Development of validation tool for antenna positioners on vehicles in motion

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Abstract

Artificial satellites play a vital role throughout the world today. They provide a broad range of services ranging from navigation to communication and reconnaissance. As antenna technology is evolving and ground based antennas are getting smaller and smaller, the demand for on-the-move solutions is growing. These antennas can be used whilst mounted on for example, a moving vehicle, where the mechanical performance of the antenna must be sufficient for the current conditions. During this project, a computer based tool that can help engineers when iterating and optimizing a two-axis gimbal type antenna design was created. The tool uses simulated and recorded data from road vehicles and boats to calculate the required torque on the two axes necessary to sustain communication with a geostationary satellite. When completed, the tool was easy to use and configure whilst not requiring much computational power.
**Sammanfattning**

Acknowledgement

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List of abbreviations

GPS - Global Positioning System
LEO - Low Earth Orbit
MEO - Medium Earth Orbit
GEO - Geostationary Earth Orbit
OTP - On The Pause
OTM - On The Move
DOF - Degrees Of Freedom
SISO - Single Input Single Output
MIMO - Multiple Input Multiple Output
IMU - Inertial Measurement Unit
CoG - Center of Gravity
CFD - Computational Fluid Dynamics
Chapter 1

Introduction

Satellite communications has come a long way since the first ever man made satellite, the Sputnik 1, was launched in 1957. Today, almost ten thousand satellites orbit the Earth, providing a means of communication for various stations, offering a wide range of services on earth [1]. Some of the most common uses for satellite communications include Global Positioning System (GPS), television, radio, internet and weather forecasting.

By the year 2021, around 400 million people in the world had no mobile internet access. In 26 countries, with over half of them in Sub-Saharan Africa, this is true for more than 20 percent of the population. This statistic is to a large extent due to a lack of infrastructure in low-income countries, often in areas with geographical barriers such as mountains or water [2]. It is fair to say that satellites have enabled ways of communication that were not possible before with regards to speed, reliability and coverage [3]. It is also likely that satellite technology will continue to play an important role in expanding coverage in remote areas [2]. Remote locations and areas with limited ground based infrastructure can relatively easy communicate and navigate with a relatively small investment using satellite technology, as long as the infrastructure in space exists. Furthermore, satellite communication and navigation can often play a critical role in the success of rescue missions or work in remote areas, such as rail-way maintenance or forest fire fighting [3]. Clearly then, satellite technology comes with many social and economical benefits throughout the world. This, together with some ethical and environmental dilemmas are presented throughout this chapter.
1.1 Types of orbit

As can be seen in Figure 1.1, there are three main categories of orbits in which satellites can operate:

- Low Earth Orbit (LEO)
- Medium Earth Orbit (MEO)
- Geostationary Earth Orbit (GEO)

![Figure 1.1: Satellite orbits and most common altitudes [4].](image)

Satellites that orbit the earth at an altitude of less than two thousand kilometers above earth’s surface operate in what is called low earth orbit or LEO. The low altitude allows for a short transmission delay but does come with drawbacks such as noticeable doppler shifts and short visible time due to the speed relative to ground. Furthermore, deterioration of the orbit due to aerodynamic drag caused by the air density at lower altitudes shortens the orbital life of the satellite [5].

Medium earth orbit, or MEO refers to satellites with an altitude of between two- and thirty-six-thousand kilometers above the surface of the earth. Satellites operating in MEO suffers from higher transmission delay compared to operation in LEO. It does however not suffer to the same extent from the mentioned drawbacks of operation in LEO [6].

The third category of orbit is located at close to thirty-six-thousand kilometers above equator and is referred to as geostationary earth orbit or GEO. Satellites that operate in GEO does not move in relation to the surface of the earth. This makes communication suitable for a wide range of antenna systems as there is no need to adjust the antenna once communication is established. The high altitude of GEO satellites does mean that transmission delays are even higher...
than that of MEO satellites. GEO satellites can see the surface of the earth at up to eighty-one degrees away from its position, however, a more practical limit for communicating with the satellite from earth is usually seventy-five degrees. As GEO satellites must be located above the equator, this means that they can never cover a small circumference around the earth's poles. It does however only take four satellites in total to cover the entirety of this area [6].

1.2 Satellites in orbit

The quantity of satellites in orbit around the earth has doubled in the last couple of years. The main reason for this is the launches of Starlink satellites into LEO by SpaceX. As of February 2023, they account for about fifty percent of all active artificial satellites [7]. Every satellite reflects light to earth, and the lower the orbit, the stronger the reflection. The increasing number of artificial satellites poses concerns among astronomers as it could disturb ground based observations and spectroscopic measurements. The issue of space debris is also a growing problem as the number of objects in orbit around earth increase. Debris can damage satellites, rendering the unit useless and creating even more debris [8].

1.3 GEO satellites and OTM design

In terms of both cosmic debris and light pollution in space, GEO satellites are a more efficient solution. The great coverage of a single satellite and its distance to earth gives this type of satellite advantages with regards to these factors compared to satellites operating in MEO or LEO.

Ovzon AB is a Swedish producer of satellite communications equipment. Their product range includes ground based terminals, both for On-The-Pause (OTP) and On-The-Move (OTM) operation. An example of such a device is the T6 OTP terminal, which can be seen in Figure 1.2.

![Figure 1.2: Ovzon T6 OTP](9)
Ovzon has also designed proprietary hardware that will be used in their own satellites to remove the need to relay the communication via a base station on earth. The Ovzon antennas communicate on the ku-band, with GEO satellites. In order to take full advantage of GEO satellites and Ovzon’s proprietary satellite hardware, the terminals on the ground must be of equal quality. Furthermore, designing an OTM terminal from scratch is a more complex problem from a mechanical point of view compared to designing OTP terminals. To evaluate different concepts and later design and choose components, one must be aware of the structural and mechanical performance demands on the device. If the device is to be mounted on a vehicle, one must first know on what kind of vehicle, but also where and under what conditions. A tool that can aid the designers during this process could not only accelerate the release of a product with global environmental, social and economical benefits, but also provide economical savings for Ovzon.

1.4 Purpose

The work to be done during this thesis is to develop a validation tool for antenna positioners on vehicles in motion. The tool will help engineers when designing movable docking stations for OTP antennas and also complete OTM antenna systems. Different designs of antenna and positioner systems should be able to be simulated on different types of vehicles under different conditions. The tool shall be configurable to allow easy iteration of each design configuration and input parameters. Running the tool shall give the engineer data on the required torques and forces needed to sustain communication with a satellite for the given design and configuration.

