York University
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CSE6400
Computer Engineering Research Project
Autonomous Sailboat

Final Report

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Contents

List of Figures

List of Tables

1 Introduction

This paper details the design and development of the autonomous sailboat project in fulfillment of the requirements of the Computer Engineering Research Project (CSE6400). This introduction reviews the need for research into the field of autonomous sail-driven water based vehicles, the general design considerations facing these vehicles and the desired goal of the project.

1.1 Why build an autonomous sailing vessel?

In recent years a worldwide interest in the development of Autonomous Surface Vehicles (ASVs) has developed. Long-term goals in this research area have been adopted by the academic community, with the most widely adopted goal being an autonomous transatlantic crossing, which was proposed by Mark Neal and Yves Briere with the creation of the Microtransat Competition [1]. Several autonomous sailing competitions (both fresh water and long-distance ocean races) have been created to help the community achieve these goals including the World Robotic Sailing Championship [2], Microtransat [1] and Sailbot [3] competitions.

When evaluating the technical challenge and appeal of this type of vehicle the first thing that is noticed is that the operating environment of these types of vehicles are more complicated and challenging in comparison to many ground-based vehicles. Current and wind disturbances make dynamic control more of a challenge than when actuators are in direct contact with a stationary surface. Also, the surface of the water (wave height, profile, speed and frequency) can play a significant role in the net motion of the vehicle and is not a characteristic of the environment that is easily measured or easily adopted into the control scheme of the vehicle.

Above and beyond these technical reasons for researching autonomous sailing vessels the most compelling reasons may have little to do with the technical details behind the craft design and control. The fact remains that almost 70% of the surface of the Earth is comprised of oceans (and is typically less well studied then the portion of the Earth's surface that is above water). The exploration and transit of this portion of the world is important to many different industries yielding many potential applications for autonomous sailing vessels including:

- Industrial shipping (and asset protection)
- Underwater exploration, surveying and mapping
- Marine life monitoring
- Military reconnaissance and surveillance

With all of these potential applications available for a project like this and with the recent global interest on environmentally sustainable technology it should be mentioned that this type of vehicle can be designed to operate while creating very little (and as low as zero) emissions.

1.2 Desired goal of the project

The goal of this research is the design and construction of a research platform capable of continuing research in the area of autonomous sailing vessels. This requires determining the information the boat needs in order to sail by itself and what parameters of the boat need to be controlled to take action on these values in order for the boat to reach its target (and accomplish any other high level goals that may be required). For the purpose of this project the main task of the boat will be open water navigation.

The solutions provided in this document assume the use of a chase boat during open water tests. Although the technical solution should allow the boat to perform open water navigation without assistance, a chase boat will allow for tests to be performed safely and with some insurance in the scenario where some part of the system fails. It is also necessary for many of the communication systems proposed in this paper.

1.3 The problem of sailing autonomously

In order for a sailboat to successfully navigate in open water three quantities need to be known:

- Apparent angle of the wind
- Current heading of the boat
- Desired heading

The apparent angle of the wind is needed in order to control the forward thrust provided by the wind source on the sail. This is accomplished by actively controlling the sails angle of attack so as to maximize the amount of wind that is being directed to the back (aft) of the boat. In reality, the thrust has to be balanced with stability. Instability occurs when a large enough component of the force of the wind on the sail goes across the hull of the boat and causes the boat to heel (see Figure 1).

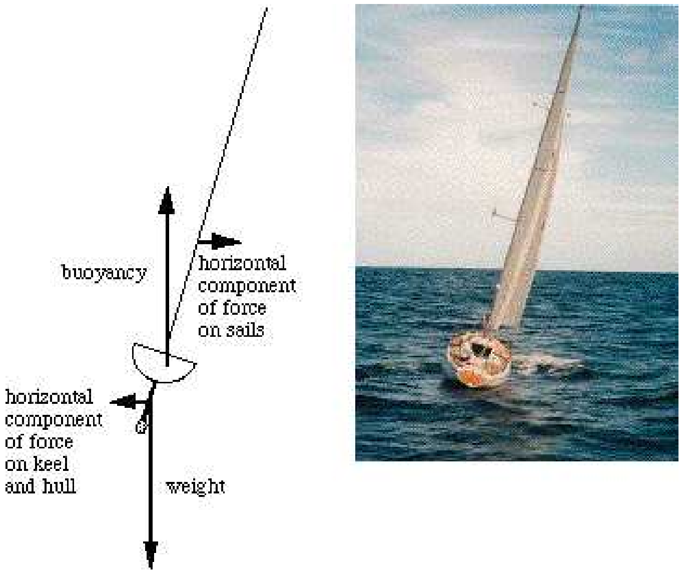


Figure 1: Heel Forces. Reprinted from [4].

The current and desired heading of the boat are both needed in order to maintain the course of the vehicle. Without this directional information the boat wouldn't be able to reach its target area.

Dynamically changing environmental conditions that are not measured above will affect the net motion of the boat (not the least of which are the current and the surface characteristics of the water) but it is assumed that the boat will be able to correct for these effects under average circumstances if the three quantities mentioned above are known.

In the case of non-open water navigation local awareness is also needed in order to provide functionality such as:

- Obstacle avoidance
- Speed determination (achieved by tracking objects that are further away over time)
- Advanced sailing decisions (i.e. sailing between another boat and the source of wind to "steal its wind")
- Local navigation (i.e. finding course markers and sailing around them)

This would indicate that under normal circumstances both absolute (global) and relative localization information will be needed by the vessel in order to make intelligent and safe sailing decisions.

Two quantities are necessary to control the boat for purposes of successful open water navigation:

- Rudder position
- Sail angle of attack

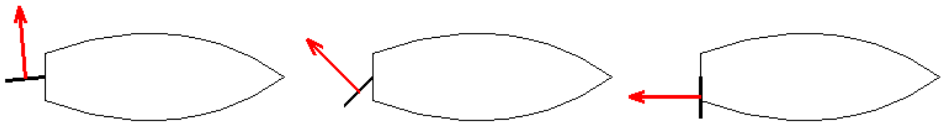


Figure 2: Rudder Forces

The rudder position is crucial for controlling the heading of the boat. Motion of the rudder away from the centerline of the hull creates a greater force on the side of the rudder closest to the front of the hull and decreased force on the other (see Figure 2). The rudder (along with the rest of the hull) will then move in the direction of lower pressure. This causes the boats heading to change (which is a necessary action for successful navigation towards a target position).

The sail angle of attack, as mentioned above, needs to be actively controlled to convert the prevailing wind into forward thrust on the sail in order to propel the boat while limiting the amount of heeling forces applied to the boat in the process.

In order to accomplish acquisition and control of these parameters a suite of sensors and actuators as well as power and a source of computation are needed. A selection of specific components that can be used to accomplish these tasks are surveyed in the following section.

2 Sailboat survey

2.1 Hull type

The hull of the sailboat is a critical component of the project, governing both the maximum performance (speed) and stability of the vehicle as a whole. The performance of the boat is in large part determined by the hydrodynamic properties of the hull. A good measure of the stability of the boat can be captured by the righting moment of the hull (a measure of the torque that is constantly applied to the boat, due to its weight distribution, in order to correct for heeling effects). The most restrictive design consideration about the hull will be its ability to carry the payload necessary for performing autonomous tasks (which is a factor of the internally accessible volume inside the hull and the buoyant properties of the hull).

2.1.1 Racing classes

Autonomous sailing competition hull restrictions

The majority of the restrictions given by the autonomous sailing community do not deal with specific hull details and designs but instead focus on maximum permitted values for certain properties of the boat (i.e. hull length). In fact, originality in hull design is generally encouraged by these competitions (often directly during the judging process). Of the three autonomous sailing competitions focused on in this paper the hull length restrictions are as follows:

Table 1: Autonomous sailing competition hull restrictions.

Competition	**Maximum Hull Length**
World Robotic Sailing Championship (WRSC) [5]	4m
Sailbot [5]	2m
Microtransat [6]	4m

RC racing classes

In Canada, there are 19 racing classes that are recognized in competition by the Canadian Radio Yachting Association (CRYA) [7]. Of these classes, the most popular class is the Soling 1M class [8]. In comparison to the size restrictions placed on boats in the autonomous sailing community, the actual design and shape of the hull determines its class in the RC racing community. In some of the classes that have fewer competitors it is often the case that all of the hulls were built from the same mould (i.e. “one-design” classes).

