Area Scanning Control System for Backpackable Robot Boats

Report for CS39440 Major Project

Author: Elizabeth Stone (eas12)
Supervisor: Dr. Mark Neal (mjn)

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Department of Computer Science
Aberystwyth University
Aberystwyth
Ceredigion
SY23 3DB
Wales, UK

Declaration of originality

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Name .....Elizabeth.Stone.....

Date .....30/04/2017.....

Consent to share this work

By including my name below, I hereby agree to this dissertation being made available to other students and academic staff of the Aberystwyth Computer Science Department.

Name .....Elizabeth.Stone.....

Date .....30/04/2017.....

Acknowledgements

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To AberSailbot I owe my love of boats, and my experience of working with robotic boats. I thank all involved during my time with AberSailbot, and for giving me experience in such a unique field.

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Abstract

This project aims to produce a control system, via feature driven development, to automate a lightweight catamaran motorboat to aid in the scanning of still bodies of water. The project is open source and portable to other smilar robotic boats.

The Aquatic Area Scanning System (AqASS) is a two-part control system written in Python and Arduino C, for use on a Raspberry Pi 3 and a Moteino micro-controller respectively. The system uses a GPS and a compass to navigate, and servomotor controlled submersed propellers and servo controlled rudders to move. The high level logic of the system is controlled by the Pi, which makes use of vector field navigation to determine a heading. The low level logic is controlled by the Moteino, making use of PID to propel the boat on a desired heading. The Pi and Moteino communicate over serial.

This project was moderately successful, producing a system that is able to control the boat to predefined locations, not necessarily via the most efficient route.

Contents

Background & Objectives

1.1 Background

1.1.1 Motivation

Academics at Aberystwyth University Geography department studied Scottish lochs two and a half years ago using a lightweight remote control boat. The study required the boat to scan the lochs using sonar sensors to build up an image of the bottom of the lochs and to locate logs on the loch floor (in order to investigate climate change using dendrochronology)[1]. In that study, the boat was controlled by RC. This project aims to make the boat fully autonomous in order to increase efficiency. Other projects since have used this boat, again controlling the boat under RC.

With these projects it was found that it was hard to properly control the boat as it is difficult to tell from shore exactly where the boat is; large flat lakes with a small boat at many tens of meters away make it very hard to see the movement of the boat. This makes it impossible to tell if the boat is travelling in a straight line. This is not good, as large areas of lake can be missed and so data from these areas is not collected, leading to incomplete data sets for analysis. Often it is not realised during the experiments that large areas have been missed until the results are processed (which may not be instantly if scanning lakes in remote locations), and so a better way of scanning water is needed.One solution is automating the boat so that it can be known for sure that every part of the lake has been scanned; a boat with a GPS will know exactly where it is and if it is going off course.

A platform like this could be useful in other areas of research, for example, for marine monitoring. The boat itself is a catamaran and is therefore extremely stable. Additional sensors could easily added to the existing hardware, or equipment (such as sondes [2]) could be easily carried to be released in remote locations.

Another use for vessel of this type would be for sending into areas too dangerous for a manned vessel to travel into (e.g. close to glaciers) or into areas where manned vessels are unable to travel to (e.g. lochs on top of remote mountains).

1.1.2 Similar Projects

Other boats have been automated in similar ways. There are teams across the world that automate robotic sailing boats and compete in yearly competitions such as the World Robotic Sailing Championships (accompanied by the Internal Robotic Sailing Conference)[3], which has run for nearly a decade, and the International Robotic Sailing Regatta [4]. Sailing boats are much more complex to control than motor powered boats (strongly relying on the angle of the wind to the boat and sails), but the basic concepts are similar; creating a system to navigate across the water demonstrating specific behaviours.

Different strategies for area scanning have been demonstrated at robotic sailing competitions, such as the World Robotic Sailing Championships and the International Robotic Sailing Regatta, both of which have an area scanning challenge where there are generally mixed results [5]. Many different control and navigation systems were discussed at these conferences [6].

A project by AberSailbot [7] has similar aims to this project, so their system was looked into. There is the use of several different systems (e.g. arduino code, boatd [8], behaviours) to make their boat function. This in ways is very useful as parts are easily swappable , but also inconvenient when there are too many layers of system to understand. The overall structure is good, and a particularly nice feature is the use of a Raspberry Pi to control high level logic and an Arduino to control all input and output; this distributed design means there is not too much processing being done on either board.

[9]

Similar to AberSailbots system, a general control system non-specific to sonar would be useful. A system that can be easily used across similar platforms.

