seen in Figure 2.3, the clients handle the communication with TCP/UDP directly while Server separates the network responsibility from the control loop with `Connection` to reduce the computational delay in the control loop. `Connection` is a network handler, which is in charge of the network communication of a current connection. It interprets all received messages into setpoints or into commands and feed them to the control loop via a `ReferenceMonitor`. All outgoing messages from the control loop are put in a mailbox, which `Connection` pulls from and sends to the other party. For details, see page 24.

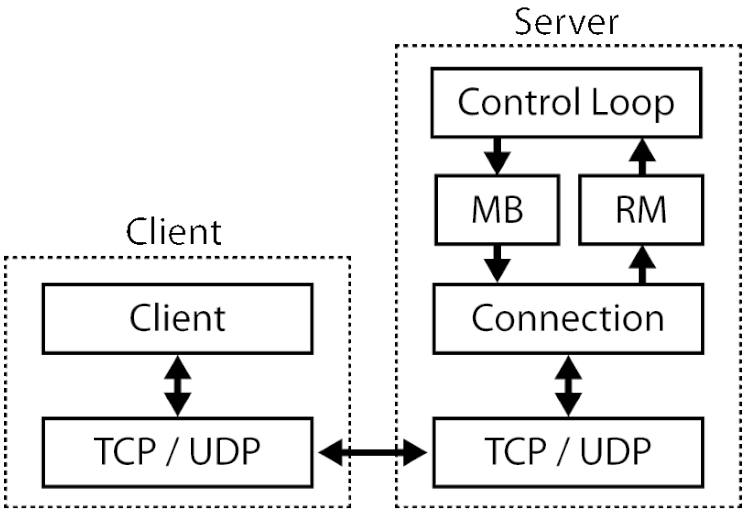



Figure 2.3: *Illustration of active network communication between Computer Client and the control loop in Server. MB stands for `MailBox` and RM for `ReferenceMonitor`.*

**Network Protocol**

First, the design of the internal protocol is described and then the implementations of the TCP and UDP versions will be introduced. A summary of the different messages is given in Table 2.3.

When a message is to be sent, it is packed into a 160 bits large package with the first 32 bits as the ID and the following 128 bits as the payload. In the beginning of the thesis a version with 8 bits ID and 32 bits of payload was used, but this resulted in a constraint on the payload. The constraint was that a direction message had only a range of -127 to 128, which was sufficient for the current problem but was an unnecessary restraint for future usage. The Gumstix board has support for the IEEE 802.11b/g standard for wireless networks, [Mei11] implying a possible connection speed of 54 Mbit/s, this would result in that a 40 bit message sent over a TCP

| Message Type | Message ID | Payload |
|---|---|---|
| Ping | 0 | Acknowledge |
| Direction Message | 1 | Pitch, Roll, Yaw, Thrust Difference |
| Trim Message | 2 | Trim Value |
| Land/Lift Message | 3 | Acknowledge |
| Terminate Message | 4 | Acknowledge |
| Close Message | 5 | Acknowledge |

Table 2.3: *Different network messages with their ID number and how the paylod is interpreted.*

connection (52 bytes head) will result in a 57 bytes package. [Dyk03] This package would be sent in $8,44 \cdot 10^{-6}$ s in a ideal situation with direct line of sight and no interference. Since the control loop has a sample time of 10 ms, this implies that 1184 different messages can be received during one period. For the 160 bit message sent over a TCP connection (52 bytes head) would result in a 72 bytes package and the package would be sent in $1.07 \cdot 10^{-6}$ s. This would enable 937 different messages to be received during one period of control. Since receiving only one message in a loop of the control is sufficient, the limitation of using eight bits is unnecessary and would perhaps constrain the accuracy for future extensions.

The data of the payload is representing different properties depending of the message type. For a command message, type 0 and 2 through 5, the first 32 bits of the payload is either 1 or 0 to determine whether it is a command or an acknowledgment to a previous command message. For a direction message, the payload consists of four integers representing setpoints for pitch, roll, yaw and difference of thrust. The setpoints of pitch, roll and yaw are to be sent to the inner loops of attitude control and the setpoint *difference of thrust* is to interpreted either as how much the thrust setpoint should change (manual flight) or how much the altitude setpoint should change (altitude control).

### TCP and UDP

The main advantage of using TCP is that the system gains a reliability of communication but also a disadvantage of slower communication. During the testing it was noticed that the disadvantage was so small that it was not noteworthy. However, this reliability is not always a requirement. When a client is sending a direction message, the Server requires only the latest input and it does not matter if occasional messages are lost during the flight.

The main advantage of using UDP for realizing the network protocol is a fast communication but at a loss of reliability since packages may be lost. During testing, it was found that the loss of packages happens more often the further apart the reciever and the transmitter where.

Both protocols are implemented in two versions of `Connection`, `TCPConnection` and `UDPConnection`.

### Network Handlers

Server uses a dedicated network handler, `Connection`, to separate the main functionality from the network communication. The purpose of this is to reduce the

computational delay of the main functionality, i.e. the control loop in Server and increase the stability of the system. A second benefit of this is the abstraction level between the network implementation and the main implementation, which implies understandability and usability.

An instance of the network handler is created when a client tries to connect to Server and there is a limit of one active instance to ensure that only one client can steer the LinkQuad simultaneously. The network handler executes a simple loop, which reads from the connection if data is available and after that it writes to the connection if there is a message to send available. The incoming messages are interpreted into setpoints and commands, which are forwarded to the `ReferenceMonitor`, which supplies the control loop with setpoints and its current state and the outgoing messages are fetched from `MailBox`.

**Mailbox**

A mailbox stores a single message that has been received or that should be sent. It can only store one message at a time but it prioritizes what messages that should be stored by looking at the id of the message. The greater the id number, the higher priority, e.g. if a Ping Message, id = 0, is stored in the mailbox, a Land/Lift Message, id = 4, will overwrite it.

However, if the new message is of the same type as the stored message, the new message will always overwrite the stored one. This is to ensure that the latest data is used at all times.

**Reference Monitor**

The reference monitor stores the latest set points and the current state that the control loop should use. An example of such setpoints are the desired attitude of the LinkQuad.

## 2.5 Serial Communication

The LinkQuad has an existing interface for serial communication to and from the SMCU and the CMCU, which enables applications on the Gumstix boards to access sensor data and send data to be used in the existing control loops. The interface supplies the user with both an existing protocol and functions to import and export data to the protocol. This section will therefore only introduce the reader to this high level protocol and its uses but will omit how it was implemented on the serial bus.

From an example given by the developers of the LinkBoard, a simple serial communication layer was implemented, which is used to send data to the CMCU. The same example was also used to implement a listener to the serial communication and thereby separating the control loop from the serial communication with a monitor. Both these parts exist in `SerialCommunicator`, see Figure 2.4.

`SerialCommunicator` is both a thread, which handles the incoming data from SMCU, and a set of functions for sending data to CMCU. This enables the control loop to send data direct to CMCU and to not waste execution time to read from SMCU.

The low-pass filter is executed in `SerialCommunicator` due to the need of a different sample time than the control loop. The SMCU can send data at a maximum

frequency of 500 Hz and is currently sending at 250Hz to `SerialCommunicator`. This is implied by the need of a high sample rate of the low-pass filter of the pressure sensor, see Section 4.2. `SerialCommunicator` puts the sensor values in `SensorMonitor`, which is shared with the control loop.

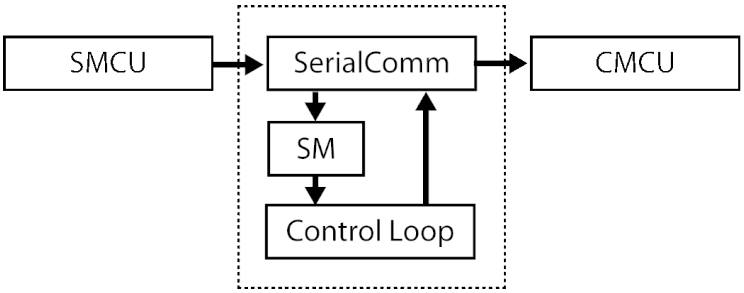



Figure 2.4: Illustration of serial communication between the control loop and the external microcontrollers. SM stands for `SensorMonitor` and SerialComm stands for `SerialCommunicator`.

**Serial Protocol to Control Microcontroller Unit**

The existing high level protocol supports arbitrary data to be sent to the CMCU packed in an array with eight floats. This can be used in the CMCU by configuring the PID loops in LinkGS to apply *receivedParamsX*, where *X* stands for the index in the float array, as a target or an input. The array is also logged and available for plotting during runtime in LinkGS.

In Table 2.4, the present use of the parameters is presented.

| Index | Data |
|---|---|
| 0 | Pitch. |
| 1 | Roll. |
| 2 | Yaw. |
| 3 | Yaw trim. |
| 4 | Set point for the altitude control. |
| 5 | Control signal. |
| 6 | Current state or PID output if manual tracking is live. |
| 7 | Altitude. |

Table 2.4: *Received parameters and their contents ordered after index. The parameters are sent from the Server to the Control MCU through a serial connection.*

#### Serial Protocol to and from Sensor Microcontroller Unit

The SMCU can supply the other microcontroller units (MCUs) with data on the serial bus. To gain access of this data a request must is sent of what sensor values that are wanted and how often these values should be sent. The request is an array which contains the identification numbers of the sensor values that are wanted. The identification numbers can be found in [AB11].

The SMCU can send at a maximum frequency of 500 Hz and at present time the Server uses a frequency of 250 Hz to run filters on the data at a high frequency. There is no need to push the SMCU after the request, the sending of data starts at once. The data is unpacked into a struct and there easily accessed for further use.

#### Serial Listener

The serial listener handles the responsibility of the high frequency communication from the SMCU, applying a low-pass filter to the noisy pressure signal and supplying the sensor monitor with the latest data.

The low-pass filter is put here to decrease the computational delay of the control and to allow it to have a higher sample frequency than the control loop, for more details see Section 4.2.

#### SensorMonitor

The `SensorMonitor` is implemented in the same way as the reference monitor but holds sensor values instead of state and position changes. It has mutual exclusive entry to all functions to ensure thread safety.

## 2.6 Logging

All of the developed applications have support of logging. The Android Client uses *adb logcat* for logging and debugging. The Computer Client and the Server use custom logging procedures, `Printer` and `FileLogger`. The logging procedures can be configured with the configuration file for the Computer Client and the Server.

#### Printer

`Printer` prints the log messages to the screen. This enables the user to follow the execution live on the screen.

#### FileLogger

`FileLogger` prints the log messages to a file, whose name is set in the configuration file.

## 2.7 Testing and Verification

This section will give an introduction to how the different functions of the system were tested and their functionalities verified.

The foundation of the system is the network communication so it was to be verified first. The protocol of network communication and the applications that use the protocol had been implemented in different languages so it was chosen to use a

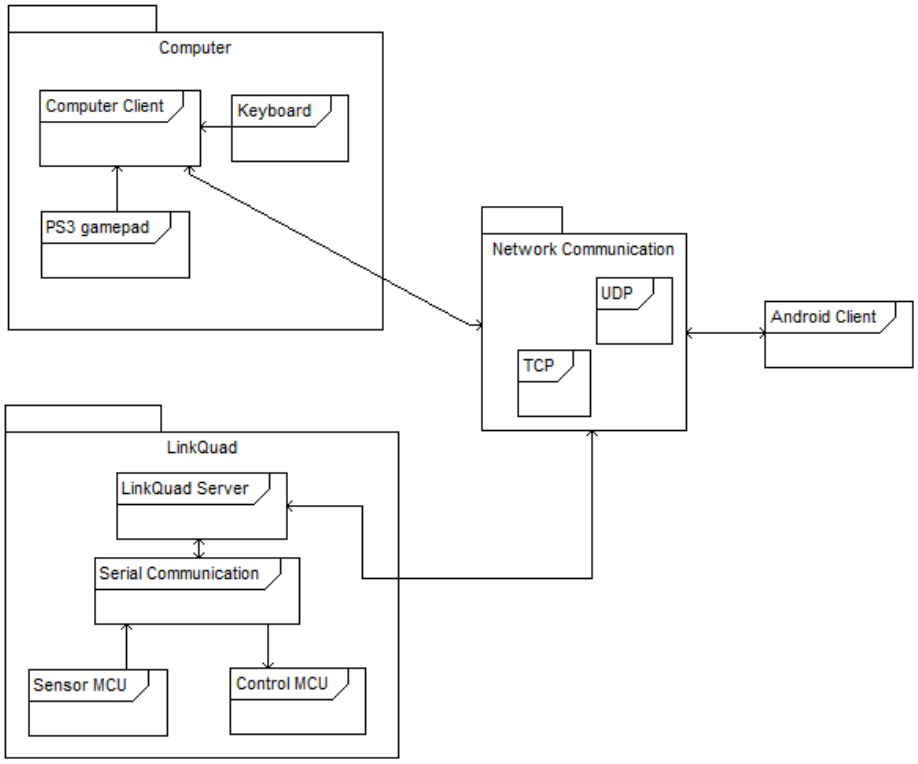



Figure 2.5: The different components of the system that was tested.

black-box technique called *black-box random testing*.[Bur03] The client sends a message, the server unpacks the message, then repacks it again and sends it back to the client. At the client, the received message could then be verified to be the same as the sent message.

It was important that every message type was tested with both normal values and values that are outside of the limits of the payload and that messages with incorrect identification numbers are tested so it is proven that they are rejected without problems. See Section 2.4 for more information about the payload. It can then be proven that the network communication can handle all of the different types of values and messages. The test set is required to be executed for both the TCP and the UDP protocols. The test set is presented in Table 2.5.

Since the development environment on the computer was equipped with debugger tools, it enabled the use of the white box technique *coverage analysis*. It implies that the execution of the code is studied and how inputs affects its flow. The goal is to verify that all code statements executes in a proper way. It is called coverage analysis since a complete coverage requires that all code statements are tested. If not, a code inspection must be done to design test cases which will maximize the coverage. Together with a black box technique *boundary value analysis*, a good set of tests could be created. The input for the tests was different messages sent from the network connection, see 2.4. The output was written to the logger and studied.[Bur03, p.72, p.101]

As for the computer client's functionality, the focus was put upon the human interface devices (HIDs). The test set was first executed by using the keyboard to

| Test number | Input | Expected output |
|---|---|---|
| Network-1 | Direction with invalid pitch value | Error |
| Network-2 | Direction with invalid roll value | Error |
| Network-3 | Direction with invalid altitude value | Error |
| Network-4 | Direction with invalid yaw value | Error |
| Network-5 | Direction with normal payload | Input |
| Network-6 | Lift | Input |
| Network-7 | Terminate | Input |
| Network-8 | Close | Input |
| Network-9 | Trim Right | Input |
| Network-10 | Trim Left | Input |
| Network-11 | Ping | Input |
| Network-12 | Incorrect Negative Message ID | Error |
| Network-13 | Incorrect Positive Message ID | Error |

Table 2.5: *The test set of the network communication - Input is messages sent from the client computer, Expected output is the message that is sent back from the server.*

create messages and then repeated for the PS3 gamepad. The test set can be seen in the Table 2.6.

| Test number | Input | Expected output |
|---|---|---|
| Computer-1 | Direction | No output, No lift off yet |
| Computer-2 | Lift, Direction | Lift off, Flight |
| Computer-3 | Lift, Direction, Land | Lift off, Flight, Landing |
| Computer-4 | Terminate | Termination message |
| Computer-5 | Close | Closing message |
| Computer-6 | Lift, Direction, Terminate | Lift off, Flight, Emergency landing |
| Computer-7 | Lift, Direction, Close | Lift off, Flight, Emergency landing |
| Computer-8 | Trim Right | Trim |
| Computer-9 | Trim Left | Trim |
| Computer-10 | Lift, Direction, Trim Left | Lift off, Flight, Trim |
| Computer-11 | Lift, Direction, Trim Right | Lift off, Flight, Trim |
| Computer-12 | Ping | Ping |

Table 2.6: *The test set of the computer client - Input is the action that the user introduces. Expected output is the log of the client.*

For the Computer Client, it was also important that the tests were done for the Unix, Mac and Windows platforms to ensure portability.

The tests on the Android Client were done by using the same test techniques and test set, Table 2.6, as the Computer Client.

In comparison with the personal computer environment it was more challenging to monitor the execution of the server program since the Server is executed on the

Ångström distribution on the Gumstix board. Because of this the black box technique *equivalence classes partitioning* was used. By letting each message being an equivalence class and creating a single test for each equivalence class, the test set can be seen in the Table 2.7. [Bur03, p.67]

| Test number | Input | Expected output |
|---|---|---|
| LQServer-1 | Direction | Server parameters |
| LQServer-2 | Lift | Beginning to send values (hover) |
| LQServer-3 | Terminate | Emergency land, end sending values |
| LQServer-4 | Close | Emergency land, close existing connections |
| LQServer-5 | Trim Right | Adding value to the yaw |
| LQServer-6 | Trim Left | Adding value to the yaw |
| LQServer-7 | Ping | Ping in logger and ping back |

Table 2.7: *The test set of the LinkQuadServer - Input is the message sent from client, Expected output is written to the server log.*

After each component or group of components had been tested, an integration test was designed to ensure reliability when combining the different components. This was done by first executing all the the different tests again but on the whole system and complementing by doing several field tests (Chapter 5).

# 3. User Control of a Quadrotor

This chapter will discuss the investigation and implementation of the clients, which allow the user to control the LinkQuad.

The user control problem originates from the need of controlling the LinkQuad without radio control (RC). Smartphones are not supplied with the same radio link capabilities as the RC so other channels of communication were required. This was solved by having a server on the Gumstix, which was connected to the Control MCU (CMCU) through a serial connection and to the clients through a wireless connection.

A client on a computer was first developed to be able to debug the network communication and the server with a keyboard. A second client on a Android smartphone was developed to steer the LinkQuad. The Android Client uses its inertial measurement unit (IMU) and a virtual joystick to control the attitude and the altitude of the LinkQuad. During the development of the Android Client, another human interface device (HID) was integrated into the Computer Client, namely a PlayStation 3®gamepad (PS3 gamepad).

This chapter will first present the investigation of the target smartphone platform and then the implementation, design and evaluation of the smartphone client. Finally, the Computer Client will be presented.

## 3.1 Android Client

The Android Client is the main application for steering the LinkQuad. The advantage of using the Android Client is that it provides an interface that is naturally mapped to the process, by using the IMU of the smartphone to steer, and a graphical interface that is naturally mapped to cultural standards and the RC controller.[Nor02, p.23]

A disadvantage is that the implementation of the virtual joystick, which set the setpoint for the altitude or the thrust, does not give the same feeling of control as the PS3 gamepad or the RC controller. This is due to the lack of physical feedback.

Another disadvantage is that Android smartphones usually have different hardware configurations, which may lead to bad performance, see Section 2.2.

The Android Client requires a rooted and properly configured Android smartphone to connect to an ad hoc network. It does not support multitouch even if the functionality exists in the code. This is purely in case of a better implementation of multitouch being developed for the Android smartphones, see Section 2.2. For more information about how to use the Android Client, see Appendix B.1.

This section will first discuss what kind of users that might use this application and what ramifications this will have for the design and implementation. Finally, the design of the different interfaces will be discussed.

## 3.2 Users and Environment

Flying the LinkQuad is not an easy task for an novice pilot and it would be even harder if the steering interface was poorly designed or implemented. Thus, it is important to know in which situations the interface will be used, which possible users exists and what their needs are for the application are. The following assumptions are made from the Department of Automatic Control at LTH.

The most likely user is a graduate student that uses the work of this thesis for his or hers thesis. He or she will probably have a strong knowledge base in embedded systems, computers and control but will not have used a quadrotor before. It is also possible that an experienced quadrotor pilot will try to use the Android Client when he or she acts as a test pilot. The least probable user is an ordinary person with nearly no experience of using the LinkQuad. In the Table 3.1, the three different types of users and theirs different sets of knowledge are displayed; the graduate, the experienced pilot and the ordinary person.

| **Type Name** | **Important knowledge and skills** | **Probability** |
|---|---|---|
| Graduate | Embedded systems and control | High |
| Quadrotor Experienced Pilot | Quadrotors and RC | Low |
| Ordinary Person | None | Low |

Table 3.1: *The possible users of the user control of the quadrotor, their possible knowledge and the probability of that they will use it.*

The graduate will use the Android Client in his own research and would want to have an application that is easy to understand and use but most important, easy to modify. The quadrotor experienced pilot will use the Android Client to do test flights or to get a new flight experience. The ordinary person is probably a friend of the graduate or to the quadrotor experienced pilot who wants to try the LinkQuad. From this set of users, it can easily be seen that the most probable user will have some but not an extensive knowledge of flying quadrotors.

This implies that the steering and the graphical interface should be as natural as possible so that a user with little knowledge of quadrotors can understand what the different controls are used for. It should also be in focus that the steering should be reminiscent of the steering interface of the RC. Since if one of the users has used a RC controller before, the introduction would be easier.

The application is not meant to be accessible for the public. Its main purpose is to be used for development and research. Therefore, the focus will also lie on making the software easy to modify and maintain.

## 3.3 Design of the Interface

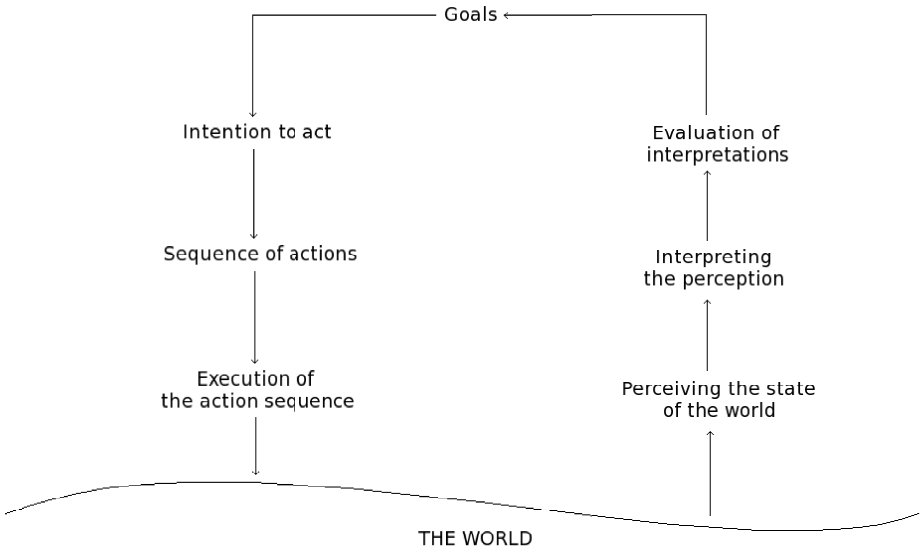



Figure 3.1: *The action cycle starts by the user having a goal. The user will then execute a set of actions needed to perfom the goal. Then the user will perform an evaluation that the actions that has been done indeed fulfill the goal.*

A human action has two aspects, execution and evaluation. The execution aspect involves the doing of something and the evaluation is the comparison of what happened with what was expected to happen (the goal). The user starts by setting a goal. The goal is then translated into an intention to do some action. The action is translated into a set of internal commands, an action sequence, that is executed upon the world. After the execution aspect has been performed the evaluation aspect starts. It starts with the human that performed the action using his or hers perception on the world. This perception must then be interpreted to his or hers expectations. Then compared (evaluated) against the intentions and the goal. Figure 3.1 describes the cycle of execution and evaluation of a users actions, the so called seven stages. [Nor02, p.45-p.51]

The seven stages can be a valuable design aid, becuase it provides a basic checklist of questions to ask to ensure that the gulfs of evaluation and execution are bridged. The checklist and the answers can be seen in Table 3.2. [Nor02, p.52-p.53]

The question were used to design the user interface by ensuring that the user can see what action he or she needs to perfom to reach the their goal. This was achieved by answering the seven questions for each interface. They were also used to ensure that the user gets the necessary feedback to ensure the user that the action that was performed indeed did fulfilled the goal of the user.