2.1.2 Monohull

Figure 3: Nirvana 2 Monohull RC Sailboat

Monohulls are the typical entry point into RC and robotic sailing. Typical boats in the RC market that are ready-to-sail (RTS) are 1m or smaller. Racing RC hulls in the 1m classes are either in the faster US 1m class (which can either be bought or built) or are in the various racing classes that only come in kit form. The problem with the US 1m class is that the hulls are narrower than any of the other 1m designs and thus are less stable when in the presence of any cross wind. The 2m RC sailing classes are almost entirely made up of homebuilt hulls.

Figure 4: Laerling Youth Sailboat

When considering monohulls in general the most beneficial aspect is the ability to make the hull design almost impossible to flip. Some hull designs, like the Laerling [9] (see Figure 4), will self-right when tipped.

Figure 5: A Crew Hiking the Sailboat

When racing, optimal performance is gained when drag is minimized, thrust is maximized and the hull is still controllable. This typically occurs when the hull is at small roll angles (i.e. the hull is almost parallel to the surface of the water). In order to achieve this, a load balancing system may need to be placed on the boat in order to "hike" (see Figure 5). Some design considerations when using a monohull include load balance, number of rudders and their placement, sail type, ballast weight and hull size.

2.1.3 Multihull

Figure 6: Poseidon Multihull RC Sailboat

Multihulls provide many differences to a monohull. Firstly, they provide a more stable platform in terms of their difficulty to tip. A core issue with multihull designs is that they aren't typically able to self-right once they have tipped. Some designs include a buoyant mast which prevents the boat from tipping completely upside down but static hulls still won't recover from this situation on their own.

As is the case with monohull designs, optimal performance is achieved under the same basic conditions (maximize thrust, minimize drag and maintain controllability). In a multihull configuration, optimal performance typically involves the boat operating at a considerable roll angle (thus removing some of the drag from the hull on the higher side of the boat). These types of manoeuvres would be problematic for some of the sensors on-board. A primary example of this would be the wind sensors (where the wind vane would then be affected by gravity more than the direction of the wind).

2.1.4 Hydrofoils

Figure 7: Multihull hydrofoil RC boat

Hydrofoils are typically mounted below the hull on a sailboat (see Figure 7). As the boat increases in speed the hydrofoils provide lift which brings most or the entire hull out of the water. This, in turn, decreases drag and further increases the speed of the hull. Typically sailboats that include hydrofoils in the design are classified as hydrofoils themselves.

2.2 Sail Type

2.2.1 Sheet sail

Traditional sheet sails are the default sail type on most consumer and RC boats. Most of the teams currently competing in the Microtransat and WRSC competitions utilize this type of sail in their designs.

2.2.2 Wingsail

Figure 8: Arc ASV With Dual Wing Sails

One advantage of a wingsail over a traditional fabric sail is that it needs a lower angle to the wind source in order to propel the vessel [10]. It also has a benefit of having fewer points of mechanical failure. The main disadvantage when using a wingsail instead of a traditional fabric sail is that there is no reliable means of reefing the sail. This means that the sail size has to be geared not only to the hull size and mass but also the expected wind range and performance expectations. Designing a wingsail that will perform well in low winds on a given hull will almost necessarily spell disaster when the boat faces high winds.

3 Survey of sub-components

3.1 On-board computing

Computing power will be needed on-board the vessel in order to interface with the sensors, determine high-level goals, provide active control signals to the actuators on-board the vessel and provide a communication interface. Due to the restrictions that autonomous sailing competitions place on the size of the hull (a maximum length of 4m in the case of the Microtransat Challenge and World Robotic Sailing Championship and under 2m in the Sailbot competition), the inner volume and payload carrying capabilities of any hull which can compete in these competitions will not allow for typical laptop/desktop computing solutions to be placed in the hull (although this would be an ideal solution for larger scale boats in future iterations of the project). Some of the alternative computing options that can be deployed in the boat have been considered here (including microcontrollers and single board computers).

3.1.1 Traditional microcontroller

Traditional microcontrollers are ideal for interfacing with many of the low level components that will be on-board the autonomous sailboat. Traditional microcontrollers allow for the highest degree of specification in their programming and thus allow for the highest level of performance and generally tighter timing constraints. This high performance level comes at an increased development time and code that is generally less portable.

Options include:

- PIC [11]
- AVR [12]
- Motorolla HCxx [13]

3.1.2 Embedded development board

Embedded development boards are another solution for interfacing with low level components. Embedded development boards typically contain a traditional microcontroller at the core of their design but have special firmware which allows basic functionality to be programmed in a high level fashion. This speeds up development time but does not allow for the maximum performance to be gained from the microcontroller.

Options include:

- Arduino [14]
- Parallax Basic Stamp [15]
- OOPIC [16]
- PICAXE [17]

3.1.3 Single board computer

Single board computers typically run some form of operating system (Windows CE, Linux, etc). Operating systems on these boards are geared to help low-level developers.

Options include:

- BeagleBoard [18]
- Gumstix [19]
- ARM [20]
- MIPS [21]
- AVR-32 [12]

3.1.4 Embedded x86

Embedded x86 PCs run a full operating system on a desktop CPU, but the motherboards have a much smaller form factor.

Options include:

- PC/104 [22]
- Mini/Nano/Pico ITX motherboards with AMD Geode [23]
- Via C3/C7 [24]
- Intel Atom processors [25]

3.1.5 Hybrid system

The best solution for on-board computing may potentially involve a combination of these options. Many systems make use of single board computers and embedded x86 architectures for high level control of the system and high level functionality (such as networking) and uses microcontrollers and embedded development boards for interfacing with the low-level hardware (such as the actuators and custom sensors).

3.2 Communications

Although communications between an autonomous boat and another system external to the boat is not necessarily required for the boat to perform its navigational requirements it is necessary to be able to instruct and communicate with the vehicle in some manner. Wireless communications to the boat can help in monitoring the system while running and it can aid in development by allowing modifications to be made to the system without any direct connection to the boat.

When considering technologies for use in the communication scheme three factors are primarily used: hardware/software support, coverage scenarios and cost. Hardware support for traditional wireless communication systems (802.11 b/g/n) coupled with a low integration cost and non-existent cost per message makes it an appealing option for the primary communications on the system. Certain types of long-range communication systems would be more useful for a system that were truly autonomous (i.e. without any chase boats) that were being sent out for data collection purposes. In this case the boat would be allowed to send information “home” no matter where it was located on its journey. The idea of a layered communications scheme is one which is present in the autonomous sailing literature [26]. Utilizing a layered communications scheme provides for a more robust system while maintaining the cost efficiency of the architecture. At zero transmission cost this can still be achieved by utilizing RF communications as a failsafe for a system whose primary form of communication is traditional wireless communications.

3.2.1 Radio-Frequency (RF)

Short range RF communications have been used in the hobby industry for decades. This communication system is typically used to directly control the various actuators onboard the vehicle and not for raw data transmission. For this reason, this solution would be ideal for providing an operator override but otherwise would not be the best solution for generic observation of the state of the system as a whole.

3.2.2 Wireless 802.11 b/g/n

This protocol will allow for short-range (typically 10’s of meters in open water) communications between the robot and a computer on a chase boat. This type of communication is readily achieved if the single board computer or embedded x86 computing options are used onboard the sailboat.

3.2.3 Cellular (3G) technology

This is the first long-range communication system discussed in this survey. This type of communication is desirable when the boat is out of range for short-range transmissions to be successful and the boat is still in an area which can receive access to the cellular network. This form of communication has costs related to it in relation to the amount of data being sent and received.

3.2.4 Generic satellite technology

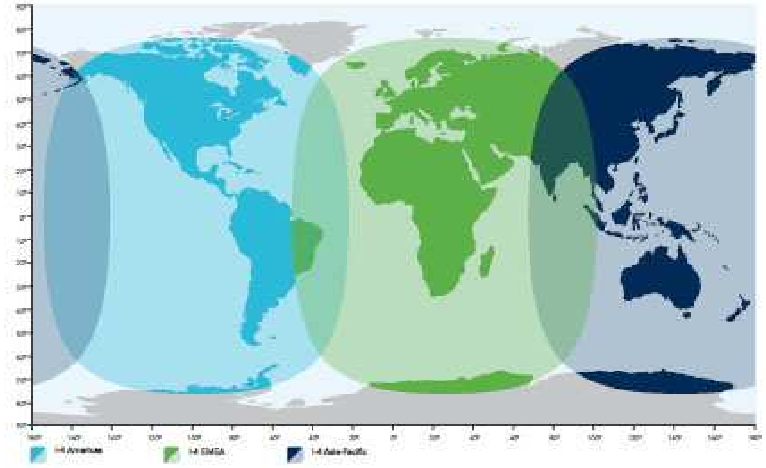


Figure 9: Inmarsat Satellite Coverage Map. Reprinted from [27].