1.2 Analysis

1.2.1 Project Description

The AqASS (Aquatic Area Scanning System) project will produce a control system for a small, lightweight, motor-powered robotic boat to enable the boat to autonomously scan any given body of water, with selectable parameters.

The most basic aim for this project is to develop code to make the boat travel in a straight line towards a selected location on a body of water. This can then be built upon to make the boat travel to a series of way-points.

Building on this, the project will then develop an algorithm for automatically selecting the most efficient course for boat to take to scan a selected area (as defined by a series of coordinates).

It will then investigate telemetry and the design of a user interface that allows the user to communicate with the boat while it is on the water, and easily select the route the user wishes the robot to take.

It may also be useful to investigate semi-autonomous functions that can be used on the boat before and after starting the area scanning, such as heading holding, station keeping or return home functions, to aid in deployment of the system.

Suitable development methodologies will need to be investigated early on in this project.

1.2.2 Proposed Tasks

The following tasks are proposed:

- **Investigate Development Methodologies**
- **RC Lake Tests and environment research.** Investigate the environment encountered by the boats and the factors that affect their motion on the water (e.g. current, wind, waves), and what can be done to detect and account for them.
- **Investigate OS and programming languages.** Research which languages are most suitable for the hardware given, and which OS would be best to use on the Pi (if any).
- **Control System Development**
  - **Investigate types of navigation systems.** Research types of system and see which type is most suitable for this project (vector field systems, bearing systems etc).
  - **Investigate Control System Architectures** See which design would be best for this type of project. It may be that a modular approach will be necessary, which would allow easy swapping of hardware.
  - **Write code to get boat to travel in a straight line to a way-point/series of way-points.** This will involve accounting for factors discovered during rc testing.
  - **Investigate ways of representing and specifying body of water to be scanned and develop an algorithm to determine the most efficient route to scan the given area.** Specifying the body may be as simple as manually entering the data points, or as advanced as having a GUI where the user may draw the outline of the water on a map.The algorithm will likely depend on the shape of the body of water, current direction and other factors. It should also consider parameters such as desired resolution of scan (which would depend upon the sonar sample rate, speed of boat, and spacing of consecutive traversals of the area).

  - **Research and Develop Telemetry System** Develop easy to use interface to pass information to and from boat. Investigate if long distance communications would be useful and viable.
  - **Investigate plausibility of (and implement) collision avoidance system.** A system to prevent the boat from travelling into shallow waters, or crashing into objects in its path (e.g. other boats, buoys). This may involve processing the data from the sonar scanner(s), thus research will need to be done into how to process this data. It may also be necessary to develop a modular system so that sonar device may be swapped easily for another similar device.

- **Test control system** The methodology used will define the frequency of testing, but tests on one or more large bodies of water would be ideal nearer the end of the project. On land tests will be carried out throughout the rest of the project.
- **Project Meetings and Project Diary** Weekly project meetings will be held with the supervisor, and a project diary will be kept to keep track of all parts of the project. The diary will be written in markdown and backups will be kept in a git repository.
- **Demonstrations**

1.2.3 Deliverables

Deliverables expected from this project:

- Mid-project demonstration
- Control system software
- Usable user interface and telemetry software
- Collision avoidance software
- Final report
- Final demonstration

1.3 Process

This project used Feature Driven Development (FDD) methodology for orginization. Upfront a desgin for the hardware and a software flow diagram was created, as can be seen in Appendix E***addinithardware. The main features were identified (Pi code, Arduino Code and Comms), and a list of tasks to be completed was then kept to work through these features according a timeline ((as in Appendix B). Sub-features were identified within the main features, as reflected in the sections of this report. The list of tasks were ordered by dependency (the first tasks on the list needed to be completed before the next tasks). The task list was kept on GitHub, removing the tasks from the to-do list after completion, and adding new ones as new tasks were identified (mostly when the next feature was being designed).

To adapt FDD to a project with a single person, it was decided that the different roles normally used in FDD were not needed and that***

Design

2.1 Overall Design

2.1.1 Hardware

The hardware to be used in this project include two servo-controlled rudders, two servomotor-controlled propellers, triple-axis magnetometer (compass), Global Positioning System (GPS) receiver and sonar scanner. The two rudders cannot be independently controlled, and neither can the two motors. The sonar scanner is not used in the final design of this system, as the project is more focused on a multipurpose control system, but a sensors module could easily be added to work with this system.

For reasons discussed in subsection 2.1.2, there will be two separate modules of the control system on two different controllers – one requiring the ability to preform high level calculations fast, with storage space for input and output files, and the other to handle interfacing with hardware. For these reasons it was decided to use a Raspberry Pi 3*** for the high level control, and a Moteino*** for the low level control. This could be easily swapped for similar systems such as a previous Raspberry Pi version (*e.g* 2, B+), or most Arduino microcontrollers respectively; these specific boards were already available to use and therefore were chosen (the Moteino was already wired into the boat from previous control systems).