1.5 Goals

Overall, the goals of this thesis are to develop a validation tool that will help engineers to design and optimize antenna positioner systems for vehicles in motion. By using this tool, engineers should be able to identify the required torques and forces needed to sustain communication with a satellite for the given design, configuration and conditions as well as optimize the design for better performance.
1.6 Delimitations

To ensure that a usable tool can be created within an 800 hour time constraint, the following limitations were made:

- Stresses on solid components are not calculated.
- Only the two-axis gimbal concept is to be implemented.
- Only simple control theory is allowed to be implemented, if necessary.
- The tool is to be made in Matlab and Simulink.
- Motor dynamics are not accounted for.
- Two vehicle types, road vehicles and boat.

1.7 Ethical considerations

Ever since the introduction of artificial satellites, military applications has been a driving force in its and its services development. The first military related task for a satellite was photographic reconnaissance, after which, development began on different ends to equip satellites with weapons that could be used against targets both on earth and in space [10]. Development was stopped in 1967 however, after an international agreement to ban weapons of mass destruction in space. To this day, no such devices are known to exist whilst military operations are a major customer of satellite services such as communication and navigation. Military operations and the ethics of warfare in itself is a complex subject and not the subject of this thesis [11].
Chapter 2

Background

2.1 Satellite communication

Satellite communication refers to information being transferred between different positions on earth through earth orbiting satellites. The artificial satellite acts as a relay station and allows for multiple data types to easily reach locations on a large section of the earth's surface. Using satellites to relay information, the communication infrastructure on the ground is to a certain extent bypassed. This has advantages as the infrastructure on the ground may be unreliable, and in many cases, does not exist [12].

Ground based antennas

To establish communication with a satellite from the ground, an antenna has to be used. Ground based antennas can take on a lot of different appearances and form factors, depending on the intended use and working principal. Antennas can work in different frequency bands as well as being designed to communicate with satellites in different orbits. The location of the satellite in relation to the ground based antenna is defined by an elevation angle and an azimuth angle, as can be seen in Figure 2.1 where the angles are defined as $\phi$ and $\theta$ respectively. The elevation angle is measured from the earth's surface at the antenna where zero degrees is parallel to earth's surface and 90 degrees is perpendicular to earth's surface. The azimuth angle is most commonly measured clockwise from north but can be defined in relation to any cardinal direction [13].
2.2 Satcom on the move

Satcom on the move refers to communication between a satellite and the ground based antenna, during which, the ground based antenna is not stationary in relation to earth. In most cases this means that the antenna is mounted on a moving vehicle or person. To keep communication live with the satellite, means that the antenna must be able to aim and adjust elevation and azimuth angles actively and automatically [14]. In this section, the Getsat range of antennas are presented, primarily due to generous available information along with a docking station concept for the Ovzon T6 OTP.

Getsat OTM terminals

The Getsat range of OTM terminals feature a rectangular antenna that can be electronically adjusted in two axes, elevation and azimuth. The elevation axis is located at or close to the horizontal center line of the antenna and, or close to, intersects the azimuth axis. These are designed for the sole purpose of on-the-move operation. One example of such a device is the Getsat Micro SAT [15]. This product is not intended to be manually adjusted and its layout of components of the complete antenna system is very different from for example the Ovzon T6 OTP. The Getsat Micro SAT can be seen in configurations with and without its protective radome in Figure 2.2.
Docking station for Ovzon T6

Work has been carried out to create a movable docking station for the Ovzon T6 OTP antenna. This solution is not a full OTM solution but rather allows for automatic aiming of the antenna when stationary. The mechanical principle when the T6 terminal is mounted on the docking station is similar to that of the Getsat OTM terminals in the sense that there is one elevation axis perpendicular to a rotary table that rotates in the azimuth plane. The elevation axis is mounted at the bottom of the antenna instead of across the middle to allow for unobtrusive visuals when retracted. The azimuth angle is controlled by a direct drive rotary table and the elevation angle is controlled by a stepper motor through a planetary gearbox [16]. The final design proposal can be seen in Figure 2.3.

During the development of this docking station, a number of other design concepts were generated, some of which can be seen in Figure 2.4.
As can be seen in Figure 2.4, the right most concept differs from the other ones in the sense that it relies on a linear actuator and a linkage for elevation adjustment. This concept was taken further by the project group but was ultimately not chosen to be further evaluated into the final proposal as the advantages over the final one did not outweigh possible difficulties and disadvantages.

2.3 Two axis gimbal

A gimbal is a stabilization device, often used for cameras, antennas or other equipment where good control of orientation is important. Consisting of a constellation of pivoting frames, whose motion is often controlled by motors, orientate the mounted equipment with one Degree Of Freedom (DOF) per pivot axis. For cameras mounted on vehicles, a three axis gimbal is common, where each one axis controls tilt, pan and roll respectively and relative to a coordinate system fixed on the base of the gimbal. To provide usable footage, a camera must be pointed in the right direction and therefore adjusted in tilt and pan but also the image must be oriented correctly, in essence adjusted correctly in roll [17]. A three axis gimbal with a camera can be seen in Figure 2.5.
For antenna purposes, a two-axis gimbal where the roll axis is removed is often sufficient. In this type of inertially stabilized system, the pan and tilt axes are commonly referred to as azimuth and elevation, respectively. Depending on the frequency band and its polarization more specifically that is being used for communication, roll angle has either no effect on the transmission or is treated internally inside the antenna. For example, some GetSat terminals communicate using the ka-frequency band, which is circularly polarized and does therefore not need to take roll angle into account or treat the signal internally. Ovzon, on the other hand, runs its services the ku-band which is linearly polarized and does therefore need to compensate for roll misalignment with the signal. In all current Ovzon-developed antennas, this is treated internally inside the antenna. This means that for the purposes of this project, if a gimbal-type docking station is to be modeled, it will only require two axis, such as for the GetSat and Ovzon solution [19].