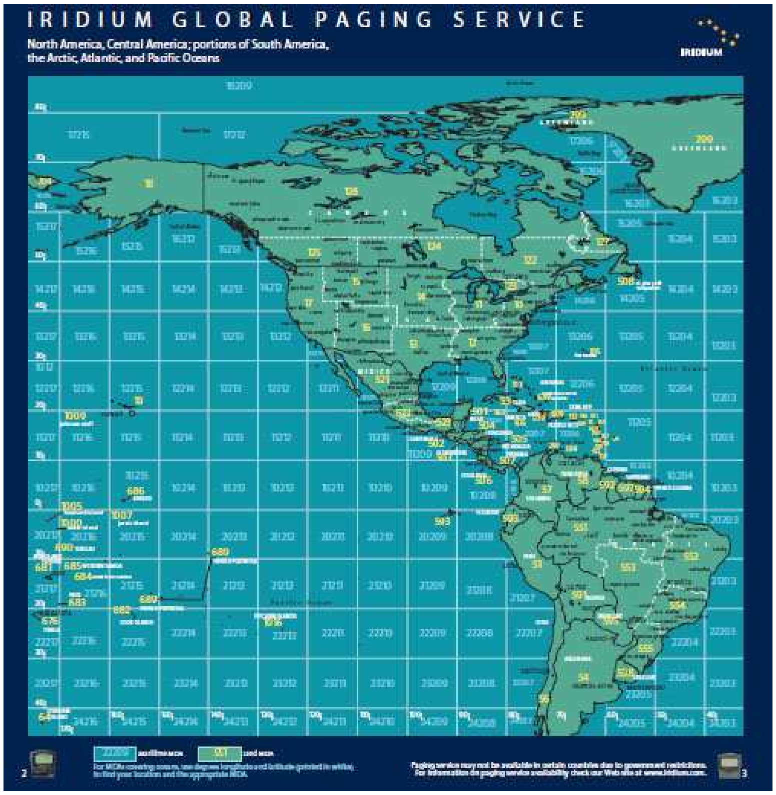


Figure 10: Iridium Satellite Coverage Map. Reprinted from [28].

Another long-range form of wireless communications, this method of communication has the least susceptibility for failure over long journeys. There are models of satellite modems that are designed specifically for marine applications and two satellite networks which have coverage over the Atlantic Ocean: Inmarsat [27] (see Figure 9) and Iridium [28] (see Figure 10). The modems that work on these networks allow for small packets of information to be forwarded via email to any computer on the internet. The transmission fees for this type of communication are the highest of the technologies surveyed.

3.2.5 Communication Technology Comparison

Table 2: Communication Technology Comparison

Communication Type	**Transmission Range**	**Integration / Hardware Cost**	**Transmission Cost**
RF	≈ 2m (line of sight) [29]	\$100-\$500	\$0
Wireless 802.11	10's of meters (both antennas omni directional) / 3km (directional antenna at base station) [26]	≈ \$100	\$0
Cellular (3G)	no coverage maps over water	≈ \$175	>0.05/MB (min. \$30/month)
Satellite (Inmarsat Fleet Broadband)	see Figure 9	Fleet Broadband FBB150 \$7000 CAD	\$5-\$14 CAD / MB
Satellite (Iridium Short Burst Data)	see Figure 10	Iridium 9601 SBD Transceiver ≈ \$500 USD	\$21 USD / month and \$1.30 / 1,000 bytes

3.3 Position and speed over ground

As mentioned in the introduction, one of the three quantities which need to be known in order for a sailboat to successfully navigate in open water is that of the desired heading. One way of generating this information indirectly is that of knowing your current latitude and longitude and a target latitude and longitude. For this reason the position over ground is going to be a measured value in the system.

3.3.1 Global Positioning System (GPS)

GPS devices are almost ideal sensors for providing information about the position and speed of the boat over the water. In open water, accuracy should be good enough for course navigation. When used close to shore or marker buoys additional differential GPS (DGPS) information can be used to increase the accuracy (see Figure 11) and correct the position of the boat accordingly. If the GPS data proves to be too inaccurate, gives too many false readings or has too low a refresh rate to prove useful then an Inertial Measurement Unit (IMU) can be used to supplement the data from the GPS receiver through the use of a Kallman filter [30].

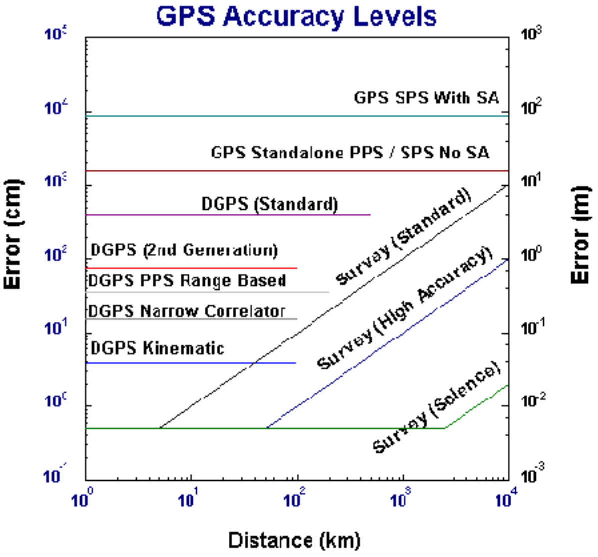


Figure 11: GPS Accuracy Levels. Reprinted from [31].

3.4 Speed through water

3.4.1 Mechanical Paddlewheel

Figure 12: Airmar Paddlewheel Speed Sensor. Reprinted from [32].

The most common type of hull speed sensor used on boats today consists of a mechanical paddlewheel or propeller which spins as it moves through the water. The speed of rotation is used to determine the speed it is moving through the water. An example of a commercially available version of this type of sensor can be seen in Figure 12.

In order to maintain the waterproof integrity of the electronics within the sensor, the core of the sensor has to be completely sealed. This is commonly accomplished in one of two ways. Both solutions rely on the embedding of magnets on the paddles in the paddlewheel.

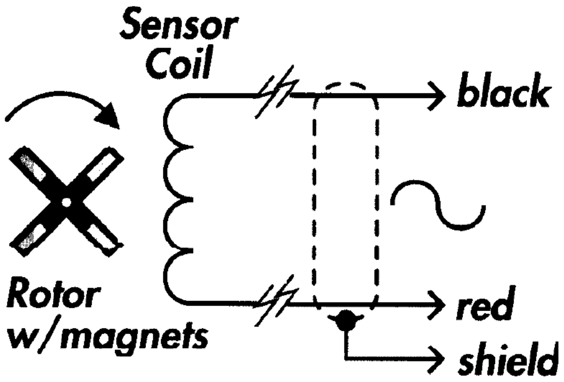


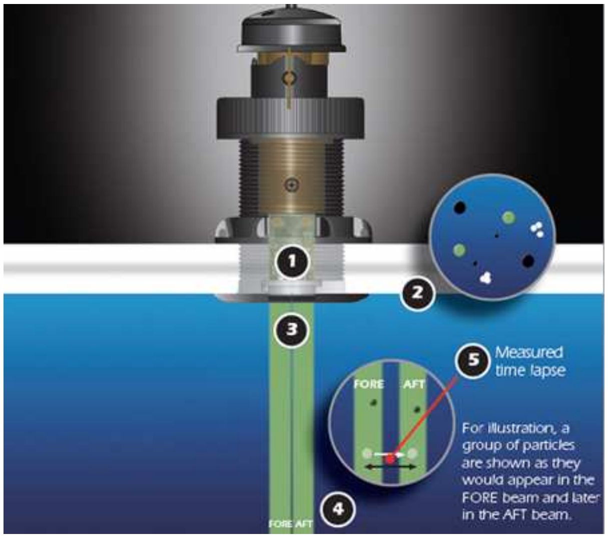
Figure 13: AC Paddlewheel Concept Drawing. Reprinted from [33].

The AC version of the sensor utilizes an AC coil in the core of the sensor [33, 34] (see Figure 13). When the paddlewheel rotates around the core the change in magnetic field generates a sine wave signal in the coil. The frequency of this signal corresponds to the speed of rotation of the paddlewheel. Given the fact that the current is induced in the coil by the changing magnetic field, there is no power needed to make the sensor work.

The DC version of the sensor makes use of one (or more) hall effect sensors in the core of the sensor [34]. In this instance, when the wheel rotates about the core a DC square wave pulse is produced on the output of the sensor. Again, the frequency of the signal corresponds to the speed of rotation of the sensor.