The final layout for the hardware is shown in Figure 2.1, with the GPS on the Pi and all other hardware on the arduino.

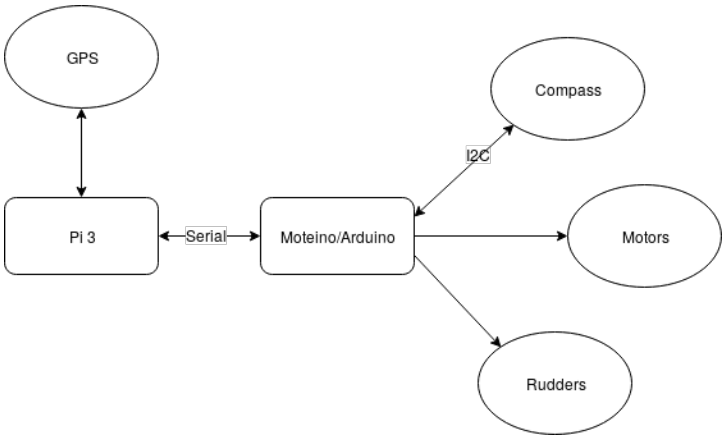


Figure 2.1: Final hardware design. The arrows indicate a flow of data in the corresponding direction, where labels*** indicate the communication protocols used.

2.1.2 Software

The control system has two separate components; one performing high level computations for global navigation and one performing low level control for local navigation. Global navigation is deciding where to go without worrying about the details of how to get there (so planning a course, or route to take), deciding at each new location which heading is best to travel on. Local navigation has no concept of an overall course, plan nor map and only decides how best to stay on a given heading, controlling the relevant actuators.

As can be seen in ***flowdiagram, in this system the high level controller is given GPS co-ordinates to build a map and uses the current GPS location to determine a suitable heading to take. This is the communicated to the low level controller. The lower level controller receives a heading and handles all input and output

necessary to keep the boat propelled on a desired heading (in this case a compass, two motors and two rudders).

***flow diagram

The two separate systems are used because if instead one big system was used on a single controller, the high level logic could delay the low level logic and prevent the motors and rudders being updated at regular intervals. This would not be good as this reduces the control over the direction of the boat (a PID controller needs short update intervals on both input and output to be able to function correctly[10]), and could ultimately result in the boat being unable to make progress in the desired direction.

Another aspect of the overall design is its modular nature, as can be seen in Figure 2.2 and Figure 2.3. The system can be easily adapted to interface with different hardware, which is advantageous as hardware can be easily updated or traded to suit individual needs; as this project is open-source (under the GPL3 license[11]) and intended to be used by others, this feature is important. To achieve this, each piece of hardware has a driver written to control it through specified functions, which the main system can then use to interface with the hardware. This keeps hardware-specific code separate to the main logic of the control system.