It is common to model two-axis gimbal systems as two Single Input Single Output (SISO) systems when designing control strategies. Each of the two axes are then treated independently and any effect from input to one of the axes on the output on the other axis is neglected. The gain in simplicity of the SISO control strategies can outweigh the possible inaccuracies inherited from neglecting that the state of one of the axes will affect the dynamics of the other. A more accurate model for control strategies is to treat the full two-axis gimbal model as a Multiple Input Multiple Output (MIMO) system. The coupled dynamics has been proven problematic for control strategies however, and for control purposes, one must be aware of how and what gives rise to the coupled dynamics [20].

2.4 Drive and transmission

Readily available OTM terminals for services comparable to Ovzon’s services use electric motors to control the elevation and azimuth angles. It is possible to use a direct drive arrangement on one or more axis. One example of this is the rotary table for the azimuth axis in the fore mentioned docking station concept for Ovzon T6. More common is some kind of transmission between the motor and the axis. Belt drives, worm gears or spur gears are some examples this type of transmission. A spur gear transmission in a planetary configuration is the type that ultimately became the choice in the Ovzon T6 docking station concept. Common for these rotary transmissions is the constant gear ratio between the motor and the rotation axis of the antenna [16].
Chapter 3

Simulation and data collection

Simulation tools are widely available for antenna systems, vehicle dynamics and mechanical systems. Existing tools and methods that may be of help during development and validation are presented in this chapter.

3.1 Matlab

MATLAB is provided by MathWorks as a programming language and numerical calculation software. The software and language is widely used in engineering and other fields for tasks such as data analysis and modelling. Working with MATLAB, the user can, among other things, write and perform numerical computation, mathematical calculations and plot data. It also includes a library of built-in functions and toolboxes for certain tasks such as control system design. The syntax of MATLAB is similar to many programming languages but optimized for numerical calculations, making it easy to get started with and use for calculations [21].

3.2 Simulink

Simulink is developed and provided by MathWorks. It is a graphical programming language used for modelling and simulating systems, which can be among others, mechanical, electrical or signal processing systems. The graphical user interface uses blocks to create a block diagram of the system. Each block represents mathematical operations, such as addition or multiplication or configurable models of for example, control systems or mechanical systems. Simulink is widely used academically as well as in industries such as automotive and telecommunication. Being a part of MATLAB, the user can set up models
where the graphical model in Simulink runs in conjunction with a MATLAB model [22].

3.3 IPG Carmaker

IPG Carmaker is a software developed by the IPG Automotive for simulating and testing the behavior of ground vehicles and its systems in a virtual environment. The software is used by automotive manufacturers as well as universities, for designing, testing, and validating vehicle systems and components. Included in Carmaker is a wide range of simulation models and tools for vehicle dynamics, power train, driver assistance systems, and other automotive systems. The models in Carmaker can be configured by the user to match a certain and specific vehicle design. Using the software allows for simulation of a range of different driving conditions, as well as vehicle dynamics control systems. The simulation is physics-based and can provide comprehensive reports on simulation results [23].

3.4 Boat dynamics data collection

Defining a boat as a rigid body submerged and moving through a fluid, its dynamics can be described by six degrees of freedom. In translation this is surge, sway and heave and in rotation, roll, pitch and yaw [24]. The six degrees of freedom can be seen in Figure 3.1.

![Figure 3.1: Rigid boat DOF [25].](image-url)
2D+t model

The 2D+t model is used for simplified calculations on planing hulls. The hull is modeled as a rigid wedge that represents a v-shape hull with a constant dead rise angle along its full length. Usage of the 2D+t theory has gained increased attention and various authors have improved and added functionality to it. Originally only used for steady state analysis of pitch and heave of planing hulls in calm water, models have until now been developed to also estimate behaviour in waves and also roll. The extensive research, validation and low computing power needed of the 2D+t method makes it a good tool for designers and researchers. Comparatively, computational fluid dynamics simulations of planing craft is very complex and process power demanding. Its results are considered fairly accurate compared to real world tests [26].

Field tests

To determine the dynamic behaviour of a boat on the water, the most reliable way is to make field tests. A 6 DOF Inertial Measurement Unit (IMU) and GPS can be used to measure all of the crafts motions if it is defined as a rigid body as per Figure 3.1.

Scale model

Scale models is often a good way to test the dynamic behaviour of a boat. During development of new hulls, scale models allow for faster iteration and a lower cost compared to full scale prototypes. The tests are often done with the model suspended with the desired degrees of freedom in a pool. To translate the results from a scale model to something applicable on a full scale craft, the Froude scaling conversion factors can be used [27]. The Froude scaling laws applies to the important physical entities listed in Figure 3.2.
Computational fluid dynamics

Computational Fluid Dynamics (CFD) refers to numerical simulations used to analyze fluid flow, often in or around geometries. In the context of boats, CFD can be used to study the performance of a hull shape in terms of for example drag and stability. By simulating the flow of water around a boat, CFD can be a useful tool when designing or testing hulls. Whilst being a very commonly used tool for ship design and displacement hulls, the tool is not as explored for smaller planing hulls. Simulation of planing hulls requires vast processing power to be viable, especially for non-symmetrical and non-steady-state conditions [28].
Chapter 4

Modelling, simulations and final data collection

With the purpose of creating a computer based tool that can increase the efficiency of the design process of OTM antennas, the work was divided into two major parts. Vehicle dynamics data collection and implementation being one of them and modelling of the antenna dynamics being the other. With the goal of starting a vehicle dynamics database with common use cases and manoeuvres for cars, trucks and boats, computer based simulation was used for cars and trucks whilst field measurements was used for boats. The data from the ground vehicle simulations and boat tests were imported into Matlab, post processed and made available to be imported by the simulation tool. All geometrical transformations necessary to decide a satellites position in relation to the mounting position of the antenna on the vehicle were applied.

The parameterized mechanical representation of the antenna system as two bodies was created in Matlab. First of all, a geometrical model where location of the axes in space, in relation to each other and the mass properties of the bodies was created. After this, the equations of motion around the elevation and azimuth axes of the coupled MIMO system were defined. The two major parts of the tool that were merged into the complete product where the user can select a vehicle, conditions and evaluate the performance of the antenna are presented in this chapter.
4.1 Data collection

Ground vehicle and speed boat data collection is described in this section.

