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A Critical Analysis of Design Flaws in the Death Star

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Report submitted in partial fulfilment of the requirements of the module Project (E) 448 for the degree Baccalaureus in Engineering in the Department of Electrical and Electronic Engineering at Stellenbosch University.

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Abstract

English

The English abstract.

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Nomenclature

Acronyms and abbreviations

USV	Unmanned Sailing Vessel.
GPS	Global Positioning System.
RC	Radio Controlled
CAD	Computer Aided Design
$Pcontroller$	Proportional controller
PI	Proportional Integral
PID	Proportional Integral Derivative
$FPGA$	Field Programmable Gate Array
SPI	Serial Peripheral Interface
IMU	Inertial Measurement Unit
PWM	Pulse Width Modulation
$NMEA$	
$ASCII$	American Standard Character for Information and Interchange
ADC	Analog to Digital Converter
$UART$	
PWM	Pulse Width Modulation
$FAT32$	File Allocation Table, 32 bits
LSB	Least Significant Bit

Chapter 1

Introduction

1.1. Background

The ocean covers 71% of the earths surface and 80% of it remains unmapped, unobserved, and unexplored. The ocean produces over half of the air we breathe and absorbs 50 times more carbon dioxide than our atmosphere currently does. It regulates our climate and the weather patterns by transporting heat from the equator to the poles. It provides sustenance to millions of people around the world. Many medicinal products that help to fight cancer, arthritis and heart disease come from the ocean. Marine transportation makes up a huge portion of global trade, which supports the economies of the world. Without the ocean, life as we know it would not be possible and the planet would become uninhabitable.

The rapidly growing global population and consequent resource consumption is impacting the local and global environment negatively through physical and chemical pollution. The release of carbon dioxide into the atmosphere contributes to climate change, ocean warming, ocean acidification and the rise in sea levels. When released into the ocean, chemical wastes such agricultural fertilizers result in ocean deoxygenation. Many other forms of pollution such as untreated waste water and micro and macro plastics have an environmental impact that as of yet is only partially known.

Ocean research has led to our current understanding of the huge role the oceans play in supporting life on this planet. The continuing research and exploration of our oceans will aid in assessing the growing negative impact human activity has on the oceans, and by better understanding this impact, more effective solutions can be developed. Ocean research requires large amounts of funding and human resources to support it. As of 2015 the United States had 4000 ocean science researchers, roughly 50 nationally maintained ocean research vessels and in 2013 had an annual national ocean science expenditure of $12.5 trillion [?]. These ocean research vessel cost from $10000 to $40000 a day to operate, with the crew itsef being one of the biggest expenses [?].These expenses can increase greatly when research missions to remote areas of the globe are conducted, many of these areas being hard or even impossible to access via research vessels.

Advancements in robotics and the development of unmanned vehicles can help bring down the cost and complexity associated with ocean research missions as well as increase the quality of research done. Unmanned sailing vessels(USV) will be able to travel long distances over the ocean, for long periods of time, to remote and inaccesable locations and with little power consumption. USV's can be equipped with various high quality sensors such as hydrophones that are used in marine research. The integration of solar panels with USV's can further increase the range and duration they are capable of.

1.2. Problem Statement

To design and develop the navigational and control systems for an unmanned sailing vessel that will enable it to sail along a predetermined route with a relative degree of accuracy. The route to be travelled is defined by a set of GPS coordinates.

1.3. Objectives

This section will state the objectives that need to be achieved in order to address the problem statement.

1. Design and develop a digital compass that compensates for tilt.
2. Determine and compare the accuracy of bearing obtained from a GPS reciever and that from a digital compass.
3. System must be capable of logging operational data to a micro-SD card.
4. Design and implement necessary navigational algorithms: Determine distance and bearing between two GPS coordinate.
5. Design and develop sail control system.
6. Design and develop rudder control system.
7. Design and implement tacking manuovre into system.

1.4. Summary of Work

1.5. Scope

Chapter 2

Literature

2.1. Sail Theory

This section covers the sailing theory that is required for the sections that follow, and is taken from the official manual of the american sailing association [?]. Fig. ?? illustrates the anatomy of a typical sailboat. The anatomy of a sailboat is as follows:

- Hull: Watertight floating body of the sailboat that gives it form and supports all parts of the part.
- Keel: Fixed fin on the underside of the sailboat that provides sideways resistance needed to counter the force of the wind on the sails.
- Stern: The back-end of the sailboat.
- Bow: The front-end of the sailboat
- Starboard: When standing at the stern, facing the bow, starboard is the right side of the boat.
- Port: When standing at the stern, facing the bow, port is the left side of the boat
- Rudder: Fin located beneath the stern. The angle of the rudder is adjusted to steer the direction of the sailboat.
- Helm: The mechanism by which the rudder angle is adjusted.
- Mast: Vertical beam attached to the hull which houses the mainsail
- Mainsail: Sail that attaches to the mast of the sailboat.
- Jib: sail that attaches to the bow and the top of the mast.

When on a sailboat the direction of the wind relative to the boat is known as the apparent wind, the direction of the wind relative to a fixed point - a point that has a zero velocity - is known as true wind. When the sailboat has a velocity that is not zero -

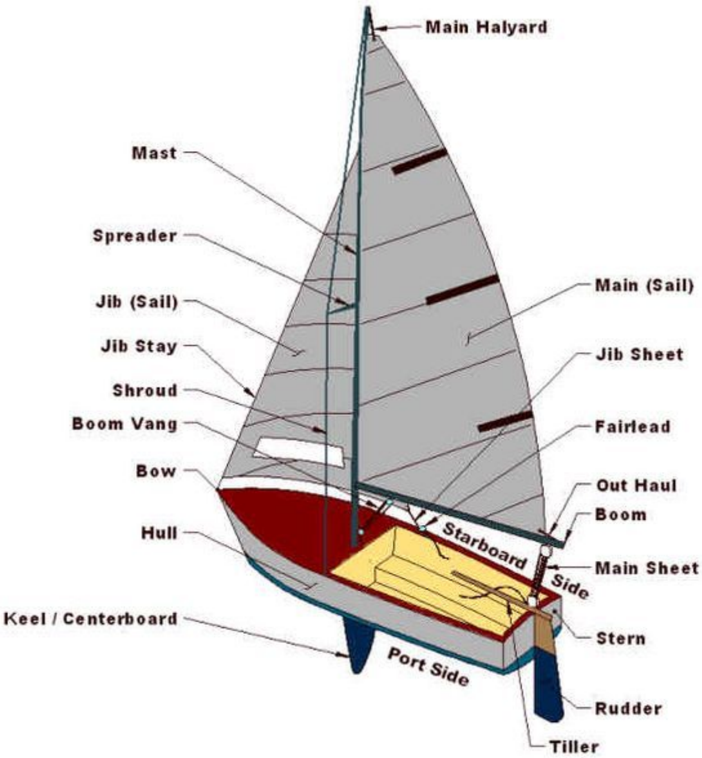

Figure 2.1: Sailboat anatomy [**?**]

sailboat not standing still - the apparent wind has a velocity that differs from the velocity of true wind. Fig. **??** illustrates this concept.