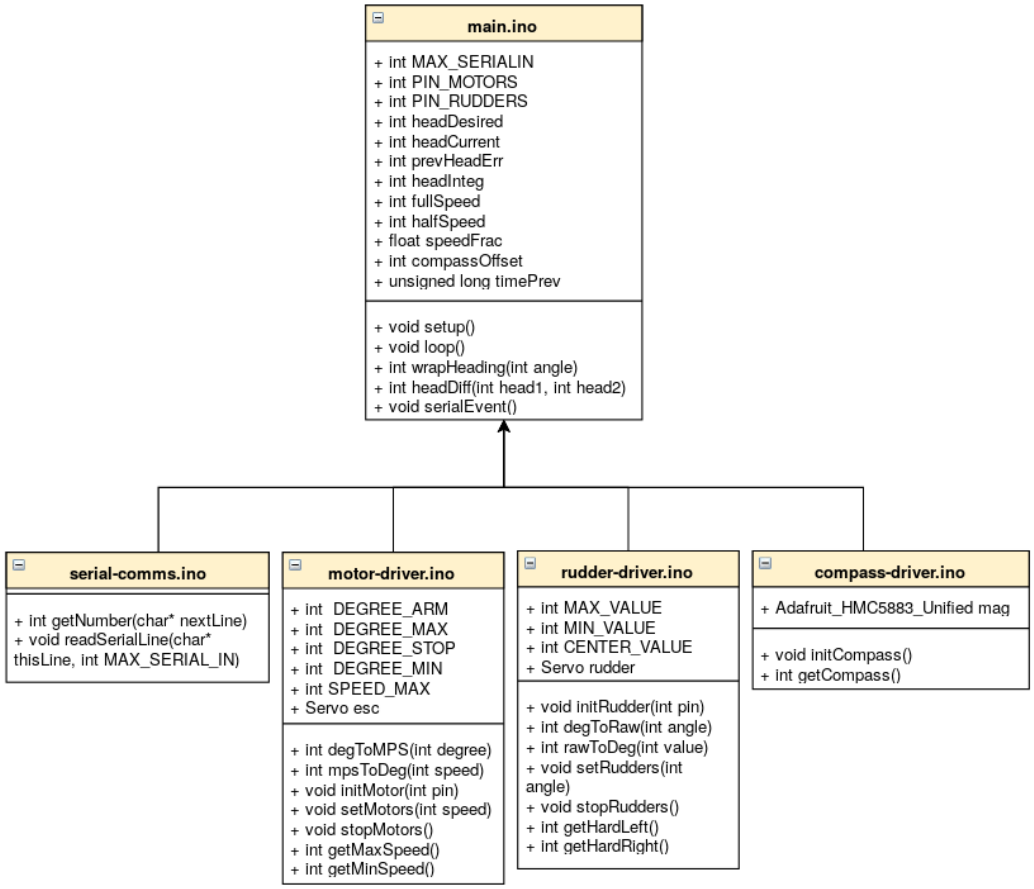


Figure 2.2: Outline of the file structure, functions and constants of the low level code. The modular nature can been seen.

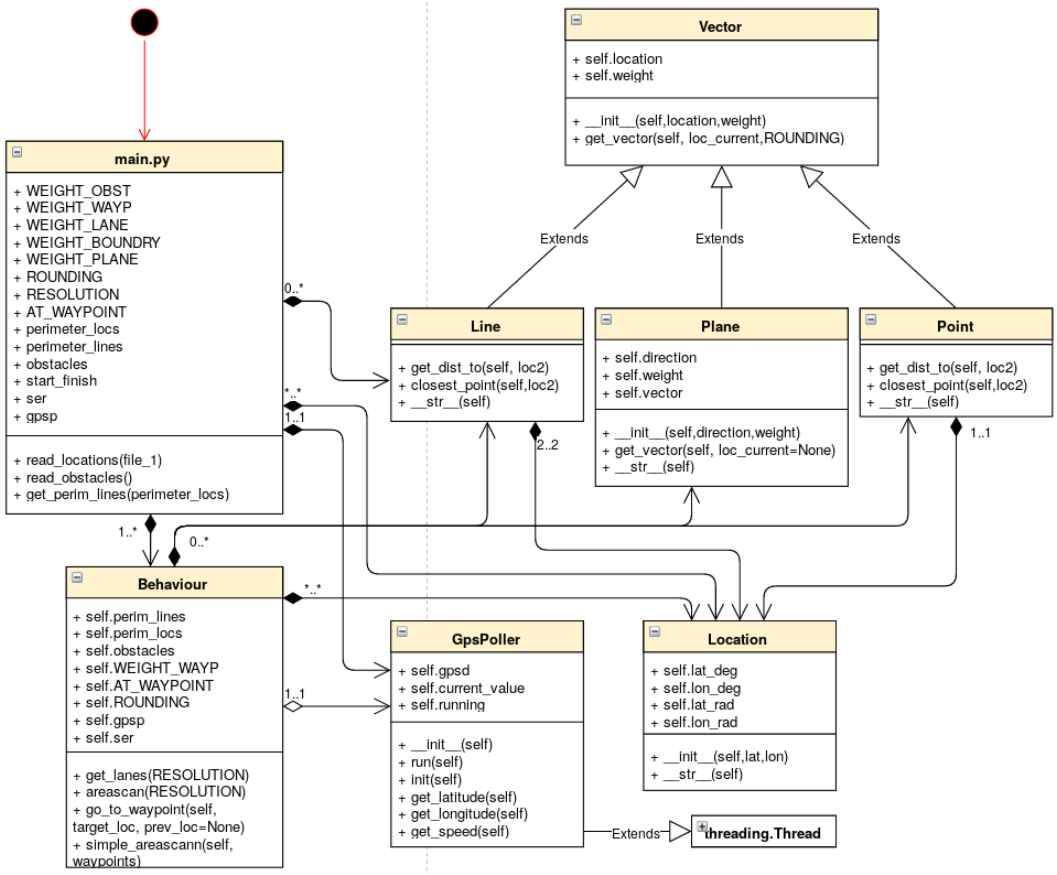


Figure 2.3: UML Class diagram describing the final design of the high level code. Arrows that originate at at black diamond means the originating class contains a new instance of the end class. An arrow originating at a clear diamond means the originating class contains an instance of the end class which has not been created by the originating class.