Table 3.2: *Using the seven stages to ask design questions. (page 1 of 2)*

| **Questions** | **Menu Interface** | **Connections Settings Interface** | **Steering Interface** |
|---|---|---|---|
| How easily can one determine the function of the device? | This question was solved by adding Menu item names that were self explaining. For an example Connection Settings handles the information needed for the Steering activity to connect to the Server. | The item from the Menu, which is the only road to travel to this activity, has a clear and understandable name that describes what the task is in this activity. | The item from the Menu, which is the only road to travel to this activity, have a good explaining name that describes what the task is in this activity. The task contains many normal controls that are quite describing for this application giving a good hint of what it is used for. |
| How easily can one tell what actions are possible? | The names of the Menu items explain what can be done. | By having describing labels above the field and in the toggle button it is quite simple to see the three actions that can be made. Write in the ip-address, toggle the communication protocol and also checking the local address of the network that the smartphone is connected to. | Every button has text bound to it that describes its functionality, but it is not as easy to determine what the green button or the joystick is used for. No labels could be added due to lack of space. This was solved by describing it's functionality in the manual. |
| How easily can one determine the mapping from intention to physical movement? | This is more an Android question. By choosing understandable names as Menu items Android provides the solution of just touching the Menu item to travel through them. | This is more an Android question. By choosing understandable names the Android provides the solution of just touching the field or button to interact with them and the labels gives a good hint of what task the item solves. | It is easy to understand what the buttons do due to the labels but again the green button and joystick are the hardest to map. This is easiest solved by testing against the LinkGS. |
| How easily can one tell what state the system is in? | The menu activity only has one state, either the user is in the menu or the user already has clicked on a menu item and navigated to a new activity. | The are two states that are important to know. First, if the smartphone is connected to the LinkQuad network. Second, the different states of the connection settings. The connection settings can be seen in the ip-adress field and the toggle button that is used to change the connection settings. | This is easily verified because of the feedback log that always print the values of the controls and what the Android Client does. |

Table 3.3: *Using the seven stages to ask design questions. (page 2 of 2)*

| **Questions** | **Menu Interface** | **Connections Settings Interface** | **Steering Interface** |
|---|---|---|---|
| How easily can one perform the action? | If a user wants to change the connection settings he or she only needs to touch the menu item Connection Settings and he or she will navigate to the Connection Settings activity. Touch screen and understandable names provide quick and easy navigation. | When the user has navigated from the menu to the Connection Settings, he or she needs to touch the ip-address field and fill in the ip and then choose which protocol he or she wants to use. This and checking that the smartphone is connected. Then confirming by touching the ok button is the only things he or she needs to do to perform this task. Consequently maximum of four touch actions, two touch actions, one write action and one inspect action are needed to perform the whole task. | First the right connection settings need to be set, this can be as much as four different actions or zero actions if it is already configured correctly. Then in the menu navigate through the launch button to the steering activity. Then the user is free to steer the LinkQuad directly by natural mapped controls and an automatic altitude control. This gives that the user at maximum needs to perform five actions, minimum one action, to be able to steer the LinkQuad. |
| How easily can one tell if the system is in the desired state? | The menu itself has no purpose besides being a hub for navigation. Therefore the menu only has one state that can be seen by checking if the menu is shown. | The are two states that are important to know. First, if the smartphone is connected to the LinkQuad network. Second, the different states of the connection settings. The connection settings can be seen in the ip-adress field and the toggle button that is used to change the connection settings. | This is easily verified because of the feedback log that always print the values of the controls and what the Android Client does. |
| How easily can one determine mapping from system state to interpretation? | By clicking on a menu item the user travels directly to that menu items corresponding activity. | Easiest checked by saving some settings and test to connect. | This is easily verified because of the feedback log that always print the values of the controls and what the Android Client does. |

Table 3.4: *The evaluation performed by asking three students at the Lunds University five simple questions.*

| **Question** | **The German exchange student** | **Swedish Master's thesis student 1** | **Swedish Master's thesis student 2** |
|---|---|---|---|
| How easy can you see the functionalities of the controls? | It seems pretty intuitive. I think I could use it after a couple of seconds. | Not really familiar with the UDP and TCP option. | Very easy. Nice, large icons. |
| Is the joystick easy to use or does it contain any faults? | In upwards downwards direction the joystick feels a litle too digital in comparison to an analog one. | The joystick control was a bit tricky if you compare to an analog one. | Works nice. Hard to really know how it works since you can't actually feel what you are doing. |
| After getting an fast introduction to the application, how would you connect to the LinkQuad? | Using Connection Settings enter the correct IP-Adress then press Ok, after that press Launch. | Connection settings, enter IP-number and choose protocol and after that press launch. | Enter connection settings and enter the IP address, then choose the proctocol and then press launch. |
| After that, how would you steer the LinkQuad? | By tilting the phone and using the joystick. | First press lift to take off and then press toogle button and tilt to steer. Use the joystick to go up or down or turn. | You control the altitude and yaw with the joystick and the pitch and roll angles by tilting the phone while pressing the accelerometer button. |
| Would you say that the application is user friendly? | Yes | Yes | Yes, I think so but haven't tried it that much. |

The Seven Principles were used to break down complex tasks into more simple ones and to design an interface where the user can execute tasks and actions intuitively. These principles were used to decide what actions that the user should be able to do and how the actions should be mapped to the controls. [Nor02, p.188]

**The Seven Principles** (for transforming difficult tasks into simple ones)

- Use both knowledge in the world and knowledge in the head.
- Simplify the structure of tasks.
- Make things visible: bridge the Gulfs of Execution and Evaluation.
- Get the mappings right.
- Exploit the poser of constraints, both natural and artificial.
- Design for error.
- When all else fails, standardize.

From the investigation of the users, it was found that it was important to have a naturally mapped application, whose functionalities are reminiscent of those of the RC controller. The design and positioning of the controls were therefore taken forth by using natural mapping principles. [Nor02, p.23-p.27]

The questions and principles were complemented by an evaluation that was performed by asking three students at Lund University, that had not used the application before, five simple questions about the design. The questions and the answers can be seen in Table 3.4. All of the three students were graduate students with knowledge in embedded systems and control but with no prior experience with quadrotors.

By using the seven design questions, the seven principles, natural mapping principles and the evaluation the following design decisions were made.

| **Input** | **Orientation** | **Set point** |
|---|---|---|
| Green button + tilt | North-South | Pitch. |
| Green button + tilt | East-West | Roll. |
| Joystick | North-South | Add/subtract altitude. |
| Joystick | East-West | Yaw. |
| Trim Right | - | Yaw trim right. |
| Trim Left | - | Yaw trim left. |
| Land or Lift | - | Land/Lift. |
| Terminate | - | Terminate. |

Table 3.5: *Mapping of controls on the Android Client.*

When designing the mappings of the controls (Table 3.5) it was important that it would be an easy task to execute the controls as well to understand what they do. This is the reason why the seven principles were used to choose how the mapping should be done. Because of the criteria that the controls should be naturally mapped, which in general is a very good idea to do anyway, the focus was on designing these natural maps by the principle of design for errors. The reason of focusing on the designing for errors principle can be seen in the tilting task. If the user did not have

to press down a button while using the IMU to steer the LinkQuad, it could result in disaster because of tilting that is not meant for the LinkQuad, such as failing to close the application and then putting the smartphone into the pocket.

By using error design and natural mapping the different tasks could be made as simple as possible without losing any safety and in the same time fulfilling the seven principles. The simplification of the tasks is that each task has one unique mapping short of the *Land or Lift* map. Since of space issues in the graphical interface led to that they had to share the same button.

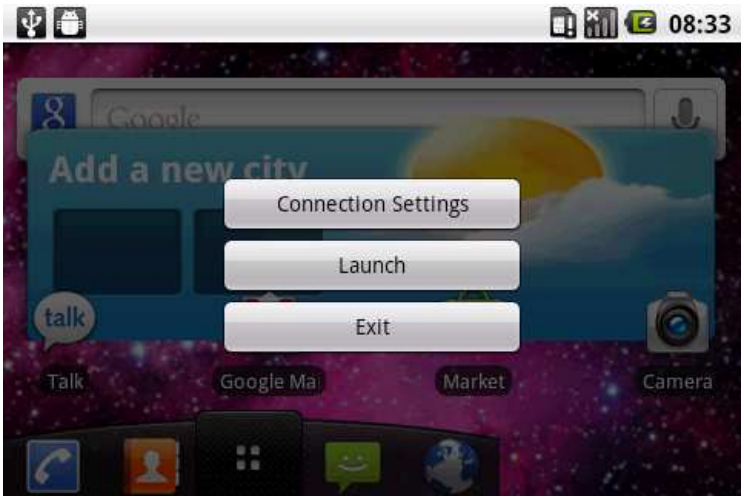



Figure 3.2: *The menu interface - The menu view of the Android Client.*

When the user uses the Android Client he or she always has a goal and the menu is just the road to that goal. Therefore, it is important that the menu is effective to use. This is the same problem as the seven principles, breaking a complex task into simple ones.

To be able to connect to the LinkQuad some connection details are needed such as the ip-address and what network protocol is going to be used, user datagram protocol (UDP) or transmission control protocol (TCP). It could always be solved by prompting when the Launch button is pressed, but that would be unnecessary because usually that information is the same all the time. This was solved by adding the menu item Connection Settings which stores the information so it can be reused when connecting. The two other menu items are the Launch which connect to the LinkQuad and start the steering and the last are quite self explanatory. The evaluation, Table 3.4, and the seven questions, Table 3.2, shows that keeping the menu small was a good choice because it is only the road to the action that the user wants to perform. The menu interface that was designed can be seen in Figure 3.2.

Regarding the design of the menu interface the Connection Settings interface has one task with two important settings that it needs to store: the ip-address and the communication protocol. The easiest way to break down this task is to have one field with an artificial constraint of only accepting valid ip-addresses to store. The other setting is what network protocol that should be used. This is solved by using a toggle button to toggle between the TCP and UDP options, having TCP as default because it is the safest protocol.

This and by adding utility labels that describe the button and the ip-address field makes it easy to understand what the task is and where to do it. Another feature is

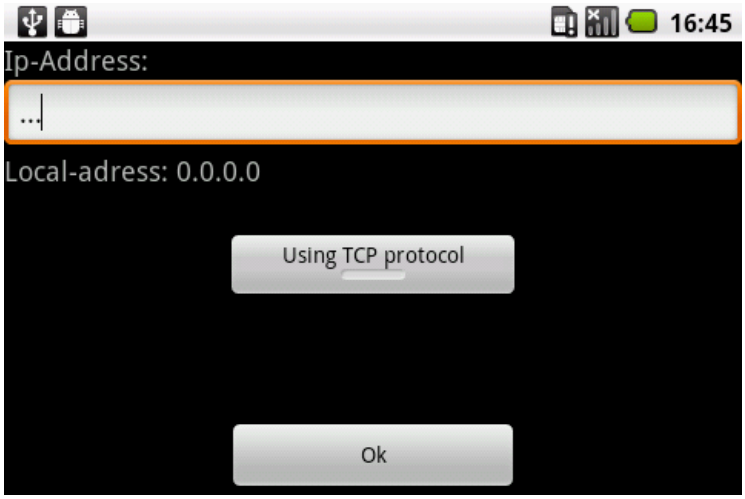



Figure 3.3: *The Connection Settings interface - This view takes care of the connection settings.*

that the Connection Settings interface should give the user feedback if the smartphone is connected to the network and what local address it obtained. Having no local address is the same as the smartphone not being connected to the LinkQuad. This so that the gulf of execution and evaluation are bridged. The answers in Tables 3.2 and 3.4 shows that this was indeed the case. By storing the data between sessions it is also ensured that this task is not always necessary. The Connection Settings interface that was design can be seen in Figure 3.3.

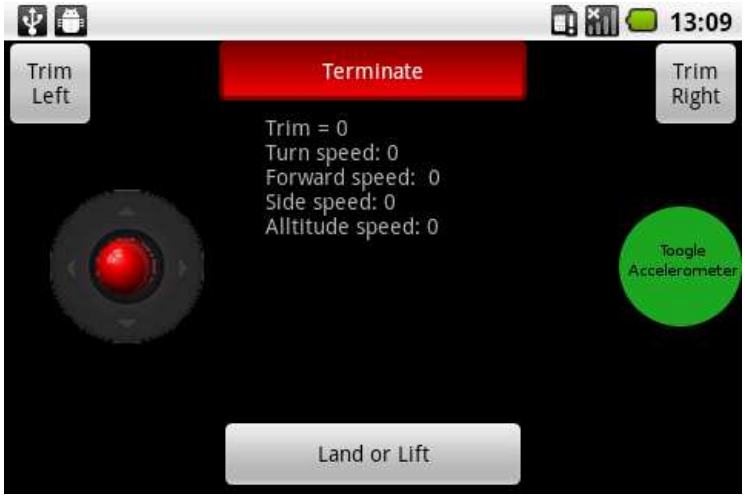



Figure 3.4: *The Steering interface - In this view all the action regarding the flight of the LinkQuad is made.*

While enabling the steering of the LinkQuad with the Android Client in a way that is reminiscent of how the RC is used, several functions that the user should be able to perform were created. The user should be able to change both the attitude and the altitude of the LinkQuad. These functions would enable the Android Client to steer the LinkQuad. Some more functions were added to enable termination of the Server and automated lift and land functions.

By using the mapping of controls, see Table 3.5, a natural mapping is retrieved using

the IMU, buttons and a virtual joystick. The terminate button was decided to be red with white text because of using a standard solution of mapping dangerous actions gives a good impression of that pressing the terminate might not be a safe action. The trim buttons were placed with the trim right button on the right side and the trim left button on the left side. In order to use a natural mapping of the trimming of the yaw. The green button that is used to activate the IMU readings of the pitch and roll values was placed on the right side to be easily pressed by the thumb while the rest of the hand holds the smartphone.

It was chosen to have the button in a green color because the color is used in traffic lighting when the users should start walking. This indicates to the user that pressing the button is probably going to start something, like in this case the reading of the pitch and roll values from the IMU. Since the green button is positioned to the right, the joystick is put on the opposite side to allow use with the other thumb. The evaluation, Table 3.4, shows, however, that the choice of using a joystick has its disadvantages. The seven questions can be used to solve these problems, see Table 3.2

All of the three students thought it was hard to get the feeling of the position of the joystick when they used it. Since that a virtual joystick does not give any physical feedback of its state as an analog joystick does. This concern was shared by the developer and it is stated that the Android Client is a good substitution for the RC controller but should not be used when controlling the thrust power. This because controlling the thrust is an delicate operation and without feeling or maybe having control it could result in disaster. Altitude control however does not need as much delicacy. So it is recommended to use the Android Client with the altitude control.

The land/lift button was placed at the bottom of the screen to decrease the odds that the user would accidentally press the wrong button. This was also a general idea when placing the buttons, to have lot of free space to decrease the number of accidents. A text log was placed in the middle of the screen to give the user direct feedback of the internal state and the actions that are performed. This so that the user would be able to evaluate that what he or she did actually was what was intended. The Connection Settings interface that was design can be seen in Figure 3.4.

**Implementation**

This section describes and gives an insight of how the Android Client was implemented and designed.

Because of how the flow of the code works in Android applications which work with short lived activities it was hard to implement a continuous loop that listens to the network while checking what the user does at the interface. This was instead solved by a steer activity creates a thread that takes care of the network communication and functions as the state machine while the steer activity takes care of the user interface. This is also a general solution in the implementation to break loose the interface from the functionality by using the default functionality of the Android activities.

The network implementation for the Android Client was implemented using the structural design pattern *Template Method*. [Gam96, p.325-p.330] The *Template Method* pattern was used to create a abstract class `Connection`, which supplies the network using classes with a common interface to a generic connection. This to ensure that future users do not need to bother about the specific implementations of the network communication. For further details, see Section 2.4.

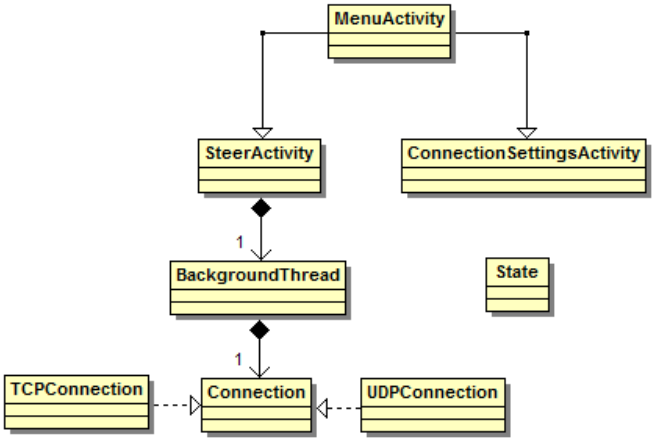



Figure 3.5: *The class diagram of the Android Client.*

More information about the implementations will follow in the sections below. In Figure 3.5 a simple class diagram shows the basic structure of the application. The activities act as the interface to the user while the `Connection` act as the network link to the Server. Every calculation and operation that are executed due to interaction with the interface is carried out in the `BackgroundThread`. The following sections will describe where the patterns are used and some of the structure and implementation of the application.

***State*** The program has a static class `State` that holds the current properties of the process, e.g. if the LinkQuad is airborne or which IP-address the client should connect to.

***MenuActivity*** The menu view is nothing but that a table representation with three normal buttons. Each button except one links to a new activity with a new view.

***ConnectionSettingsActivity*** The field where the ip-adress is inserted is a simple EditText field. The problem with a EditText field is that it accepts all types of inputs. This has been taken care of by having a parser that checks if the inserted data is a valid ip-address, if valid it will set the connection address in the State to the given address. The second feature of this is that it fetches the ip-address for the connection to the wifi that the smartphone has, if no connection it will return " 0.0.0.0 " which means no address was found, and thus no connection. This feature is implemented by using WifiManager that is a Android SDK class.

***SteerActivity*** The steering view has five buttons. The Terminate and Land/Lift button are normal buttons that directly links to an onTouch function that is declared in the SteerActivity class. The green button is a little different since it is a ImageButton and it implements a onTouchListener that it used to sense if the button is pressed or not, that so the user can use the button together with tilting, using the IMU of the smartphone. The left and right trim buttons work in the same way.

In the begining of the thesis it was thought of using the yaw of the smartphone to control the yaw of the LinkQuad. But because of the badly implemented IMU no good values were received and it was agreed to use a virtual joystick instead.

The virtual joystick was a little more complex to implement, it was implemented using two ImageViews and one FrameView. One of the ImageViews were the

background and the second was the joystick knob. These two ImageViews was merged into the FrameView that is used as the boundaries of the joystick. By using an onTouchListener the position of the knob ImageView can be captured and used to calculate the altitude and yaw value.

An effort to implement the functionality to be able to press the green button while using the joystick was also made, it succeeded but it was noticed that the Android multitouch was badly implemented. The current implementation are not using multitouch for this reason.

The design problem with the joystick added with the implementation problem of not being able to use the multitouch, disabling the use of the joystick and the IMU simultaneously, made it near to impossible to fly the LinkQuad with thrust control because the pilot needs to be able to use both at the same time. A normal case is when the LinkQuad tilts, the previous vertical thrust is split into two effective components, one vertical and one horizontal. This means that the vertical thrust is reduced and that the pilot needs to counteract this reduction as he is setting setpoints for the attitude control. This counteraction is handled by the altitude control.

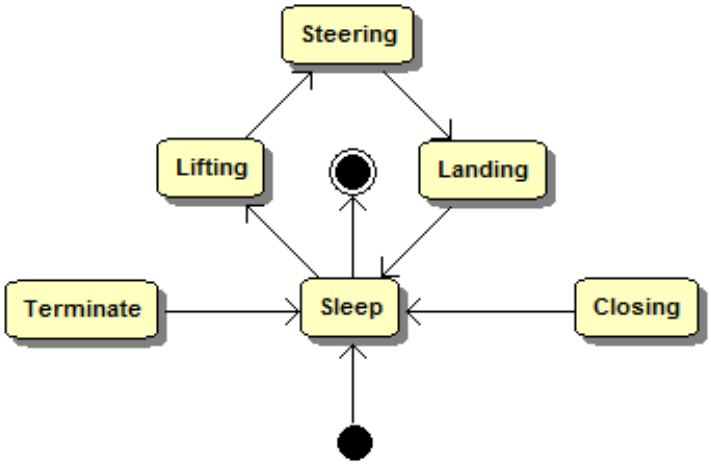



Figure 3.6: *The state machine diagram of the Android Client.*

By doing an action on the steering interface the user changes the current state in the state machine, Figure 3.6. If this basic functionality had not been implemented, the code complexity of programming the behavior of the Android Client would be massive. So instead of having this massive untraceable code a state machine was implemented in the `BackgroundThread`. This to be able to change state depending on what action the user had done and by the state machine itself. For an example, if the user wants the LinkQuad to lift from the ground and become airborne, he or she presses the lift/land button and the state machine changes the current state into lifting, sending the lift command to the Server and then later by itself changes to the steering state. This to enable the steering of the LinkQuad. It is important that the Android Client and the Server state machines are in sync because if one of the state machines thinks that the LinkQuad is airborne but the other thinks it is on the ground serious problems will happen. This was counteracted by having the basic states of the Android Client structured in the same way as the Server and doing much testing. But the Android Client does vary much from the Server because the user has more freedom of choosing the next state by his or her actions on the interface.

***Connection*** To communicate the commands and data that we create or fetch in the steering activity a customized message protocol with TCP or UDP is used. This protocol is described in Section 2.4.

Because the different low-level implementations of the UDP and TCP, the code complexity would increase much if one would implement them both directly into the code every time a network operation should be done. So by creating a *Template Method* the problem is abstracted away and the *Template Method* acts as the network connection to the rest of the application by providing its own send and receive functions. Implementing this *Template Method* as the abstract class Connection enables the implementation of the same functionality for both TCP and UDP by creating two implementations, `TCPConnection` and `UDPConnection`, of the abstract class `Connection`.

The `PhoneMessage` is a class/struct that describes what a message should look like and give functions to easily make a sendable package. It is used to make it easy to handle messages and being able to make changes in message structure without having a lot of dependencies to the rest of the code.

**Field Tests**

The design and the implementation were field tested by four different tests. The first test was to connect the Android Client to the Gantry Crane, Section 4.1, and steer it with the IMU as well as with the joystick. The second test was to connect to the Server aboard the LinkQuad and control the panning of the external camera. The Third test was done by studying the pulse-width modulation (PWM) output while trying to steer the LinkQuad with the motors shut down. The last test was flying the LinkQuad with altitude control.

It was noticed in these tests that steering with the IMU was much more easy than steering with the joystick. The IMU gave a smooth control over the steering whilst the joystick gave a more rough steering experience. It was also noticed that the pitch and roll inputs gave a proportional reaction in all of the tests. Also the joystick behaved in a similar fashion but it was easy to loose the grip of the joystick which made it hard to use it without looking on it. When using the Android Client with altitude control in the final test it was noticed that the Android Client behaved equally with the Computer Client. More information about the result of the flight can be found in Chapter 5.

For these reasons the Android Client should be used with altitude control and not with thrust control.

## 3.4 Computer Client

The Computer Client is an alternative to the Android Client. It supplies the user with two options of inputs, a keyboard or a PS3 gamepad, but lacks graphical feedback on the screen. This is due to the need of keeping the pilot focused on the LinkQuad and to its main purpose, which was to be used as a tool in tests.

The advantage of using the Computer Client instead of the Android Client is the higher accuracy of the PS3 gamepad and the fixed inputs of the keyboard. However, the disadvantage of using the keyboard is the loss of variable inputs. Also both the HIDs need to have an extra computer to run the Computer Client on.

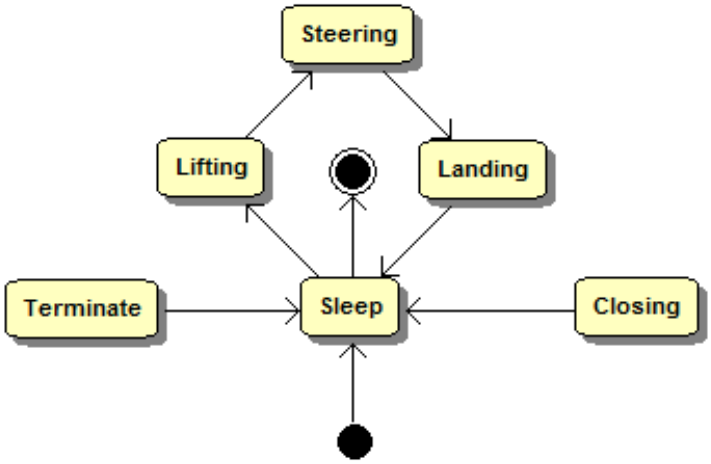



Figure 3.7: The state machine diagram of the Computer Client.

The Computer Client can connect to the Server with either a TCP connection or an UDP connection via an ad hoc network. The user inputs are then interpreted into different commands or setpoints and are sent to the Server, which will use them in different parts of the control system.

Since the client was originally considered as testing tool, the design of the client differs slightly from the rest of the application. The other applications, Android Client and Server, have a dedicated class for network communication. The network communication for Computer Client became instead the main functionality, `WifiClient`, since its main purpose is to periodically read inputs from the user and send them to the Server.

`WifiClient` fetches user inputs from the abstract class `UIListener` and its implementations `KeyStrokeListener` and `PS3Listener`. This design pattern is called *Template Method*, which allows a template to specify a skeleton of operation and deferring some steps to subclasses. [Gam96]

The state machine from Android Client was also introduced in `PS3Listener`, see Figure 3.7. It was put in `PS3Listener` to ensure the same behaviour as the Android Client, but not to hinder the simple nature of `KeyStrokeListener`.

The protocol-specific implementations of the network communication, `TCPClient` and `UDPClient`, were also designed according to the Template Method pattern. [Gam96]

A class diagram of the Computer Client can be seen in Figure 3.8.

### Keyboard

The keyboard interface was developed to test the communication between Server and Computer Client. Any type of keyboard which is connected to the computer running Computer Client can be used as a HID. The values that are interpreted into messages are static values which are binary. The keyboard must therefore only be used to test communication and never to fly the LinkQuad itself.

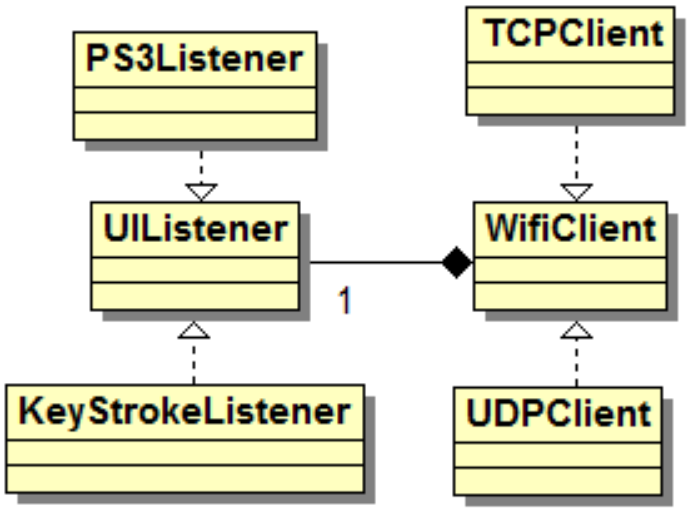



Figure 3.8: The class diagram of the Computer Client.