The sail of a sailboat acts similar to that of a airplane wing - it produces lift when orientated correctly. It is this lift that propels the sailboat forward. The orientation of the sail relative to the apparent wind therefore determines how much force is applied to the boat, any component of this force that acts perpendicular to the centerline of the boat is canceled by the apposing force of the water on the keel. The act of changing the orientation of the sails is know as 'trimming the sails'. To generate a maximum amount of forward force on the sailboat, the sail must be positioned to capture as much of the winds energy as possible. The direction of apparent wind determines the directions that

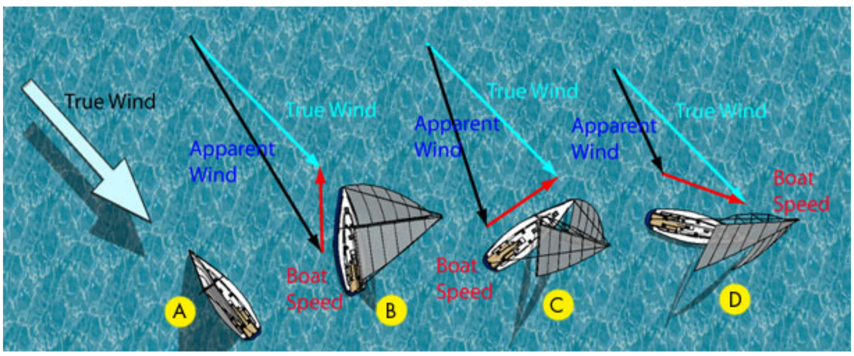

Figure 2.2: Apparent wind [**?**]

the sailboat can/cannot sail, these directions are known as points of sail and are measured relative to the direction of apparent wind. Fig. ?? illustrates the points of sail of a sailboat. It should be noted that there is a range known as the 'no-sail zone' in which a sailboat cannot sail. This range is measured 45° to both sides of the apparent wind when sailing directly towards the apparent wind.

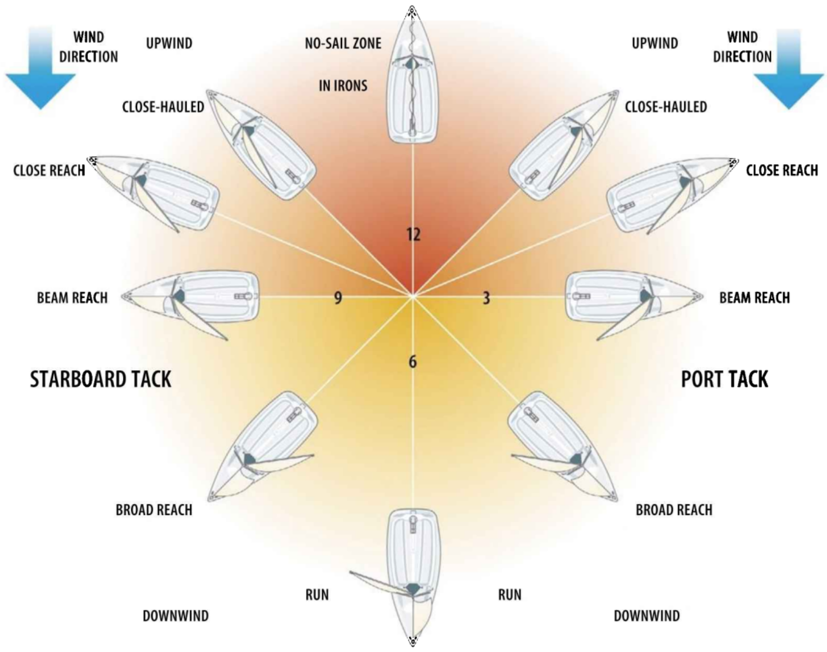

Figure 2.3: Point of sail [?]

Point of sail is traditionally measured analogous to a clock, as shown in Fig. ??. For the purpose of this report point of sail will be defined as the angle between apparent wind direction and the direction of travel of the boat, measured clockwise in degrees. A sail direction of 0° will then correspond to 12'oclock in Fig.?? and 180° will corresponding to 6'oclock measured clockwise. The position of the mainsail will be defined by the angle between the mainsail and the centerline of the sailboat to either the starboard or port side.

If the desired destination is within the no-sail zone, a manoeuver known as 'tacking' can be performed to reach the desired destination. When sailing with he wind blowing on the starboard, its on the starboard tack, and when the wind is blowing on port side, the boat is on port tack. Tacking is the act of turning the bow of the sailboat through the no-sail zone. Assume the boat is on starboard tack and point of sail is 45°, after some distance has been travelled the bow is turned through the no-sail zone to attain a port tack and a point of sail of $-45°$, this 'zig-zag' motion is done continuously until the desired destination is reached.

Another important manoeuver is the 'jibe', which is defined as the action of changing from a starboard tack to a port tack. An example of this occurring is when point of sail changes from 160° to 100°, initially apparent wind will be port side but after crossing over 180° the wind will be starboard side, during this crossover the mainsail will often swing from starboard to port.

2.2. Related Work

2.2.1. Unmanned Sailing Vessel by Philip van Schalkwyk

Philip is a mechatronics graduate who designed and developed an unmanned sailing vessel for his final year project at Stellenbosch University [?].

Objectives

The purpose of the project was to design and develop an USV that is capable of semi-autonomous sailing. The objectives are as follows:

- Design and develop a low-cost digital compass that produces accurate readings with tilt compensation.
- Design and develop a a low-cost mechanical wind vain that consists of a digital compass for wind direction sensing.
- Retrofit a RC sailing vessel with a micro-controller, digital compass, wind direction sensor, GPS unit and micro-SD card.
- Design and implement navigational and control systems to enable autonomous sailing.

Method Used

A RC sailing vessel was retrofitted with a micro-controller that would read data from sensors and adjust the rudder and sail position in order to sail along a desired path. The system consisted of a micro-controller, GPS receiver, a micro-SD card, an digital compass, wind direction sensor and two servo motors - one to control the sail and one to control the rudder angle. The micro-controller that was used was a Espress ESP-WROOM-32 micro-controller which is relatively low cost and has a 240 MHz clock speed. The electronic compass was used to determine the current bearing of the vessel, it was designed and developed using a magnetometer, accelerometer, gyroscope and tilt compensation algorithms. The MPU9250-6500 9-axis sensor module was used for the electronic compass as it consists of a magnetometer, accelerometer and a gyroscope. A mechanical wind vain was designed with CAD software and printed with a 3D printer. The wind vain was fitted with a magnetometer - also the MPU9250-6500- which was used to determine the bearing of the wind vane and therefore the wind direction. The GPS receiver that was used for the navigational system was a Neo M8N GPS, it would log positional data to the micro-SD card.

A proportional controller was used to control the rudder position. The desired heading/bearing was calculated using the current GPS coordinates obtained from the GPS receiver and the target GPS coordinates. A sample would then be taken from the electronic compass which would give the current bearing of the vessel, the difference the current bearing and the desired bearing is the error signal. The proportional controller would then determine the rudder angle given this error signal, and the servo motor controlling the rudder would be adjusted accordingly.

The main sail position was determined by the samples taken from the wind direction sensor and the current bearing. Only three point of sail classifications were used for the sail positions : close-hauled, beam-reach and run. This was done to give more time to navigational and rudder control systems. If it was determined that angle of attack was less than 45 deg the vessel would tack into the wind. This was achieved by calculating the bearing to either side of the no-sail zone, the vessel would then sail with one of these bearings for 50 meters and then change to the other bearing. The vessel would alternate along these bearings until the target destination was reached.