***Further to the reasons discussed in subsection 2.1.1 for the use of an Arduino microcontroller, the Arduino is a cheap and easily obtainable micro-controller [12], and Arduino C can be used on similar micro-controllers such as the moteino[13], so is useful for anyone wanting to use this software on their own boats. In this implementation, a Moteino was used (though some code was also tested on an Arduino Uno and worked the same). Arduino C was used as *** ***further detail about pi,, and why python was chosen (easy to develop in, dynamic typing useful for maths, support community and modules, etc)

The final overall design has not changed much from the original design (which can be found in Appendix E). *** The main difference are...

To handle the structure organisation and messaging, the use of the Robotic Operating System (ROS)[14] was considered. ROS is often used throughout the robotics industry, implementing base standards for a robot control system. Having researched how to use ROS, and speaking to those who have implemented it in similar scale projects[15], it was found unsuitable for this project: it is hard to work with, with many layers of dependencies, and lots of time must be spent implementing it*** with little benefit for a project of this scale. ***maybe move to design of comms?

2.2 Detailed Design

2.2.1 Arduino Code

2.2.1.1 PID Controller

The local navigation system needs a way*** to keep the boat steady on a heading. A PID control loop can be used to control the rudders to adjust the boats' heading. PID is a feedback control loop*** which adjusts an actuator based on feedback from sensors on the state of said actuator, in order to attain a set state. The three different variables can be adjusted to control the variation of a state over time, and prevent undesirable outcomes (such as overshoot, overdampening etc)***.

Alternative systems ...***

The main use of PID is in the control of the boats heading. As the boat points off the desired heading, the PID should cause the rudders to move at an angle proportional to the change in heading to bring the boat back to the correct heading. ***say more

The use of a PID controller was also considered to control the speed of the boat. *** The motors could also be PID controlled, as this would mean that the boat will go at a steady speed despite its environment (e.g. strong wave, wind) which, if used for sonar scanning of a lake (or sensor readings of any type), readings would be at approximately the same distance apart (as it is most likely that the readings will have to be taken at every given time interval***). This would be useful, but complex to implement. The feedback to say how fast the boat is going is only measurable by the GPS, and this only gives the *** average speed between co-ordinates, which is only updated once a second. There are two limits with this: firstly, when not travelling in a perfectly straight line the measured speed will be less than the actual speed, which posses problems when the boat turns a tight corner and thus appears to have moved no distance. Secondly, the readings for speed being given only once a second is not fast enough for PID to properly work; PID works best with as small as possible time steps*** and a second is too large. Thus it was decided to not control the speed by PID.

With speed, there is an added complication that, when turning a tight corner, it is best to not travel at full speed as this increases the turning circle and means the boat must travel further to make it bake on course. It is better to travel slower while turning tight corners.

2.2.1.2 Hardware Drivers

It would have been desirable to have an interface that the each driver could implement, to make it easier for alternative drivers to be easily implemented, but Arduino C does not support this feature. It would also have been ideal if the separate .ino files in a folder were not automatically included in the main code as having this means that if there are multiple drivers with the same functions (e.g. a compass driver which controls hardware and a compass driver that simulates a compass) in the same file it will not be possible to tell when a function is called which driver it will use. There is no way of specifying this in the main code, so the only way to change this is by removing the drivers not currently wanted from the folder (placing them in a different folder).

Due to these limits on the language the drivers are not as useful as they could have been, but this design is still better than having the harware code in the main code which would mean the hardware could not be easily swapped.

To find how this specific hardware had been controlled before, code was obtained from the previous system used on this boat (see Appendix H). It was noted that the rudder servos were controlled in the same way as any other (with 90 being the central point) using the arduino Servo library. For the motor servos it was noted that an arming value was needed to be set for a set amount of time during the setup for the motors to be able to work, and that a value greater than 90 will turn the motors in the direction to go forward.

***Both rudders are stuck together and cannot be turned in separate directions, as with the motors. Both motors are controlled off the same pin on the moteino and so differential steering was not possible. This means both motors will always run at the same speed. This limits the types of movement available from the boat as it is not possible to turn on the spot. A consideration must therefore be given elsewhere in the code for large turning circles.

2.2.2 Pi Code

2.2.2.1 Navigation

For global navigation there are several different designs commonly used; waypoint navigation[7] and vector field navigation[6; 16]. Waypoint navigation is the simplest to implement as this involves creating waypoints and heading directly for them, one after another, using the robots current location and desired location. It may also be extended to use cross track error to bring the boat back on the line between the previous waypoint and the next waypoint (as this minimises the distance travelled).