**PS3 gamepad**

The PS3 gamepad uses the Bluetooth HID protocol and is thus registered as a joystick on computers, which support the HID protocol. Since it is registered as a joystick, one can use any simple gaming library to access the input from the PS3 gamepad. In Computer Client, the choice fell upon Simple DirectMedia Layer (SDL) since it could be used on several platforms and it was easy to apply.[QNX11]

Computer Client uses SDL to collect the available inputs at an instant as events and stores their values and states. When all available events have been collected, all values and states are interpreted to produce a correct message which is put it in the outgoing mailbox, see Section 2.4 for details on mailboxes. After that the procedure is periodically repeated.

The controls of the PS3 gamepad are mapped to match the existing RC controller with some adjustments for the nature of the sticks of the PS3 gamepad and the accessibility of the software. The RC's mapping can be found in Table 3.6, an image of the controller can be found in Figure 3.10, the PS3 gamepad's mapping can be found in Table 3.7 and an image of the gamepad can be found in Figure 3.9.

As can be seen in Figure 3.10, the left stick is not fixed in an upright position. Since it is used almost as a throttle, it does not have any springs and has instead notches along the axis to keep the stick in the given position.

The PS3 gamepad does not have this behavior on its left stick and therefore, the thrust is implemented as an adding/subtracting function on the left stick in the same way as the Android Client. For an example, to increase thrust, the stick is moved upwards and downwards to decrease the thrust. Other differences are the lack of control of the camera since it is out of scope of this thesis and the lack of mode control. The missing mode control is due to that the interface to the existing software does not allow access to this property.

| Stick/Switch | Orientation | Set point |
|---|---|---|
| Left stick | North-South | Thrust. |
| Left stick | East-West | Yaw. |
| Right stick | North-South | Pitch. |
| Right stick | East-West | Roll. |
| Top left knob (CTRL 7) | - | Camera pan. |
| Top right slider (CTRL 5) | - | Camera tilt. |
| Top right toggle switch (SW 6/7) | - | Mode operator. |

Table 3.6: *The mapping of controls on the RC controller.*

| Stick/Switch | Orientation | Set point |
|---|---|---|
| Left stick | North-South | Add/subtract thrust. |
| Left stick | East-West | Yaw. |
| Right stick | North-South | Pitch. |
| Right stick | East-West | Roll. |
| Cross | - | Land/Lift. |
| Circle | - | Emergency land. |
| Top left front button (L1) | - | Yaw trim left. |
| Top right front button (R1) | - | Yaw trim right. |

Table 3.7: *The mapping of controls on the PS3 gamepad.*


Figure 3.9: *A PS3 gamepad seen from the top.*


Figure 3.10: *The original RC controller.*

# 4. Slung Load Control on a Quadrotor

This chapter will discuss how the slung load control was investigated and which different problems that were found and which problems were solved.

The slung load control problem originated from the intention of flying with a load attached to the quadrotor with a string. This would result in an oscillative behaviour that would perhaps affect the quadrotor as the load would act as a pendulum. The LinkQuad has a lifting capability of 300 g according to the manufacturer UAS Technologies Sweden AB and this was the target mass of the load to be controlled. The quadrotor was to be able to carry this load and to cancel out its oscillative behaviour and disturbances in hover.

The existing control of the LinkQuad consisted of attitude control and an open loop control of the thrust. To reduce the complexity of the slung load problem to a two dimensional problem, it was decided to close the loop of the thrust as an altitude control. The quadrotor would then be able to cancel out the oscillations by moving in the horizontal plane, which is a problem that could initially be investigated on the gantry crane, an existing lab rig consisting of crane with a slung load that can move in the horizontal plane. On this lab rig, a model of the load could also be developed and evaluated.

The subproblems of the slung load control were to develop an altitude control, to develop a model of the slung load, develop a slung load control on the gantry crane and integrate all these solutions into a final slung load control on the quadrotor.

The chapter will first present the gantry crane experiment and the deriving of a model of a slung load. After that, the sensors that were investigated and the low pass filter of the pressure sensor that was developed to decrease noise will be introduced. Third, the altitude control will be presented and finally, a short motivation to why the full integration was not successful will end the chapter.

## 4.1 Gantry Crane Control

The gantry crane is an existing lab process, originally developed by Per-Ola Larsson and Rolf Braun and used in courses at the Department of Automatic Control, Lund University. The lab process consists of a cart on a rail with a movable arm, which has a slung load attached at the end, see Figure 4.1. This process can approximate the slung load problem on the quadcopter if altitude control is assumed and the tilting of the load’s pivot point is disregarded. It was therefore considered as a good exercise to introduce position control of the cart with set points sent from Computer Client and Android Client, while the slung load is kept perpendicular to the floor.

The original control on the rig makes the slung load follow a circular trajectory while it keeps the cart centered on the rail. The slung load could be modeled as a spherical pendulum in the original control with the following equations of motion:

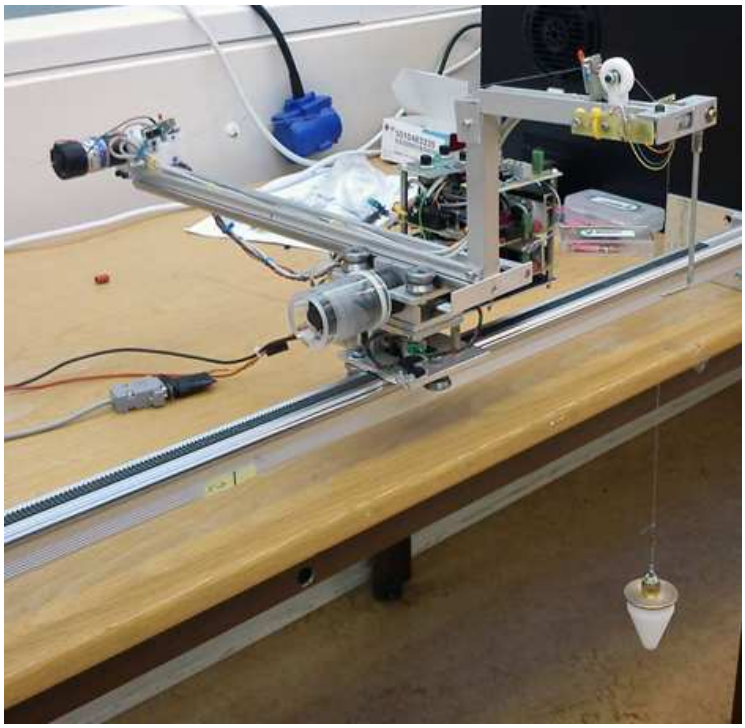


Figure 4.1: *The gantry crane process.*

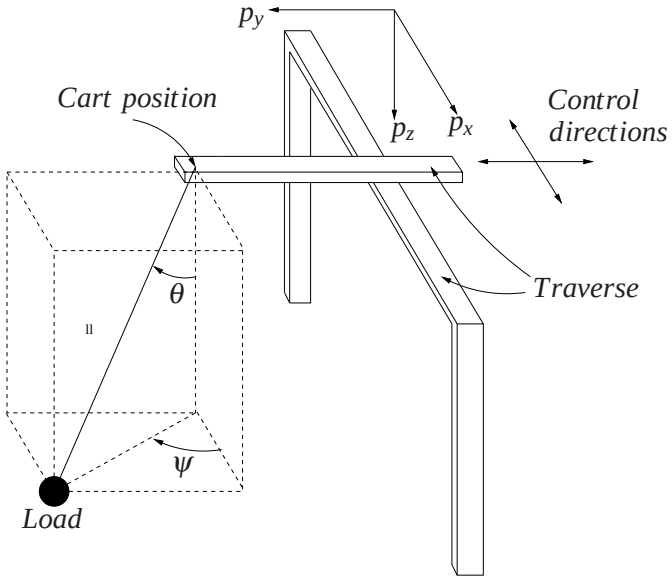



Figure 4.2: *Crane layout and coordinates. The cart position, i.e. the pivot point of the crane load, can be moved in the* $(p_x, p_y)$*-plane. Courtesy of Per-Ola Larsson.*

$$\begin{aligned} &2l\dot{\theta}\dot{\psi}\cos\theta + l\ddot{\psi}\sin\theta - u_x\sin\psi + u_y\cos\psi = 0 \\ &g\sin\theta + l\ddot{\theta} - \frac{1}{2}l\dot{\psi}^2\sin 2\theta + u_x\cos\theta\cos\psi + u_y\cos\theta\sin\psi = 0 \end{aligned} \tag{4.1}$$

where $u_x(t)$ and $u_y(t)$ are accelerations in the corresponding rail directions and $\theta(t)$ and $\psi(t)$ are the angles of the load, see Figure 4.2. The new control could not use

this model, because of a singularity at the downright position. This singularity is visible when the equations are linearized and written as a linear time-invariant (LTI) system.

The downright position is chosen as linearization point, see (4.2), and through a simple reformulation of Equation (4.1), the model can be expressed as (4.3).

$$\begin{pmatrix} p_{x0} \\ \dot{p_{x0}} \\ p_{y0} \\ \dot{p_{y0}} \\ \theta_0 \\ \dot{\theta}_0 \\ \psi_0 \\ \dot{\psi}_0 \\ u_{x0} \\ u_{y0} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{4.2}$$

$$\ddot{\psi}(t) = \underbrace{\frac{-1}{l\sin\theta(t)}}_{\text{Problem}} \left(-u_x(t)\sin\psi(t) + u_y\cos\psi(t) - 2l\dot{\theta}(t)\dot{\psi}(t)\cos\theta(t)\right). \tag{4.3}$$

[LB08] When (4.3) is linearized with respect to $u_x$ and $u_y$ and the linearization point, a singularity is introduced at the downright position, $\theta = 0$.

This problem implied that another approximation of the load had to be found and the first attempt was to use two traversed simple pendulums. This proved successful so no further research was done. The model's derivation follows below.

The motion of a simple pendulum is described by

$$ml\frac{d^2\theta}{dt^2} = -mg\sin\theta \tag{4.4}$$

where $\theta$ is the angle, $m$ is the mass, $l$ is the length and $g$ is the acceleration due to gravity, see Figure 4.3. By assuming that the amplitude of oscillation is sufficiently small and that $sin\theta \approx \theta$ as an linearization, it can be simplified to (4.5) as a new equation of motion.[BB05]

$$\frac{d^2\theta}{dt^2} + \frac{g}{l}\theta = 0 \tag{4.5}$$

This LTI system can be expressed on state space form, see (4.6).

$$\begin{pmatrix} \dot{\theta} \\ \ddot{\theta} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -\frac{g}{l} & 0 \end{pmatrix} \begin{pmatrix} \theta \\ \dot{\theta} \end{pmatrix} \tag{4.6}$$

The two simple pendulums had definitions of load angles that differed from the spherical pendulum in the original model. However, the original angles were derived from two angular sensors' values, $\alpha$ and $\beta$, see Figure 4.4. The simple pendulums were defined so that they were aligned along each axis in Figure 4.4 and this implies

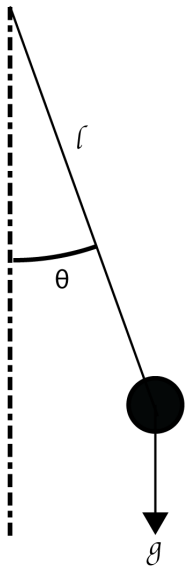



Figure 4.3: *A simple pendulum.*

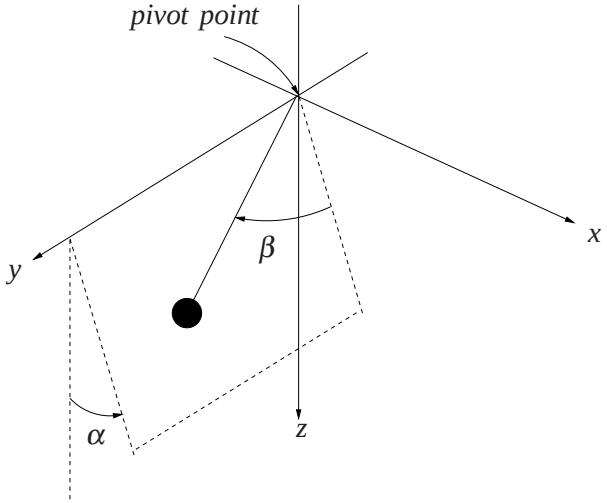



Figure 4.4: *Definitions of angles $\alpha$ and $\beta$ measured by angle sensors. Courtesy of Per-Ola Larsson.*

that one simple pendulum could use $\alpha$ as angle $\theta$ in Equation (4.5) and one could use $\beta$.

The modified model can be described as a LTI system,

$$\begin{pmatrix} \dot{p}_x \\ \ddot{p}_x \\ \dot{p}_y \\ \ddot{p}_y \\ \dot{\alpha} \\ \ddot{\alpha} \\ \dot{\beta} \\ \ddot{\beta} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{g}{l} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{g}{l} & 0 \end{pmatrix} \begin{pmatrix} p_x \\ \dot{p}_x \\ p_y \\ \dot{p}_y \\ \alpha \\ \dot{\alpha} \\ \beta \\ \dot{\beta} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \\ \frac{1}{l} & 0 \\ 0 & 0 \\ 0 & \frac{1}{l} \end{pmatrix} \begin{pmatrix} u_x \\ u_y \end{pmatrix} \quad (4.7)$$

where $p_x$ and $p_y$ describe the position of the cart, $\dot{p}_x$ and $\dot{p}_y$ are the velocities of the cart, $\alpha$ and $\beta$ are the angles from Figure 4.4, $l$ is the length of the load arm and $g$ is the acceleration due to gravity.

This model is mass independent, which is attractive for the later application on the quadrotor since it can then be loaded with a variety of loads and the model would not have to be altered.

When the new approximation had been derived, it was introduced to the existing Simulink-files of the process and the control loop was to be modified. The existing control consisted of a linear quadratic regulator (LQR) and since the system was easily converted from using a spherical pendulum to using the new model the LQR was kept with some modifications to the cost matrices to keep the load hanging straight down. The final cost matrices can be found in (4.8).

$$Q_1 = \begin{pmatrix} 100 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 100 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 100 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 100 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 100 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \quad Q_2 = \begin{pmatrix} 10 & 0 \\ 0 & 10 \end{pmatrix} \tag{4.8}$$

The focus was instead shifted to making a reference generator that could be controlled from Android Client or Computer Client. The main goal of the reference generator was to allow control of the position of the cart via the network protocol, that had been developed in parallel. This way, the clients of the system and the protocol could be tested on a real process to seek out missing parts and test its performance. The reference generator borrowed the necessary functionality of Server and it was adjusted to fit into a MATLAB S-function. A S-function is a way to implement the functionality of a Simulink block in C or C++ and by doing so, introducing i.e. network communication. The S-function became a simple version of Server, which could interpret direction messages into set points of the cart's position.

This was introduced into the modified Simulink files and run successfully with both Android Client and Computer Client steering the rig.

## 4.2 Sensors

A solution to the problem of altitude control and control of the slung load requires some sensors. The LinkQuad has a set of sensors, e.g. an accelerometer and a pressure sensor, that can be reached through a serial bus to the Sensor MCU (SMCU). The control of the slung load requires another sensor as well. This was to be solved by attaching an angle sensor to the LinkQuad and anchor the slung load to it.

This section will discuss first the angle sensor that was built originally for the gantry crane experiment and which was ported to the LinkQuad. Second, the pressure sensor will be introduced and how its noisy behaviour was filtered.

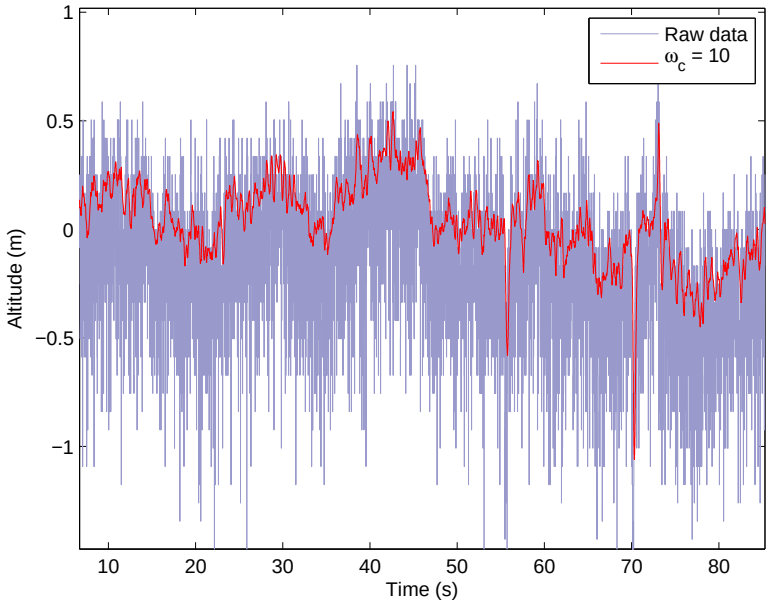



Figure 4.5: Raw and low pass filtered data from the pressure sensor, converted into meters, when the quadrotor sits on the ground with motors off. The natural variations in the atmospheric pressure can have a magnitude up to 1 m.

### Angle Sensor

The two angle sensors that was to be attached to the LinkQuad bottom were two Hall effect sensors. They measure each of the angles of the slung load $\alpha$ and $\beta$, see Figure 4.4 and were to be combined to derive the slung load's position as it was done in the experiment of the gantry crane, see Section 4.1.

The design was an exact copy of the design of the head of the gantry crane developed by Rolf Braun. The sensors were attached to the base of a fork, which was attached to the wire of the slung load. The base tilts and actuates each sensor as the fork swings along with the wire of the slung load.

### Pressure Sensor

Pressure sensors are not normally used indoors to measure the altitude since the pressure changes continously. The lack of other distance sensors, such as ultrasonic or infrared distance sensors, implies that the pressure sensor is the only altitude sensor on the existing platform which could be used for measuring the altitude.

When the pressure sensor on the LinkQuad was used the first time, it was observed that the raw sensor data was very noisy. Even when the LinkQuad was completely still the pressure sensor's variance was about one meter, see Figure 4.5. This would be very bad since that could lead to the LinkQuad oscillating with a magnitude of one meter. To counter this, a low pass filter was designed to filter the noisy values and give a more accurate signal without introducing too much delay. A second aspect to consider was occasional spikes in the pressure that could come from the opening and closing of doors in the surroundings. If these spikes were allowed to enter to the control loop, the altitude could be misinterpreted by several meters.

***Pressure to altitude conversion*** A conversion from pressure to altitude was

required to use the pressure sensor to calculate the altitude of the LinkQuad. The conversion formula was provided by the developers of the LinkQuad and can be seen in (4.9).

$$altitude = \frac{101325 - 1000 \cdot p}{11.9} \tag{4.9}$$

The pressure sensor provides the pressure $p$ in kPa. Since the altitude over sea level is sought after, the pressure $p$ is subtracted from the average pressure at sea level in Pa. The conversion factor, $\frac{1}{11.9}$, converts the pressure difference to altitude in decimeter.

***Low-pass Filter*** During the development of the low-pass filter, several different types of filters were tested in MATLAB by using the pressure data from real flights with known altitudes and spikes from door openings. By testing the different filter types, it was shown that a complex filter did not produce any better result than using an simple filter, e.g. a first or second order filter. Filters that were considered were the first and second order Butterworth filters. Filters of higher order, e.g. Chebyshev filters, were also considered in the beginning but since the simpler Butterworth filters were proven to be sufficient the focus remained on these.

Each filter type was evaluated with several cut-off frequencies on a generic flight sequence from the ground to 2 m altitude and back to the ground. At the end a spike was generated from a door being slammed shut. The properties of the different filter outputs that were studied were how much delay the filter produced and how much it dampened the noise.

The first order filter has almost no delay at all cut-off frequencies, and a damping of the spike to less than 1.5 m but it lets noise with a magnitude of 0.3 m or more through, see Figure 4.7, except 0.5 Hz where instead too much delay was introduced, see Figure 4.7b.

The second order filter had a delay at lower cut-off frequencies than 2 Hz, but it had also an improved damping of the noise at this frequency, see Figure 4.8b. The higher cut-off frequencies had much less delay but also had less dampening of the noise, see Figure 4.8f and Figure 4.8h. The cut-off frequency of 2 Hz was chosen to be implemented, since it dampened the noise to less than 0.2 m and the spike of 2.5 m to 1 m without introducing too much delay, see Figure 4.8d and Figure 4.8c.

If the first order Butterworth filter with cut-off frequency at 1 Hz is compared to the chosen filter, it has a similar performance. It was not chosen since it implies more noise at a lower cut-off frequency. Higher cut-off frequency implies that faster control is possible and this is discussed further on page 73 in Section 4.3.

The second order continous time Butterworth filter's transfer function in the is

$$G_{\text{lp}}(s) = \frac{\omega_c^2}{s^2 + \sqrt{2}\omega_c s + \omega_c^2} \tag{4.10}$$

and it needs to be discretized into a digital filter so it can be implemented in Server. The Server receives the pressure data from the SMCU at a sample time of 4 ms so this is chosen as the sample time $h$ for the discrete low pass filter. The discretization can be done by zero-order-hold sampling to the pulse-transfer function $H(z)$.

$$G(s) = \frac{\omega_0^2}{s^2 + 2\zeta\,\omega_0 s + \omega_0^2} \implies H(z) = \frac{b_1 z + b_2}{z^2 + a_1 z + a_2} \tag{4.11}$$

where

$$\begin{aligned} b_1 &= 1-\alpha\left(\frac{\zeta\omega_0}{\omega}\gamma+\beta\right) & \omega &= \omega_0\sqrt{1-\zeta^2} \\ b_2 &= \alpha^2+\alpha\left(\frac{\zeta\omega_0}{\omega}\gamma-\beta\right) & \alpha &= e^{-\zeta\omega_0 h} \\ a_1 &= -2\alpha\beta & \beta &= \cos(\omega h) \\ a_2 &= \alpha^2 & \gamma &= \sin(\omega h) \end{aligned}$$

and $\omega_0$ is given in radian per seconds (rad/s). The pulse-transfer function can be written on backward shift form as

$$H(z) = \frac{b_1 z + b_2}{z^2 + a_1 z + a_2} \iff H(z^{-1}) = z^{-1}\frac{b_1 + b_2 z^{-1}}{1 + a_1 z^{-1} + a_2 z^{-2}}$$

This gives the filter's equation

$$\begin{aligned} & y_f(kh) = H(z)u(kh) \\ \implies \quad & y_f(kh)z(1 + a_1 z^{-1} + a_2 z^{-2}) = u(kh)(b_1 + b_2 z^{-1}) \\ \iff \quad & y_f(kh+1) + a_1 y_f(kh) + a_2 y_f(kh-1) = b_1 u(kh) + b_2 u(kh-1) \\ \iff \quad & y_f(kh+1) = -a_1 y_f(kh) - a_2 y_f(kh-1) + b_1 u(kh) + b_2 u(kh-1) \end{aligned}$$

where $y_f(kh)$ is the filtered signal, $u(kh)$ is the input sample of the signal to be filtered and $kh$ is the time instant $t = kh$ when the computer samples the values. This is advantageous since the output can be calculated a sample in advance and there will be minimal computational delay when the output is to used.

With $\omega_0 = \omega_c = 2 \cdot 6.2831853$ rad/s and $\zeta = \frac{1}{\sqrt{2}}$, the final filter can be seen (4.12)

$$y_f(kh+1) = 1.929y_f(kh) - 0.9314y_f(kh-1) + 0.001234u(kh) + 0.001205u(kh-1) \tag{4.12}$$

The Bode plot of the filter can be seen in Figure 4.6.