Due to the mechanical nature of the sensor it is prone to wear and tear. When these sensors are installed on traditional passenger boats they are also susceptible to biofouling. This typically occurs in low velocity (< 1m/s) water as above this speed the organisms have difficulty attaching to the submerged surface [35]. Therefore many passenger boats, when left docked in the water for extended periods of time, have these types of speed sensors foul with biological material growing in the paddlewheel enclosure (preventing the proper rotation of the wheel).

3.4.2 Ultrasonic



For illustration, a group of particles are shown as they would appear in the FORE beam and later in the AFT beam.

Figure 14: Airmar CS4500 Ultrasonic Water Speed Sensor. Reprinted from [36].

The speed of the water going past the hull of the boat can be measured using a pair of ultrasonic transducers (see Figure 14). The two transducers are placed close together (typically in the same sensor package), one pointed towards the front (fore) of the boat and one pointed towards the rear (aft). This method relies on the presence of small particulates being present in open bodies of water. The time between detecting echoes from particles at the fore sensor and the aft sensor determines the boat speed.

3.4.3 Pitot Static Tube

A pitot tube can be used to measure fluid flow velocity. The pitot tube is positioned pointing in the same direction as the direction of flow you want to measure and by measuring the change in pressure on the tube you can use Bernoulli's equation to calculate the velocity of the fluid flowing past the tube. These tubes are also used to measure airspeed on planes.

3.5 Wind speed and direction

3.5.1 Mechanical

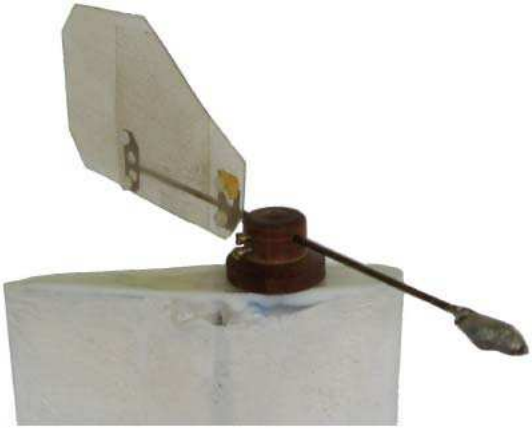


Figure 15: A mechanical wind sensor used on Aberystwyth Universities Autonomous Sailboats. Reprinted from [10].

Mechanical wind sensors typically consist of a wind vane that is connected to some type of rotary potentiometer (see Figure 15). This design only captures the direction of the wind and not its speed. These sensors have the benefit of being relatively easy to build and work with but have several drawbacks (as noted in Neal et. al. [10]):

- they can be problematic to waterproof (as the potentiometer has to be able to spin)
- they have poor performance in light winds
- mechanical wear may take place over time
- when the boat lists the mechanical wind vane will change direction and give erroneous wind direction
- most potentiometers have a small dead band where they cannot make accurate measurements

3.5.2 Mechanical (Contactless)

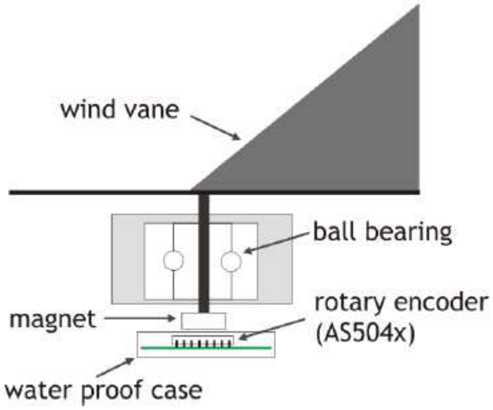


Figure 16: A schematic of a mechanical wind vane where the position is determined using a contactless magnetic encoder. Reprinted from [10].

The University of Porto has developed a contactless mechanical sensor for determining wind direction that is used on their FASt autonomous sailboat [37]. The design still makes use of a wind vane that has a magnet attached to it and a stationary rotary encoder which measures the change in magnetic field that is induced when the wind vane is rotated (see Figure 16). The reading from the rotary encoder can then be used to determine the wind direction. An added benefit of this design is that the electronics used to measure the direction can be completely encased in a waterproof container (or can be covered in an epoxy resin) essentially solving the problem of waterproofing this portion of the system.

Figure 17: Anemometer and Wind Vane (Davis Instruments). Reprinted from [38].

An anemometer can be built in a similar fashion using a hall effect switch and a multi-cup rotor. Instruments containing both a wind vane and an anemometer using contactless sensors are available in commercial packages (see Figure 17).

3.5.3 Ultrasonic

Ultrasonic wind sensors provide a means of measuring both wind direction and speed in a single instrument. These sensors typically consist of one transmitter and multiple receivers. The speed can be determined using time of flight calculations or looking at the change of phase in the transmitted signal at the receivers. The direction can be determined through the use of multiple receivers and computing the differences in the time it takes for the transmitted signal to reach the various receivers. Ultrasonic sensors have been built before for use on autonomous sailboats [10]. Commercial ultrasonic wind sensors are typically meant for use on land or on larger yachts and weigh at least 2 pounds (which is only suitable for larger boats).

3.6 Heading

3.6.1 Tilt-compensated compass

In order to get the boat's heading some type of compass will be needed. Many of the initial autonomous boat designs of the teams currently in existence made use of a basic digital compass [39, 40]. The problem with using a traditional digital compass is that when the boat tilts the working plane of the compass is also tilted which induces an error in the sensor reading. Some teams have compensated for this mechanically through the use of a gimball [39] and some have bought a tilt-compensated compass (typically through the use of flux gate technology) [39, 26].

3.7 Local Awareness

For the purpose of this report, the term "local awareness" refers to any information which yields relative information between an object or target and the boat (as opposed to information about some global state such as a GPS co-ordinate). Information that aids in the robot's local awareness can be used for tasks such as:

- obstacle avoidance
- speed determination (by tracking objects that are far away)
- advanced sailing decisions (i.e. sailing between another boat and the source of wind to "steal its wind")
- local navigation (i.e. finding course markers and sailing around them)

This section of the component survey describes various sensor types which add to the robot's local awareness.

3.7.1 Cameras

Vision systems are a common form of feedback for robotic systems. Cameras placed on the boat with a sufficiently large field of view can aid in providing sufficient feedback for the tasks mentioned at the beginning of the section.

3.7.2 Sonar/Radar

Sonar and radar are typical forms of remote sensing systems used for obstacle detection on boats. Sonar (Sound Navigation and Ranging) sends out acoustic waves while radar (Radio Detection and Ranging) sends out electromagnetic waves. Both technologies rely on the return of these waves to determine properties of their surroundings (distance, shape, size, speed, etc). Because electromagnetic waves attenuate quickly in water, radar is mainly used for above ground readings. Conversely, sound waves penetrate water with relative ease. For this reason sonar is preferred for making underwater readings. Performance is determined based on conditions like salinity, temperature and depth of the water. Radar systems have been deployed on some of the autonomous sailboats racing in competition today [26].

3.8 Automatic Identification System (AIS)

Figure 18: Altek Marine Electronics Corp. (AMEC) CYPHO-101 AIS Receiver. Reprinted from [41].

Automatic Identification Systems (AIS) [42, 43] are currently required on all international carrier ships (over 300 or more tonnes) and all commercial passenger ships. AIS transmitters contain a GPS receiver (and potentially more sensors to transmit pitch, roll, steering rate, etc of the boat) and transmit this information over very high frequency (VHF). Having an AIS receiver onboard the autonomous sailboat would allow for position, heading and additional information to be known (with low latency) for the majority of commercial ships in the area. This type of sensor would be very helpful for path planning and collision avoidance for long distance journeys. The Altek Marine Electronics Corp. (AMEC) CYPHO-101 AIS receiver [41] (shown in Figure 18) costs roughly $350 (and a VHF marine antennae would need to be purchased separately) and is completely waterproof for extreme use.

3.9 Safety Systems

Many of these subsystems would not be suitable for smaller (2m and under) R/C boats but would be suggested for larger autonomous sailboats. These systems become more important as the amount of time the boats are expected to remain sailing increases.

3.9.1 Moisture Sensors

Of the systems mentioned in this section moisture sensors are inexpensive and can be used on almost any size boat. The FASt team makes use of two moisture sensors that have been made from gold plated PCB material [37]. These would be ideal sensors to be placed in the hull and could indicate to the chase boat when any water is present inside the hull.

3.9.2 Automated Bilge Pump

Figure 19: Micro Bilge Pump. Reprinted from [44].