Results

The e-compass was tested against a magnetic compass and the results showed the average error in bearing to be 5.84°, the e-compass did however produce a consistent spike at 180° across multiple tests. Tests that were done with the GPS receiver showed that the positional accuracy of the GPS receiver was sufficient for the navigational system and data-logging. The wind sensor that was developed was unable to provide wind direction data consistently, a possible explanation for this is that the length of the I^2C connection is too long and therefore the capacitance in the lines caused a low pass filter effect on the signal. In the final tests that were conducted to verify the successful operation of the control systems, the point of sail classification was set to run initially and sail adjustments were not taken throughout the duration of the test - due to the wind sensor not working. The results of the final test showed that the rudder control system was capable of keeping the vessel on a near constant heading, with a maximum absolute error of 6○. This test was conducted between two GPS coordinates and the vessel therefore sailed on a fixed bearing between them. Fig **??** shows the results of this final test.

Remaining challenges

The rudder control system designed by Phillip was capable of accurately tracking a desired bearing during tests. Proportional integral control could not be implemented due to the consistent error that occurred during the e-compass testing. The USV that was developed

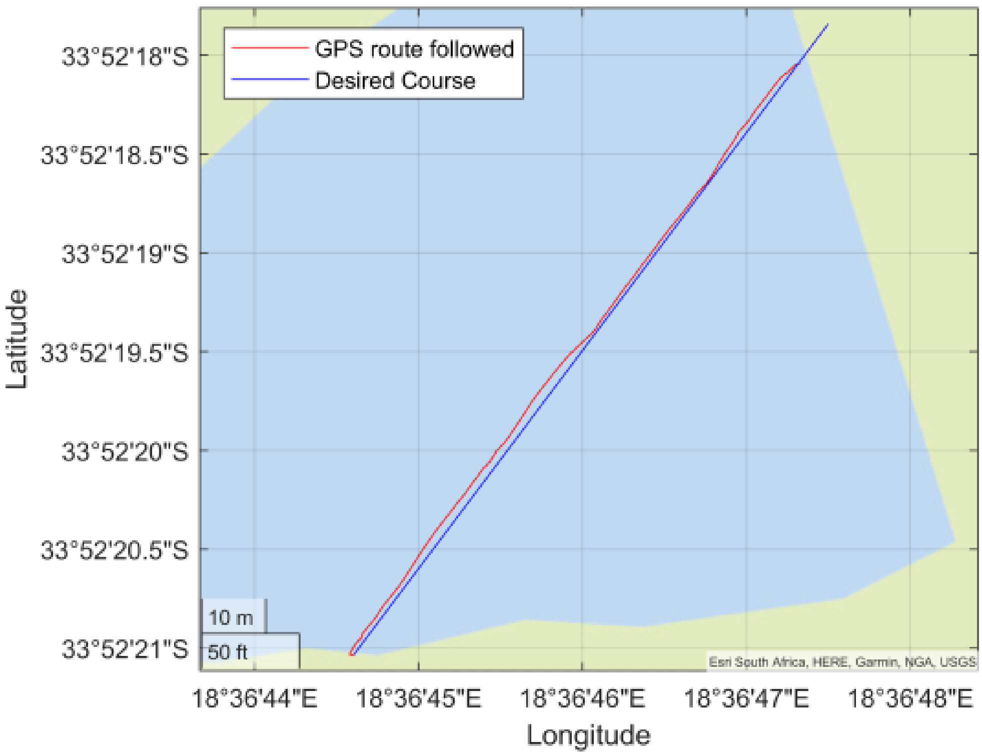

Figure 2.4: Test results showing deviation of vessel from ideal trajectory [?]

does not however have the ability to dynamically adjust the sail position according to the relative wind direction, and is therefore unable to achieve the desired performance if wind direction is not constant. Tests where also not conducted to verify the tacking capabilities of USV.

2.2.2. Design and Implementation of a Control System for a Sailboat Robot

Objectives

- Determine the dynamic equations that govern the behavior of a sailboat.
- Use the dynamic equations to design - through simulation- a simple, however effective, controller that can be applied to different types of sail boats.
- Develop a prototype sailboat to implement and test a controller which was designed through simulation.

Method Used

The system that is developed for an autonomous sailboat consists of two processing units, a combination of sensors, and actuators/servos. Two processing units are used for a more flexible system. The one processing unit is a ATMega2560 which is built into an arduino, and is used to handle low level control decisions that should be executed in real time. The arduino communicates with the various sensors and implements the control algorithms used to control the actuators in a stable manner. The other processing unit is a Raspberry Pi which is responsible for high level navigation decisions, planning and external communication. The Raspberry Pi is connected to a base station via a XBee radio link of up to 1.6 Km. The two two processors communicate with each other via a RS-232 serial connection. The sensors that are used consist of a GPS receiver (EM-406 SiRF III), and a three axis digital compass (actual component used is not specified). A wind sock is used to determine wind direction and this is then transmitted to the system from the base station via XBee. Digital compass is calibrated to compensate for local magnetic declination.

The approach used to design an appropriate control system for an autonomous sailboat is to mathematically model the dynamics of the sailboat, and then through simulation, identify the optimal parameter values of the controller. Determining the dynamics that govern the behavior of a sailboat are divided into calculations of hydrodynamics, moment of inertia, viscous damping, lift, effort sail and centre of mass. These calculations are combined to form Eq. **??** which is used as the control law that governs sailboat control. In Eq. **??** M_a refers to the hydrodynamics, C_{rb} is dynamics(including centre of mass), C_a refers to hydrodynamics related to coriolis and centripetal forces, D_k term is the lift moments generated by the keel and D_h are the lift forces acting on the hull.

$$(M_{RB} + M_A)\dot{\upsilon} = \tau_s + \tau_r - (C_{RB}(\upsilon) + C_A(\upsilon))\upsilon - (D_k(\upsilon) + D_h(V))V - g(\eta) \qquad (2.1)$$

Two controllers are initially developed: a PID controller for rudder control, and a fuzzy controller, which controls the sail position. By making use of Eq. **??** and simulation software (MATLAB) optimal parameter values are found for the PID controller. This approach is faster than the traditional method of adjusting the parameters, however since the mathematically model does not truly represent the sailboat the parameter values found are used as initial values to be further adjusted through experimentation.

The rudder controller takes in an error signal as its input and outputs the appropriate control signal to the rudder actuator. The error signal is determined as the difference between the actual bearing of the sail vessel and the desired bearing of the sail vessel. Desired bearing is calculated using current GPS location of the vessel and the target GPS location. The actual bearing of the sail boat is determined from the digital compass.

The sail controller takes wind direction as its input and adjusts the sail position accordingly, the controller also takes into account limits of the sail vessel i.e. the dead-zone/no-sail zone.

In the sailboat prototype that is developed, the D parameter used in rudder control is disregarded, mainly because of instability, which is generated due to intensification of high-frequency noise caused by the derivative.

Results

In the simulation the optimal gains for the rudder controller are: Kp = 0.68, Ki = 1.125 and Kd = - 0.130. These controller gains were used as initial values to be fine-tuned through multiple tests done with the prototype sailboat. After conducting the tests the resulting adjusted rudder controller gains were: kp = 2.3 and ki = 0.8. The tests that were done compared the use of a proportional controller and a PI controller for the rudder control, Fig.**??** shows the results of one of the tests. Note that the sailboat was initially placed to face 90° from target location. In all tests that were conducted the prototype sailboat reached the specified target coordinates, the PI controller, however, performed better than the P controller with less deviation from the ideal trajectory.