Vector field navigation is much more complex than waypoint navigation. Different objects, movements and behaviours can be described by equations that put a "force" on the boat *** (so obstacles would have a repulsive force, and waypoint an attractive force). The forces will depend (in most cases) on distance from a the location of a waypoint or obstacle. These forces are therefore directional and can be represented as a vector. By adding the vectors, an overall force is found which is the direction (and perhaps speed) the the boat should go at. This is much more complex to visualise than waypoint navigation, but for achieving complex behaviour the code is much simpler with vector fields and is much more efficient.

The waypoint navigation cannot easily handle avoidance of an obstacle; a series of points around the obstacle must be plotted, whereas with vector fields a point with a repulsive force can be added at the obstacles location with a weight that relates to the size of the obstacle. The obstacle can be easily remembered throughout the rest of the robots navigating with no extra logic needed, whereas with waypoint navigation a new course must be plotted around the obstacle every time the robot approaches it.

2.2.2.2 Behaviours

The behaviour of the robot should be selectable and easily changeable, therefore a `Behaviour` class was designed to hold functions that control the behaviour. The `Behaviour` class holds the obstacles, boundaries, gps instance, serial communication instance, and useful constants. This means that between different functions called on a `Behaviour` instance, the obstacles and boundaries will remain the same so consecutive behaviours can easily be run.

There are simple behaviours and much more complex behaviours the robot could use to sucessfully scan a lake.

The simplest behaviour possible is navigating toward a single point. More complex than this is navigating to a series of points. These two behaviours are very common ***. Another behaviour, commonly called station keeping, is very useful [5; 7]. This is where the boat navigates to a location, then stays there for a set time. This would be particularly useful in some applications of the system (dropping equipment from a set location, taking stationary readings in specific locations) as well as being useful for deploying and retreiving the boat; the boat can be told to wait in a set location for a set amount of time before starting the scan, and when done can return to a finish location and wait there until someone can retrieve it (more useful when being deployed at sea than from a shore).

With this project it is hard to find existing algorithms that instruct a robot to scan an area in the most efficient way: path finding algorithms would find the shortest route between two specified points, but would not yield the most efficient way to navigate to every point within an area. This problem is similar to the travelling sales man problem[17] in that the shortest route between many points needs to be found, but in this case the points are generally in a predictable layout, so a computationally heavy algorithms like those

needed to solve the travelling salesman problem[18] are not needed.

2.2.2.3 GPS Driver

To begin with the GPS was going to be attached to the Arduino...***.

In the end it was decided the GPS should be placed on the Pi. In order to control it it was best to make a driver for it, again so that it could be easily swapped for new hardware, but also to enable different systems to be used to interface with it. GPSD is very commonly used with Python to interface with a GPS, as it handles it very well and makes the data from the GPS easily readable. Therefore it was decided to use GPSD.

2.2.2.4 Vector Classes

Having decided in subsubsection 2.2.2.1 to use vector field navigation ***

2.2.2.5 Logs

2.2.3 Arduino-Pi Communication

***Need a way of sending messages both ways between the pi and Arduino. It would be complicated to have both the pi and Arduino able to initiate messages between them, as this could cause clashes. A slave/master system is more appropriate, with the pi as the master, sending the initial messages.

The messages will consist of a single letter (e.g. 'e'), or single letter followed by a number in brackets (e.g. 'h(276)') if a number is required. This is for efficiency; the as messages on the Arduino are stored as a char array and so must be compared char by char, rather than a simple comparison of strings (comparison of strings would make extracting the number that needs to be saved more challenging, and would probably result in the String being converted into a char array). It is sufficient enough to use a single letter for the meaning of the message; and there are only 4 meanings that need to be transmitted, so there is no danger of running out of letters to use.

***The use of brackets means that the code can be sure exactly where the number is expected to start and end – if there was no character signifying the end of the message, if an extra number was transmitted accidentally by another part of code, or through noise on the connection, then the number read could be very wrong. It also makes defining the end of the message easier, as it may not be known how the message will be terminated (a new line, carriage return or null terminator are all valid options).

It would be ideal to have a confirmation message to so that the message had been received every time a message is sent, but implementing this seems too over engineered for this system; if a single message is missed, there will be a new message in around a second. The only place where there needs to be confirmation, is during the shutdown sequence. Here the Arduino needs to turn the motors off before it is safe for a person to pick it out of the water, and so a missed message saying to shutdown cannot be ignored. Therefore, during shutdown the pi will ask the Arduino to sleep by sending the letter 'e', and will expect it to respond with 'e' if the message is received. If the pi does not get the response within a set time*** it will send the message again. If after five*** attempts the Arduino still has not responded, it can be assumed something has gone wrong and that the python code should exit anyway.