On a larger hull a traditional bilge pump (marketed for recreational boaters) could be added to the design in order to remove small amounts of water that may get into the hull over a long journey. Some hobby brands do exist in the market and may be retrofitted into the boat design [44] (see Figure 19).

3.9.3 Attention Lights / Fog Horn

Lights and a fog horn would be essential safety measures for the design if it were intended to be used on long journeys and in harsh weather conditions.

3.10 Actuators

3.10.1 Speed and Direction

Actuators must be in place on the boat in order to control the motion of the sailboat. The rudder must have an actuator attached in order to steer the boat. The sail boom must also be driven by an actuator (either directly, for rigid sails or wing sails, or indirectly, via a rigging system) in order to provide a means of adjusting the angle between the sail and the source of wind. Servos are typically used for these purposes in hobby R/C boats. When full size hulls are used DC motors are typically needed to deal with the high torque requirements. One solution is to use the motors from automatic sliding doors in vans. Although the power performance is not the best in these motors they have locking gearboxes which will keep the rudder and sail positions in place without a constant supply of power to the motor.

3.10.2 Reefing Mechanism

Ideally the reefing mechanism would provide a means of being adjusted on-the-run which would require yet another actuator. Changing the area of the sail will allow for adjustments to be made based on the wind speed. An additional benefit of providing a mechanism of reefing the sail is that in extreme conditions or shut-down/out-of-range situations the sail can be completely let out so that the boat stays (more or less) in place.

3.10.3 Weight distribution system

In order to achieve peak performance, the boat must be able to redistribute weight which will require another set of actuators on-board. One option includes placing existing payload which is critical for the boats operation (e.g. batteries) on a 2D plotter which would allow the boats center of mass to be shifted in order to get the boat to plane.

4 Current System Design

4.1 Hull

Two hulls are currently in various stages of development for this project. Both have benefits and disadvantages which are described below.

4.1.1 Mini 12

(a) On Land (b) Sailing

Figure 20: Mini 12 Sailboat

Table 3: Mini 12 Hull Overview. Reprinted from [45].

Length:	1.14 m
Draft:	21.6 cm
Weight:	0.45 kg
Combined sail area:	0.34 sq. m

The Mini 12 RC racing class [46] was designed in Canada with the Soling 1 Meter design as a start point. The re-design kept the rigging and sail set in-tact from the Soling design but modified the profile of the hull and keel so that it is more of a tapered design (called a wine glass hull). This change in hull profile, coupled with the rudder being placed in-line with the keel, helps the boat sail without trouble in weeded areas. A similar racing class (East Coast 12-Meter [47] racing class) has been developed in the United States using a very similar hull in their class specifications.

The Mini 12 Racing hulls are all made from the same fibreglass mould (i.e. the Mini 12 class is a "one-design" class). This keeps the degree of reproducibility of the hull extremely high but the methods for getting this are extremely controlled (and expensive). The cost of modifying the boat or rebuilding the boat for various reasons is extremely high and is thus the greatest setback for using this design long-term.

4.1.2 Soling 1 Meter

Figure 21: Victor Soling 1m RC Sailboat. Reprinted from [48].

Table 4: Soling 1 Meter Hull Overview

Length:	39.30”
Height:	64.5”
Sail Area:	600 sq. in.
Beam:	9.25”
Keel Depth:	8.5”
Min.Weight of Racing Class:	10lbs
Power:	4 AA Batteries (For RC Components)

The Victor Soling 1m kit [48] (see Figure 21) was the original choice for the hull in this design. It was chosen based on numerous discussions with many RC sailing enthusiasts. Based on these discussions, this boat will hold an additional 5 pounds of payload over-and-above the required electrical components (i.e. servos and the batteries to power them). The hull (when built from the kit) should have enough space to hold the components required for this project. An additional benefit of using this kit instead of other ready-to-sail RC boats is that this model is more stable then boats designed to compete in the US 1m class. This is due to a hull which is almost twice as wide and a keel whose weight can be made to suit the current weight distribution in the boat.

The benefit of using this boat over the Mini 12 hull is the cost of development and the additional cost of servicing over the life of the boat. Replacement parts are easy to acquire and additional decks can be purchased and modified in order to suit the placement of any of the electronic components that need to be placed in the hull. This low cost of development also encourages rapid prototyping of concept designs which still utilize a monohull (such as using a wing sail or rigid sail as opposed to the typical sheet sail). The ability to quickly change the mass of the keel based on payload distribution and sailing conditions is also of benefit when stability is the primary concern.

4.2 Sail Type

A typical sheet sail will initially be used in this design. Both the Mini 12 and the Soling utilize a similar rigging system and the same size sail set. This makes it a convenient initial option.

4.3 On-board computing

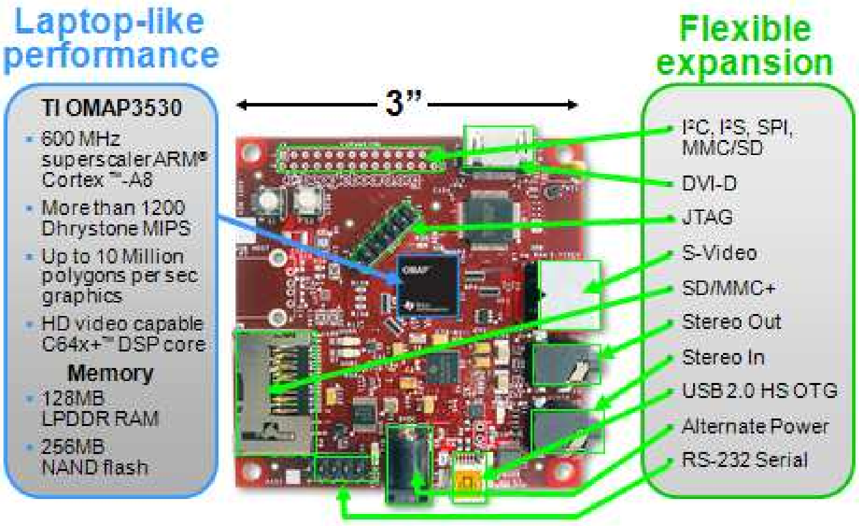


Figure 22: BeagleBoard Layout and Specs. Reprinted from [49].

A hybrid design is being used in this project. A BeagleBoard [18, 49] running Angstrom [50] is used for high-level tasks (see Figure 22). Arduino Duemilanove [51] development boards are used for interfacing with some of the low level hardware. If timing constraints cannot be met or development costs become too high in the future some interfaces may be switched to basic PIC [11] or AVR [12] microcontrollers.

4.4 Communications

The main source of off-board communication is Wireless 802.11 b/g/n. Before the project is tested in open water a typical RC receiver may be added to the system. This would allow for the boat to be controlled manually when the boat goes out of range of the wireless networking setup. An additional reason for using an RC receiver is that they typically come with a failsafe mode. When the boat goes out of the range of the RC receiver the boat can be switched into a default state allowing for the boat to be retrieved. In order to allow both the autonomous and RC systems to be in place on the boat a switching relay system would likely have to be used.

4.5 Position and speed over ground

Figure 23: Pharos USB GPS receiver. Reprinted from [52].

A USB GPS receiver is used in this design. A unit, such as the Pharos USB GPS receiver (PB010) [52], provides GPS information in a compact package (see Figure 23). This particular unit provides the data in the NMEA [53] standard.

Table 5: Pharos GPS Statistics. Reprinted from [52].

Acquisition time in open sky:	Cold start: 35 sec Hot start: 1 sec
Reacquisition:	0.1 sec
Position update:	1 Hz
Accuracy:	Position: < 10 meters Velocity: 0.1 meter/second

4.6 Speed through water

This type of sensor won't be present in the initial boat design.

4.7 Wind speed and direction

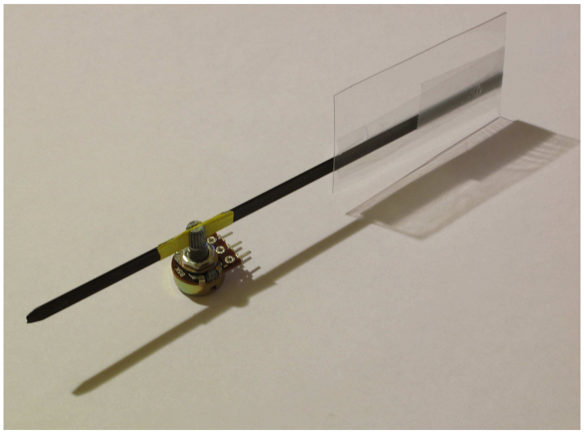


Figure 24: Custom Built Potentiometer Based Wind Vane

A low-weight potentiometer and wind vane assembly is used to measure the wind direction. A sensor weighing more than this would upset balance on a smaller 1m RC sailboat. For these reasons the assembly has been built specifically for this project (see Figure 24). As mentioned earlier, potentiometer-based wind vanes have their downfalls. These issues were mostly overcome using the following techniques:

- The mechanical stop in the potentiometer was removed manually to allow for full 360°
- The “dead zone” of the potentiometer is compensated for by time averaging the output of the sensor as well as calculating the absolute deviation of all averaged values from the first recorded value in the sequence. This will filter out readings from the “dead zone” where the potentiometer reading is floating but will also filter out readings where the wind direction is changing rapidly over the time interval.
- The resistance to movement of the rotary joint in the potentiometer was partially compensated for by adding a water resistant lubricant to the rotary shaft. This allows for the potentiometer to work in all but the calmest of wind conditions.