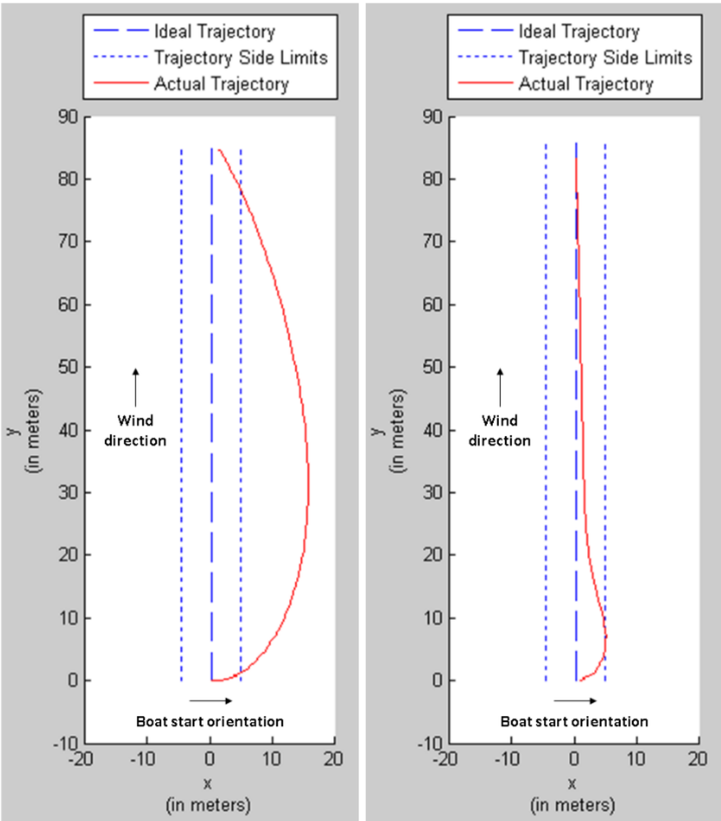

Figure 2.5: Test results on water; P controller shown left and PI controller on right [**?**]

Remaining challenges

The system that was designed and developed does not incorporate an onboard wind direction sensor but instead receives the wind direction data from a base station via XBee.

The sail vessel will therefore not be capable of travelling distances over which the apparent wind direction around the vessel differs from the wind direction around the base station. Aside from this, the system that was developed addresses the problem statement in section **??**; the purpose of the following sections is then to duplicate the above system.

2.2.3. FASt - An autonomous sailing platform for oceanographic missions

the purpose of this project was to design and develope an autonomous sailing boat to enter the Microtransat competition - competition for fully autonomous sailing boats wherein the goal is to cross the atlantic ocean [**?**].

Objectives

- Design and construct a high performance and light-weight sailboat of suitable size.
- Design and develope an electronics system that will enable long distance autonomous navigation and control of the sailboat.
- The electronics system must include a communication subsystem for short range and long range communication.
- The electronics system should have a low power consumption and powered by a power source that is recharged via photovoltaic cells.

Method Used

The sailboat hull shape was inspired by modern racing oceanic yachts and was constructed with fiber glass and epoxy resin. The total length of the sailboat is 2.5 m with a mast height of 3.4 m. It features two independently controlled rudders and two sails which are controlled simultaneously

The electronics system was divided into 5 subsystems: computing, communication, sensors, actuators and power management. The computing system consists of a 32-bit RISC microprocessor running with a maximum clock speed of 50 MHz, ROM memory which holds the bootstrap code and various digital modules that interface the processor with the sensors and actuators. The computing system was implemented using a FPGA, the one that was used was a Suzaki SZ130 which is built around a Xilinx FPGA. The board includes central Microblaze processor running at 50 Mhz, 32 MB of SDRAM, 8 MB of SPI flash memory, a serial interface (RS232) and ethernet port implemented externally to the FPGA. The board has 86 input/output pins available, which connect directly to the FPGA. The computing system runs uCLinux which a version of linux which has been simplified and adapted for embedded applications running processors with no memory management unit. The advantage of using an FPGA is that many of the processing and interfacing functions of the system can be implemented in custom hardware and therefore are not managed by a micro-processor; this allows the use of a micro-processor that runs at significantly lower clock speeds and thus lower overall power consumption.

The communications subsystem consists of a conventional WiFi router (LinkSys WRT54GC), a GSM modem (Siemens MC35), a IRIDIUM SBD modem (model 9601) and a radio control receiver. The WiFi router is to provide convenient short range communication with a laptop, mainly for the purpose of software development, debug and communication purposes. While at sea missions, the GSM modem and IRIDIUM SBD modem will enable small volume communications to take place. The GSM module enables communications within a range of a few kilometers from shore, the IRIDIUM SBD modem communicates via satellite connection and allows and therefore has a global range. The radio control receiver allows for manual control over the sailboat using a 4 channel proportional control RC transmitter.

Sensors used consist of a wind vane, anemometer, boom position sensor, digital compass (LinkSys WRT54GC), GPS receiver(uBlox RCB-4H), inclinometer, voltage monitors, ambient light sensor, interior temperature and a set of water sensors. The wind vain and boom position sensors were custom built using a magnetometer (Austria Micro Systems AS5040) and are used in the sail position control system. The anemometer is a conventional cup rotor that makes use of a hall effect switch, its main purpose is for data collection and data logging during sea missions. The digital compass and the GPS receiver are used for navigation and data logging purposes. The inclinometer is used to determine heel angle which is used to reef the sails. It should be noted that the sailboat that was developed does not have the ability to adjust the area of the sail i.e. reef, the inclinometer was included for future iterations of the project that possess have this ability. The voltage monitors are used to monitor the voltage of the batteries. The ambient light sensor is used to monitor light intensity which affects the voltage produces by photovoltaic cells. Specific hardware was designed and implemented in the FPGA to interface these sensors with the RISC micro-processor.

The actuators in the system consist of two standard high-power RC servos which provide independent control of the two rudders. The two sails are both controlled simultaneously by a DC geared motor. Although having a low efficiency the DC geared motor is extremely robust, and once position and un-powered the gearbox locks the motors shaft in place. Traditional servo motors consume power in holding a certain shaft position in response to an applied force on the shaft. The use of the DC geared motor is therefore advantageous as sail position is only adjusted when changing course or if a change in wind direction occurs, therefore no power is consumed in keeping the shaft fixed in reaction to the force applied by the wind. A multiplexer was implemented in hardware to select the source data that is routed to the actuators, if a RC connection is established then this data is selected, otherwise data from the computing system is selected.

The power management system consists of a 45 Wp solar panel (Solara SM160M), two 95 Wh Li-ion batteries, a battery charging circuit and a highly efficient power supply. A wind generator was considered to compliment the photovoltaic cells but ones available commercially are too large and heavy for this application. The total power consumption of the system was measured to be 560 ma.