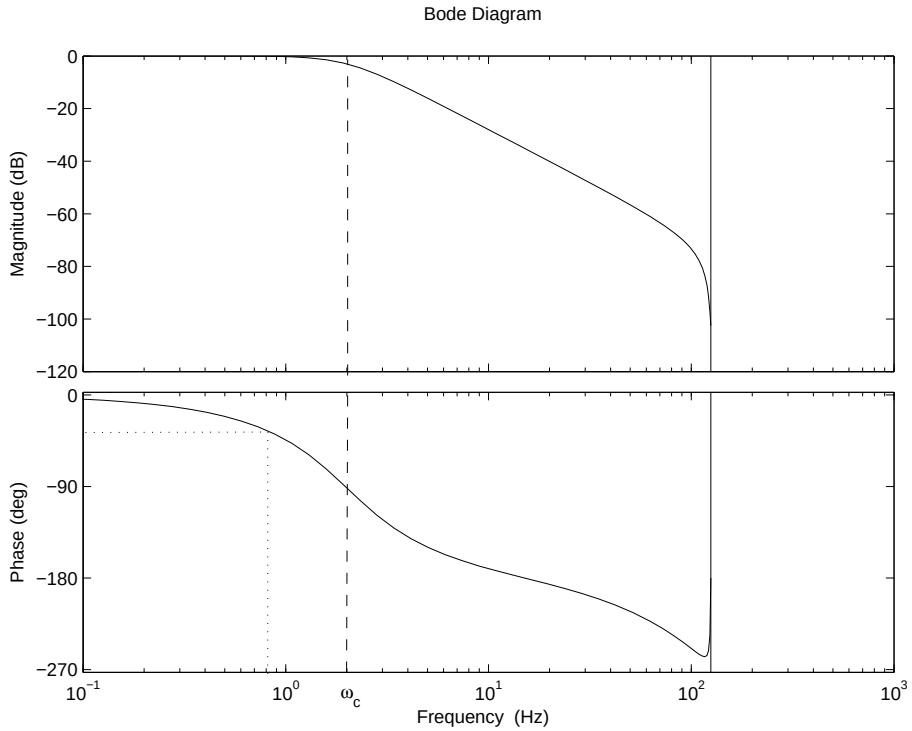
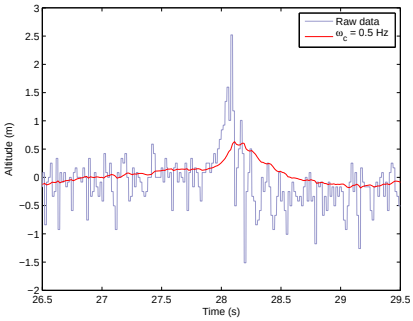
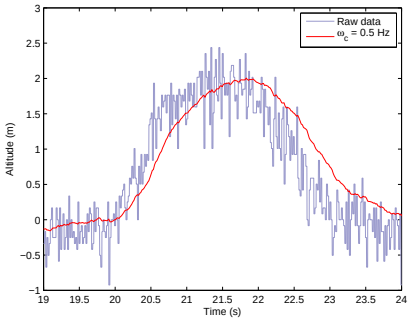


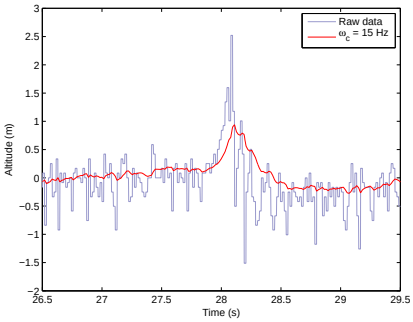

Figure 4.6: *Bode plot of the discrete second order Butterworth filter with cut-off frequency $\omega_c = 2$ Hz. The dashed line marks the filter's the cut-off frequency and the dotted line the open loop system's cut-off frequency.*



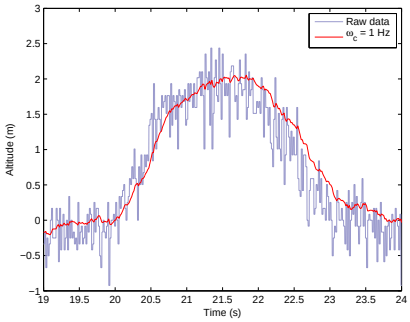

(a) $w_c = 0.5\ Hz$



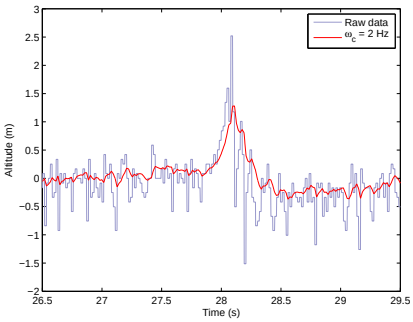

(b) $w_c = 0.5\ Hz$



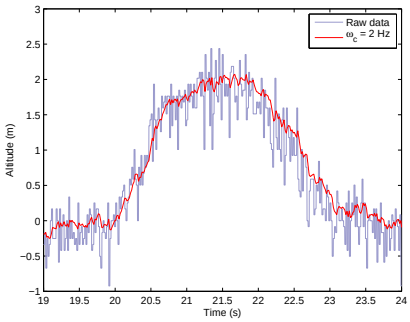

(c) $w_c = 1\ Hz$



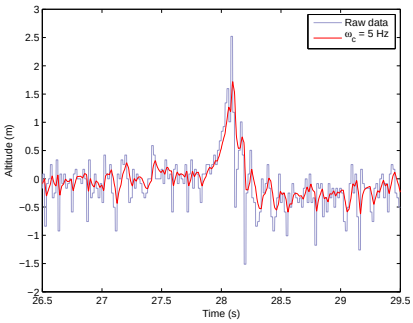

(d) $w_c = 1\ Hz$



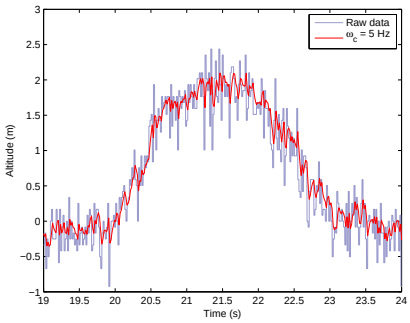

(e) $w_c = 2\ Hz$




(f) $w_c = 2\ Hz$

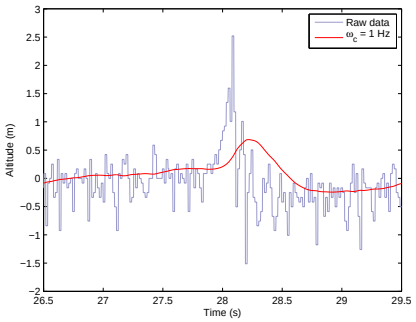



(g) $w_c = 5\ Hz$

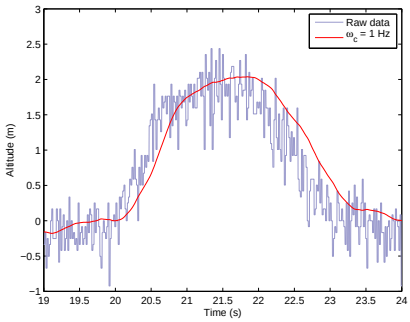



(h) $w_c = 5\ Hz$

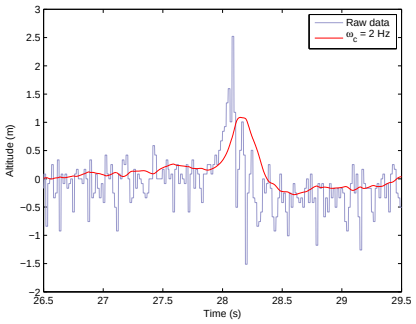
Figure 4.7: *Low pass filtered pressure sensor with a first order Butterworth filter with different cut-off frequencies. The left plots show how a spike from a door is filtered and the right plots show a climb to 2 m altitude followed by a descent to the ground again.*



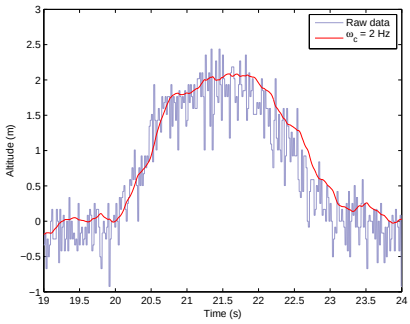

(a) $w_c = 1\ Hz$



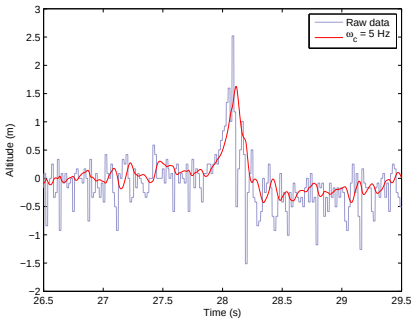

(b) $w_c = 1\ Hz$



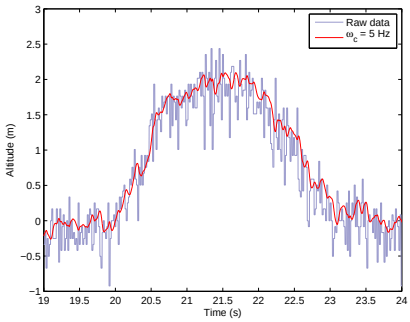

(c) $w_c = 2\ Hz$



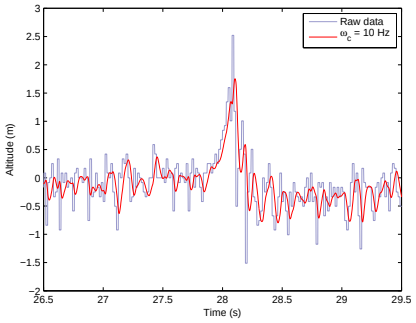

(d) $w_c = 2\ Hz$



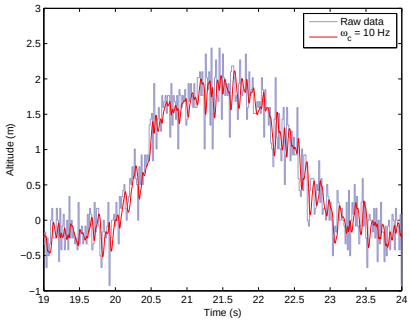

(e) $w_c = 5\ Hz$




(f) $w_c = 5\ Hz$




(g) $w_c = 10\ Hz$




(h) $w_c = 10\ Hz$

Figure 4.8: *Low pass filtered pressure sensor with a second order Butterworth filter with different cut-off frequencies. The left plots show how a spike from a door is filtered and the right plots show a climb to 2 m altitude followed by a descent to the ground again.*

## 4.3 Altitude Control

The existing control consisted of attitude control and an open-loop control of the thrust of the rig. The thesis problem of controlling a slung load required both a control of the slung load's angles and an altitude control for closing the loop of the thrust. A state machine was added to allow different modes of operation, such as *flying*, *lift off* or *ground*, where different settings are to be used.

This section will discuss the following subjects in given order:

- Model of the LinkQuad.
- Altitude Control.
- State Machine.
- Control of the Slung Load.

**Model of the LinkQuad**

A model of the LinkQuad was needed to simulate its behaviour in and evaluate controllers without the risk of damaging the rig. It was to be as simple as possible and still accurate enough to give confidence in the controllers' performance. The model was to be derived from existing work, since the authors lack enough knowledge in system identification and mechanics to be able to derive the model from scratch.

Etter, Martin and Mangharam [EMM11] derived a simple model of a quadrotor's mechanics,

$$\begin{pmatrix} \ddot{X} \\ \ddot{Y} \\ \ddot{Z} \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Rotation matrix}} \begin{pmatrix} \sin(\theta)\frac{T_{tot}}{m} \\ \sin(\phi)\frac{T_{tot}}{m} \\ \cos(\theta+\phi)\frac{T_{tot}}{m} - g \end{pmatrix} \tag{4.13}$$

where $\theta$ is the pitch angle, $\phi$ is the roll angle, $\psi$ is the yaw angle, $m$ is the mass, $g$ is the acceleration due to gravity, $X$,$Y$ and $Z$ are the world coordinates and $T_{tot}$ is the thrust from all four propellers. These equations are complemented with integrations to get velocities and position and the angles are assumed to be stabilized with PID controllers.

This model has its disadvantages, since it does not account for inertia and takes thrust as input. It was therefore altered to take the existing input range from the radio controller, $[0..1000]$, and to convert that input into thrust inside the model.

The conversion between input and thrust was initially investigated in two experiments where input was compared to the resulting acceleration. The first experiment was to let the quadrotor hover and the second experiment was to maximize the input to find the maximum acceleration. Since the quadrotor hovers, the acceleration from the propellers equals the acceleration from gravity, thus $a_{\text{hover}} = g$. The maximum acceleration was found to be close to $2g$. Assuming that the relationship between input and acceleration is linear, see (4.14), the constant $c$ were derived with the mass $m = 1.4$kg and accelerations from the experiments, see (4.15).

$$c \cdot u = T_{tot} = ma \implies c = \frac{ma}{u} \tag{4.14}$$

$$c_{\text{hover}} = \frac{1.4 \cdot g}{590} \approx 0.02326$$
$$c_{\max} = \frac{1.4 \cdot 2g}{900} \approx 0.0303 \tag{4.15}$$

The relationship is nonlinear, but it was decided to be linearized around the hover position since it is the area it will operate in most of the time.

The initial investigations of the modified model showed that its behaviour looked like a quadrotor's but to confirm this, real input signals were fed to the model and the altitude output was compared to the real process' altitude. The constants from the experiment were found to imply a behaviour in the model which did not coincide with the real behaviour. The conversion constant $c$ was therefore altered to $c = 0.0234$. It gave a matching behaviour between the model and the real data and by interpreting the error in later parts of simulation as an error from the double integration, a behaviour in the model that imitates the real process was found, see Figure 4.9. The small dip below zero after two seconds in the real process' altitude is due to the pressure change from starting the propellers.

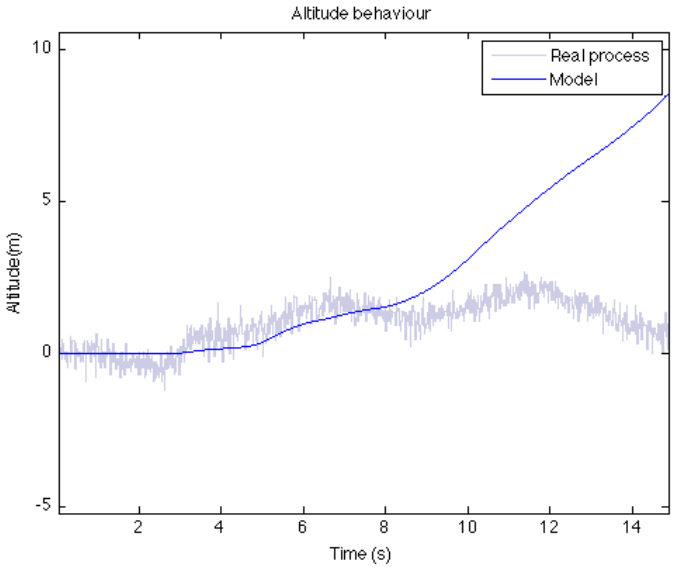



Figure 4.9: *Comparison between the real process and the model with* $c = 0.0234$.

Another model, which was developed in another thesis [Son11] as a part of the LinkQuad project, was also investigated to see if it was more accurate. This model was also linearized around the hover equilibrium, but it considered more dynamics than the other model.

The system was written on state-space form as

$$\dot{x}(t) = Ax(t) + B \begin{pmatrix} u_1(t) \\ u_2(t) \\ u_3(t) \\ u_4(t) \end{pmatrix}, \tag{4.16}$$

where $u_i$ is the pulse-width modulation (PWM) input to motor $i$ and the states are

$$x(t) = \begin{pmatrix} \dot{X}(t) \\ \dot{Y}(t) \\ \dot{Z}(t) \\ \dot{\theta}(t) \\ \dot{\phi}(t) \\ \dot{\psi}(t) \\ T_1(t) \\ T_2(t) \\ T_3(t) \\ T_4(t) \end{pmatrix} \tag{4.17}$$

where $\theta$ is the pitch angle, $\phi$ is the roll angle, $\psi$ is the yaw angle, $m$ is the mass, $g$ is the acceleration due to gravity, $X$,$Y$ and $Z$ are the world coordinates and $T_{tot}$ is the thrust from all four propellers. These equations are completed with integrations to get position and angles. All other variables are specified in Table 4.1.

The state matrix

$$A = \begin{pmatrix} 0 & 0 & 0 & \frac{g}{m} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{g}{m} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{m} & -\frac{1}{m} & -\frac{1}{m} & -\frac{1}{m} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{I_{yy}} & 0 & \frac{1}{I_{yy}} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{I_{xx}} & 0 & -\frac{1}{I_{xx}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\beta & \beta & -\beta & \beta \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & A_m & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & A_m & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & A_m & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & A_m \end{pmatrix} \tag{4.18}$$

and the input matrix

$$B = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -\gamma & \gamma & -\gamma & \gamma \\ B_m 2\sqrt{aT_0} & 0 & 0 & 0 \\ 0 & B_m 2\sqrt{aT_0} & 0 & 0 \\ 0 & 0 & B_m 2\sqrt{aT_0} & 0 \\ 0 & 0 & 0 & B_m 2\sqrt{aT_0} \end{pmatrix}, \tag{4.19}$$

where

$$\beta = \frac{d}{aI_{zz}} + \frac{A_m I_{\text{prop}}}{2a\Omega_0 I_{zz}} \tag{4.20}$$

and

$$\gamma = \frac{I_{\text{prop}} B_m}{I_{zz}}. \tag{4.21}$$

| Variable | Description | Measured value | Value from the model |
|---|---|---|---|
| $g$ | Acceleration induced by gravity | 9.82 $\text{ms}^{-2}$ | 9.82 $\text{ms}^{-2}$ |
| $m$ | Mass of the LinkQuad | 1.4 kg | 1.2 kg |
| $I_{xx}$ | Inertia around the body's x-axis | Not measured | $9.56 \cdot 10^{-3}$ $\text{Nms}^2$ |
| $I_{yy}$ | Inertia around the body's y-axis | Not measured | $9.85 \cdot 10^{-3}$ $\text{Nms}^2$ |
| $I_{zz}$ | Inertia around the body's z-axis | Not measured | $15.2 \cdot 10^{-3}$ $\text{Nms}^2$ |
| $I_{\text{prop}}$ | Propeller inertia | Not measured | $2.46 \cdot 10^{-6}$ $\text{Nms}^2$ |
| $A_m$ | First motor constant | Not measured | $-9.56$ $\text{s}^{-1}$ |
| $B_m$ | Second motor constant | Not measured | $8.49 \cdot 10^{7}$ deg $\text{V}^{-1}\text{s}^{-1}$ |
| $a$ | Thrust constant | Not measured | $1.59 \cdot 10^{-7}$ $\text{Ns}^2$ |
| $d$ | Drag constant | Not measured | $2.93 \cdot 10^{-9}$ $\text{Nms}^2$ |

Table 4.1: *Variables of the model in equations* (4.16) *through* (4.21)

This model differs from the one in equation (4.13), since it considers inertia of the rig and the propellers, as well as properties in the motors. Also, the input is the PWM input, which is the same unit as the inputs to the real motors.

However, when the model was simulated with the values given in the original model, it behaved different from the real LinkQuad, e.g. the thrust input to hover was much smaller. It would thereby be necessary to do some experiments to do a proper system identification of the model's variables. The system identification was considered to be time consuming and the first model was used to evaluate controllers. Since it could only be said to be reliable during the first ten seconds, no longer sessions were used.

Neither of these models handles the different aerodynamic effects that can occur on the real process and this contributes to the difference between the real process and the models. Examples of such effects are listed below:

- Blade flapping.
- Turbulence.
- Ground effect.

When the quadrotor is moving in the horizontal plane, the advancing blade of a rotor has a higher velocity relative to the air than the retreating blade. Since the lift depends on the velocity of the airflow over the blade, a difference between the two blades is induced. This difference causes the blade to flap up and down once every revolution making the rotor plane tilt away from the direction of motion. This has numerous effects on the dynamics of the quadrotor, i.e. stability in attitude. [HHWT07]

Turbulence increases or decreases the effect of the rotors since the rotors' lift depends on the airflow velocity. This effect has been visible when flying indoors and

the air started to circulate within the room, the quadrotor could suddenly lose or gain height. This can also bee observed when wind affects the propeller.[Joh80]

Ground effect is a phenomena that occurs when a rotor aircraft is close to the ground, i.e. an altitude of half the length of rotorblade or less. The rotors constrain the rotor wake and creates a pillow of air. This pillow implies that the rotors can rotate at a slower speed and still maintain the same thrust.[Joh80]

All of these properties affect the process in such a way that the models can not be accurate enough. The first model has therefore been used to get pointers to how the controller should be tuned, but the final parameters of the controller have been found empirically.

### Altitude Control

The gantry crane experiment was so successful that the solution was preferably to be reused. To remove the aspects of vertical motion, the altitude control became a subproblem to the slung load problem.

This section will discuss the following subjects:

- Coordinate systems.
- Choice of sensors.
- Design of the controller.
- Discretization of the controller.
- Tuning of the controller.

***Coordinate Systems*** Two different coordinate systems will be used in this section and will be introduced here.

The first coordinate system is called world coordinates $[X, Y, Z]$, where $X$ is horizontal, parallel to the equator and positive in a westbound direction. $Y$ is horizontal, perpendicular to the equator and positive in a northbound direction. $Z$ is vertical and positive in a direction from the center of the Earth. It can be used to define the absolute position of a quadrotor.

The second coordinate system is called body coordinates $[X_B, Y_B, Z_B]$, where $X_B$ is parallel to the axis of the front and back rotors and positive towards the front rotor. $Y_B$ is parallel to the axis of the left and right rotors and positive towards the left rotor. $Z_B$ is parallel to the normal of the plane spanned by $X_B$ and $Y_B$ and positive in an upwards direction.

***Choice of Sensors*** The LinkQuad was supplied with an existing inactive solution to an absolute positioning control, which altitude control is a part of. It was supposed to use a global positioning system (GPS) unit in combination with a pressure sensor to get an absolute position of the quadrotor, but this control was however untested and inactive on the thesis' version of LinkBoard.

The first challenge of the altitude control was to find a good measurement of the altitude and there were different ways to solve this problem, see Table 4.2. The choice fell upon using the low pass filtered pressure sensor for its simplicity and its ability to be used both indoors and outdoors.

| No. | Solution | Motivation to decision |
|---|---|---|
| 1 | Pressure sensor, filtered with a low pass filter. | Simplest solution. It is, however, relying on the environment. see section 4.2. |
| 2 | Integration of accelerometers and gyroscopes. | Drift and bias errors makes it unreliable. |
| 3 | Sensor fusion of the pressure sensor, the accelerometers and gyroscopes in a Kalman filter, which accounts for drift and bias. | Most accurate solution, however complex and time consuming to develop. |
| 4 | GPS combined with the pressure sensor. | The GPS loses its connection indoors. |
| 5 | Camera positioning system from a related thesis. | Limited area of operation. |

Table 4.2: *Suggestions for measuring the altitude of the quadrotor.*

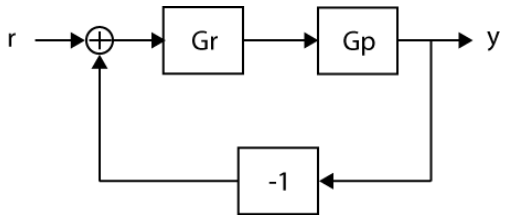



Figure 4.10: *Illustration of how the controller closes the loop around the process.*

***Design of the Controller*** The second challenge was to find the simplest controller that could achieve asymptotic stability. A way to do this was to find the closed loop transfer function and study its poles and zeros. The process itself can be approximated as simple double integrator,

$$y = \frac{1}{ms^2}u = G_p u \tag{4.22}$$

where the input $u$ is acceleration, the measured output $y$ is the altitude and $m$ is the mass of the system. Closing the loop as in Figure 4.10 gives the closed loop system

$$G_{cl} = \frac{G_r G_p}{1 + G_r G_p} \tag{4.23}$$

as a transfer function from the reference value to the output.

The initial investigation of possible controllers considered five types of controllers; P, PI, PID, PD and I. The controllers' poles and zeros could now be studied using the transfer function in (4.23) and the transfer function for each controller.

A P controller, $G_r = K$, increases the system gain but does not asymptotically stabilize the system. When the gain $K$ is altered the poles' to the origin is altered but they remain on the imaginary axis, see Figure 4.11a. Since the P controller is only stable and since it does not have any integral action, it will not suffice.

A PI controller, $G_r = K(1 + \frac{1}{sT_i})$, introduces two unstable complex poles or one unstable real pole, depending on the values of $K$ and $T_i$, see Figure 4.11b. This controller was therefore disregarded.

A I controller, $G_r = \frac{1}{sT_i}$, also introduce two unstable complex poles, see Figure 4.11c, and was thereby disregarded.

A PD controller, $G_r = K(1+sT_d)$, moves the poles into the asymptotically stable area but it does not improve the performance. Their placement can be altered by adjusting $K$ and $T_d$, but since the pressure sensor is noisy, an increase in the derivative action would amplify the noise. Second, the controller does not have any integral action. All this factors implied that this controller was disregarded.

Finally, a PID controller, $G_r = K(1+\frac{1}{sT_i}+sT_d)$, was investigated. It implies a closed loop transfer function

$$G_{cl} = \frac{K_m}{T_i}\frac{T_iT_ds^2+T_is+1}{s^3+K_mT_ds^2+K_ms+\frac{K_m}{T_i}}, \qquad K_m = \frac{K}{m} \tag{4.24}$$

which implies a possibility to freely place the poles by altering the values of $K$, $T_i$ and $T_d$, see Figure 4.11e. Therefore, this was the controller to be used.

However, for asymptotic stability, the poles must be situated in the left half plane and for a transfer function with a third order denominator

$$s^3+a_1s^2+a_2s+a_3$$

this holds only if all coefficients are positive and

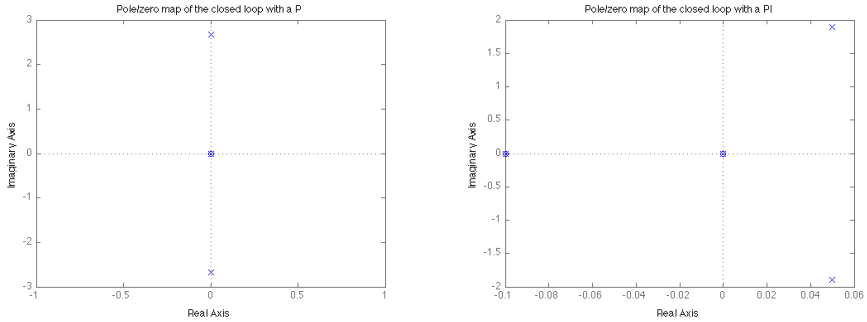
$$a_1a_2 > a_3$$

[Häg09, p 46]

For this system, these equations imply that

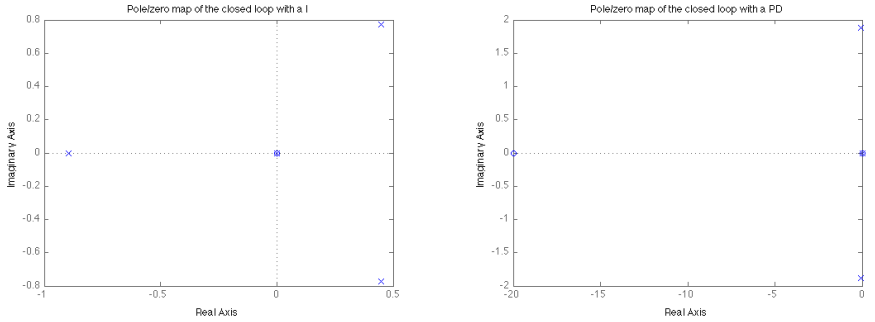
$$\begin{aligned} K &> 0, \\ T_i &> 0, \\ T_d &> 0, \\ T_d\left(\frac{K}{m}\right)^2 &> \frac{1}{T_i} \end{aligned} \tag{4.25}$$

for the system to be asymptotically stable.