4.8 Heading

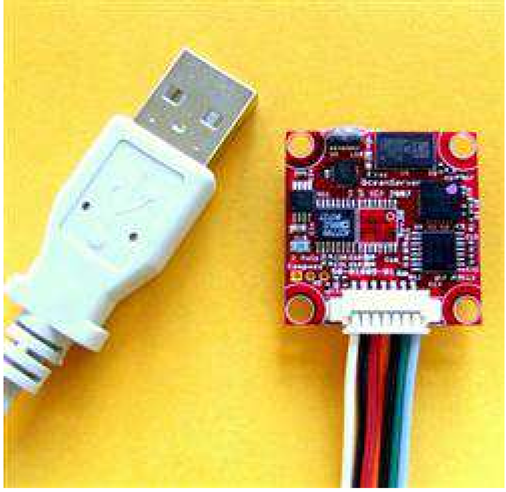


Figure 25: Ocean Server OS5000 3-Axis Tilt Compensated Digital Compass. Reprinted from [54].

A tilt-compensated compass will be used for this purpose. One potential solution would be the Ocean Server OS5000 3-Axis Tilt Compensated Digital Compass [54] (see Figure 25).

4.9 Local Awareness

Multiple light-weight USB web cameras will be placed on the hull. These will be used for basic local navigation tasks (i.e. locally tracking buoys).

4.10 Safety Systems

This design may make use of custom designed moisture sensors if placement of the additional electronics will allow for these sensors to act as a warning. Given the relatively small volume of the hull moisture sensors may not give advanced warning of a leak (as the rest of the electronics would likely be exposed at the same time as any moisture sensors placed in the hull). Additional safety features would definitely not be used in this design due to weight and space constraints.

4.11 Actuators

Rudder Servo

Figure 26: Hitec HS-85BB Premium Micro Servo. Reprinted from [55].

The rudder is controlled by a Hitec HS-85BB Premium Micro Servo [55] (see Figure 26) via a custom armature running from the servo mount to the rear of the boat.

Table 6: Hitec HS-85BB Premium Micro Servo Statistics

Motor Type:	3 Pole
Bearing Type:	Top Ball Bearing
Speed (4.8V/6.0V):	0.16 / 0.14 sec @ 60 deg.
Torque oz./in. (4.8V/6.0V):	42 / 49
Torque kg./cm. (4.8V/6.0V):	3.0 / 3.5
Size in Inches:	1.14 x 0.51 x 1.18
Size in Millimeters:	28.96 x 12.95 x 29.97
Weight ounces:	0.67
Weight grams:	18.99

Sail Servo

Figure 27: Hitec HS-815BB Mega Sail Servo. Reprinted from [56].

The sails are controlled through a sheet (string) system. This allows for the maximum angle of the sails from the centerline of the boat to be controlled (not the absolute position) through the lengthening and shortening of a sheet (line) attached on the end of the sail boom opposite the pivot point of the boom. The sheets are rigged through the deck and attached to a custom built arm (see Figure 28) which is attached to the hub on the HS-815 Servo [56] (see Figure 27). This arm was built to help prevent many of the failure modes associated with the servo arm that is packaged with the servo. The packaged Hitec arm is known for snapping the sheets when in use (which causes the entire rigging of the boat to have to be re-done). The arm itself has also been reported to deform and/or break when the sails are generating maximum thrust in high-wind situations. Tests where the servo has been operated under various wind conditions both via computer and via remote control has yet to cause a situation where human intervention is needed.

Figure 28: Rigging Setup on Mini 12

Table 7: Hitec HS-815BB Mega Sail Servo Statistics

Motor Type:	3 Pole
Bearing Type:	Dual Ball Bearing
Speed (4.8V/6.0V):	0.19 / 0.14
Torque oz./in. (4.8V/6.0V):	275 / 343
Torque kg./cm. (4.8V/6.0V):	19.8 / 24.7
Size in Inches:	2.59 x 1.18 x 2.26
Size in Millimeters:	65.79 x 29.97 x 57.40
Weight ounces:	5.40
Weight grams:	153.09

4.12 Weight Budget

Table 8: Weight Budget

BeagleBoard [57]	37 g
Hull Components	≈ 10 lb = 4535 g
Sail Servo (Hitec HS-815BB)	152 g
Rudder Servo (Hitec HS-85BB)	19.2 g
GPS (Pharos USB GPS receiver) [52]	0.04 lb = 18 g
Wind Sensor	TBW (≈ 10 g)
Ocean Server OS5000 3-Axis Tilt Compensated Digital Compass [54]	< 2 g
Web Camera	TBW (≈ 100 g)
RC Power (4 AA Batteries)	120 g
Computing Power (4 AA Batteries)	120 g
Assorted Components (USB Hub, Cables, etc)	TBW (≈ 1 lb = 453 g)
Total	5566.2 (12.2 lb)

TBW - To be weighed

4.13 Power Budget

Table 9: Power Budget - Computing

BeagleBoard [57]	350 mA
Arduino Duemilanove [51]	40 mA per IO pin + 50 mA for 3.3 V voltage supply pin = 40 mA * 6 + 50 mA = 290 mA
GPS (Pharos USB GPS receiver) [52]	50 mA
Wind Sensor	1 mA (assuming 5 kOhm potentiometer)
Ocean Server OS5000 3-Axis Tilt Compensated Digital Compass [54]	35 mA
Assorted Components (USB Hub, Cables, etc)	TBM
Total:	436 mA + Assorted Components (est. 600 mA)
Computing Power Source (4 AA Energizer Rechargeable NiMH Batteries)	2500 mAh
Runtime on a single charge:	≈ 5 hrs

TBM - To be measured

Table 10: Power Budget - RC Component Budget

Sail Servo (Hitec HS-815BB) Idle:	8 mA No Load Running: 700 mA
Rudder Servo (Hitec HS-85BB)	Idle: 8 mA No Load Running: 280 mA
RC Power (4 AA Energizer Rechargeable NiMH Batteries)	2500 mAh

5 Software and Control Systems

5.1 Software Components

Currently two subsystems are fully programmed on the Arduino uC and three monitor applications have been built for the BeagleBoard. Software systems for the sail and rudder servos, a digital compass and the wind vane have been implemented on the Arduino. Monitor programs for the BeagleBoard have been implemented to receive and send those values to the Arduino as well as monitor the USB receiver.

5.1.1 Servo Control

On the Arduino, a communications interface for both the rudder and sail servos have been implemented. Sending a serial message over the USB port to the Arduino with the following structure "r<angle>x" will set the rudder angle to the angle specified. Similarly, sending a command "s<angle>x" will set the sail angle.

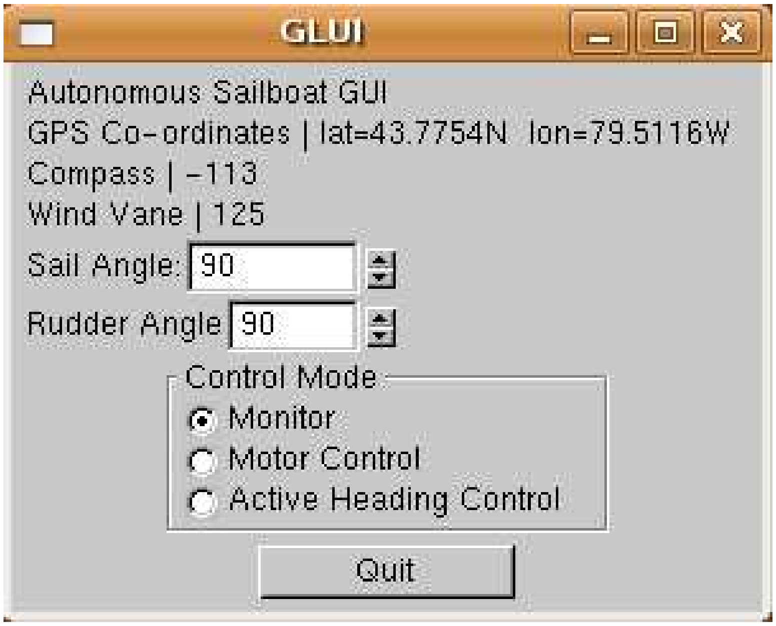
5.1.2 Digital Compass

While waiting for the tilt-compensated compass an interface for a common digital compass (Hitachi HM55B Compass Module [58]) was added to the system. The Arduino receives the compass reading and sends it out over the serial USB communication line in order to update the corresponding monitor program.