The software is divided into five modules that implement the five main tasks: hardware interface, helm, sail, skipper and logger. The hardware interface implements all the driver software needed for the processor to communicate with sensors,actuators and configuration parameters. The helm implements the PI controller used to control the rudder position according to wind direction and desired bearing. The commands supported by this module include keeping a fixed bearing, maintaining the angle of apparent wind and performing tacking or gibing maneuvers. The sail module is responsible for controlling the sail position according to wind speed and direction and a set of rules that define best sail angle. This module also implements reefing of the sails - the sheet is eased when heel angle is greater that a certain value. The skipper module sends commands to the helm and sail modules and is responsible for higher level navigation such as deciding what course to follow and when to perform certain sailing maneuvers. The logger module listens to all the other modules and stores relevant data in a log file.

Results

This article does not cover the testing of the system described above and therefore the validity of the design cannot be verified. The article does however highlight important hardware and software design features to consider when attempting to design an autonomous sailing vessel

Remaining challenges

The system made use of an FPGA to implement the central computing system as well as interface with the sensors and actuators of the system. While this does decrease the power consumption of the system it also greatly increases the complexity of the design. Many modern micro-controllers already incorporate the hardware needed to interface with the various sensors and actuators used in this system.

Given that the scope of this project stated in section **??**, low power consumption of the system, although important in long distance sea missions, is not of vital importance for the purpose of designing and developing the navigational and control systems for an autonomous sail vessel.

The system included functionality that is not needed for the purpose of this project. Some of this functionality includes the simultaneous control of two sails, two rudder servo's, boom position sensing, wind speed sensing, heel angle sensing, a power supply that incorporates rechargeability and photovoltaic cells, and a communications subsystem for short and long range communication with the vessel.

2.2.4. Establishing frame of reference

It is important to establish a fixed frame of reference which can be used to determine the orientation of a vessel at sea. The fixed frame of reference that will be used in this report is the industry standard "NED" (North, East, Down) coordinate system. The NED coordinate system is orientated such that at any position on the earth the x-axis is aligned with true north, the y-axis is aligned with lines of latitude and points east, the z-axis is aligned with the vector that represents the acceleration of gravity. The x,y-plane is therefore tangent to the sphere of the earth. The inertial frame of the sailing vessel is fixed to the body of the sailing vessel and is the perspective that a person on the sailing vessel would have. The x-axis of the inertial frame of the sailing vessel is aligned with the centerline of the vessel and points from the stern to the bow, the y-axis is aligned perpendicular to the centerline of the vessel and points to the starboard side, the z-axis is aligned with the mast of the vessel and points downwards. This concept is illustrated in Fig. ??.

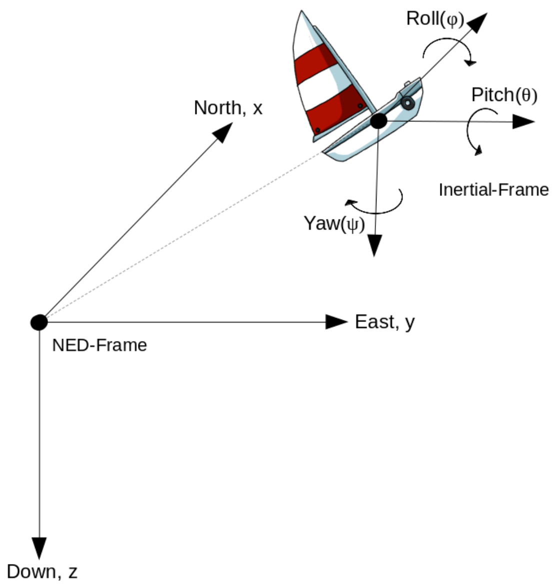

Figure 2.6: NED frame of reference

Rotation of the inertial frame about the x-axis is known as the roll angle (ϕ), rotation about the y-axis is the pitch angle (θ), and rotation about the z-axis is the yaw angle (ψ). For all axes, clockwise rotation is taken to be positive rotation. Given that the roll, pitch, and yaw angles are all known it is possible to transform the inertial frame back to the NED frame using transformation matrices in Eq. ??, ??, ?? [?].

$$\mathbf{R_{x,\phi}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \tag{2.2}$$

$$\mathbf{R_{y,\theta}} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \tag{2.3}$$

$$\mathbf{R_{z,\psi}} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.4}$$

2.2.5. Magnetic declination

A traditional handheld magnetic compass will align itself with the earths local magnetic field lines, which in theory run from the magnetic south pole to the magnetic north pole. This means that a magnetic compass will point to magnetic north. However in practice this is not true, the earths magnetic field lines are not constant, and depending on where measurements are taken there will exist an angle of error. True north is defined as

True north, also known as geographical north, is defined as the point where all lines of longitude intersect. Magnetic north is the point to which a magnetic compass aligns itself, and varies across the globe as well as with time. The direction of magnetic north differs depending location because earths magnetic field lines do not travel a linear path from magnetic south to magnetic north, this is illustrated in Fig. **??**.

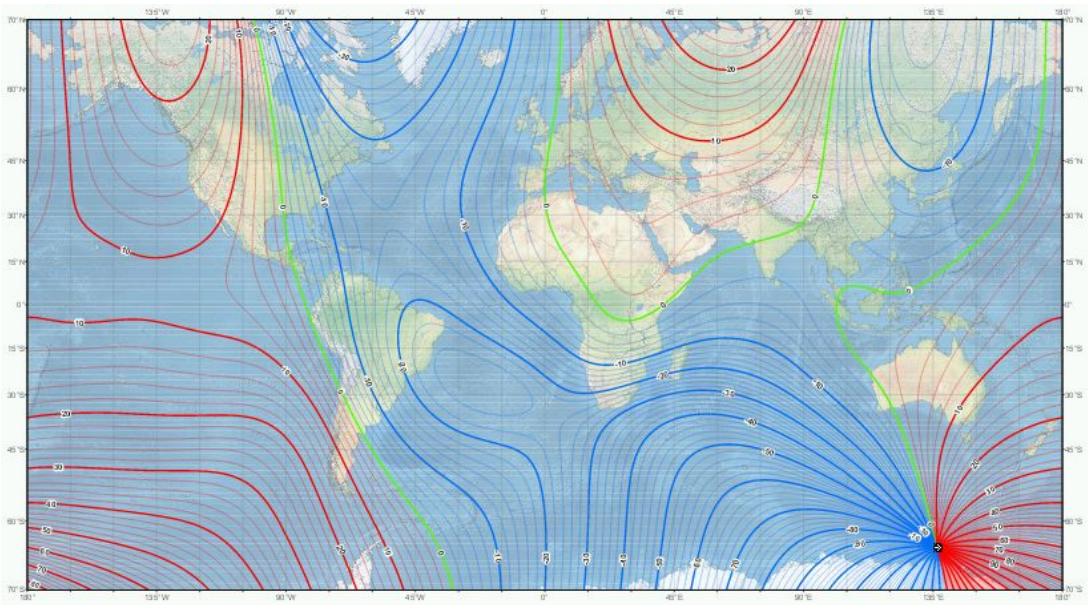

Figure 2.7: Magnetic declination across the globe [**?**]

Magnetic declination is an angle of correction used to determine true north from a local magnetic north reading. Magnetic declination takes into account the variance of local magnetic field lines and the angle between magnetic north and true north. Magnetic declination therefore differs across the globe. The National Oceanic and Atmospheric Administration (NOAA) keeps track of magnetic declination across the globe as it changes with time. The magnetic declination in Stellenbosch is $25.77^\circ \pm 0.59^\circ$.