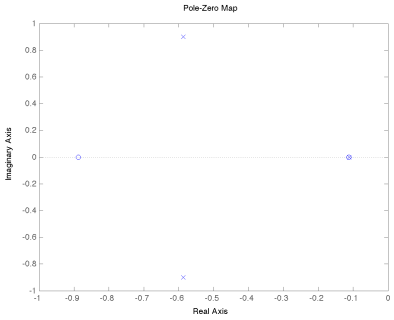

(a) Pole/zero map of the closed loop system with a P controller.

(b) Pole/zero map of the closed loop system with a PI controller.




(c) Pole/zero map of the closed loop system with a I controller.

(d) Pole/zero map of the closed loop system with a PD controller.




(e) Pole/zero map of the closed loop system with a PID controller.

Figure 4.11: *Pole/zero maps of the closed loop system with the considered controllers.*

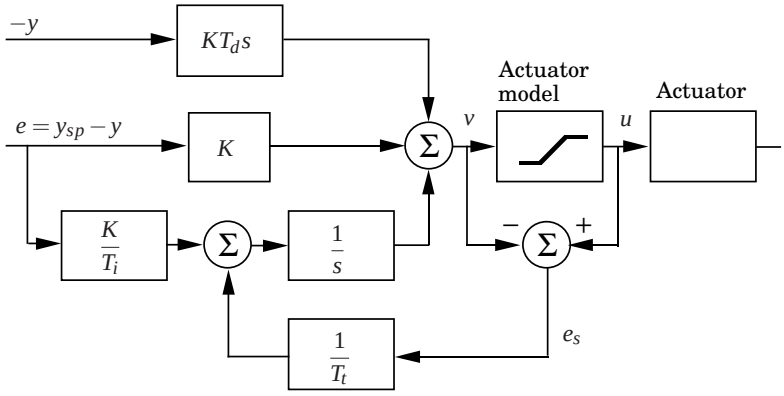



Figure 4.12: *Parallel PID implementation with anti-windup feedback. The anti-windup is active when saturation in the motors occurs and $e_s \neq 0$. It is otherwise equal to zero and does not affect the control. Courtesy of Karl Johan Åström and Tore Hägglund.*

This PID controller was extended to handle limited derivative gain, integrator windup and bumpless transfer from manual operation to automatic control.

The derivative action can result in a very large amplification of measurement noise and must therefore limited. This was done by the following approximation of the derivative part

$$sT_d \approx \frac{sTd}{1+sT_d/N} \tag{4.26}$$

This approximation works well at low frequencies while at high frequencies the gain is limited to $N$. Furthermore, it is not good to let the derivative act on the setpoint signal.

The PID controller becomes then

$$U(s) = K\left(R(s) - Y(s) + \frac{1}{sT_i}(R(s) - Y(s)) - \frac{sT_d}{1+sT_d/N}Y(s)\right) \tag{4.27}$$

where $U(s)$, $R(s)$ and $Y(s)$ are the Laplace transforms of the control signal $u(t)$, the setpoint signal $r_c(t)$ and the measurement signal $y(t)$.[WÅÅ09, p.50]

The motors of the LinkQuad can easily be saturated since their PWM inputs are limited to the range $0-1000$. If the controller saturates, the integral action may then integrate up to a very large value. Its value may become so large that when the error is later reduced, it may take a while until the integral action returns to a normal value. This behaviour is called integrator windup and can be counteracted with so called anti-windup. This can be done by modeling the motors as a saturation and adding an extra feedback loop to the integrator. The feedback loop takes the difference between the input to and the output from the saturation as the error $e_s$ and feeds it through the gain $1/T_t$, see Figure 4.12. The error $e_s$ is zero when the motor is not saturated and when a saturation occurs the feedback loop tries to reduce $e_s$ back to zero again. The time constant $T_t$ is called the tracking-time constant.[WÅÅ09, p.52]

The anti-windup functionality can be used to introduce bumpless transfer from manual operation to automatic control. The integral action will track the manual input if the manual input is connected to the anti-windup according to Figure 4.13. The error $e_s$ will have a value only if the output from the PID differs from the manual input, thus the feedback loop makes the integral action follow. However, it will not make the manual input track the PID loop. This can be done by applying an integrator to the manual input and connect an equal tracking loop to that integrator. [ÅH06]

The tracking of automatic input was disregarded in this application since the switch from automatic to manual often occurs when the LinkQuad is about to crash or is to be brought down manually. The standard routine for this action is to make a main mode switch via the radio control (RC) on the LinkQuad from semi-automatic to manual mode. The manual mode is set up in LinkGS to only contain tested settings and take inputs from the RC controller while the semi-automatic mode allows other inputs combined with the manual inputs. The controllers of the manual mode are separated on the Control MCU (CMCU), whose source code is closed, and it is therefore not possible to implement the tracking in this manual input. The tracking of the controller in the manual input was disregarded in the available software as well since the majority of manual takeovers are made with a main mode switch.

One issue that the current controller can not handle fast enough is the loss of vertical thrust when the quadrotor tilts. When the quadrotor tilts to move, the previously vertical thrust becomes divided into two effective components, where one is vertical and one is horizontal, see Figure 4.14. It is therefore necessary to do a feedforward part of the tilting action that can compensate for this loss of thrust.

If the LinkQuad is seen as a plane with a normal $\vec{n}$, the tilt angle $\alpha$ can be found as the angle between the normal vector and the gravity acceleration $\vec{g}$, see Figure 4.15. In the body coordinate system, the normal is defined as $\vec{n} = [0\ 0\ 1]$ and $\vec{g} = [g_x\ g_y\ g_z]$. and by using the geometric interpretation of the scalar product $\vec{n} \cdot \vec{g}$,

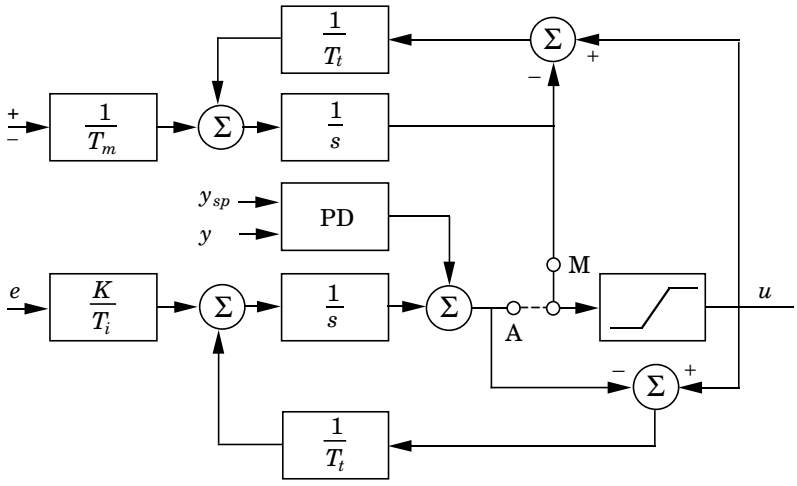



Figure 4.13: *Parallel PID implementation with bumpless transfer by manual tracking. As for anti-windup, the goal for bumpless transfer is to make the integral action track so the same feedback loop can be used with some modification. Courtesy of Karl Johan Åström and Tore Hägglund.*

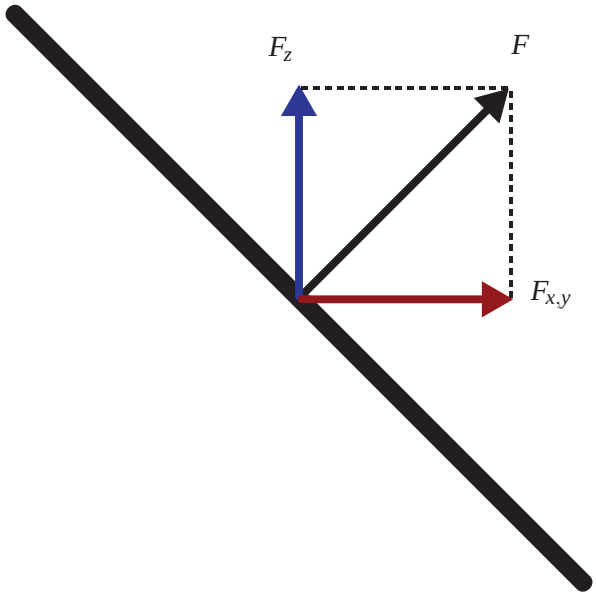



Figure 4.14: *The upward thrust of the quadrotor is split into two effective components, one vertical and one horizontal.*

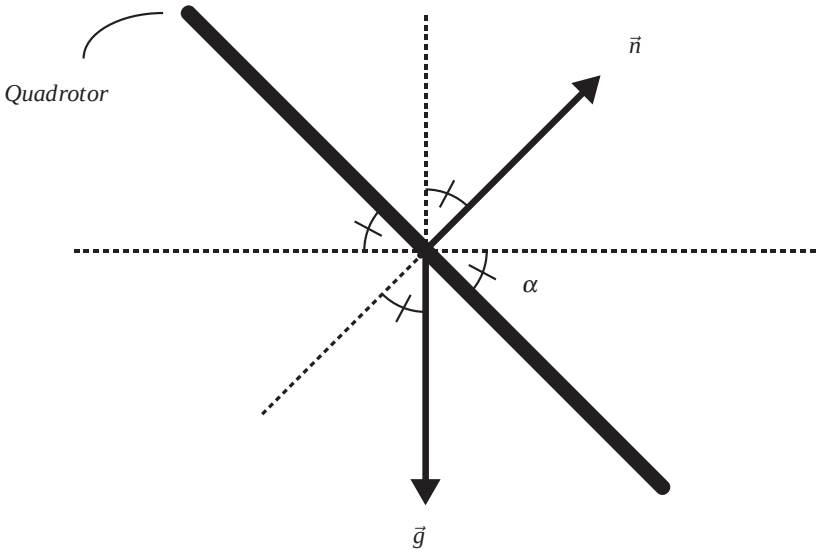



Figure 4.15: *The tilt angle $\alpha$ between the quadrotor and the horizontal plane is the same as the angle between $\vec{n}$ and $\vec{g}$ since $\vec{n}$ is perpendicular to the quadrotor.*

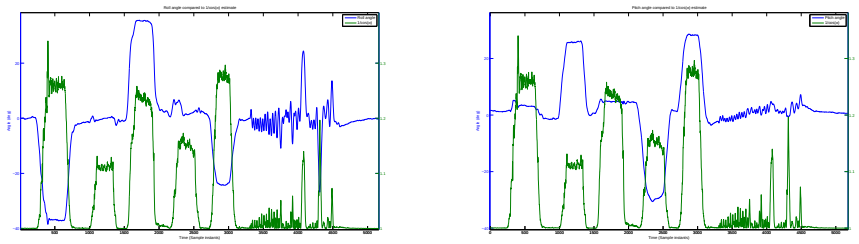
see (4.28), $\alpha$ can be approximated according to (4.29).

$$\vec{n} \cdot \vec{g} = \|\vec{n}\| \|\vec{g}\| \cos\alpha \tag{4.28}$$

$$\cos\alpha = \frac{\vec{n} \cdot \vec{g}}{\|\vec{n}\| \|\vec{g}\|} = \frac{g_z}{\|\vec{g}\|} \tag{4.29}$$

Instead of performing a time consuming lookup for the arccos function, the value $\cos\alpha$ can be used advantageously as a feedforward of the tilting. If the output from the PID controller is scaled with $1/\cos\alpha$, it will be unaffected if $\alpha = 0$ and increase if $\alpha$ increases. This implementation is also independent of advanced trigonometry to define $\alpha$ from the existing pitch and roll angles.

The key for using this approximation is to find the gravity acceleration vector and this can be done if the origin of the coordinate system is placed at the accelerometer. The output vector from the accelerometer can then be used as an approximation of $\vec{g}$ in (4.29) and its performance can be seen in Figure 4.16.



(a) Roll angle (blue) and $1/\cos(\alpha)$ (green) (b) Pitch angle (blue) and $1/\cos(\alpha)$ (green)

Figure 4.16: *Pitch and roll angles compared to the output from the approximation of* $1/\cos(\alpha)$. *The experiment consisted of three parts. First, the quadrotor was tilted* $30^\circ$ *in both directions along each axis* $X_B$ *and* $Y_B$. *Second, it was tilted* $30^\circ$ *in between the two axes to verify the behaviour in all directions. Finally, the quadrotor was shaken and tilted slightly in different directions to study how accelerations affected the approximation of* $1/\cos(\alpha)$.

The final controller can be seen in Figure 4.17. It is a parallel implementation of a PID controller with anti-windup tracking, manual tracking and a feedforward solution for the tilting. It is integrated into the existing control according to Figure 4.18.

***Discretization*** Since the PID controller was to be implemented on a computer, it had to be discretized. Each part's discretization will be presented and discussed separately.

The proportional part is static so it requires no approximation.

$$P(kh) = K(r(kh) - y(kh)) \tag{4.30}$$

where $kh$ is the time instant $t = kh$ when the computer samples the values and $h$ is the sample time.

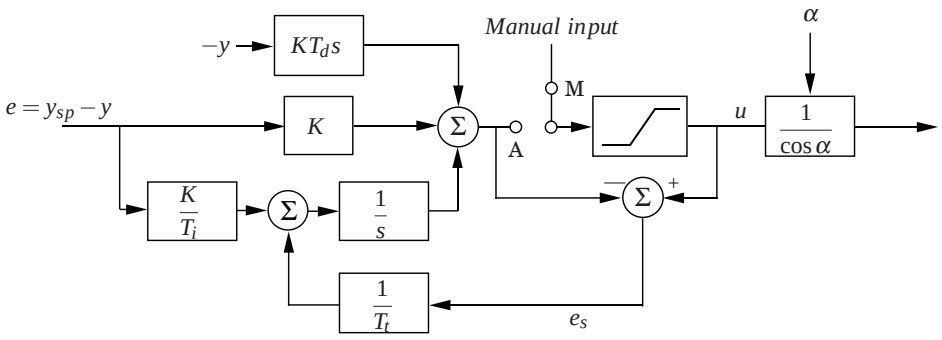



Figure 4.17: *The final controller: Parallel implementation of a PID controller with anti-windup tracking, manual tracking and a feedforward solution for the tilting.*

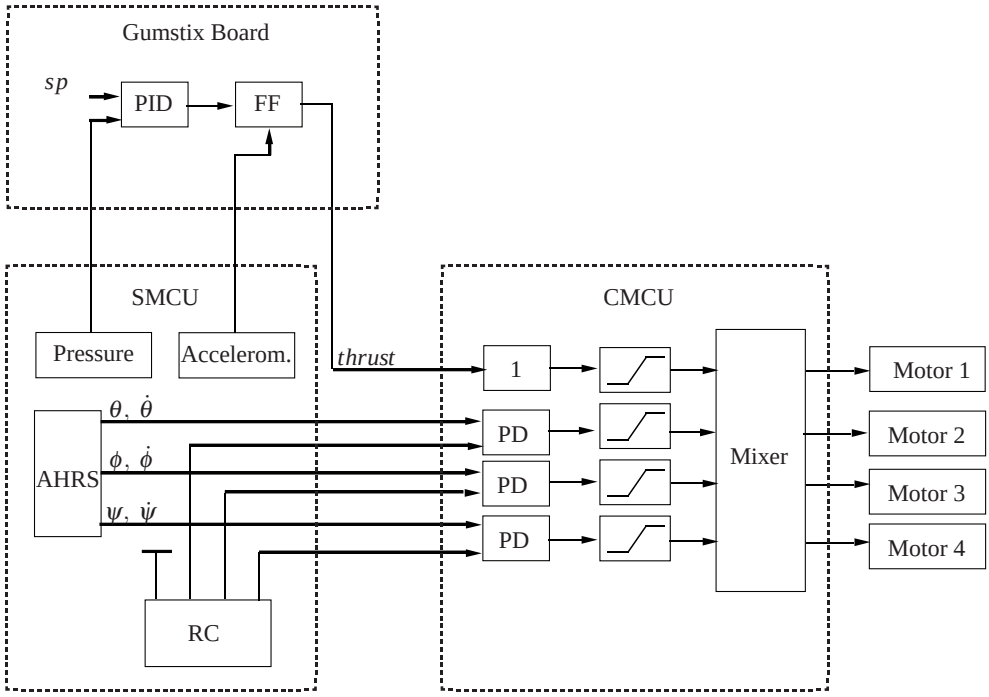



Figure 4.18: *The modified control: The setpoints for the attitude control and the estimated angles from AHRS are still sent from the SCMU to the CMCU. The thrust input from the RC receiver has been overridden by the altitude control loop from Figure 6.1. It receives its setpoint sp from the wireless network and the sensor values from the SMCU. The PID output and the feedforward gain is calculated on the Gumstix Board and forwarded to the old thrust controller at the CMCU. At the CMCU, the controllers' outputs are calculated, saturated, mixed into individual PWM outputs and sent to the motors.*

The integral action given by (4.31) is approximated with a forward approximation, resulting in (4.32). However, the tracking for anti-windup and bumpless transfer needs to be included into the approximation, see (4.33). The integral part depends only on present values to calculate the future value. It can therefore be updated after the control signal has been put to the process thereby reducing the computational delay.

$$I(t) = \frac{K}{T_i} \int^t e(s)\, ds \tag{4.31}$$

$$I(kh+h) = I(kh) + \frac{Kh}{T_i} e(kh) \tag{4.32}$$

$$I(kh+h) = I(kh) + \frac{Kh}{T_i} e(kh) + \frac{h}{T_t} e_s(kh) \tag{4.33}$$

The derivative action can not be discretized with a forward approximation since it might become unstable then. Therefore, it is instead approximated by backward

approximation since the result is always mapped to be stable.

$$D(kh) = \frac{T_d}{T_d + Nh} D(kh - h) - \frac{KT_d N}{T_d + Nh}(y(kh) - y(kh - h)) \tag{4.34}$$

[WÅÅ09]

The control signal becomes $v(kh) = P(kh) + I(kh) + D(kh)$ for the PID controller and when the model for the motors' saturation and the feedforward signal, which are both static, are added the final control signal becomes (4.35).

$$u(kh) = \frac{1}{\cos\alpha} \text{sat}(v(kh)) \tag{4.35}$$

***Tuning*** The major part of the tuning was done by *rule-based empirical tuning* on the model described in (4.13). The rules are:

- Increasing the proportional gain decreases stability.
- Error decays more rapidly if integration time is decreased.
- Decreasing integration time decreases stability.
- Increasing derivative time improves stability.

[ÅH06]

The methods to study the performance and stability has been simulating step responses and bumpless transfers in Simulink and plotting the Bode plots of the closed and open loop systems and the transfer function for disturbances. However, after two crashes with parameters designed for the simulated model, the entire tuning was focused on Bode plots and by studying the real performance of the quadrotor.

Besides rule-based empirical tuning, there are five other aspects to consider while tuning; the cut-off frequency of the open loop system, the cut-off frequency of the low pass filter, the noisy signal's effect on the derivative part, the sample time of the controller and the sample time of the pressure sensor. All these properties affect the stability of the closed loop system and how fast responses that are possible.

The pressure signal can be noisy, even after low-pass filtering, so the derivative gain must be chosen such that the noise is not amplified and corrupts the control signal. This can be done by choosing $T_d$ sufficiently small so the noise does not pass through. However, this can collide with the condition from (4.25), $K_m T_d > 1/T_i$, where a too small $T_d$ might introduce instability.[Häg09] This also matches the theory of rule-based empirical tuning.

The sample time $h$ of the controller can be chosen using two rules of thumb. The first rule of thumb

$$h\omega_c \approx 0.05 \text{ to } 0.14, \tag{4.36}$$

where $\omega_c$ is the crossover frequency (in radians per seconds) of the continous-time system, gives a Nyquist frequency is roughly 23 to 70 times higher than the crossover frequency. This implies a good approximation of the continous system to a discrete system. [WÅÅ09, p. 45] The crossover frequency for the closed loop system is $\omega_c \approx 7.45 \text{rads}^{-1}$, which implies $0.0067 < h < 0.0188$

The second rule of thumb ensures that the sampling period is so short that the phase lead is not affected and does not affect the derivative action too much. It is formulated as (4.37) and the final parameters of the PID controller, $T_d = 0.27$ and $N = 8$, implies $0.0068 < h < 0.0203$.

$$\frac{hN}{T_d} \approx 0.2 \text{ to } 0.6 \tag{4.37}$$

[Årz09]

Combining these two conditions, the sample time $h$ should be within 0.0068 s and 0.0188 s so the actual sample time of 0.01 s is properly chosen in the middle of the interval.

The cut-off frequency of the open loop system determines the speed of control and is dependent of the low-pass filter's cut-off frequency. The second order Butterworth filter has a phase shift of $-90^\circ$ at the cut-off frequency and it increases for higher frequencies, see Figure 4.19. The choice of the open loop system's cut-off frequency should be done so that the filter's characteristics, the phase shift, does not affect the open loop system's phase margin so that is unstable. To do this, the controller must be tuned such that a sufficient phase margin for stability is achieved and the system still has a fast response to inputs.

A theoretical PID controller has a maximum phase shift of $+60^\circ$ and since the derivative gain is limited, the actual controller has a maximum phase shift of $+50^\circ$, see Figure 4.20. As the phase shift has to be positioned so that it creates a positive phase margin for stability, the positioning of the cut-off frequency of the open loop system is limited by the low-pass filter's phase shift. The parameters where thereby chosen to give a phase margin $\phi_m = 15.1^\circ$ and a gain margin $A_m = 4.73$. According to rules of thumb[Häg09, p.54], the gain margin is valid but the phase margin is small. However, this is a design choice since increasing the phase margin would decrease the speed of the system.

The saturation limits were originally set to 0 and 1000 as these were the limits of the PWM inputs to the motors. However, after a flight were the controller saturated, it was observed that it was impossible for the inner loops to maintain the attitude. This is due to the fact that the inner loops control pitch and roll by increasing the thrust on one rotor and decreasing the trust on the opposite rotor on the same axis. The same behaviour would occur if the motors were saturated in the bottom, thus making the quadcopter drop and perhaps turn itself upside-down.

The saturation limits were therefore set to $u_{\text{low}} = 200$ and $u_{\text{upper}} = 900$ to avoid constraining the inner loops' stabilization of the attitude.

The final parameters of the controller can be found in Table 4.3 and an evaluation of the final altitude control can be found in Section 5.

**State Machine**

The system requires different behaviour in different situations, i.e. the motors should be inactive on the ground. A state machine was introduced to handle the different states of operation and the following states were identified: Ground, Lifting, Flying, Landing, Emergency Landing, Stopping and Stop, see Figure 4.21 for a sketch of the transitions and the states.