5.1.3 Wind Vane

The potentiometer-based wind vane is interfaced with the Arduino as a simple analog sensor. The filtering that is done on the sensor readings is done on the Arduino and the resulting angle is sent out over the serial USB communication line. If the sensor readings are viewed as being too random then NaN is returned by the Arduino (to denote a potential dead zone reading).

5.1.4 Monitor Programs



Autonomous Sailboat GUI

GPS Co-ordinates | lat=43.7754N lon=79.5116W

Compass | -113

Wind Vane | 125

Sail Angle: 90

Rudder Angle 90

Control Mode

● Monitor

○ Motor Control

○ Active Heading Control

Figure 29: Monitor Application GUI

The monitor programs implemented on the BeagleBoard make use of the Boost C++ Library [59]. The Boost library provides a cross-platform mechanism for many functions needed in this project (including serial communication, socket communication and threading). This results in code that has a great deal of portability for future iterations of the autonomous sailboat project. A graphical user interface (GUI) based application has been built around these monitor programs for ease of use (see Figure 29).

5.2 Current Control System

As of the writing of this paper a rudimentary control system has been developed with attempts to maximize the thrust generated by the prevailing wind on the sail as well as maintain a specified heading of the boat. This is accomplished by controlling the sail angle of attack and the rudder position given the inputs from a compass and a wind vane.

Sail Angle of Attack

The sail angle of attack is controlled linearly with change in apparent wind direction. For this setup the sails are pulled in tight along the center line of the boat when the wind is coming from straight in front of the boat and is 90° away from the centerline when the wind is coming from straight behind the boat. The maximum sail angle can be controlled directly by controlling the servo position.

This control roughly maximizes the thrust produced by the wind on the sails. In order to truly maximize the thrust a lookup table would need to be used (as the relationship between apparent wind angle and sail angle is closer to a tangent curve than a linear relationship).

Rudder Position

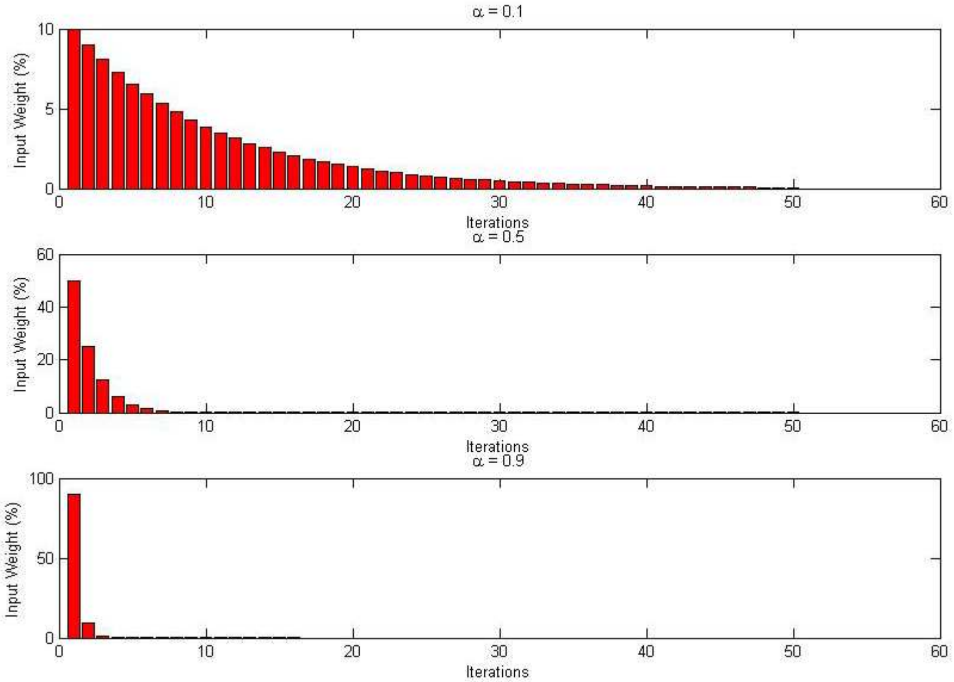


Figure 30: Contribution of the input at the first iteration to the exponential controller at time N

The rudder position is controlled using an exponential controller. This type of controller places greater emphasis on the latest sensor input while the previous sensor readings still have some effect on the output from the controller. The mathematical form of the exponential controller is essentially an exponentially weighted moving average and can be defined as follows:

$$C_N = \alpha I_N + (1 - \alpha) C_{N-1} \tag{1}$$

Where:
α - weighting factor
C_N - controller output at time t=N
I_N - input driving controller at time t=N

Figure 30 shows the effect a sensor input at time 0 has on the output of the controller at time N (given different values of α in the controller). The results of using this controller on the rudder with the difference between the desired heading and the compass heading being used as the input results in a smooth and responsive positioning of the rudder (and will probably be sufficient for controlling the rudder throughout the duration of the project).

5.3 Future Work

5.3.1 Short Course Navigation

In order to build an initial system that can perform successful open water short course navigation the GPS data will need to be integrated into the current control system (in order to actively set the desired heading of the boat). In order to navigate around the physical waypoints a camera (or other form of local awareness sensor) will have to be added to the control system in order to provide relative position information between the boat and the waypoint. A simple path planner will also be needed (in order to keep the boat in “sailable” positions).

5.3.2 Path Planning

Basic Path Planning

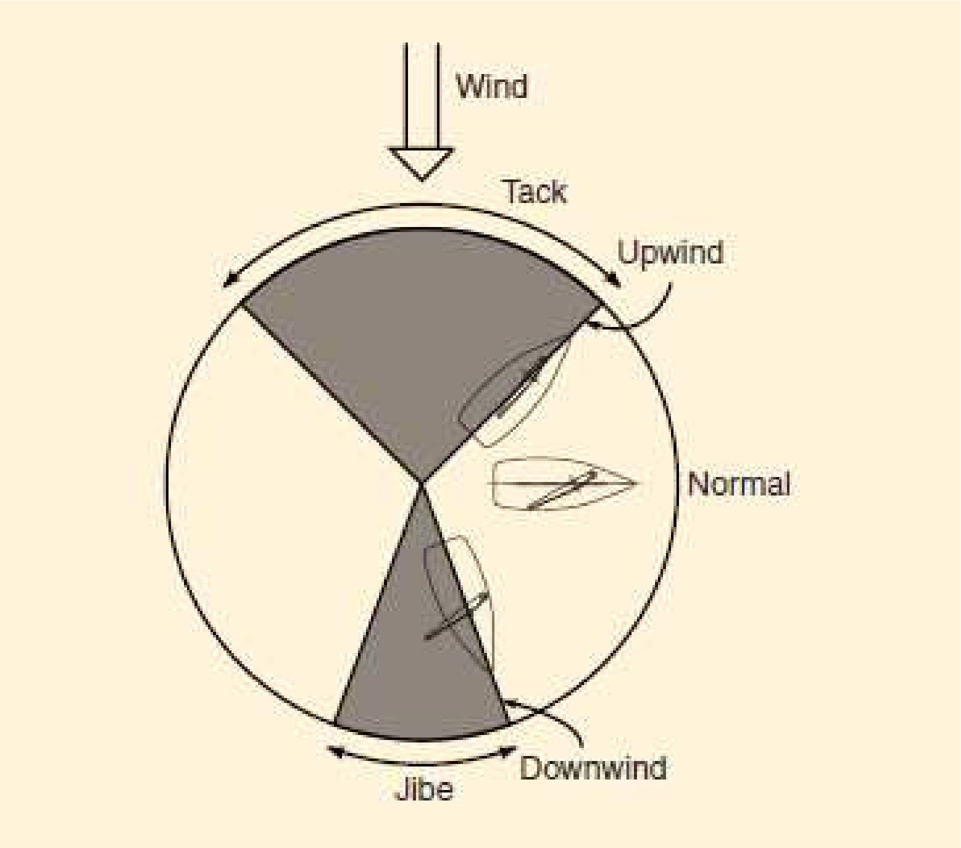


Figure 31: Sailable Regions For A Typical Sailboat. Reprinted from [30].