Chapter 3

System Design

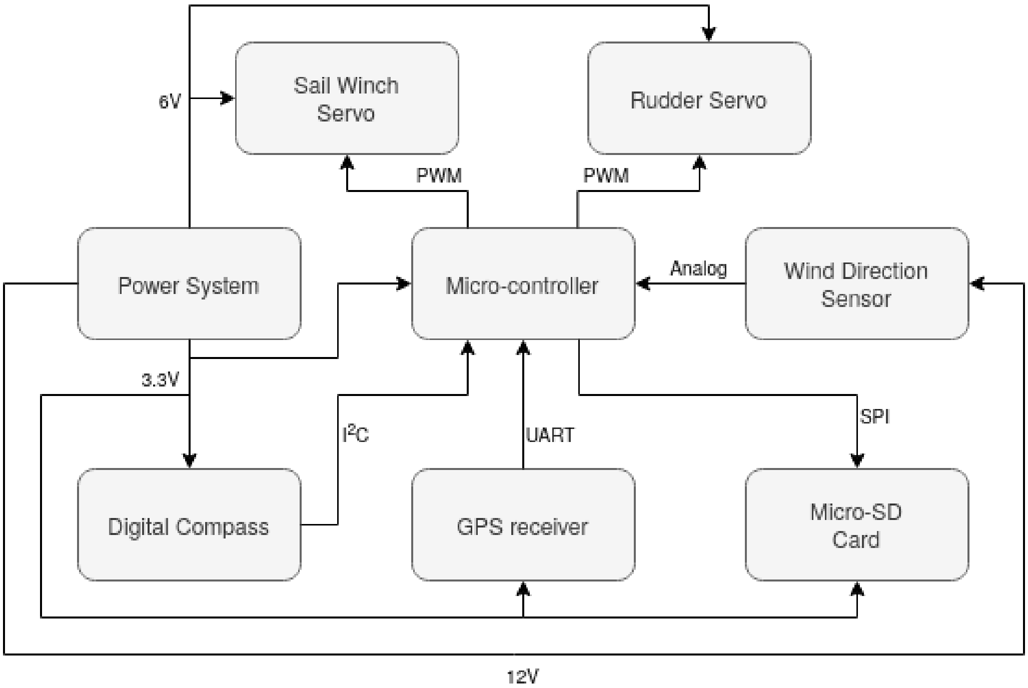

Figure 3.1: System Diagram

3.1. Sail Vessel

The sailing vessel houses the entire system illustrated in Fig. ??. Designing and developing a sailboat is a complex task on its own, requiring expertise and experience in many fields, some of which include aerodynamics, hydrodynamics and material design. Given the complexity of this task and the time constraints of the project, an existing RC sailboat was used. A Dragonflite 95 RC sailboat [?] was modified to incorporate the system illustrated in Fig. ??. The Dragonflite is 950 mm in length and has an overall weight of two kilograms. It features two sails (mainsail and jib), a carbon fibre mast and moulded carbon fibre keel with zinc alloy ballast bulb. The sailboat is operated with a 2.4Ghz 4-channel digital proportional transmitter which communicates with a 2.4Ghz 4-channel receiver. The

Dragonflite 95 comes preinstalled with a rudder servo motor as well as a sail winch servo motor. The sail winch servo controls both the mainsail and the jib simultaneously. The receiver and two servo motors are powered with a 6v battery source (4 AA batteries). The transmitter and receiver were removed as they are not needed in the development of a autonomous sailboat.

3.2. Micro-controller

Two options were considered for the micro-controller: the Adafruit BlackPill STM32F411 development board [**?**] and a Adafruit STM32F405 Feather [**?**]. The Adafruit BlackPill has an Arm 32-bit Cortex-M4 CPU, which has a clock speed of 100MHz, 512KB flash memory, 128kB SRAM, and has a power efficiency of $100\mu A/MHz$. The Adafruit feather has an Arm 32-bit Cortex-M4 CPU, with a clock speed of 168 MHz, 1MB flash memory, and has a power efficiency of $238\mu A/MHz$. Despite the higher price and power consumption of the Adafruit Feather, it was chosen for this system as it has a higher clock speed, which is needed for the navigational and control systems. The Adafruit feather also has a jst connection for a lithium-polymer battery as well as a 3.3V regulator.

3.3. Wind direction sensor

The direction of apparent wind is needed to determine the optimal positioning of the sails. Wind direction sensors that were considered where: an ultrasonic anemometer, a mechanical wind vain, and the development of a wind direction sensor using four electret microphones and correlating the signals. The ultrasonic anemometer that was considered was the WS303U by Sentec Meteorology, it was not used because it is too large for the sailing vessel. The development of a wind direction was not done because of the time constraints of the project. The mechanical wind vain was chosen as the most viable option. The sensor used was the FST200-202 [**?**] made by firstrate sensor company. This sensor is designed for outdoor environments such as weather stations and boats, it therefore has excellent resistance to extreme weather conditions and erosion. The sensor works in wind speeds greater than 0.8 m/s, has a 22.5° resolution and ±3° accuracy. It features automatic temperature compensation and operates in a temperature range of $-20°C$ to $+85°C$. The sensor has a working voltage of 12 30VDC, and its output is a 4-20 mA signal.

3.4. Servo motors

Two servo motors are required: one for controlling the mainsail, and the other for controlling the rudder. The decision was made to use the preinstalled servo motors as the vessel was designed operate with these specific servo motors, it also keeps system design costs low. The manual specifies that a metal geared servo is used for rudder control and a sail winch servo is used to control the sail position. Aside from this, no other information is given in the manual about the servo motors.

3.5. GPS receiver

The GPS receiver is used to determine the GPS coordinates and speed of the sailing vessel. GPS coordinates of the vessel are needed to calculate the reference bearing (used in rudder control), which is the bearing between current position and the target position. All GPS receivers on the market are accurate to within 2.5m, component choice is therefore dependant on factors such as price, power consumption and update rate.The GPS receiver that is used is a ATGM336H-5N [?] module. It was chosen because it has a high tracking sensitivity, low power consumption and is low cost. Supply voltage of the receiver is 3.3V and it communicates via a UART interface. It has a tracking sensitivity of -162dBm, consumes $< 25mA$ during continuous operation, has a first positioning time of 32 seconds, maximum update rate of 10Hz, and also features built in antenna short circuit protection.

3.6. Digital compass

The digital compass is used to determine the bearing of the sailing vessel, which is compared to the reference bearing to determine if the vessel is off course. It is required that the compass be able to perform tilt compensation, as the vessel will not always be on a level surface out at sea. If the digital compass is tilted and used to determine bearing without tilt compensation, the bearing will not be accurate. To perform tilt compensation a magnetometer is needed to determine magnetic field vector, and a accelerometer is needed to determine the acceleration due to gravity vector. An IMU is a device that contains both a 3-axis magnetometer, 3-axis accelerometer and 3-axis gyroscope. The two options that were considered were a AltIMU-10-V4 [?] made by Pololu Electronics and a MPU-9250/6500 9-axis IMU [?]. Both options feature 16-bit ADC with signal conditioning. The Alt-IMU-10-V4 also features a digital barometer which is not needed for the purposes of this project. The MPU-9250/6500 was chosen for its low cost when compared to the AltIMU-10-V4. The MPU-9250/6500 has a supply voltage of 3.3V, an operating current of 3.5mA and an I^2C interface.