The original plan was to have different behaviours if a load was attached to the quadcopter or not so two different state machines were planned initially. The state

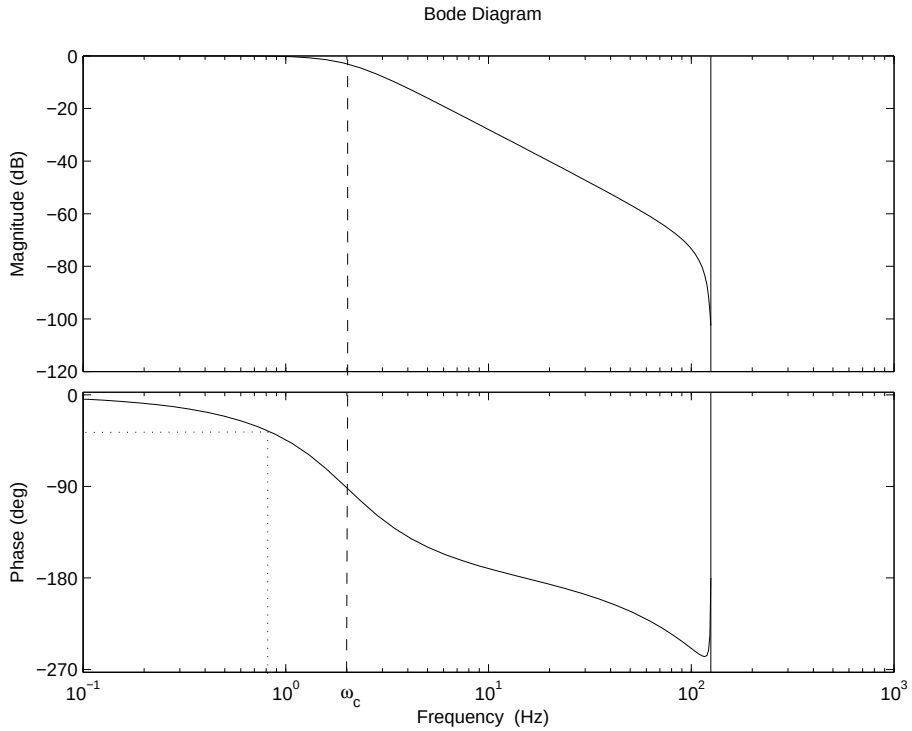



Figure 4.19: *Bode plot of the discrete second order Butterworth filter with cut-off frequency $\omega_c = 2$ Hz. The dashed line marks the filter's the cut-off frequency and the dotted line the open loop system's cut-off frequency.*

| Parameter | Value |
|---|---|
| $K$ | 20 |
| $T_i$ | 5 |
| $T_t$ | 10 |
| $T_d$ | 0.27 |
| $N$ | 10 |
| $h$ | 0.01 |
| $u_{\text{low}}$ | 200 |
| $u_{\text{upper}}$ | 900 |

Table 4.3: *The final parameters of the controller.*

machine for handling the load was, however, not implemented, see Control of a Slung Load. Instead the state machine for unloaded behaviour has three different implementations: One for manual flight with either Android Client or Computer Client, one for doing takeovers from manual flights with the RC controller and one with autonomous lift off and flying capabilities. All three versions rely on the user to control the quadcopter in the horizontal plane. Their desired behaviours are listed in Table 4.4

The two first versions were successfully implemented but the autonomous altitude control's Landing state was not implemented. This was due to the lack of faith in the

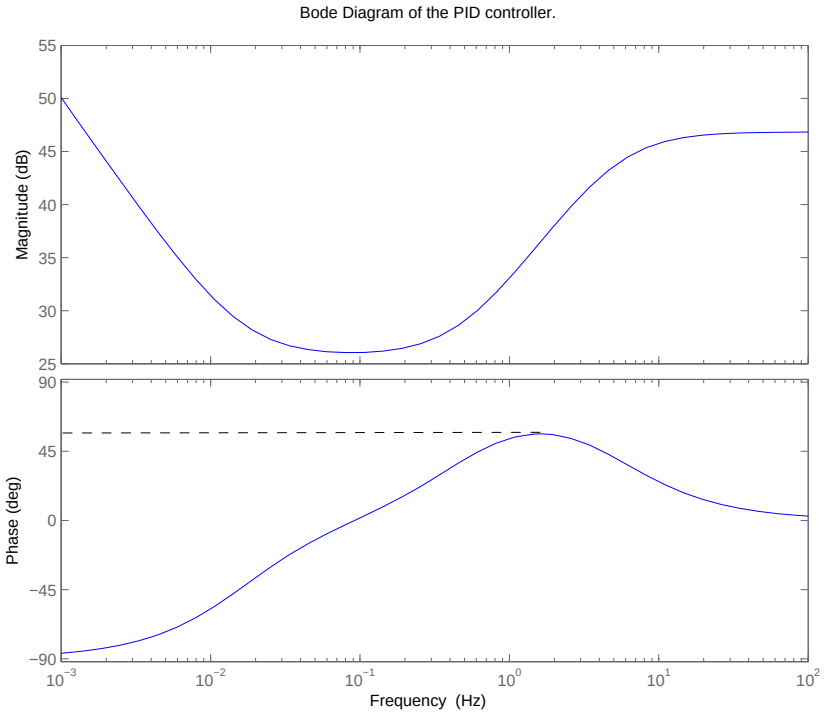



Figure 4.20: *Bode plot of the PID controller with* $K = 20$, $T_i = 10$, $T_d = 0.27$ *and* $N = 10$.

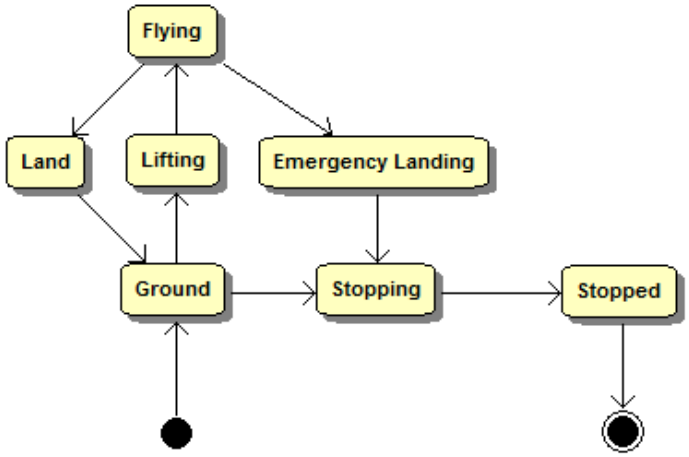



Figure 4.21: *The state machine for the control.*

pressure sensor's accuracy when the ground was to be determined. Even if the quadrotor was to land from a flat surface where a reference value for the ground had been taken on lift off, it could not be guaranteed that the pressure at the ground is the same at the time of landing. This is due to the continous natural variations of the atmospheric pressure, see Figure 4.22.

The first intuitive solution would be to set the thrust to just less than required to hover and slowly descend to the ground. This is sadly not possible due to ground

Table 4.4: Desired behaviour of each state in the different state machines.

| **State** | **Manual flight with clients** | **Altitude control without autonomous liftoff and landing** | **Altitude control with autonomous liftoff and landing** |
|---|---|---|---|
| Ground | The quadrotor should be on the ground with motors turned off. | The quadrotor should be able to fly with the RC controller and the controller should track the thrust input from the user. | The quadrotor should be on the ground with motors turned off. |
| Lifting | This state was not required so the state machine goes straight to Flying. | This state was not required so the state machine goes straight to Flying. During the mandatory loop through the lifting, the behaviour is the same as for ground. | The quadrotor should lift off to a set point of two meters above the ground. When it has stabilized around the set point, it should hand over the responsibility of setting the set point to the user by going to Flying. |
| Flying | The quadrotor should take the set points sent from the clients and forward them to the inner loops on the LinkBoard. | The quadrotor should take over the altitude control and it should take the set point from either of the clients. It should also be able to fly manually in the horizontal plane with set points from the client. | The quadrotor should take the set point to the altitude control from the user via Android Client or Computer Client and should be able to fly manually in the horizontal plane with set points from the client. |
| Landing | This state was not required so it was disabled to avoid crashes. | This state was not required so it was disabled to avoid crashes. | The quadrotor should land the quadrotor and go to Ground on a successful landing. |
| Emergency Landing | This state was not needed so it was disabled to avoid crashes. | This state was not required so it was disabled to avoid crashes. | This state is the same as Landing except it goes straight to Stopping after a successful landing. |
| Stopping | This state was not required so it was disabled to avoid crashes. | This state was not required so it was disabled to avoid crashes. | All motors should be turned off and all values zeroed out, thereby disabling the quadrotor. |
| Stop | This state was not required so it was disabled to avoid crashes. | This state was not required so it was disabled to avoid crashes. | Stopping has been successful and the software is shut down. |

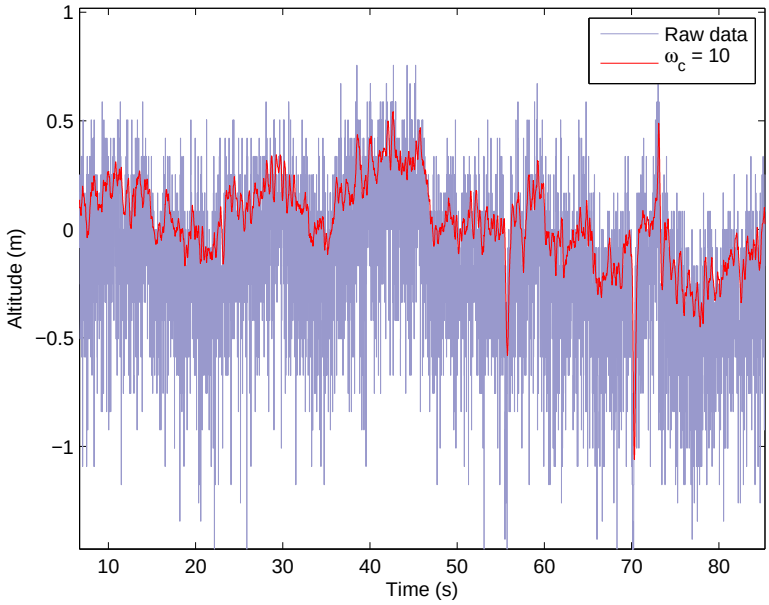



Figure 4.22: *Raw and low pass filtered data from the pressure sensor, converted into meters, when the quadrotor sits on the ground with motors off. The natural variations in the atmospheric pressure can have a magnitude up to 1 m.*

effect, turbulence and battery depletion causing the quadrotor to require a variable thrust to hover continously.

Another solution that was discussed was to set the setpoint at 1 m above the ground and after the quadrotor had stabilized around the setpoint, it would do a slow descent according to the first intuitive solution. This was an interesting solution that was implemented to some extent in Emergency Landing but was never tested due to bad weather conditions during the final week of the thesis.

The problem with the atmospheric pressure variations was not such an issue for the Lifting state since it could be implemented to do an aggressive step response to a secure height, e.g. 2 m. The problem of this state was to determine when to switch to flying and allow the user to affect the set point. It is not sufficient to just say that the switch should be made when the quadrotor is close to the set point. If the quadrotor overshoots the set point and a scared user gains access to the set point, he/she can pull down the set point to ground level to ”stop” the quadrotor resulting in a crash.

A second condition has to be added and a good property to study would be the velocity. If the quadrotor is close to the set point and has a low velocity, the transition to Flying can be made. All that is needed then is the derivative of the altitude and that has already been developed in the controller. Since the derivative action of the PID controller calculates the derivative of the altitude, it can be used in the second condition. As the PID controller is on parallel form, it is easy to access the derivative action and no modifications are required.

The control itself is the same throughout the states in the state machine and no parameter changes are made anywhere. However, the PID controller does support bumpless parameter changes and it would be interesting to study if other parameters would improve the performance at lift off and landing situations.

For further details about the software design of the state machine, see Section 2.3.

## 4.4 Control of the Slung Load

The original plan was that the altitude control was to be sufficiently good to make the control of the slung load on the quadrotor very similar to the one developed for the gantry crane. However, multiple factors, such as lead time for hardware and underestimated complexity of subproblems, contributed to delaying this task so much that it was not executed due to lack of time.

# 5. Experiments and Results

This chapter presents the experimental results of the experiments that were carried out on the LinkQuad.

Unfortunately, due to a malfunction of the gantry crane, data is not available. The rig could not be repaired during the course of the thesis.

The chapter begins with a presentation of the experiments which is followed by a review of the logged experiment.

## 5.1 Experiments

During the thesis, six experimental sessions were carried out on the integrated system. Each session is presented in Table 5.1, where a short summary is given together with the locale and the atmospheric pressure of the day. The two environments for flying were the green in front of the building, where the department of Automatic Control resides, and the ball room of the student union at LTH, see Figure A.5 and Figure A.6 in Appendix A.

Before the experiments begun, the LinkQuad exterior had the appearance as in Figure A.1 in Appendix A. After a crash in Experiment 2, the exterior and the chassis of the LinkQuad was broken in half and the repaired quadrotor can be seen in Figure A.2 and Figure A.3 in Appendix A.

Experiment 3 was the only experiment that was logged and will be reviewed in the next section.

## 5.2 Review

During Experiment 3, the following properties were studied: bumpless transfers between manual and automatic altitude control, the low-pass filter, positive and negative step responses, the feedforward action and how well the clients were integrated into the system. These aspects will now be analyzed in the given order.

**Bumpless Transfers**

The first occurence of bumpless transfer from manual to automatic control was under ideal conditions, see Figure 5.1a. The quadrotor had no velocity in any direction and was hovering at an altitude of 1.5 m. The result was a bumpless transfer.

During the second bumpless transfer from manual to automatic control, the quadrotor had a velocity along the $Z$ axis, see Figure 5.1b. The result was a small bump in altitude after the transfer, but it is rejected within ten seconds and never reaches a magnitude larger than 0.8 m.

**Low-pass Filter**

The low-pass filter was studied during a manual take-off and flight and it had already converged on the ground before the logging started. The filter's output was

compared to the raw data in Figure 5.2a and it suppresses the noise to a magnitude of 0.2 m or less without any phase delay.

The filter was then compared to the simulated ideal version of the same filter and both real and simulation data are consistent, see Figure 5.2b

**Step Responses**

The two positive step responses had settling time of two seconds, which exceeded the expectations of response time, see Figure 5.3a and Figure 5.3b. There was some stationary error but this is believed to originate from varying turbulence and since the slow integral action was not fast enough to suppress this, it remained. Both step responses have a small overshoot and do not oscillate too much and both this properties are advantageous as the quadrotor flies indoors.

The control signals in Figure 5.4a and 5.4b were hard to interpret since the thrust to hover varied over time, which is considered to be induced by turbulence. However, the control signal is not very aggressive in any changes as its full range is 0 - 1000 and it is kept within 475 and 540 at both steps.

The feedforward action might have been aiding the PID control in both step responses and it might be the reason to why the PID output was never changed to any great extent. Its effect was visible throughout the step response in Figure 5.4a and becomes visible at the step change in Figure 5.4b. As the feedforward action was designed to aid with fast increases of the thrust at tilting and not at reductions, a worse response time should occur at the negative step response.

The step change of -1 m can be seen in Figure 5.5a and the altitude had settled

| ID | Summary | Locale | Average Pressure |
|---|---|---|---|
| 1 | Altitude control was achieved with a bumpless transfer from a manual flight at an altitude of 5 m. It was filmed but not logged. | The green. | Unknown. |
| 2 | Altitude control was achieved with a bumpless transfer from a manual flight at an altitude of 2 m and a step change to 5 m was successful. However, the log was lost during a crash. | The green. | Unknown. |
| 3 | Altitude control was achieved twice with bumpless transfers from a manual flight at altitudes of 1.5 m and 2 m. Two step changes of 0.8 m and 1.5 m upwards and one step change of 1 m downwards were successful. Both clients were used to set the setpoint for the altitude control and send commands to the state machine. | The ball room | 100.9275 kPa |

Table 5.1: *The experiments that have been carried out on the integrated system throughout the thesis. The two locales for flying were the green in front of the building, where the department of Automatic Control resides, and the ball room of the student union at LTH*

within 8 seconds with a stationary error with a mean of 0.1 m. The proportional part of the controller can be seen in the edge at the step change at time 92.6 s in Figure 5.5b. The initial slow response and the overshoot was probably due to the integral action. This behaviour is desirable if the pressure sensor would react to any pressure spikes, e.g. from the slamming of doors.

In Figure 5.5b, two saturations and aggressive behaviour caused by the feedforward action can be observed. This will be further discussed in the next section.

### Feedforward Action

In retrospect, corrupt values from the approximation of $\frac{1}{\cos(\alpha)}$ were observed that had not affected the flight in any visible way to the observers, see Figure 5.6a and Figure 5.7a. However, it saturated the control signal to both its maximum and minimum values during a short period of time and if this period of time would be larger it could have severe effects on the process, see Figure 5.6b.

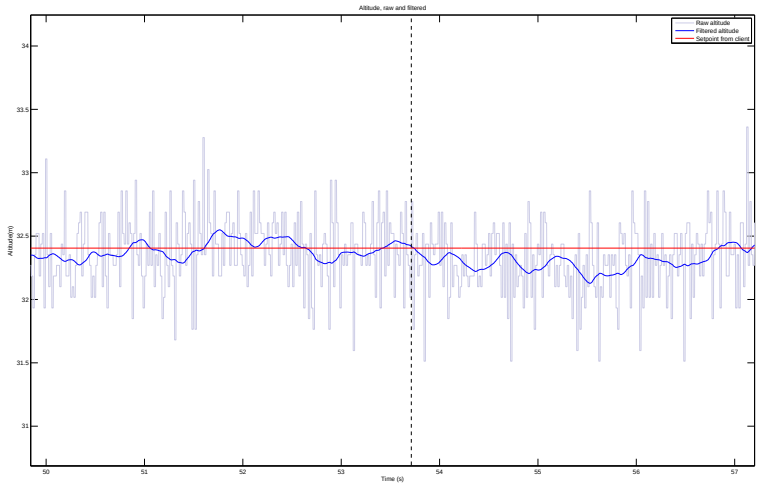
This bad behaviour originated from an unknown acceleration along the $Z_B$ axis, see Figure 5.7b, which could be a bad value from the sensor since the quadrotor had no sudden gain of altitude following the peak of acceleration.

### Clients

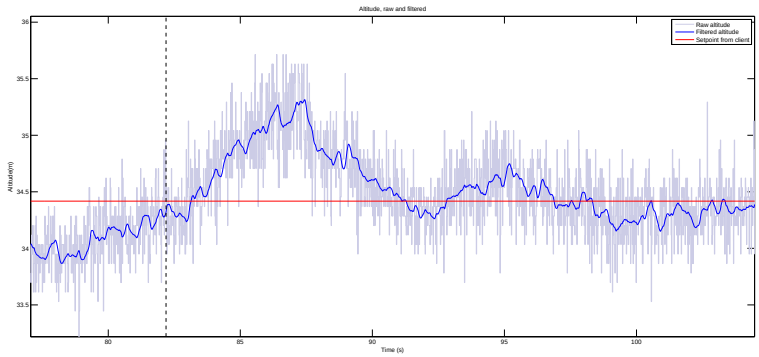
Both clients were successfully integrated and supplied the user with the same behaviour for similar tasks.

The Android Client was used to produce the bumpless transfer in Figure 5.1a and the positive step response in Figure 5.4a.

The Computer Client was used to produce the bumpless transfer in Figure 5.1b, the positive step response in Figure 5.4b and the negative step response in Figure 5.5b.

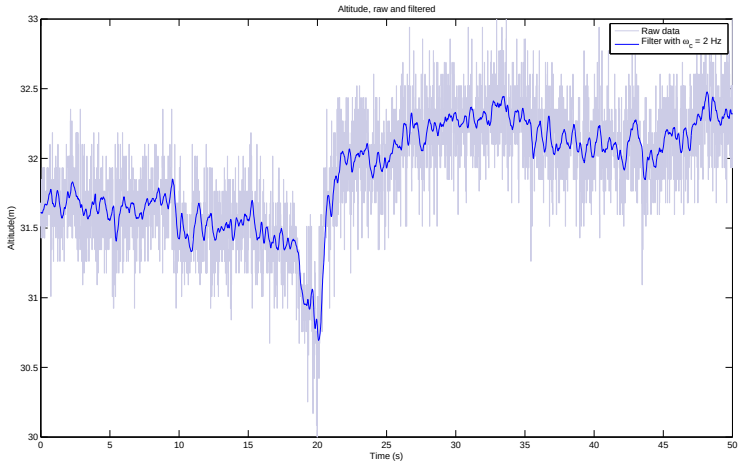



(a) The transfer from manual to automatic occurs at the dashed line at an altitude of 1.5 m. The quadrotor was in an almost perfect hover with no velocity in any direction.

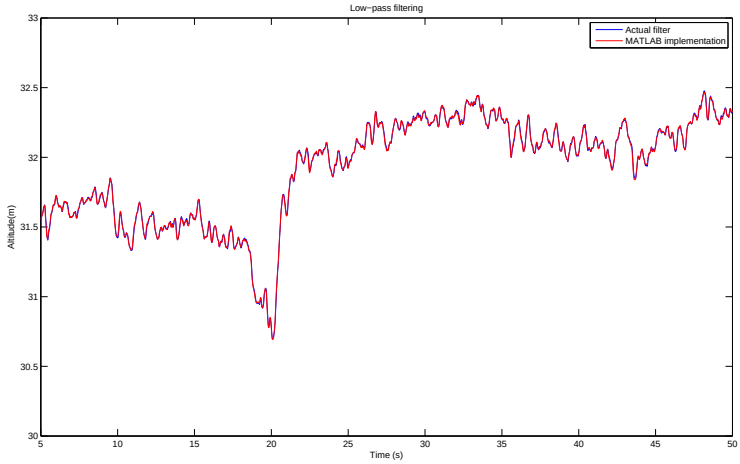



(b) The transfer from manual to automatic occurs at the dashed line at an altitude of 2 m. The quadrotor had a velocity directed upwards at the transfer, but the control cancelled out its effect within ten seconds and the bump did not exceed 0.8 m.

Figure 5.1: *The altitude at the bumpless transfers.*

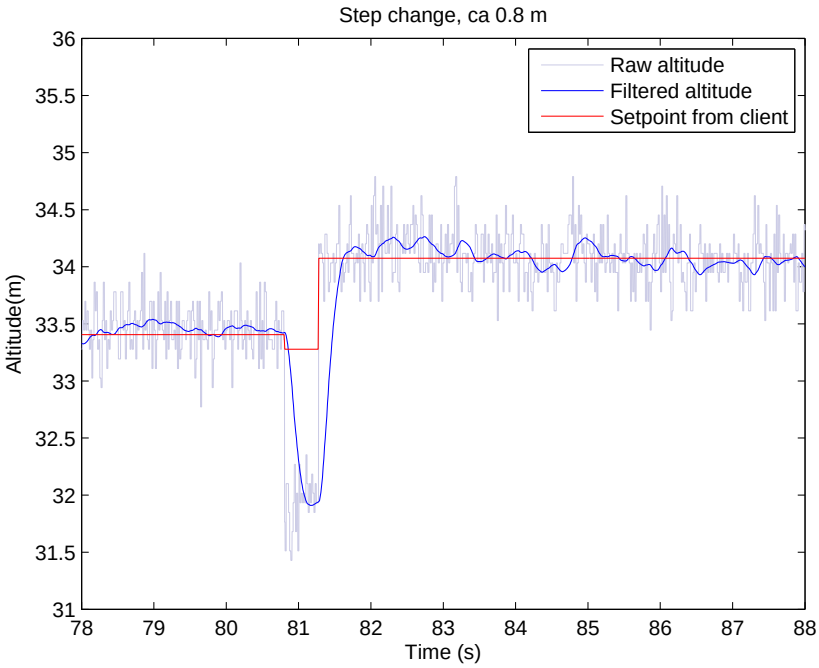



(a) The actual second order Butterworth low-pass filtering with cut-off frequency $\omega_c = 2$ Hz compared to the raw output. The raw output is grey and the low-pass filtered signal is blue.

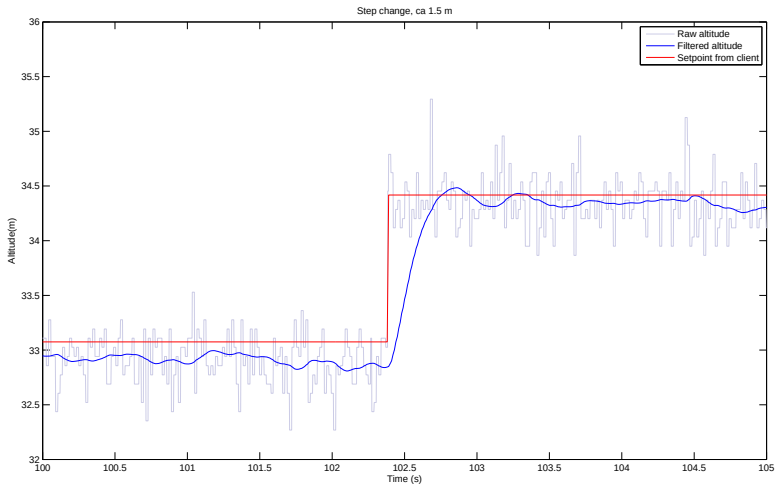



(b) The actual second order Butterworth low-pass filtering with cut-off frequency $\omega_c = 2$ Hz compared to an ideal implementation of the same filter in MATLAB. The actual low-pass filtering is blue and the MATLAB filtering is red.

Figure 5.2: *A study of the low-pass filter during a manual take-off and flight indoors. The altitude is defined from the pressure at sea level (1 atm = 101.325 kPa) and due to a high pressure on the day of the experiment, the altitude for the ground became 31.5 m above sea level, instead of the actual 80 m. The dip below 31.5 m around the time 20 s is due to an increase in pressure from the motors.*

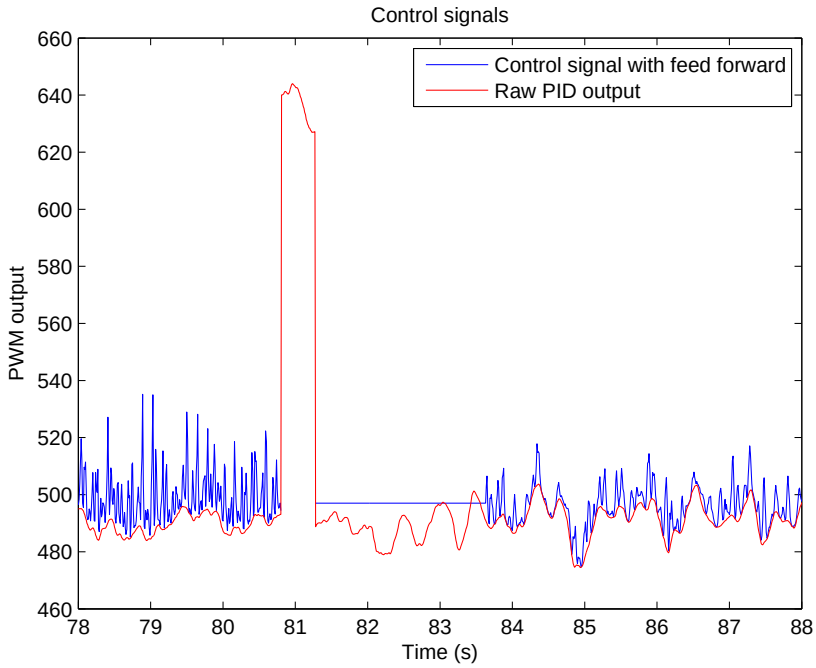



(a) The response in altitude to a step change of circa 0.8 m. The step change is roughly set since it is induced by a user of the Android Client.The data for the data in the time interval 80.85 s - 81.25 s is corrupt due to the built-in logger's tendency to backtrack and overwrite parts of the log. The same occured for the control input for this sequence. The setpoint is red, the raw altitude is grey and the filtered altitude is blue.