The most basic, and essential, path planner for an autonomous sailboat will provide means for the boat to perform tack and jibe manoeuvres when a straight line course to the target is either not possible or not efficient. For typical sailboats there is a fairly large region of headings that the boat will not be able to travel in (see Figure 31). This region is located about the heading which causes the prevailing wind to go straight from the bow (front) to the stern (back) of the boat and the range of headings is typically over

20° about this heading (with optimal performance typically occurring when the boat is at least 45° away from this position [30]).

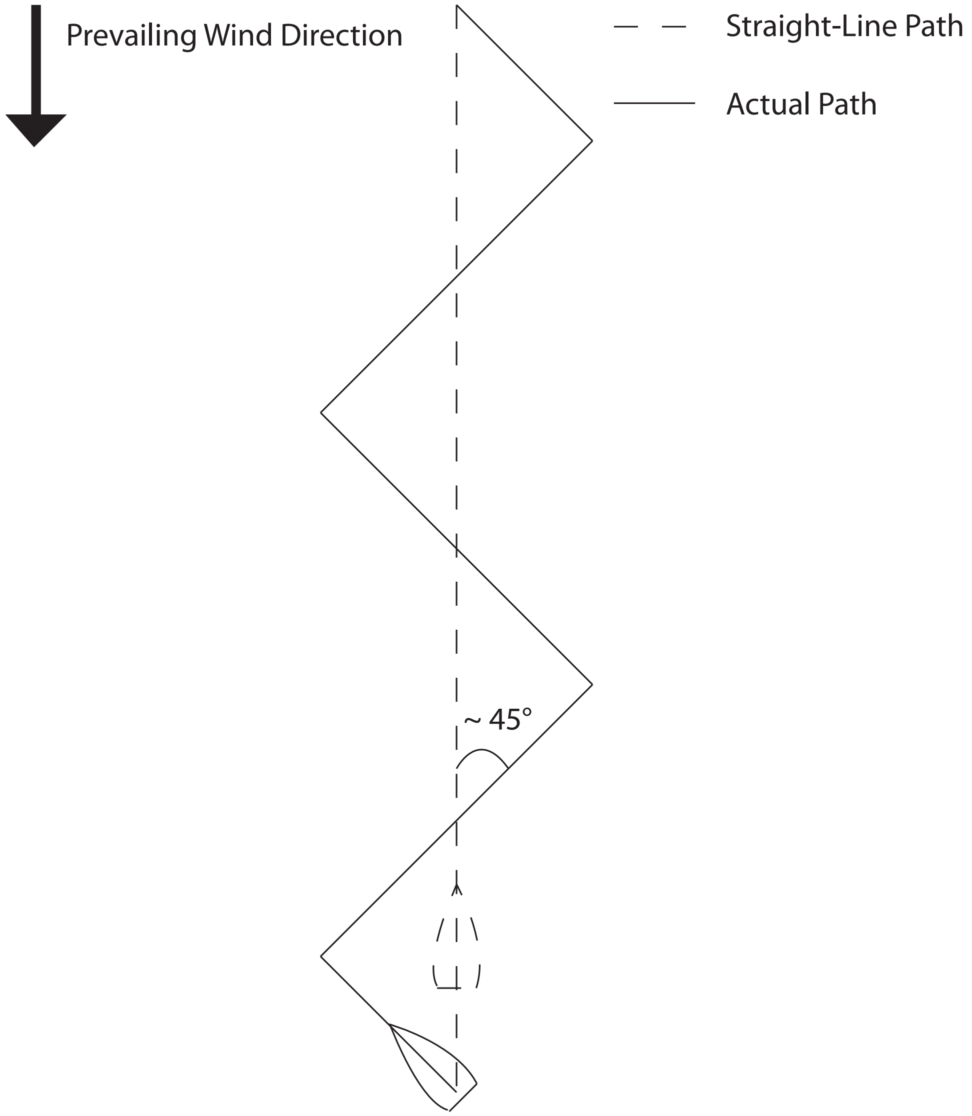


Figure 32: Tacking Upwind

If the desired heading of the boat lies in this range then a tack manoeuvre is performed by the boat. When tacking, the boat sails as close to the desired heading as possible (while achieving decent performance) until it gets far enough away from the straight-line trajectory that the boat can then sail back across the straight-line trajectory. This causes the boat to zig-zag across the straight line trajectory that would take the boat straight from its initial position to its target position (see Figure 32).

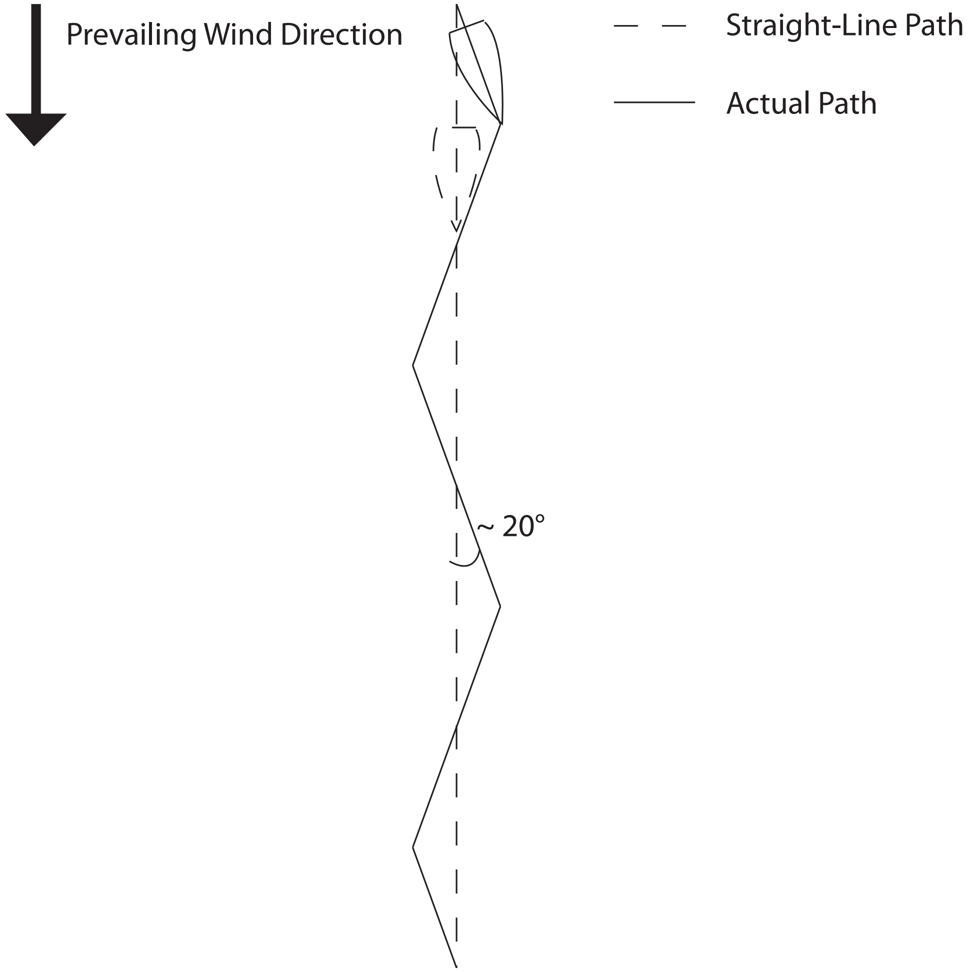


Figure 33: Jibing Downwind

Jibing is the "mirror image" manoeuvre for a sailboat when sailing downwind. Although it is possible for a sailboat to sail directly downwind, this comes with a decrease in performance (as a sailboat can only sail as fast as the wind when sailing directly downwind) and stability. The angle the boat takes to the straight line path when jibing is typically around half of the angle used when tacking (which balances the increased speed with the increase in distance). As with tacking, jibing causes the boat to take a zig-zag path along its course (see Figure 33).

Advanced Path Planning

Advanced global and local path finding will be required for this boat to be able to make long journeys autonomously. The A* path finding algorithm [60] is used for global path finding by the Avalon project [30]. Local awareness information can be utilized for dynamic conditions (locating boats and other obstacles which change or are not present on initial geographic information). If the boat contains a satellite communication modem then up-to-date weather information can be used to further refine the path planning algorithm. A variant of A* (D* or some similar variant [61, 62, 63]) can be used for efficient updating of the planned path based on these dynamic obstacles.

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