Implementation

3.1 Tools

*** See Appendix D Originally this software was developed using PlatformIO (see Appendix D) as this gives a more C like file structure to the code, and allowed drivers to be easily imported into test files to allow the drivers to be tested. Unfortunately PlatformIO is not easily installed on a Raspberry Pi, where as the Arduino IDE can be easily installed, and so the code was adapted to be used with the Arduino IDE (see Appendix D).

This project used git for version control and for backing up code. As this project is open-source, it is held on GitHub under the GPL-3 license[11] and is therefore available for others to use.

3.2 Hardware

The first step before writing the lower level Arduino was was to decide exactly which type of Arduino was to be used and which environment the code would be developed in. There was found to be very little difference between different Arduinos (apart from which pins are defined for different functions). As there is not much hardware (only three pieces, requiring 4 pins) it was decided there was no need to move away from the Moteino board already in the boat as it fits the requirements (enough pins, uses 3.3V output, can use serial to communicate with it). An arduino Uno was used during some of the early stages of coding as the Moteino was stuck to the boat so could not be used outside of the Robotics Lab. Later a Moteino not attached to the boat was used for development, before uploading code to the boats' moteino (as early development may have caused the hardware attached to the boats' moteino to act in unexpected ways).

It also had to be decided which board would control the higher level logic. A Raspberry Pi 3[19] was the most suitable board available; has multiple USB ports for the GPS and Moteino to be connected to, has WiFi for easy control (can easily SSH in to start the code, see output on a separate machine from some distance, can edit code from another machine) and is small and lightweight. Previous attempts to give this boat a control system have used small laptops (which are considerably bigger than the Pi) or no seperate board for high level control at all (reducing the computing power of the system considerably).

3.3 Arduino Code

3.3.1 PID Controller

The PID was implemented using the difference between two headings (the current heading and the desired heading) as P. Finding the difference between two headings was challenging due to the use of a circular scale, as it is not simply subtracting one value from the other as would be the case with a linear scale (the smallest angle between 5 and 355 degrees is 10, but by simply subtracting these values you get 350 or -350). With this circular scale, the values wrap at 360.

There are solutions that are extremely simple which use trigonometric functions to calculated the difference between the two headings easily, preserving the sign (which indicated a clockwise/anticlockwise turn). But these functions are computationally inefficient, so it is best to avoid using them where possible.

A more efficient way is using the equations below to calculate different angles between the headings:

$$(360 - A) + B \tag{3.1}$$

$$B - A \tag{3.2}$$

$$(B - 360) - A \tag{3.3}$$

The result of Equation 3.1 , Equation 3.2 and Equation 3.3 with the lowest absolute value is the smallest angle that can be moved through to get from A to B. A positive result indicates a clockwise turn, and negative indicates an anti-clockwise turn. Which equation gives the smallest result is dependant upon which quadrant the two heading lie (0-90,90-180,180-270 or 270-360). This solution works, but may not be the most efficient solution.

During the tests in subsection 4.8.2, there appeared to be a mistake in these equations. The correct equations are shown above, but originally Equation 3.3 read as $(360 - B) + A$ which was incorrect.

To tune the PID loop, different methods of tuning were researched. The two main methods investigated were the Ziegler-Nichols[20] method, and manual tuning. According to a review of these methods by Wikipedia [10], the manual tuning requires experience whereas the Ziegler-Nichols method does not. Because this robot is a boat and tuning of the PID requires access to a large body of water for the boat to move on, it was impractical to tune the PID manually, so it was decided to use the Ziegler-Nichols method instead.

To make the boat turn tight corners it was decided to make the boat travel at half the maximum speed that the boat can travel at.

3.3.2 Rudder Driver

To calibrate the rudders, a test program was used that took the rudders left, right and centre to test if the directions were correct, and to see if the limits were too high or low.

3.3.3 Motor Driver

Due to the modular design of the system, and given that all parts relating to the motors should be easily swappable, it was decided that the main code should only perform logic in units of ms^{-1} rather than the raw motor values (which here is given in degrees). This is so that any motor working with different units or scales can still be used.

Therefore, the driver includes functions that translate from the scale the motors use to ms^{-1} and back. The maximum, minimum and stop raw values are held in the driver, and can be translated and returned to the main program by calling `getMaxSpeed`, `getMinSpeed` and `getStopSpeed` for the main program to work with (e.g. find a half max forward speed, by finding the average of `getStopSpeed` and `getMaxSpeed`). There is also a `stopMotors` function that will stop the motors (which is useful at the end of the program). There was the idea to detach the motors from the pin to prevent them being written to later in the program, but this would instead cause the values written to the motors to be left floating (changing randomly over time) which would be undesirable and dangerous (if removing the boat from the water at the end of a run, the motors could start turning at any speed at any time).