4.1.1 Ground vehicles

To create the beginning of a database of driving conditions for use in the final product, it was decided by the project to use IPG Carmaker to build environments and driving scenarios. Two generic vehicle models, developed by IPG were used, one truck and one car, where the truck is simulated with and without a typical two-axle trailer. Two testing environments were created to simulate a range of manoeuvres. The first testing environment consists of a straight stretch of tarmac with multiple lanes. The second testing environment that was built consists of a large area of tarmac with an accessible speed bump. Each ground vehicle type is tested in a double lane change manoeuvre, a steering angle ramp turn and over the speed bump at a variety of different speeds. The car and the truck, with and without the trailer can be seen during the double lane change manoeuvre in Figure 4.1.

![Figure 4.1: Truck with trailer, truck and car.](image)

Double lane change

The double lane change manoeuvre tests were conducted at 30, 50, 70 and 90km/h for trucks and also 110 km/h for cars. The path of the manoeuvre was constructed to achieve a 3.5m side ways movement to the right within 25m of road followed by the same movement to the left, back to the lane where the manoeuvre was started. The defined route for use in all double lane change manoeuvres can be seen in Figure 4.2.
Figure 4.2: Double lane change manoeuvre.

Steering angle ramp

The steering angle ramp simulation was performed for each vehicle type and configuration at 30, 50, 70 and 90 km/h for trucks and also 110 km/h for cars. This test was performed on a large section of flat tarmac where the vehicle was accelerated up to the desired speed, followed by a linear steering wheel angle ramp from zero to 720 degrees with a duration of 20 seconds. The resulting route of an arbitrary configuration of this test can be seen in Figure 4.3.

Figure 4.3: Steering wheel angle ramp test route.

Speed bump

The speed bump simulation was performed at the speeds recommended for a certain trapezoidal speed bump design according to R ISEP 10. The recommended speed bump design and speeds can be seen in Figure 4.4.
The different speed bump profiles were modeled in IPG Carmaker and simulations proceeded. In Figure 4.5, a screen capture from the simulation of a truck with no trailer at 50 km/h can be seen.

**Parameters**

The inertial data that was collected from the simulations were with respect to three different coordinate systems. These coordinate systems are:

- **Fr0**
  - Earth fixed coordinate system.
- **Fr1**
  - Vehicle body fixed coordinate system.
- **FrX**
  - Road following coordinate system. The XY-plane approximately follows the road surface. The origin is located in the middle of the two rear tyre contact points and X points towards the middle of the two front tyre contact points.
The parameters and the corresponding coordinate systems that are saved from the test runs for post processing can be seen in Table 4.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Coordinate system</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td>s</td>
<td>-</td>
<td>Time</td>
</tr>
<tr>
<td>( v_x )</td>
<td>m/s</td>
<td>Fr1</td>
<td>Translational velocity, x</td>
</tr>
<tr>
<td>( v_y )</td>
<td>m/s</td>
<td>Fr1</td>
<td>Translational velocity, y</td>
</tr>
<tr>
<td>( v_z )</td>
<td>m/s</td>
<td>Fr1</td>
<td>Translational velocity, z</td>
</tr>
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<td>x</td>
<td>m</td>
<td>Fr0</td>
<td>Translational position, x</td>
</tr>
<tr>
<td>y</td>
<td>m</td>
<td>Fr0</td>
<td>Translational position, y</td>
</tr>
<tr>
<td>z</td>
<td>m</td>
<td>Fr0</td>
<td>Translational position, z</td>
</tr>
<tr>
<td>( \dot{v}_x )</td>
<td>m/s(^2)</td>
<td>Fr1</td>
<td>Translational acceleration, x</td>
</tr>
<tr>
<td>( \dot{v}_y )</td>
<td>m/s(^2)</td>
<td>Fr1</td>
<td>Translational acceleration, y</td>
</tr>
<tr>
<td>( \dot{v}_z )</td>
<td>m/s(^2)</td>
<td>Fr1</td>
<td>Translational acceleration, z</td>
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<tr>
<td>( \phi )</td>
<td>rad</td>
<td>FrX</td>
<td>Roll angle</td>
</tr>
<tr>
<td>( \Theta )</td>
<td>rad</td>
<td>FrX</td>
<td>Pitch angle</td>
</tr>
<tr>
<td>( \psi )</td>
<td>rad/s</td>
<td>FrX</td>
<td>Yaw angle</td>
</tr>
<tr>
<td>( \dot{\phi} )</td>
<td>rad/s(^2)</td>
<td>FrX</td>
<td>Roll rate</td>
</tr>
<tr>
<td>( \dot{\Theta} )</td>
<td>rad/s(^2)</td>
<td>FrX</td>
<td>Pitch rate</td>
</tr>
<tr>
<td>( \dot{\psi} )</td>
<td>rad/s(^2)</td>
<td>FrX</td>
<td>Yaw rate</td>
</tr>
<tr>
<td>( \ddot{\phi} )</td>
<td>rad/s(^2)</td>
<td>FrX</td>
<td>Roll acceleration</td>
</tr>
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<td>( \ddot{\Theta} )</td>
<td>rad/s(^2)</td>
<td>FrX</td>
<td>Pitch acceleration</td>
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<tr>
<td>( \ddot{\psi} )</td>
<td>rad/s(^2)</td>
<td>FrX</td>
<td>Yaw acceleration</td>
</tr>
</tbody>
</table>

4.1.2 Speed boat

It was decided by the project to conduct field tests on planning craft to collect data that can be used for simulation. The data was collected using a Samsung Galaxy S20 and more specifically, its LSM6DS0 6 DOF IMU and GPS. The output from the relevant hardware inside of the S20 was recorded and accessed using the downloadable application called HyperIMU. This application allows the user to access an number of physical and virtual sensors in the device. After configuration of the application, the user can record and save the sampled data in a chosen format.
In total, five sensors were recorded during the test runs and are presented here:

- LSM6DS0 Acceleration Sensor
  - Linear acceleration part of the LSM6DS0 sensor.

- LSM6DS0 Gyroscope Sensor
  - Gyroscope part of the LSM6DS0 sensor.

- Linear Acceleration Sensor
  - Linear acceleration part of the LSM6DS0 sensor. The data is filtered to remove the gravitational acceleration from the output.

- Orientation Sensor
  - Uses the LSM6DS0 to determine the orientation of the device in space with regards to the direction of gravity.

- GPS
  - Records geographical position.

The data was recorded for all sensors with a sample rate of 5ms, the minimum stable sample rate for the device and application. The coordinate system used by the device can be seen in Figure 4.6.