3.7. Micro-SD card

The Micro-SD card is used for data-logging purposes, it allows for data from tests to be stored and analysed at a later time. Data that is logged during water tests include:

current position, current bearing, desired bearing, bearing error, distance to target, wind direction, and tracking speed. A micro-Sd card socket made by Pololu [**?**] was used, and features a SPI.

3.8. Power system

The power system consists of three separate power sources. The rudder servo and sail winch servo are powered by a 6v battery source consisting of four 1.5V alkaline batteries in series. The Adafruit feather is powered by a 5000mAh 3.7V lithium polymer battery. The Adafruit feather is used to power the micro-SD card socket, GPS receiver, and digital compass. The wind direction sensor is powered with two 9V alkaline batteries in series. The use of one 12V power source with a 3.3V regulator was initially considered. Three separate power sources were chosen because the power consumption of the system is such that two 9V alkaline batteries would only power the system for 2.13 hours, which was considered insufficient.

3.9. Metrics

Digital compass

Successful operation and accuracy of the digital compass is determined with two separate tests.

The first test is done to test the accuracy of the digital compass. The setup is as follows: the digital compass undergoes extensive calibration, the digital compass as well as a handheld magnetic compass shown in Fig. **??**, are placed on a flat piece of wood and spaced such that they do not interfere with each other, the wood is rotated in steps of 10° anti-clockwise, each step readings from the handheld compass and the digital compass are taken and compared, because of the sample deviation present in the digital compass 10 samples are taken each step and an average is taken for comparison.

The second test is done to determine the successful operation of the tilt compensation algorithm that is used. The setup is the same as the first test, but this time a pitch angle of 10° is applied to the digital compass, the handheld compass is still placed flat. Again the wood is rotated in steps of 10° anti-clockwise, and again ten samples are taken from the digital compass on each step, the average of these samples is used for comparison. The results of this test are compared with the results from the first test - where the digital compass had a pitch and roll angle of zero.

Accuracy of the digital compass needs to be compared with that of the GPS receiver. If the GPS receiver is capable of determining the bearing with better/or even the same degree of accuracy as that of the digital compass, and doing so with the same sampling period, then the use of a digital compass in the system does not make sense. It should be noted that the GPS receiver is only capable of determining bearing when the velocity of the system is greater than zero. The test done to compare the accuracy of these two components is as follows: The GPS receiver is carried along a path of constant bearing and with a velocity similar to that of the maximum velocity the sailboat is capable of, bearing samples are then taken at a frequency of 10Hz (maximum sampling frequency of the receiver), the same is then done for the digital compass, digital compass is held such that it points to the end point of the path throughout the test. The digital compass must be calibrated before the test. The results of the two tests are then compared.

Navigational calculations

The successful operation of the algorithm used to determine distance between two points is verified using the following experimental setup: a target GPS coordinate is given to the system, the current GPS coordinates are obtained from the GPS receiver at varying distances from the target and distance is calculated, distances that samples are taken are physically measured out before the test is done, an average of ten distance calculations are done for each change in distance.

Data logging

To verify the system is capable of logging data as well as test the successful operation of the GPS receiver, a simple test is conducted. The experimental setup is as follows: The system is carried along a path, the GPS receiver will take samples at a rate of 10Hz, the GPS coordinates will then be logged to the micro-SD card on each sample, results are then analyzed to determine if path that was logged corresponds to the actual path travelled.

Sail control

A test will be conducted to verify accuracy as well as successful operation of the sail control system. The experimental setup is as follows: wind direction sensor will be adjusted in 10° increments with 0° corresponding to center on no sail-zone, corresponding change in sail position will then be measured from the centerline of the boat.

Rudder control

The first test will test the operation of the rudder control out of the water. A target GPS coordinate will be chosen and given to the system, the system will then be carried along a path of constant bearing ending in the target coordinate, the current position, desired bearing, actual bearing and error signal will be logged throughout the test.

The second test will be done on the dam by the Maties canoe club. The experimental setup is as follows: a target coordinate is programmed into the system and the digital compass is calibrated, the sailboat is placed at a starting point such that the point of sail is 180° i.e. wind directly from behind, the sail position is set at 80°, data is logged throughout the test. The data that is logged is: current GPS coordinate, distance to target, desired bearing, actual bearing, bearing error signal and rudder PWM value.

Sytem

A similar test will be done on water at the Maties canoe club to verify the successful operation of the entire system - navigational and control systems. The test is similar to the second test done for the rudder control except the sail control will be excluded, and the setup is as follows: a target coordinate is programmed into the system and the digital compass is calibrated, the sailboat is placed at a suitable starting point, data will be logged throughout the test. The data that is logged is: current GPS coordinate, distance to target, desired bearing, actual bearing, bearing error signal, rudder servo PWM value, apparent wind direction, sail position value, sail servo PWM value.

Chapter 4

Detail Designs

4.1. Micro-controller

The Adafruit STM32F405 feather has a supply voltage of 3.7V and consumes up to 80mA when operational, it is powered by a 5000mAh 3.7V lithium polymer battery connected with a jst connection. The board features a 3.3V regulator which is to regulate the battery power, there are also pins to distribute the 3.3V regulated power off-board. The 3.3V regulator is used to power the GPS receiver, MPU-9250/6500 IMU, and the micro-SD socket. The board has a USB-C female connector which is used to load the main program and for debugging during the design process. The board is capable of running circuit python, which was used in the development of this project.

4.2. GPS receiver

The GPS receiver has a power supply voltage of 3.3V and is powered by the Feathers 3.3V regulator. It is connected to a pin on the feather which is configured as UART, with a BAUD rate of 9600. The GPS receiver continually receives data at a frequency which is set during the configuration process, in this case its every second. Data sent by the GPS receiver is in the form of ASCII encoded sentences which follow the NMEA protocol [**?**]. The NMEA protocol defines a number of ASCII identifiers which occur at the beginning of each ASCII sentence, they are used to identify the type of data contained in the sentence. Table **??** shows the specific NMEA sentences which are relevant to this project and their corresponding ASCII identifiers.

4.3. Wind Direction Sensor

The wind direction sensor has a supply voltage in the range 12 30VDC, and is powered by two 9V alkaline batteries in series. It outputs a $4 - 20mA$ analog signal, which is connected directly to pin A4 of the Feather. Pin A4 on the Feather connects to a 5V tolerant pin on the STM32F405 micro-controller. This pin was configured to use one of

Table 4.1: NMEA sentence information

Sentence identifier	Description
$GPGGA	Global Positioning System Fix Data (Time, Latitude, Longitude)
$GPGLL	Geographic Position, Latitude / Longitude and time.
$GPGSV	GPS Satellites in view
$GPVTG	Track Made Good and Ground Speed.
$GPRMC	Recommended minimum specific GPS/Transit data (Latitude, Longitude, Speed over ground in knots, Track angle made true, Magnetic variation)

the micro-controllers 12-bit ADC, which has a sampling range of $0V$ to $3.3V$. A shunt resistor with a value of 160Ω is connected to the sensor output. This value was calculated to produce a voltage over the resister in the range of $642mV$ to $3.2V$. The Actual voltage range measured over the shunt resister was $642mV$ to $3.07V$.