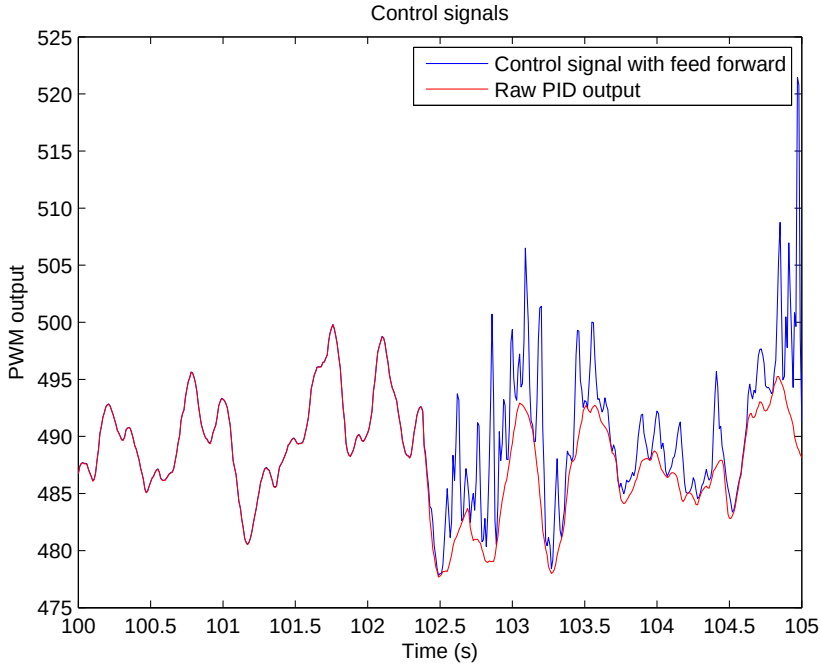



(b) The response in altitude to a step change of circa 1.5 m. The step change is roughly set since it is induced by a user of the Computer Client. The setpoint is red, the raw altitude is grey and the filtered altitude is blue.

Figure 5.3: *Two upwards step responses. The filtering of the altitude is done in retrospect with MATLAB.*

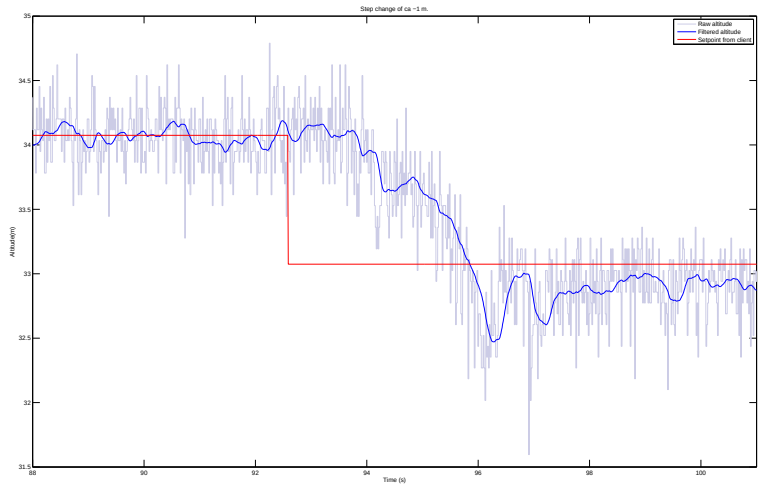



(a) The control signal to the step change of 0.8 m in Figure 5.3a. The effect of the feedforward gain is visible throughout the experiment since the quadrotor was oscillating with a very small angle. The data for the control with feedforward gain (blue) in the time interval 80.85 s - 83.60 s is corrupt due to the built-in logger's tendency to backtrack and overwrite parts of the log. The same occured for the raw PID output (red) in the time interval 80.85 s - 81.25 s.

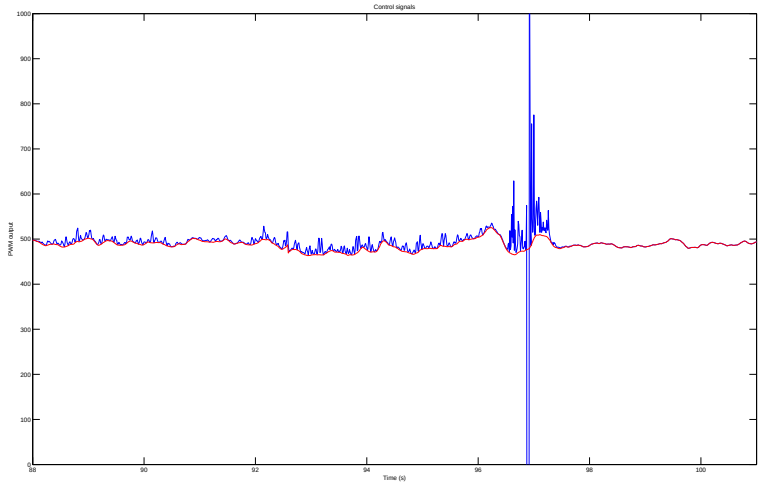



(b) The control signal to the step change of 1.5 m in Figure 5.3b. The quadrotor was level and maintaining its altitude without any feedforward action until the step change occured. When the quadrotor started to accelerate upwards, it also started oscillate with small angles and the feed-forward part compensates but does not dominate. The effect of aerodynamic disturbances, such as turbulence, can also be seen on the control signal here. The required thrust to hover and climb varies over time, e.g. the thrust to hover at time 101.1 s is the same as the thrust to climb at 102.6 s.

Figure 5.4: *The control signals to the step responses in Figure 5.3.*

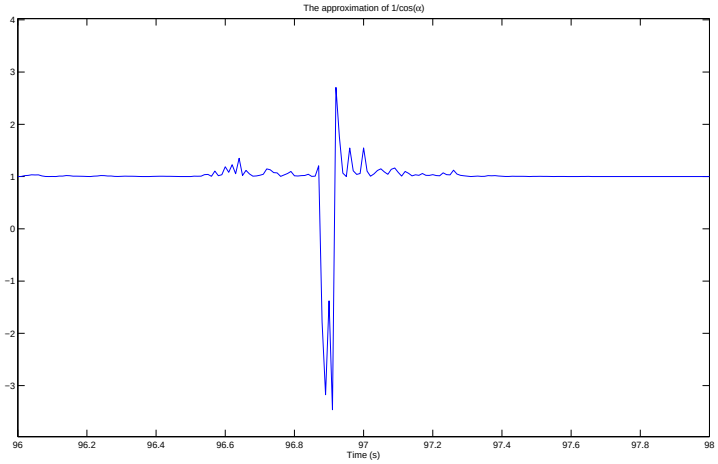



(a) The response in altitude to a step change of circa -1 m. The slow integral action shows clearly as it approaches the new setpoint. A small overshoot can be observed but is rejected within three seconds. The step change is roughly set since it is induced by a user of the Computer Client. The setpoint is red, the raw altitude is grey and the filtered altitude is blue.

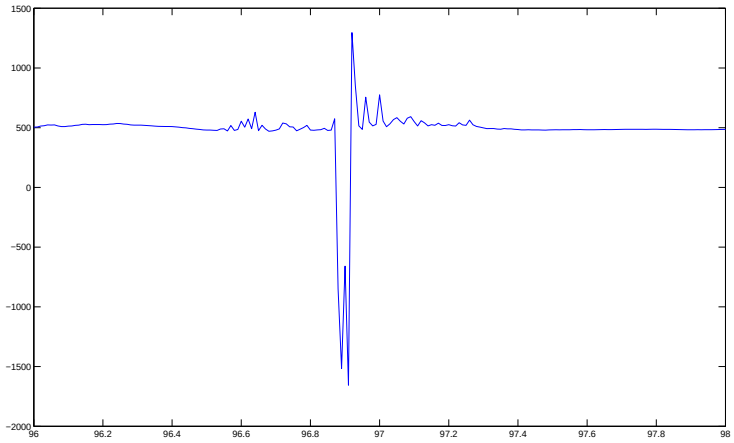



(b) The control signal to the step change of -1 m. The quadrotor was level and maintaining its altitude with only a minor feedforward action until the step change occured. When the quadrotor overshot the set point and came close a table, the pilot started to tilt the quadrotor to move it away from the table. The feedforward action behaves properly in the time interval 96.5 s - 96.85 s, but after 96.85 s it saturates the control signal in both limits due to a unknown value from the accelerometer. See Figure 5.6a for details on this subject.

Figure 5.5: *A downwards step change and the corresponding control signal. The filtering of the altitude is done in retrospect with MATLAB.*

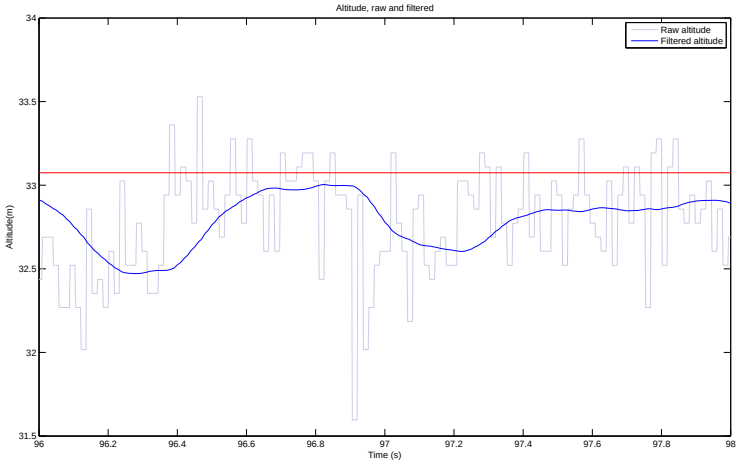



(a) The approximation of $\frac{1}{\cos(\alpha)}$.

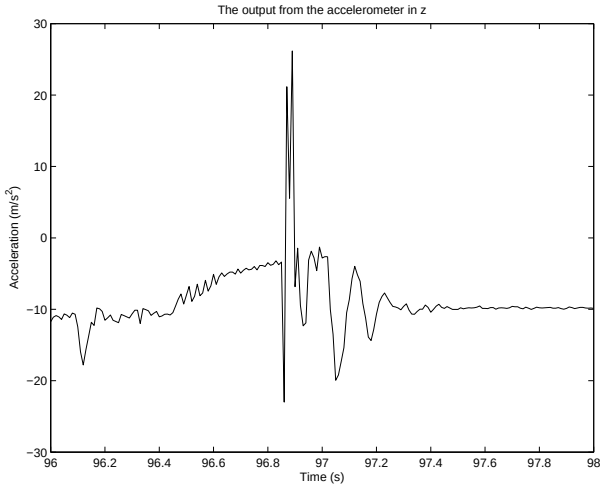



(b) The unsaturated control signal. The saturation limits are 0 and 1000 and are here removed to show how the bad behaviour of the approximation dominates the control signal.

Figure 5.6: *Corrupt values from the approximation of* $\frac{1}{\cos(\alpha)}$ *was observed in retrospect. It saturated the control signal to both its maximum and minimum values. It originates from an unknown acceleration along the* $Z_B$ *axis, which could be a bad value from the sensor since the quadrotor has no sudden gain of altitude following the peak of acceleration. The corrupt value affected the control signal during a short period of time and could thereby never cause a great impact on the process. The plots continue in Figure 5.7.*




(a) The raw and filtered altitude.




(b) The acceleration along the $Z_B$ axis.

Figure 5.7: *Plots continued from Figure 5.6.*

# 6. Conclusions

The conclusions of the thesis are presented here along with suggestions of possible future work.

## 6.1 Gantry Crane

The gantry crane experiment was successful and a simple model of a slung load was derived and tested.

The slung load was originally thought of as a spherical pendulum but that model could not be used since it introduced a singularity in the downright position. The model was approximated instead by using the fact that the two angle sensors of the crane were parallel to one axis of motion of the cart each. The slung load could therefore be approximated as two traversed simple pendulums that were defined along these axes. The final model, as a LTI system

$$\begin{pmatrix} \dot{p}_x \\ \ddot{p}_x \\ \dot{p}_y \\ \ddot{p}_y \\ \dot{\alpha} \\ \ddot{\alpha} \\ \dot{\beta} \\ \ddot{\beta} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{g}{l} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{g}{l} & 0 \end{pmatrix} \begin{pmatrix} p_x \\ \dot{p}_x \\ p_y \\ \dot{p}_y \\ \alpha \\ \dot{\alpha} \\ \beta \\ \dot{\beta} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \\ \frac{1}{l} & 0 \\ 0 & 0 \\ 0 & \frac{1}{l} \end{pmatrix} \begin{pmatrix} u_x \\ u_y \end{pmatrix} \quad (6.1)$$

where $p_x$ and $p_y$ describe the position of the cart, $\dot{p}_x$ and $\dot{p}_y$ are the velocities of the cart, $\alpha$ and $\beta$ are the angles of the angle sensors, $l$ is the length of the load arm and $g$ is the acceleration due to gravity.

This model is mass independent, which is attractive for the later application on the quadrotor since it can then be loaded with a variety of loads and the model would not have to be altered.

A problem that can occur when using this model on the quadrotor is that the attachment point of the load will tilt when the quadrotor tilts. This still needs to be solved by introducing the quadrotor's equations of dynamics in the model, see Section 4.3.

## 6.2 Pressure Sensor

The low-pass filter is a second order Butterworth filter with a cut-off frequency at 2 Hz. This filter dampens the noise and random spikes while it does not introduce too much phase delay so that the pressure sensor can be used reliably as an input to the PID controller.

## 6.3 Angle sensor

The fork and attachment point were finalized during the last week of the thesis and there was no time to test its functionality on the quadrotor.

## 6.4 Altitude Control

The altitude control consists of a PID controller with a feedforward gain for the tilt angle. It acts upon a low-pass filtered signal from a pressure sensor as a measurement of the altitude and receives its setpoints from the Computer Client or the Android Client via a wireless network connection.

The controller is a parallel implementation of a PID controller with limited derivative gain, anti-windup, bumpless transfer from manual to automatic and a feedforward gain for the tilt angle, see Figure 6.1 for the continous version. This was discretized with a sample time of 0.01 s and parameter values $K = 20,\ T_i = 10,\ T_d = 0.27$ and $N = 10$. The anti-windup and bumpless transfer is implemented by having the integral action track either the saturation or the manual input by a feedback loop with gain $T_t = 10$.

The feedforward action's purpose is to aid the PID controller with a fast counteraction of the loss of thrust when the quadrotor tilts and divides its pure vertical thrust into one vertical and one horizontal effective component. This is done by applying a gain of $1/\cos\alpha$, where $\alpha$ is the tilt angle, to the control signal of the PID controller. This results in a gain of 1 when the angle is 0 and an increased gain as the angle grows. However, large gains during short time intervals were observed during an experiment and were found to originate from unknown acceleration spikes along the $Z_B$ axis. These acceleration spikes could not be traced in the measurements of the altitude and are assumed to be measurement errors in the accelerometer. Since this is not a required part of the system and this behaviour could cause a crash if these unknown accelerations occur over a longer period of time, it should not be used until the hardware can be guaranteed to be flawless or that the time interval of these spikes is observed to be constrained to a short period of time. An alternative solution would be to introduce a low-pass filter to dampen the undesired spikes, but this might impair the performance of the feedforward action.

The controller exists in a state machine to allow different modes of operation, such as lifting, landing and flying, but only the flying mode was properly tested due to poor weather conditions hindered further test sessions.

The entire solution of the modified control is shown in Figure 6.2.

## 6.5 Android Client

The Android Client is the client application for the Android smartphone. The Android Client uses its inertial measurement unit (IMU) to set setpoints to the attitude control of the LinkQuad and it uses a custom implemented virtual joystick to set setpoints for the LinkQuad altitude and yaw angle. The interface and behavior was designed to mimic the radio control (RC) controller. This was done by using a natural mapping of the controls so that if the user had used the RC controller before then the controls would be familiar. The mapping of the controls was also natural

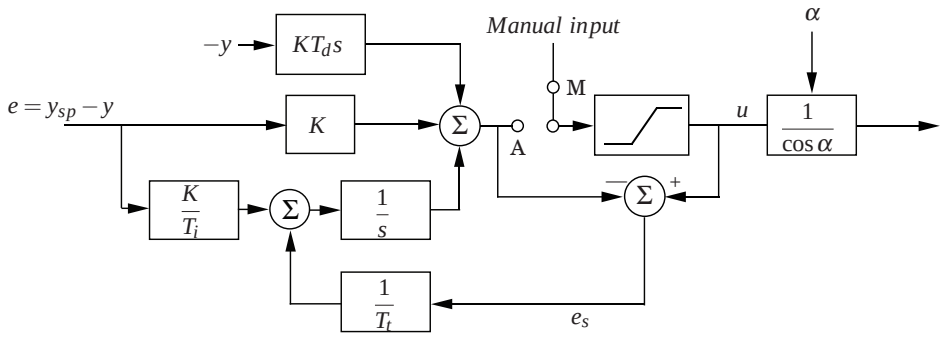



Figure 6.1: *The final controller as a continous system: Parallel implementation of a PID controller with anti-windup tracking, manual tracking and a feedforward solution for the tilting.*

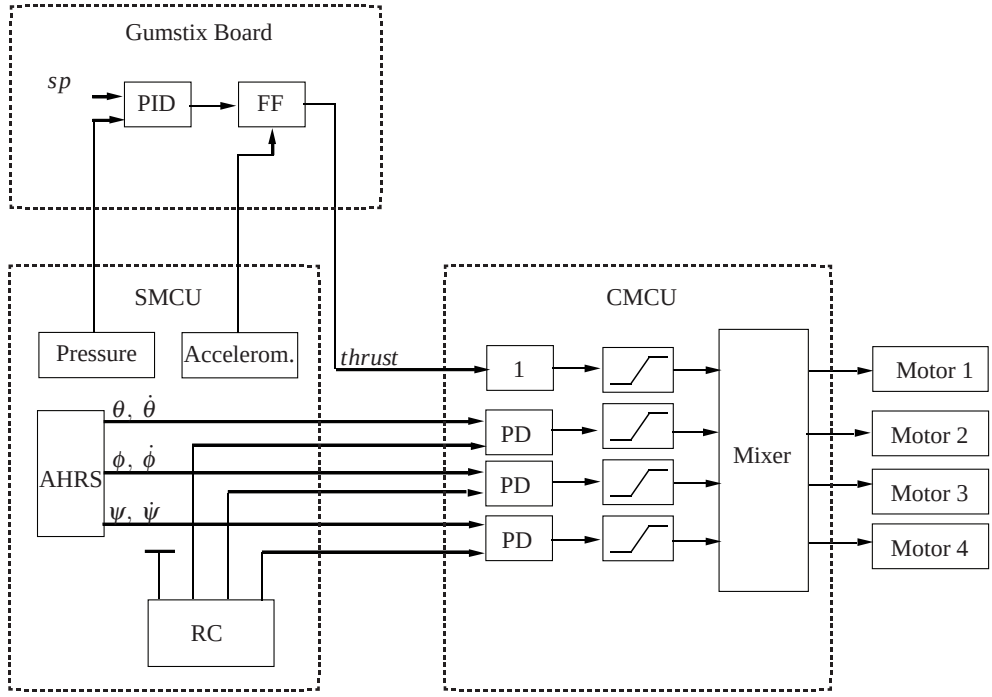



Figure 6.2: *The modified control: The setpoints for the attitude control and the estimated angles from AHRS are still sent from the SCMU to the CMCU. The thrust input from the RC receiver has been overridden by the altitude control loop from Figure 6.1. It receives its setpoint sp from the wireless network and the sensor values from the SMCU. The PID output and the feedforward gain is calculated on the Gumstix Board and forwarded to the old thrust controller at the CMCU. At the CMCU, the controllers' outputs are calculated, saturated, mixed into individual PWM outputs and sent to the motors.*

mapped towards the process in the sense of if the user tilted the smartphone forward then the LinkQuad would also tilt forward. The Android Client mainly uses the IMU and the virtual joystick to steer the LinkQuad.

During the evaluation of the Android Client, it came forth that the virtual joystick

was hard to use. This can be best understood if it is compared to an analog joystick. An analog joystick provides the user with a physical feedback of the position of the joystick which gives a feeling of the steering. The virtual joystick however is implemented in a touch screen that can not provide this physical feedback. Therefore the user instead wants to look on the control to make sure that it provides the right value. This makes it hard to steer the LinkQuad at the same time.

The joystick could not be used simultaneously as the IMU was used, which resulted in that the pilot could not counteract the loss of vertical thrust when he or she sets the setpoints of the attitude for the LinkQuad. This is due to the lack of a well implemented multitouch on the Android smartphone.

These two reasons, that the virtual joystick was hard to use and that multitouch was not available, resulted in that the Android Client should not be used with manual thrust control. The Android Client should instead be used with altitude control which implies that the quadrotor does not require the simultaneous inputs from the IMU and the joystick.

The mappings of the controls are listed in Table 6.1.

| **Input** | **Orientation** | **Set point** |
|---|---|---|
| Green button + tilt | North-South | Pitch. |
| Green button + tilt | East-West | Roll. |
| Joystick | North-South | Add/subtract altitude. |
| Joystick | East-West | Yaw. |
| Trim Right | - | Yaw trim right. |
| Trim Left | - | Yaw trim left. |
| Land or Lift | - | Land/Lift. |
| Terminate | - | Terminate. |

Table 6.1: *Mapping of controls on the Android Client*

## 6.6 Computer Client

The initial purpose of the Computer Client was for debugging and testing. First, it was used to verify the functionality of the network communication, but during the development of the Android Client a new feature was added. This feature was the human interface device (HID) PlayStation 3®gamepad (PS3 gamepad) that could be used instead of the keyboard, which was used during the testing of the network communication. The PS3 gamepad can supply the software with multiple simultaneous inputs with a higher resolution than a smartphone, thus enabling the pilot to accurately control several aspects of the quadrotor at the same time. Because of this the Computer Client was successfully used to do the first test flight with manual thrust control indoors. The Computer Client however lacks a proper graphical interface since the Computer Client was originally designed to be used for debugging and testing. Which leaves much to improve for the user handiness.

The mapping of the controls are listed in Table 6.2.

| Stick/Switch | Orientation | Setpoint |
|---|---|---|
| Left stick | North-South | Add/subtract thrust. |
| Left stick | East-West | Yaw. |
| Right stick | North-South | Pitch. |
| Right stick | East-West | Roll. |
| Cross | - | Land/Lift. |
| Circle | - | Emergency land. |
| Top left front button (L1) | - | Yaw trim left. |
| Top right front button (R1) | - | Yaw trim right. |

Table 6.2: *The mapping of controls on the PS3 gamepad.*

## 6.7 Server

The Server where designed to allow communication to the LinkQuad through a wireless connection, to enabling steering of the LinkQuad. This was done by creating a network protocol that the clients use to communicate with the Server. The Server then controls the LinkQuad by sending data through a serial connection to the Control MCU (CMCU). The serial connection together with some configuration of the inner control loops enables the Server to send control signals to the attitude and thrust control of the LinkQuad.

The Server consists of the following parts:

- Serial communication.
- Network communication.
- Control loop in a state machine.

The serial and network communication was placed in a thread each and separated from the control loop to reduce the computational delay of the control loop. The low-pass filter was also put in the thread of serial communication to be filtered at a higher sample frequency than the control loop.

## 6.8 Future Work

There are many parts that can be improved or added to this project.

**Network Communication**

In the present version, a single connection exists between the client and the Server. The stability of the communication could be improved by extending to two connections. One connection should then be a transmission control protocol (TCP) connection for command messages, e.g. terminate, and one connection should be a user datagram protocol (UDP) connection for direction messages. This way, the system would benefit from the speed of UDP and the stability of TCP.

**Sensors**

The accuracy of the estimation of altitude can be improved significantly if sensor fusion with a complementary filter or a Kalman filter can be used where the pressure

sensor's value is used together with the accelerometer. This could reduce the effect from the natural variations in atmospheric pressure and increase the dampening of spikes from doors and other disturbances. For example, a Kalman filter with a model of the process, which takes the pressure and accelerations as inputs, could be used. The pressure should then be used as the major input and the accelerometer should be used determine whether to disregard spikes in the pressure signal or not.

### Altitude Control

The different modes of the state machine needs to be tested further to the extent that it can be relied upon to work both indoors and outdoors.

The altitude control consisting of a PID controller could also be extended to an adaptive solution since the characteristics of the process varies with several factors, e.g. wind, turbulence and atmospheric pressure.

The computing power of a Gumstix computer-on-module board is more than enough to run the current software so it could be interesting to introduce a full Kalman filter and investigate if more accurate values and estimates of the position and attitude of the quadrotor can be achieved than the original estimation.