![HyperIMU coordinate system](image)

*Figure 4.6: HyperIMU coordinate system*

To ensure stable and secure mounting of the device, a holder was designed in CAD software and 3D-printed in plastic. The holder has provision for the device...
and an external battery that can be connected to the device if the battery of the device itself would be considered too low. The case is shaped like a cuboid with flat surfaces to ease mounting of the assembly to any horizontal surface onboard the craft using double-sided tape. The design of the holder can be seen in Figure 4.7.

![Figure 4.7: Holder for Samsung Galaxy S20 and auxiliary battery.](image)

For each tested craft, the device was mounted to a horizontal surface when the craft was stationary, as close to the Center of Gravity (CoG) of the craft as possible whilst still being practical to operate. The device was mounted with its Y-axis parallel to the X-axis of the craft and its Z-axis parallel to the Z-axis of the craft. This was corrected for upon import into MATLAB so that the IMU recording uses the coordinate system as per Figure 3.1. Recordings were made during S-shaped evasive manoeuvres with 50 and 100 percent steering wheel input in speed increments of ten knots up to a speed where this is no longer possible or safe. The manoeuvre consists of four steps that the captain needs to execute:

1. Ensure that the craft travels at the correct speed with constant throttle input.
2. Turn the steering wheel starboard to the correct input as quick as possible.
3. When the craft has settled in the turn, and any transient handling effects have disappeared, turn the steering wheel port to the correct input as quick as possible.
4. When the craft has settled in the turn, and any transient handling effects have disappeared, turn the steering wheel back to the center as quick as possible.
Marell M12

The first subject for field tests, as seen in Figure 4.8, was a M12 by Marell Boats AB. The M12 is an 11.7 meter long aluminium craft with an empty boat displacement of 6500 kg. The test subject was fitted with two outboard motors, providing a total power output of 1200 horsepower.

![Marell Boats AB M12](image)

Figure 4.8: Marell Boats AB M12.

The measuring equipment was mounted to the aluminium base of the drivers seat. This position is solidly mounted to the welded aluminium hull, deck and cabin assembly and a horizontal surface when the craft is stationary. It was also the point closest to the CoG of the craft whilst still being practical for mounting and operating the device whilst on the move. The mounting position inside the cabin can be seen in Figure 4.9.

![Measuring equipment mounting position](image)

Figure 4.9: Measuring equipment mounting position.
The device was aligned using a square and part of the aluminium deck and hull assembly as a datum. It was mounted using thin, high strength double sided tape and can be seen in its position in Figure 4.10.

![Figure 4.10: Close up of the measuring equipment and its position.](image)

X Shore 1

The second subject for field tests, as seen in Figure 4.11, was an X Shore 1. This is a fully electric leisure craft with a displacement of 1.7 tonnes, a length of 6.5 m and a top speed of 30 knots. Propulsion is achieved from a single straight shaft inboard electric motor with a maximum power output of 125 kw.

![Figure 4.11: X Shore 1.](image)
The measuring equipment was mounted to the bottom of the center stairs according to Figure 4.12. This mounting position is part of the composite hull and deck structure and a horizontal surface when the craft is stationary. It was also the point closest to the CoG of the craft whilst still being practical for mounting and operating the device whilst on the move.

\[\textbf{Figure 4.12: Measuring equipment mounting position.}\]

The device was aligned using the rear, vertical part of the mid step as a datum. It was mounted using thin, high strength double sided tape and can be seen in its position in Figure 4.13.

\[\textbf{Figure 4.13: Measuring equipment mounted.}\]
4.2 Data import

In order to compute all calculations, the recorded and simulated data must be processed to be ready for use. For the road vehicle simulations, all saved parameters had the correct units and coordinate systems for the calculations to be done. For the boat tests however, the recorded IMU data used the wrong coordinate system, degrees instead of radians and did not include angular accelerations. This was solved by post processing the data upon import into MATLAB. All recordings from the real and virtual sensors are transformed to the correct vehicle fixed coordinate system according to Equation 4.1.

\[
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix}
= 
\begin{bmatrix}
  0 & 1 & 0 \\
  -1 & 0 & 0 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix}_{\text{IMU}} \tag{4.1}
\]

Furthermore, the recordings from the gyroscope and orientation sensor were converted to use radians instead of degrees by multiplying each element with \( \frac{\pi}{180} \). Lastly, the angular accelerations were calculated using the gyroscope sensor data, \( \bar{\omega} \), according to Equation 4.2.

\[
\dot{\bar{\omega}} = \frac{d}{dt} \bar{\omega} \tag{4.2}
\]

4.3 Transforms

The position of the GEO satellite, \( q_{E_{sph}} \), as can be seen in Figure 4.14 is defined in an earth fixed, spherical coordinate system, \( E_{sph} \) by an azimuth angle, \( a_e \) and an elevation angle, \( e_e \) according to Figure 2.1. The \( a_e \) angle is defined from the longitudinal center line, or the x-axis of the vehicles initial position in a horizontal plane. The \( e_e \) angle is defined as perpendicular to \( a_e \), measured from the horizontal plane. The radius, \( r \) is not important as any translation of the vehicle body in relation to the satellite contributes to negligible angular change. Therefore, the position of the satellite is defined by the unit vector and \( r = 1 \).

\[\text{Figure 4.14: Arbitrary point } q, \text{ ground fixed XYZ, vehicle fixed xyz [30].}\]
In order to determine the angle of rotation around the azimuth, \( a \) and elevation, \( e \) axis of the antenna needed to point at the satellite, the rotation of the mounting position on the vehicle in relation to \( E_{sph} \) is used. The azimuth, \( a \) and elevation angle, \( e \) are defined in a spherical coordinate system \( A_{sph} \), whose origin is coincident with the origin of \( E_{sph} \). With the vehicle in its initial position, all axes of \( A_{sph} \) are coincident and in the same direction as \( E_{sph} \). With the end goal of calculating \( a \) and \( e \) of the satellite, or \( q_{Asph} \) in \( A_{sph} \) for every time step of the test run, the transformation matrix \( R_{xyz} \) for rotation around the \( x \)-axis, \( \Phi \), \( y \)-axis, \( \Theta \) and \( z \)-axis, \( \Psi \), was determined as per Equation 4.3.