All pins on the STM32F405 micro-controller are capable of sinking or sourcing $25mA$ maximum, there is therefore no chance of the sensor damaging the micro-controller pin. A digital buffer was initially considered to prevent the micro-controller from loading the sensor output circuit, but was not used as the ADC inputs are high impedance. The STM32F405 data sheet [?] specifies that for an ADC input, the max external impedance allowed for an error below 1/4 of the LSB as $50K\Omega$. The shunt resistors value is multitudes smaller than this.

4.4. Servo Motors

Both the rudder servo motor and the sail servo winch are powered by a 6V source consisting of four 1.5V alkaline batteries. The rudder servo motor is connected to pin A2 of the feather, the Sail winch servo motor is connected to pin D9 of the Feather. Both these pins are configured to output a 50HZ PWM signal, with a duty cycle set by the rudder and sail position controllers. The rudder angle is measured from the centre line of the boat, this corresponds to the neutral position of the rudder. Positive rudder angle is measured from neutral position to the starboard side of the vessel, negative rudder angle is measured from the neutral position to port side of the vessel. Sail position is measured in degrees from the centre line of the vessel to either the port or starboard side. The maximum and minimum PWM values for both servo motors was determined experimentally and is summarized in table **??**, along with the corresponding angles.

The PWM duty cycle value is stored in a 16 bit register and is determined using Eq. **??**.

$$duty\_cycle = (\frac{PWM\_value}{1000}) \cdot 2^{16} \tag{4.1}$$

Table 4.2: Servo motor PWM limits

Servo motor	PWM_Min	PWM_Min corresponding angle	PWM_Max	PWM_Max corresponding angle
Rudder	48	60°	102	−60°
Sail	72	0°	120	80°

4.5. Micro-SD card

The micro-SD card socket has a supply voltage of 3.3V and is powered with the Feathers 3.3V regulator. It is connected to the Feather using a SPI interface. The micro-SD card sockets MOSI, MISO, and clock lines are connected directly to the corresponding pins on the Feather, the chip select line is connected to pin 6 of the Feather. The micro-SD card is formatted with the FAT32 file system, and as, such writing to the micro-SD card is done with FAT32 protocol.

4.6. Digital compass

The MPU-9250/6500 IMUhas a supply voltage of 3.3V and is powered by the Feather boards 3.3V regulator. It is connected to the Feather via a I^2C connection. The IMU has an address pin which is grounded. The purpose of the address pin is for setting the LSB of the I^2C, this allows two IMU's to be connected to the same bus, which is not needed in this case.

4.6.1. Tilt Compensation

To perform tilt compensation, firstly pitch and roll angles of the inertial frame of the vessel must be found. Eq. **??** is used to transform a sampled acceleration vector back to the NED frame of reference, where there exists only a z-component with magnitude 9.81 m/s^2. In this eqution $\mathbf{A}_s$ represents the acceleration vector which has been sampled from the IMU, g is acceleration due to gravity and $\mathbf{R_{x,\phi}}$, $\mathbf{R_{y,\theta}}$, $\mathbf{R_{z,\psi}}$ represent equations **??**, **??**, **??** respectively.

$$\mathbf{R_{y,\theta}} \cdot \mathbf{R_{x,\phi}} \cdot \mathbf{A_s} = \begin{bmatrix} 0 & 0 & g \end{bmatrix}^T \tag{4.2}$$

Expanding Eq. **??**, gives Eq. **??**. The components of the sampled acceleration vector are A_{sx}, A_{sy} and A_{sz}.

$$\begin{bmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\phi & -sin\phi \\ 0 & sin\phi & cos\phi \end{bmatrix} \begin{bmatrix} A_{sx} \\ A_{sy} \\ A_{sz} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} \tag{4.3}$$

Expanding Eq.?? further gives Eq.??,then Eq. ?? and ??.

$$\begin{bmatrix} cos\theta & sin\theta sin\phi & sin\theta cos\phi \\ 0 & cos\phi & -sin\phi \\ -sin\theta & cos\theta sin\phi & cos\theta cos\phi \end{bmatrix} \begin{bmatrix} A_{sx} \\ A_{sy} \\ A_{sz} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} \tag{4.4}$$

$$A_{s,x}cos\theta + A_{s,y}sin\theta sin\phi + A_{s,z}sin\theta cos\phi = 0 \tag{4.5}$$

$$A_{s,y}cos\phi - A_{s,z}sin\phi = 0 \tag{4.6}$$

Roll angle ϕ can be found using Eq.?? which results from rearranging terms in Eq.??

$$\phi = \arctan(\frac{A_{s,y}}{A_{s,z}}) \tag{4.7}$$

By substituting roll angle ϕ into Eq.?? - which is derived from Eq.?? - pitch angle θ is found.

$$\theta = \arctan(\frac{-A_{s,x}}{A_{s,y}sin\phi + A_{s,z}cos\phi}) \tag{4.8}$$

Now that pitch and roll angles of the inertial frame of the vessel are known, a sampled magnetometer vector - $\mathbf{B_s}$ - can be transformed to the NED frame of reference. This is done using Eq.??, where $\mathbf{B_r}$ is the transformed vector. Eq.?? is not used here as this will eliminate yaw angle ψ whixh in needed to determine the resulting bearing

$$\mathbf{B_r} = \mathbf{R_{y,\boldsymbol{\theta}}} \cdot \mathbf{R_{x,\boldsymbol{\phi}}} \cdot \mathbf{B_s} \tag{4.9}$$

Eq.?? is then expanded, giving Eq.?? and Eq.??.

$$\begin{bmatrix} B_{r,x} \\ B_{r,y} \\ B_{r,z} \end{bmatrix} = \begin{bmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\phi & -sin\phi \\ 0 & sin\phi & cos\phi \end{bmatrix} \begin{bmatrix} B_{s,x} \\ B_{s,y} \\ B_{s,z} \end{bmatrix} \tag{4.10}$$

$$\begin{bmatrix} B_{r,x} \\ B_{r,y} \\ B_{r,z} \end{bmatrix} = \begin{bmatrix} B_{s,x}cos\theta + B_{s,y}sin\theta sin\phi + B_{s,z}sin\theta cos\phi \\ 0 + B_{s,y}cos\phi - B_{s,z}sin\phi \\ -B_{s,x}sin\theta + B_{s,y}cos\theta sin\phi + B_{s,z}cos\theta cos\phi \end{bmatrix} \tag{4.11}$$

Eq.?? is now derived using Eq.??, where yaw angle ψ represents the tilt compensated bearing of the vessel. The ATAN2() function in python is used to determining the yaw angle, it returns a value in the range of $-180°$ to $180°$. The following check is therefore done in software: if the yaw angle in negative then $360°$ is added to it. This ensures bearing is in the range $0°$ to $360°$.

$$\psi = \frac{-B_{r,y}}{B_{r,x}} = \arctan\left(\frac{B_{s,z}sin\phi - B_{s,y}cos\phi}{B_{s,x}cos\theta + B_{s,y}sin\theta sin\phi + B_{s,z}sin\theta cos\phi}\right) \tag{4.12}$$

4.6.2. Calibration

4.6.3. Digital filter

4.7. Power System

4.8. PCB

Chapter 5

Summary and Conclusion

Appendix A

Project Planning Schedule

This is an appendix.

Appendix B

Outcomes Compliance

This is another appendix.