### Control of a Slung Load on a Quadrotor

This problem was not finished within the time of the thesis work, but the remaining steps are clearly defined as follows:

- Integrate the derived model of a slung load with the dynamics of a quadrotor.
- Verify that the angle sensors with the fork solution can be used on a quadrotor.
- Introduce control of the slung load using movement in the horizontal plane as an actuator with either linear quadratic regulator (LQR) control or two PID controllers.
- Implement a modified version of the state machine to account for the slung load at lift off and landing.

A solution for the ideal case with control for absolute positioning can be seen in Figure 6.3.

### Android

Introducing a better implementation of the yaw and altitude steering would increase the application's usability. There exists functionality to interpret the yaw of the smartphone, but it is very inaccurate in its original state. Some smartphones have a magnetometer or a gyroscope and these could be fused with the accelerometer to a more accurate measurement of yaw of the smartphone.

The implementation of multitouch is also an area that could be reinvestigated if newer versions of Android introduce a proper multitouch functionality, which is accurate and stable.

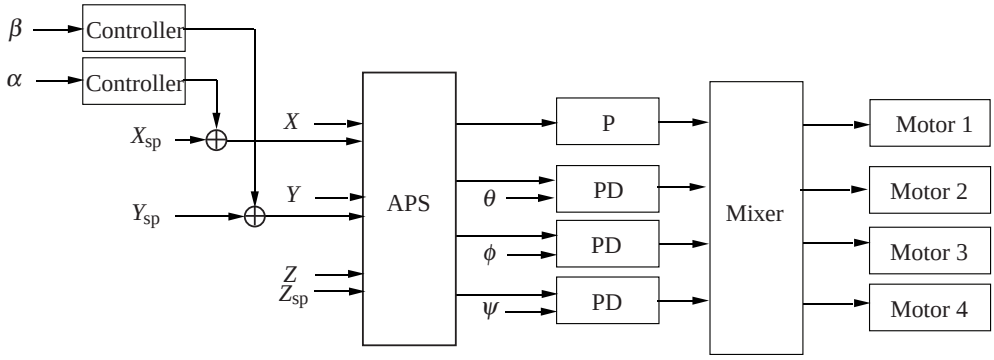



Figure 6.3: *This is a suggestion of how the slung load control could be solved in the ideal case with absolute positioning system (APS). The cascaded solution of absolute positioning is patched with the slung load controllers' output to be added to the setpoints of the X and Y control. This allows the slung load controller to position the quadrotor to reduce the angles of the load, $\alpha$ and $\beta$.*

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# A. Photos

Figure A.1: *The LinkQuad in its original state with a PS3 gamepad.*

Figure A.2: *Top view of the repaired LinkQuad after a crash from 5 m above the ground.*

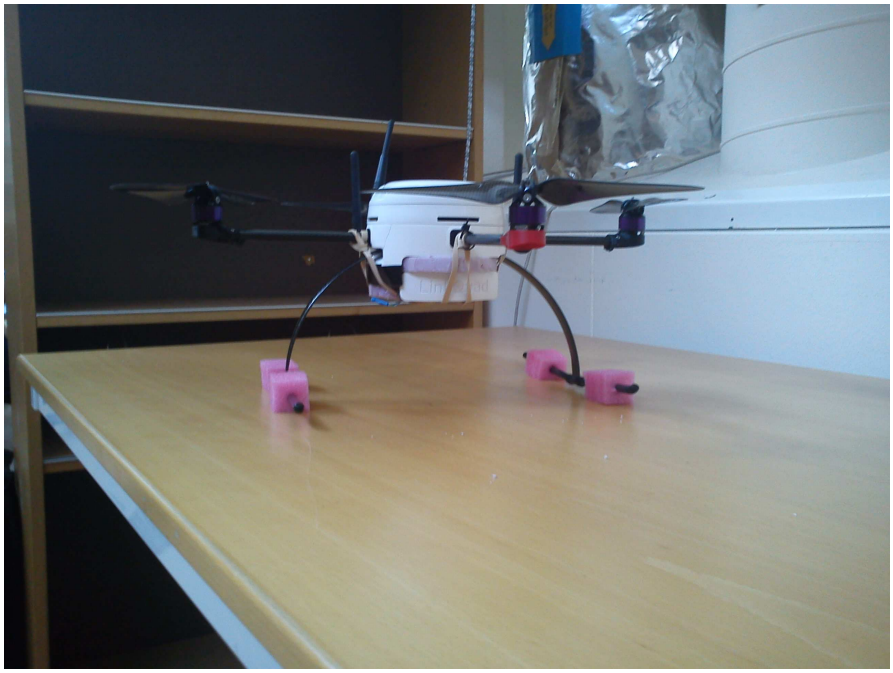

Figure A.3: *Side view of the repaired LinkQuad after a crash from 5 m above the ground.*

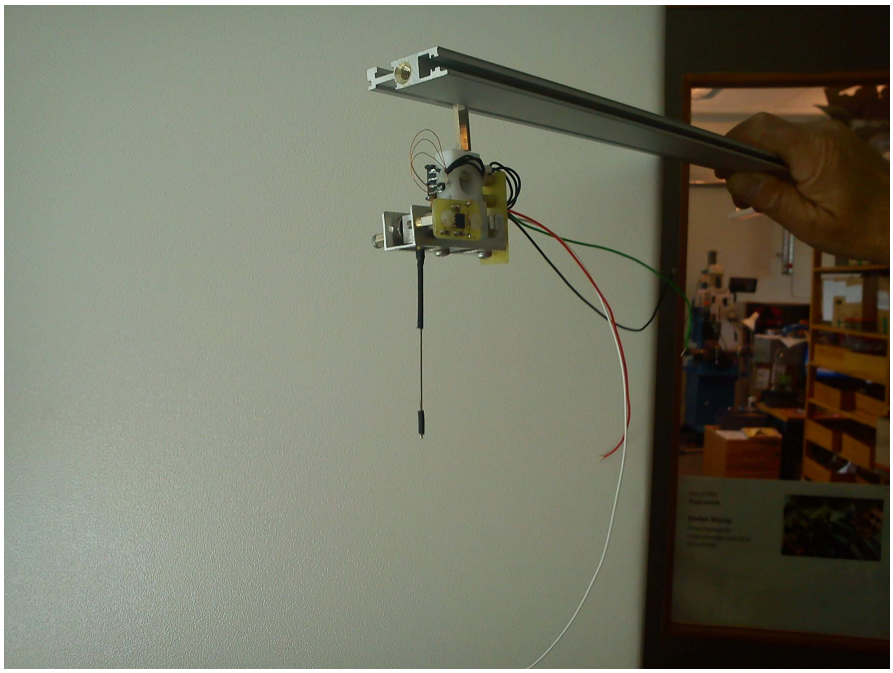

Figure A.4: *The final version of the fork sensor for measuring the angle of the load.*

Figure A.5: *The green in front of the building of the department of Automatic Control at LTH.*

Figure A.6: *The ball room of the student union at LTH.*

# B. Manuals

## B.1 Android Client

The Android Client was created for the purpose to be able to control the LinkQuad by manual steering with the tilt functionality of an smartphone. This was implemented by using java with Android SDK with the target version 2.2 of Android.

### Connecting the Android Client to a network

Connections to the Server can be made in several ways. One is that we connect the Server and the Android Client to an existing network and use that network to communicate to each others. A little more difficult way is that if we want to connect to the Server directly through a ad hoc network network. An android smartphone today (version 2.2 of android) can not connect to ad hoc network network by default. To accomplish this we need to have a rooted android smartphone and change the smartphone behavior. We solved this by using a rebuild on wpa_supplicant that we configure to accept ad hoc network connections by the guide partly made by [bla10].

### Using the Android Client

In our implementation we are always using the Android smartphone in landscape mode. The first thing we will see when we start the application is a menu containing the links connection, steering and exit as can be seen in Figure B.1.

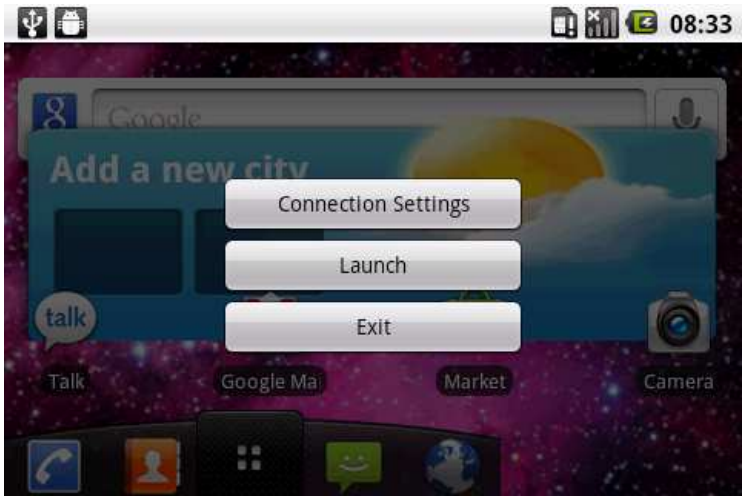


Figure B.1: *Menu Activity*

In the connection activity, Figure B.2, we will be able to change the ip-address of the device to connect to and also see our own address. This address is not set if you not are connected to any network. We will not direct connect to the device when pressing OK, it will connect when we want to start steering the LinkQuad.

When we have set the address we can go to the link steering in the menu. This will bring up a view containing 5 buttons, a text field and a joystick as can be seen in

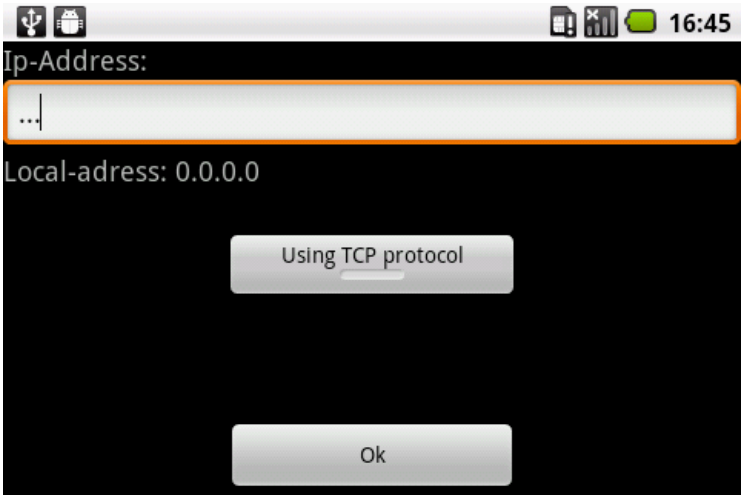


Figure B.2: *Connection Activity*

Figure B.3. In the status field messages such as if we successfully connected to the device will be printed to give us a good feedback over what is happening in the system. The button Terminate should only be used when we want to do a emergency shutdown of the engines. The Land/Lift button should be used to make the LinkQuad to land or lift from the ground. The joystick is used to change the altitude and turn the LinkQuad. To drive the LinkQuad you need to press down the green button and hold it pressed. Then the smartphone will register the pitch and roll of the smartphone and translate it to forward velocity and left strafe velocity.

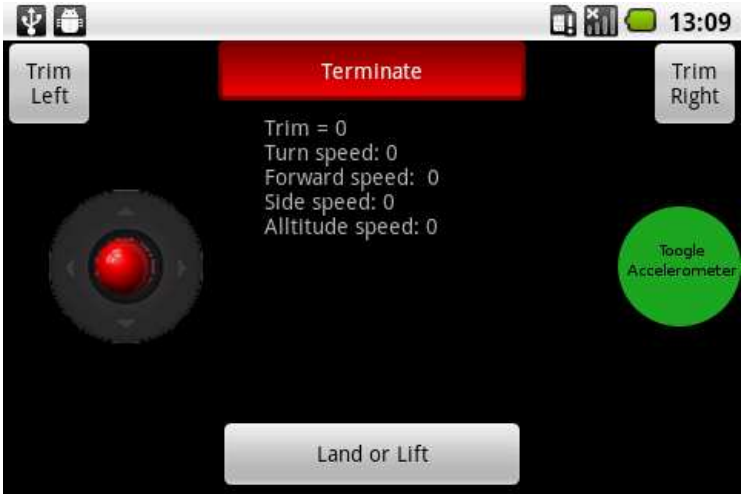


Figure B.3: *Steering Activity*

As last note of using the Android Client is that if you somehow exit the steering view of the application the Android Client sends a close message to the LinkQuad so be sure that the LinkQuad has landed safely before closing the application.

## B.2 Configuration File

This manual will give you a complete introduction to the configuration file. The settings are listed below with an explanatory text, typical values and a default value. If a setting is missing in the file, the default value will be used. Some settings are listed with a default value *mandatory* and these settings are required for the application to start. If they are missing, the application will terminate and print a read error from the configuration file.

**General settings**

***welcome-message***
Welcome message that is printed on start up of the system.
Altering this property is a good way to find out whether you are using the proper configuration file.

**Values:** Arbitrary.
**Default:** Mandatory.

***protocol***
Type of protocol that should be used for connecting to the other part.

**Values:** tcp or udp
**Default:** Mandatory.

***port***
Port of the network communication, <ip-address>:<port>.

**Values:** 49152-65535
**Default:** 50000

**Client-specific settings**

***ip***
IP-addresss to the Server.

**Values:** The IP-address of the Server in IPv4 format.
**Default:** 192.168.0.1

***send-frequency***
This is the frequency of how often the Computer Client will read the connected human interface device (HID) and send the input to the Server. [Unit: Hz]

**Values:** 10 - 50
**Default:** 20

***yaw-trim***
You often need to do minor adjustments to the setpoint of the yaw control to get the yaw rotation at an equilibrium. It is called trimming and this property is the initial trim on start up.

**Values:** Rig dependent. It can be both positive and negative.
**Default:** 0

***listen2PS3***
Choice of HID can be either a PlayStation 3®gamepad (PS3 gamepad) or a keyboard.
If this property is set to true, Computer Client will use a PS3 gamepad.
If this property is set to false, it will use a keyboard.

**Values:** true or false
**Default:** Mandatory.

***PS3-sensitivity***
The sensitivity of the axises on the PS3 gamepad can be adjusted to the user's preference. A higher value results in more dampening and a lower value results in a more sensitive control.
**Values:** 300-600
**Default:** 328

***PS3-deadzone***
Axes on a PS3 gamepad have a range of −32768 to 32767, which implies that even a sneeze can give a reading. Therefore, a deadzone is needed to remove a lot of glitching.
**Values:** 800-1500
**Default:** 1000

**Server-specific settings**

***serial-CMCU***
Path to the serial port to the Control MCU (CMCU).
**Values:** /dev/ttySX, where X is either 0, 1 or 2.
**Default:** /dev/ttyS2

***serial-SMCU***
Path to the serial port to the Sensor MCU (SMCU).
**Values:** /dev/ttySX, where X is either 0, 1 or 2.
**Default:** /dev/ttyS2

***load_attached***
You should enable this if a slung load is attached to the LinkQuad and if it should be controlled.
**Values:** true or false
**Default:** Mandatory.

There is two types of loggers, FileLogger and Printer, for two different uses. The names state the functionality well as FileLogger logs to a file and Printer prints to the screen. To use Printer as a logger, you type "printer" (case-sensitive) as a name of the log. All other strings are interpreted as the name of the file Filelogger will write to.

***main-and-network-log***
The initiation part of the program shares a logger with the network communication. This is due to they share the same thread as well.
**Values:** Arbitrary.
**Default:** printer

***control-loop-log***
This is the log of the control loop.
**Values:** Arbitrary.
**Default:** cll

***serial-com-log***
This is the log of the serial communication.
**Values:** Arbitrary.
**Default:** scl

## B.3 Ad Hoc Network Configuration on a Gumstix Board

The configuration of the ad hoc network may occasionally be lost so this manual will help you to reconfigure the setup into a working state again. (Perhaps you just want to change the name of the network and this guide will show that as well.)

First things first, write `iwconfig` to display the current configuration of the wireless devices. It should look something like this:

```
root@overo:~# iwconfig
lo        no wireless extensions.

wlan0     IEEE 802.11b/g  ESSID:"LU-LinkQuad_0_1"
          Mode:Ad-Hoc  Frequency:2.412 GHz  Cell: 02:2F:AF:A1:3E:9F
          Bit Rate:11 Mb/s   Tx-Power=13 dBm
          Retry short limit:8   RTS thr=2347 B   Fragment thr=2346 B
          Encryption key:off
          Power Management:off
          Link Quality=0/100  Signal level=-94 dBm  Noise level=-94 dBm
          Rx invalid nwid:0  Rx invalid crypt:0  Rx invalid frag:0
          Tx excessive retries:80  Invalid misc:18625   Missed beacon:0
```

Some details may vary, i.e. `ESSID` and `Cell`, which are independent details depending on your current settings. The `Cell` is the card's MAC address and it will be needed later so please note it down for future reference. If it does not look anything like that, do not worry! That is why you are reading this. However, if you see any wlan listings, please note down the MAC addresses for them as well. It might be one of those you want to use.

The settings for the wireless network interfaces are specified in the file `/etc/network/interfaces` and the naming of this interfaces are made on start up from the file `/etc/udev/rules.d/70-persistent-net.rules`. Most problems originate from differences in naming between these files and almost all settings are set in them as well, so the manual will focus on these files.

#### Existing network interfaces without ad hoc configuration

The Gumstix have two network interfaces, usually numbered wlan0 and wlan1, so if you have some other interface, i.e. wlan3, it is probably one of these, but it was auto defined in `70-persistent-net.rules`. The interface is auto defined when its MAC address is not found in the file. This can happen if you edit this file and enter a non existing MAC address as wlan0 or wlan1. You can solve this in two simple steps.

`70-persistent-net.rules` looks like this:

```
root@overo:/etc/udev/rules.d# cat 70-persistent-net.rules
```

```
# This file was automatically generated by the /lib/udev/write_net_rules
# program, run by the persistent-net-generator.rules rules file.
#
# You can modify it, as long as you keep each rule on a single
# line, and change only the value of the NAME= key.

# net device ()
SUBSYSTEM=="net", ACTION=="add", DRIVERS=="?*", (auto rowbreak)
ATTR{address}=="00:19:88:32:86:FE",          (auto rowbreak)
ATTR{dev_id}=="0x0", ATTR{type}=="1", KERNEL=="wlan*", NAME="wlan0"

# net device ()
SUBSYSTEM=="net", ACTION=="add", DRIVERS=="?*", (auto rowbreak)
ATTR{address}=="00:19:88:31:fa:88",          (auto rowbreak)
ATTR{dev_id}=="0x0", ATTR{type}=="1", KERNEL=="wlan*", NAME="wlan1"

# net device ()
SUBSYSTEM=="net", ACTION=="add", DRIVERS=="?*", (auto rowbreak)
ATTR{address}=="00:15:c9:28:d0:18",          (auto rowbreak)
ATTR{dev_id}=="0x0", ATTR{type}=="1", KERNEL=="eth*", NAME="eth0"

# net device ()
SUBSYSTEM=="net", ACTION=="add", DRIVERS=="?*", (auto rowbreak)
ATTR{address}=="00:19:88:20:fa:b6",       (auto rowbreak)
ATTR{dev_id}=="0x0", ATTR{type}=="1", KERNEL=="wlan*", NAME="wlan2"
```

In this example file, the wlan0 interface is missing in `iwconfig` output and it lists instead wlan1 and wlan2, which are neither any ad hoc networks. Assuming that the `/etc/network/interfaces`-file is properly configured for an ad hoc network, we will only need to replace the MAC address of wlan0 with the MAC address of wlan2 and do a proper reboot. (Do not forget to remove the entry of wlan2.)

```
root@overo:/etc/udev/rules.d# cat 70-persistent-net.rules
# This file was automatically generated by the /lib/udev/write_net_rules
# program, run by the persistent-net-generator.rules rules file.
#
# You can modify it, as long as you keep each rule on a single
# line, and change only the value of the NAME= key.

# net device ()
SUBSYSTEM=="net", ACTION=="add", DRIVERS=="?*", (auto rowbreak)
ATTR{address}=="00:19:88:3e:86:d8",  (auto rowbreak)
ATTR{dev_id}=="0x0", ATTR{type}=="1", KERNEL=="wlan*", NAME="wlan0"

# net device ()
SUBSYSTEM=="net", ACTION=="add", DRIVERS=="?*", (auto rowbreak)
ATTR{address}=="00:19:88:20:fa:b6",  (auto rowbreak)
ATTR{dev_id}=="0x0", ATTR{type}=="1", KERNEL=="wlan*", NAME="wlan1"

# net device ()
SUBSYSTEM=="net", ACTION=="add", DRIVERS=="?*", (auto rowbreak)
ATTR{address}=="00:15:c9:28:d0:18",  (auto rowbreak)
ATTR{dev_id}=="0x0", ATTR{type}=="1", KERNEL=="eth*", NAME="eth0"
```

If your chosen interface is not configured into an ad hoc network yet, please continue to the next section before you reboot. Verify that the interfaces are configured correctly with `iwconfig` after the reboot is done.

**Configuration of an ad hoc network**

The setup of an ad hoc network is pretty straight forward once you have gotten the naming of the interfaces working. All the settings are set in `/etc/network/interfaces` and it is here you can change the name of the network as well. In this example wlan0 will be configured to an ad hoc network and to use wlan1, just switch wlan0 with wlan1.

First, let us take a look on the file.

```
root@overo:~# cat /etc/network/interfaces
# /etc/network/interfaces -- configuration file for ifup(8), ifdown(8)

# The loopback interface
#
auto lo
iface lo inet loopback

#
# Wireless interfaces
#
#### WORKING AD HOC ##################
auto wlan0
iface wlan0 inet static
     wireless-mode ad-hoc
     wireless-essid YourOwnAdhocNetwork
     address 192.168.0.1
     netmask 255.255.255.0
######################################

#
# Wired interfaces
#
auto eth0
iface eth0 inet static
  address 192.168.1.202
  netmask 255.255.255.0
  network 192.168.1.0
  gateway 192.168.1.201
```

The file may contain a lot of garbage as well but what we want to focus on is the wireless interfaces. An entry always start with `auto <interfacename>` and after that follows it settings. If your interface has any existing settings, you can remove them now and replace with the following settings:

```
auto wlan0
iface wlan0 inet static
     wireless-mode ad-hoc
     wireless-essid YourOwnAdhocNetwork
```

```
address 192.168.0.1
netmask 255.255.255.0
```

The line starting with `iface wlan0` is mandatory and we just enter it ”as is”. The next line is where we set the wireless mode to ad hoc, instead of the mode where it is monitored by a DHCP. Then we come to `wireless-essid`, which is the ESSID of the network. When your laptop or smartphone lists the available networks, it will display this as the name of the network. The `address` is the IP-address of this interface and the one you will connect to via SSH or using Computer Client or Android Client. Finally, `netmask` is set to 255.255.255.0 to allow an address pool of 255 addresses and this should be entered on the unit you use to connect with too. (Note: Remember to set a static IP, e.g. 192.168.0.5, on the connecting unit.)

When the configuration is done, do a proper reboot.

**The Infamous Proper Reboot**

A proper reboot is done by doing either a `halt` followed by a power reset or a `shutdown` with the correct flags for rebooting, see below.

When doing a halt you will lose your SSH connection and can therefore not see when you should power down. A good praxis is to wait at least 30 seconds to let the system store the settings properly.

```
root@overo:~# halt

Broadcast message from root (pts/0) (Mon Apr 11 12:19:36 2011):

The system is going down for system halt NOW!
root@overo:~# Connection to 192.168.0.1 closed by remote host.
Connection to 192.168.0.1 closed.
```

A reboot by using `shutdown` is done by the following command line

```
root@overo:~# shutdown -r now <Message to all other processes>
```

where `-r` is the flag for reboot, `now` is the time for the reboot to occur and these are followed by an optional message to other processes running.

When doing a reboot with `shutdown`, you will also lose the SSH connection but you will not need to power down the LinkBoard. Just reconnect with the SSH connection when possible. This is how it looks in action.

```
root@overo:~# shutdown -r now Reboot incoming

Broadcast message from root (pts/0) (Mon Apr 11 12:41:37 2011):

Reboot incoming
The system is going down for reboot NOW!
root@overo:~# Connection to 192.168.0.1 closed by remote host.
Connection to 192.168.0.1 closed.
```

According to the Gumstix user community, the reboot of Gumstix might hang itself due to an issue with an audio driver. If you experience this, you might try to switch snd-soc-gumstix to snd-pxa2xx-ac97. Note: This is an untested procedure and you do it on your own risk. We take no responsibility for any effects or damage to hardware, performance or software by this procedure.

## B.4 BOM - Bill of Materials

These section contains the bill of materials (BOMs) of the applications that have been developed during the Master Thesis. The BOMs describes how to configure the environment to continue development on the applications. Makefiles for Unix and Mac OS development exists for all the applications.

**Android Client**

- Windows or Unix.
- Android smartphone with Android version 2.2 or newer and with a inertial measurement unit.
- Mini USB between the smartphone and the developer computer.
- Android SDK.
- Development platform with Android SDK capabilities (Netbeans or Eclipse).

**Computer Client**

- Windows, Unix or Mac OS X.
- Boost C++ libs and include files version 1.44, only for Windows.
- Posix C++ libs and include files, only for Mac OS X and Unix.
- HIDs as PS3 gamepad and keyboard.
- Wifi supporting connections to ad hoc network.
- Development platform (gcc, g++, Eclipse, Visual Studio...).

**Server**

- Fully equipped LinkQuad.
- Gumstix with Unix installation (Gumstix per default uses Ångström).
- Posix C++ libs and include files.
- HID such an computer to ssh to the gumstix.
- Gumstix development board.
- Development platform (gcc, g++, Eclipse, Visual Studio...).