The definition of the vehicle fixed coordinate system \( A \), which has the same axis configuration for IPG Carmaker simulation outputs and for the post processed IMU recordings according to Figure 3.1, can be seen in Figure 4.15.

\[
R_{xyz} = \begin{bmatrix}
\cos \Theta \cos \Psi & \cos \Theta \sin \Psi & -\sin \Theta \\
\sin \Phi \sin \Theta \cos \Psi - \cos \Phi \sin \Psi & \cos \Phi \cos \Psi + \sin \Phi \sin \Theta \cos \Psi & \sin \Phi \cos \Theta \\
\sin \Phi \sin \Psi + \cos \Phi \sin \Theta \cos \Psi & \cos \Phi \sin \Theta \sin \Psi - \sin \Phi \cos \Psi & \cos \Phi \cos \Theta 
\end{bmatrix}
\tag{4.3}
\]

In order to compute the transform from \( E_{sph} \) to \( A_{sph} \), the coordinates of \( q_{Esph} \) were converted to a coincident cartesian coordinate system, \( E_{cart} \), resulting in \( q_{Ecart} \). The position of the satellite, \( q_{Acart} \) in \( A_{cart} \), a cartesian coordinate system, coincident with \( A_{sph} \), was obtained by the following transformation;

\[
q_{Acart} = R_{xyz} q_{Ecart}
\tag{4.4}
\]

The last step in order to obtain the spherical coordinates of the satellite, \( q_{Asph} \) in \( A_{sph} \) a conversion from cartesian to spherical coordinates was made from \( A_{cart} \) to \( A_{sph} \). The result of this conversion follows;

\[
q_{Asph} = \begin{bmatrix} a & e & 1 \end{bmatrix}
\tag{4.5}
\]
4.4 Antenna model

The two axis gimbal antenna was defined as two rigid bodies, the antenna and the base, with two perpendicular axes. The two bodies are connected by the elevation axis and the whole assembly can rotate around the azimuth axis, which is assumed to be fixed at the mounting point of the assembly on the vehicle. This gives the antenna 2 DOF.

4.4.1 Parameters

The parameters needed to define the antenna and base assembly in terms of mechanical properties are:

- $m_T$, Antenna mass
- $m_B$, Base mass
- $D_{cc}$, Distance between azimuth and elevation axis
- $CG_T$, Antenna CoG coordinates in relation to antenna origin
- $CG_B$, Base CoG coordinates in relation to base origin
- $I_{TCG}$, Antenna inertia matrix at CoG
- $I_{BCG}$, Base inertia matrix at CoG
- $\Delta$, Antenna position
An arbitrary example of a compatible antenna and base assembly with its azimuth angle, \(a\) and elevation angle, \(e\) can be seen in Figure 4.16.

Figure 4.16: Antenna and base assembly.
The antenna component and its definition of $CG_A = [x_T, y_T, z_T]$ can be seen in Figure 4.17. The vector $CG_A$ defines the translation from the CoG to the center of the elevation axis of the antenna component.

**Figure 4.17:** Antenna component with definition of $CG_A$. 
The base component and its definition of the translation from the CoG to the azimuth axis, \( CG_B = [xB, yB] \), along with the perpendicular distance between the azimuth axis and elevation axis, \( D_{cc} \), can be seen in Figure 4.18.

![Figure 4.18: Base component with definition of \( CG_B \) and \( D_{cc} \).](image)

4.4.2 Elevation moment of inertia

To determine the inertia around the elevation axis for the elevation mechanism, the antenna inertia matrix at CoG, \( I_{TCG} \) and its location with respect to the origin, \( CG_T \) is computed with the parallel axis theorem. The inertia matrix at the origin, \( I_{TE} \), parallel to \( I_{TCG} \) is computed according to;

\[
I_{TE} = \begin{bmatrix}
I_{xx} + m_T(y_T^2 + z_T^2) & I_{xy} - m_Tx_Ty_T & I_{xz} - m_Tx_Tz_T \\
I_{yx} - m_Tx_Ty_T & I_{yy} + m_T(x_T^2 + z_T^2) & I_{yz} - m_Ty_Tz_T \\
I_{zx} - m_Tx_Tz_T & I_{zy} - m_Ty_Tz_T & I_{zz} + m_T(x_T^2 + y_T^2)
\end{bmatrix}
\]  

from which, the inertia around the elevation axis \( I_E \) can be calculated using rotation around the origin according to;

\[
I_E = e_{QE}^T I_{TE} e_{QE}
\]  

where \( e_{QE} \) is the rotation vector and \( e_{QE}^T \) the transpose of \( e_{QE} \). This vector contains the direction in the coordinate system at the origin where \( \alpha, \beta \) and \( \gamma \) are the angular rotations from the \( x, y \) and \( z \) axis respectively according to;
4.4.3 Azimuth moment of inertia

The inertia of the whole assembly that rotates around the azimuth axis is calculated in a similar manner as for the elevation axis. The major difference is that the position of the antenna, i.e. the elevation angle, $e$ affects the resulting inertia of the azimuth axis. This infers that the azimuth inertia must be computed for every time step during the simulation. The total inertia for the azimuth axis is presented below;

\[ I_A = I_{BA} + I_{TCGZ} + m_T D_{T-a}^2 \]  \hspace{1cm} (4.9)

where $I_{BA}$ is the inertia of the base around the azimuth axis, $I_{TCGZ}$ is the inertia of the antenna at CoG, parallel to the azimuth axis and $D_{T-a}$ is the distance between the CoG of the antenna and the azimuth axis. The term $I_{BA}$ is calculated using the same steps as for $I_E$ and is constant throughout the simulation. For every elevation angle, $I_{TCGZ}$ is computed according to;

\[ I_{TCGZ} = e_{Qn}^T I_{TCG} e_{Qn} \]  \hspace{1cm} (4.10)

where;

\[ e_{Qn} = \begin{bmatrix} \frac{\pi}{2} - e \\ \frac{\pi}{2} \\ e \end{bmatrix} \]  \hspace{1cm} (4.11)

and the term $D_{T-a}$ is calculated according to;

\[ D_{T-a} = D_{cc} - |CG_T| \cos(e_{cg}) \]  \hspace{1cm} (4.12)

where $e_{cg}$ is the angle between $D_{T-a}$ and $|CG_T|$ and is calculated for every time step according to;

\[ e_{cg} = e + \arctan \frac{x_T}{y_T} \]  \hspace{1cm} (4.13)

4.5 Torque equations

The calculations of the torque needed for each mechanism to act on the antenna to sustain communication with the satellite is presented in this section.

All test run and simulation data that was imported was measured on a specific point on the vehicle. In order for the tool to allow for simulation of the antenna assembly at any point on the vehicle body, the user must input the translation between the antenna mounting point and the point where the measurements
we used the vector \( \Delta = [\Delta_x, \Delta_y, \Delta_z] \) is the result of the user input. The transform from \( \dot{v} \) to \( \dot{v}_q \) is computed for every time step according to;

\[
\dot{v}_q = \dot{v} + \omega \times (\omega \times \Delta) + \dot{\omega} \times \Delta \tag{4.14}
\]

To obtain the correct forces that will be acting on the antenna assembly, gravity must be accounted for. Gravity is added to the translational acceleration vector, \( \ddot{v}_q \) according to;

\[
\ddot{v}_q^+ = \begin{bmatrix} \dot{v}_{x+g} \\ \dot{v}_{y+g} \\ \dot{v}_{z+g} \end{bmatrix} = \ddot{v}_q + g \begin{bmatrix} \sin \gamma \cos \theta \\ \sin \gamma \sin \theta \\ \cos \gamma \end{bmatrix} \tag{4.15}
\]

where \( g \) is the gravitational acceleration whilst \( \gamma \) and \( \theta \) defines the direction of \( g \) in a spherical, vehicle body fixed coordinate system. The term \( \gamma \) is the elevation angle and \( \theta \) is the azimuth angle. To compute these terms, the roll, \( \phi \) and pitch angle, \( \Theta \) are used. The term \( \gamma \) is derived according to;

\[
\gamma = \arccos (\cos \Theta \cos \phi) \tag{4.16}
\]

and the term, \( \theta \) according to;

\[
\theta = \arctan \frac{\sin \phi}{\tan \Theta} \tag{4.17}
\]

To calculate the torque around each axis, some variables are introduced. The CoG location of the base in relation to the azimuth axis is defined by \( D_{B-a} \), the distance and \( \beta \), the angle between \( D_{B-a} \) and \( D_{cc} \). The term \( D_{B-a} \) is defined according to;

\[
D_{B-a} = \sqrt{x_B^2 + y_B^2} \tag{4.18}
\]

and the term \( \beta \) according to;

\[
\beta = \arctan \frac{y_B}{x_B} \tag{4.19}
\]

The resulting torque equation for the azimuth and elevation axes can be seen in Equation 4.20 and 4.21, respectively.

\[
t_a = \dot{\omega}_a I_A + \begin{bmatrix} \dot{v}_{x+g} \\ \dot{v}_{y+g} \end{bmatrix} \left( m_T D_{T-a} \begin{bmatrix} \sin a \\ \cos a \end{bmatrix} + m_B D_{B-a} \begin{bmatrix} \sin a + \beta \\ \cos a + \beta \end{bmatrix} \right) \tag{4.20}
\]

\[
t_e = \dot{\omega}_e I_{TE} - \omega_a^2 m_T D_{T-a} |CG_T| \cos (e_{cg}) + m_T |CG_T| \begin{bmatrix} \cos (e_{cg}) \cos (a) \\ \cos (e_{cg}) \sin (a) \\ \sin (e_{cg}) \end{bmatrix} \tag{4.21}
\]
Chapter 5

Results

In this chapter, the resulting MATLAB tool is presented. The finished product can, with user input of the necessary parameters and chosen use case, calculate the resulting torque for the elevation and azimuth axis of the antenna and base assembly. The user is also presented with the state of the antenna for every time step in terms of angular position, velocity and acceleration. Furthermore the surrounding conditions such as translational and angular position, velocity and acceleration of the vehicle can be accessed by the user.
5.1 User configuration

The list of parameters that the user must enter in "mainUI.m" to initiate a simulation is presented here in Figure 5.1.

```matlab
%Vehicle of choice, Vehicle;
% 1 = car
% 2 = truck
% 3 = truck + trailer
% 4 = Marell M12
% 5 = X Shore 1
% 6 = Input from file, see ref. manual
Vehicle = {};

%Scenario, see table in ref. manual
scen = {};

%Initial satellite position: azimuth [rad]
a0 = {};
%Initial satellite position: elevation [rad]
e0 = {};

%Distance between axes (m)
Dcc = {};

%Antenna Mass (kg)
mT = {};

%Base Mass (kg)
mB = {};

%Antenna inertia matrix at CoG, (kg*m^2) [ixx,ixy,ixz;
%    iyx,iyy,iyz;
%    ixz,iyz,ixz];
IpTcg = [,,;
    ,,;
    ,,];

%Base inertia matrix at CoG, (kg*m^2) [ixx,ixy,ixz;
%    iyx,iyy,iyz;
%    ixz,iyz,ixz];
IpBcg = [,,;
    ,,;
    ,,];

%Antenna CoG to elevation axis coordinates, (m) [x,y,z]
cgT = [,,];

%Base CoG to elevation axis coordinates, (m) [x,y,z]
cgB = [,,];

%Antenna mounting position, (m) [x,y,z], see ref. manual
fq = [,,];
```

*Figure 5.1: mainUI.m input parameters.*
When all the necessary parameters have been entered by the user, the calculations can be initiated. The file "mainUi.m" will call a function "calc.m", where all calculations are performed. This will in turn call the function "veh.m", where the text files containing the vehicle simulation or test run data is imported and post-processed for use by "calc.m". When all calculations are completed by calc.m, the user is presented with the results. A simple flow chart describing this process can be seen in Figure 5.2.

Figure 5.2: Flow chart of finished tool.

The results first presented is the elevation and azimuth angle, rotational velocities and required torques together with a 3d-plot of the satellite path in the vehicle body fixed coordinate system. The distance from the vehicle to the satellite is not important and its position is therefor described without units at a distance of 1. The results from a test run of a truck without a trailer in a steering angle ramp test at 70 km/h can be seen in Figure 5.3.
Figure 5.3: Steering angle ramp test result.

The path of the satellite in the vehicle body fixed coordinate system can be seen in Figure 5.4. The path is defined by the azimuth and elevation angle of the antenna and describes how the antenna has moved throughout the simulation. During the steering angle ramp test presented here, the antenna almost completed two full revolutions around the azimuth axis, which can be seen by the continuous curve. The offset between the revolutions for the same azimuth angle is a result of a difference in antenna elevation angle, mostly due to a difference in roll angle of the vehicle.

Figure 5.4: Steering angle ramp test satellite position.

The vehicle path and longitudinal speed is also presented in a three dimensional plot according to Figure 5.5.
Furthermore, all important input data such as vehicle translational and rotational speed and acceleration in all directions are saved as variables and can be accessed if the user wishes to do so.

To validate the tool and ensure that no calculation errors are present a one-factor-at-a-time approach was used. The method consisted of creating simple and idealized input data and testing one part of each torque equation at a time. For each test, the result was compared to manual calculations and free body analysis. Using this method, analyzing the final part of the calculation, any faults in a previous step of the code could be detected and solved.
Chapter 6

Discussion and conclusions

In this chapter, a discussion about data collection and the modelling approach is presented.

6.1 Data collection

The decision by the project to include multiple vehicle types in the product was made for a number of reasons. Foremost of which, is the fact that the simulation tool was not aimed to suit a specific development project. With the purpose of being able to try different configurations, use cases and be applicable to as many product development projects as possible, it was decided that the chosen road vehicles and planing craft within the size range tested are the most likely applications for future products.

It was deemed during project planning that the project would not have sufficient resources to create user configurable vehicle dynamics simulation models within the boundaries of the MATLAB/Simulink environment. Therefore, the decision was made to import data from field tests or simulations. This has an apparent disadvantage as the end user is limited to the data that is delivered together with the tool. It does mean however, that the user does not need to have enough knowledge about vehicle dynamics to configure such a model. Instead, the user can choose between use cases that are easy to relate to and understand, with vehicle data typical of its kind. Furthermore, this approach to building the tool means that it is designed to import recorded inertial data. This in turn means that the user can always perform their own field tests or simulations on their vehicle of choice and add their own data sets to the library.

6.1.1 Speed boats

During development of the tool, the project gained access to two different types of speed boats for field tests and data collection. This was a result of contacts
within the industry and the time and place of the tests was largely determined by the opportunity. During both of the tests, the conditions were very calm and little to no waves were present on the water. This means that only negligible wave induced inertial reactions were recorded. This is a major drawback to the data set on boats as it is probable that waves might cause the largest accelerations on a moving craft. The list of manoeuvres to be tested for each craft originally included fewer manoeuvres but with different angle of attack against the waves. The intent was to test with the waves approaching the craft at 0, 45, 90, 135 and 180 degrees to the center line of the craft. By observing the conditions, the decision was made to increase the number of configurations of the evasive manoeuvre and instead neglect the direction of wind and waves to make the most of the available time with each craft.

The data-set created by the project is a good starting point and shows what kind of accelerations that can be expected during normal to sharp manoeuvres of two different speed boats. When using the tool to design a solution for a specific application, it is often the case that the specific craft is certified for certain conditions and in turn is designed for certain g-forces. The tool allows the user to create artificial data to mimic this for testing.

6.1.2 Road vehicles

The decision to simulate road vehicles in IPG Carmaker was made due to a number of reasons. Arranging field tests for different vehicle types for the chosen conditions would have been a more time consuming and unreliable process. The fact that the project had previous experience of the Carmaker software and that it includes many typical vehicle models contributed to why this method was chosen. One major advantage of using simulation to collect data is the repeatability of the process. This means that one can be sure that if only one variable of the simulation is changed, for example, the speed, this is the only difference to the simulations made at different speeds. This can be an advantage in the final product as the user will have an easier time when comparing the results.

The choice of vehicle models to simulate were made with respect to what types seemed the most likely to be used for an OTM applications within the Carmaker library. For both trucks and cars, the inertial data was collected from the chassis fixed coordinate system. This is accurate for normal cars whilst trucks of the type simulated has a suspended drivers cabin. It is likely that the user might want to use the inertial reference frame of the cabin instead as the cabin roof can be a good spot to mount antenna equipment. The reason for not including the suspension dynamics of the cabin is that there were no typical data available for this within Carmaker.
6.2 Modelling approach

The tool is programmed with the main purpose of solving two torque equations, one for the azimuth axis and one for the elevation axis. This approach meant that the resulting torques for each axis is exactly what is needed to keep the antenna pointing exactly at the satellite. Doing it this way as opposed to simulating the performance of the system with a certain torque input was a result of the delimitations that motor dynamics should not be included and that only simple control theory was allowed, if necessary. It was deemed by the project to be the best way to arrive at usable and reliable results. It has resulted in some artefacts, as expected, resulting in torque requirements that would not be necessary in real world applications. For example, a very small sudden change in azimuth angle of the satellite in relation to the antenna, where the azimuth acceleration is very large for a short period of time will yield a large spike in required torque. In reality, a small angular misalignment between the antenna and satellite is allowed and this tool cannot account for that. Instead the user can analyse the actual amplitude of change in azimuth to conclude how to treat this information. Despite the drawbacks of the chosen approach, it clearly rhymes with the goals of the project. The purpose of this the project was not to create an advanced simulation tool with many complex parameters. Neither was it supposed to be used instead of other simulation softwares for final sign off of a new product. Its purpose was to give engineers in a fast moving development project, whom may not have sufficient time or knowledge to execute many advanced simulations, an easy way to test and iterate their design in different conditions during the early stages of development.
Chapter 7

Future work

In this chapter, potential improvements and future work on the tool is presented.

7.1 Data collection

The data sets can be expanded to allow for simulation of more use cases. This is something that can both happen naturally as the tool is being used as the user may create their own or be provided by stakeholders in the project, or by a third party. For instance, the tool does not include any data on cars or trucks not being driven on asphalt. Such environments could be created in Carmaker using ".crg" files of certain terrain. The option to connect the MATLAB program to Carmaker could also be included, which could allow for easy creation of new driving conditions by the user. With regards to boats, a built in model using for example the 2d+t theory could be implemented to allow the user to create simple test cases of their own choice. Furthermore, other vehicle types can be used in the program, as long as their inertial data is available.

7.2 Modelling approach

In terms of expanding on the mathematical model, new force and torque equations can be added to allow for simulation of antennas of a different design than the two-axis gimbal type. Due to the simple nature of the program, its difficult to add more features or expand the model to, for example, simulate the antenna using torque input. To do this, a complementary model should be created using much of the same transforms and calculations but perhaps in Simulink to allow for easy modelling of motor dynamics and control strategies.
Bibliography