In `initMotors`, there is a five second delay after the motors are set to their armed value, which is required by this type of motor before any other values will work (as noted in Appendix H). This delay may be larger than necessary, but ensures that the minimum time is definitely reached.

The difficult part of this design is that it may not be known what speed the motors move the boat at, and this will vary under different conditions (e.g. high winds, strong currents).

The motors were calibrated by firstly using a simple test program (`test-motors.ino`)that sends varying raw values to the motors and seeing how the motors respond. It was found that the theoretical maximum value of 180 was too high for the motors and so the motors would not turn on.

3.3.4 Compass Driver

The compass library is based around the Adafruit code libraries (see Appendix C) designed to be used with this compass. The example code to use the library was copied and adapted for use with this system; notably the heading was converted from radians to degrees.

By testing this simple driver on the compass, it was found that the compass readings were not correct. It was assumed that a simple zero error would be the problem, but further testing revealed this was not the case (see results in Appendix F). The compass measured different changes in degree at different bearings even though it was being moved through the same angle. Thus the initial design of simply adding an offset to the compass would not work.

To investigate this further, the compass was glued into the boat which was placed on a wheeled platform and rotated through different angles. A calibrated compass was placed on the boat. The boat was turned in steps of 20^o from 0^o to 340^o according to the boats compass, and the actual heading according to the calibrated compass was recorded. By plotting this on a graph (Figure 3.1) in LibreOffice Calc (see Appendix D) it was clearly visible that there was not a linear trend between the boats compass headings and the real headings.

To compensate for this, a trend line was plotted through the points and the resulting equation was used to transform the compass headings into actual headings.

An important point to note about this equation is that when the actual heading becomes 0, the points will shift on the graph so that a trend line cannot be found to closely match the points. For this reason, the value the compass reads as 0 (due north) was recorded, and any values greater than this must have 360 taken away from them before being passed to the transformation. The results of this can be seen in figure 3.1.

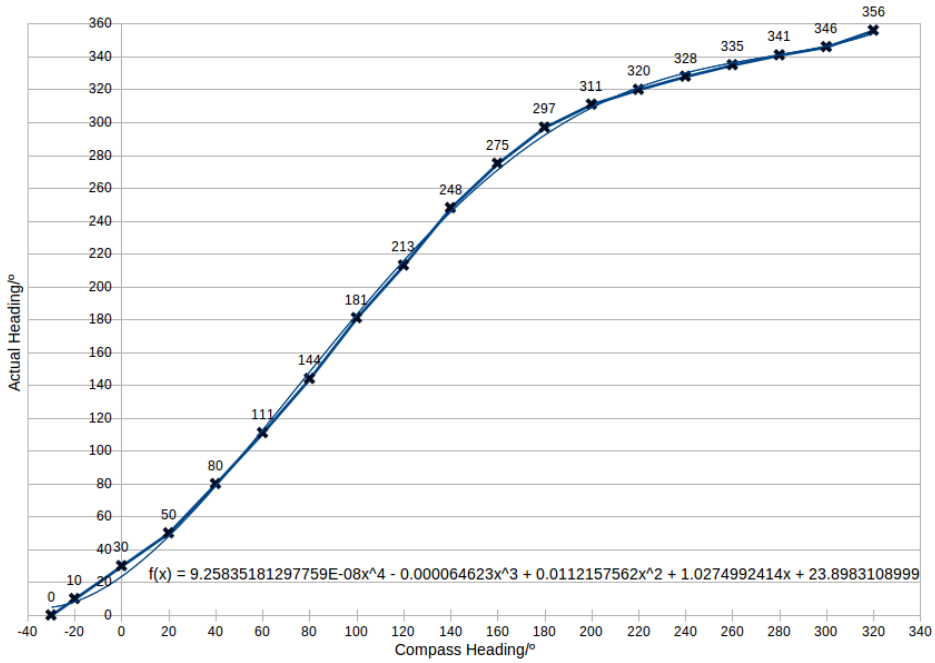


Figure 3.1: Graph of compass heading vs actual heading. The equation is that of the trend line.

This transformation was added to the compass driver, so that any values returned to the main program will be calibrated. It was checked that values of 360^2 could be held by a float in Arduino C as this comes to a very large number (1.68^{10}). Fortunately floats can be between 3.4028235×10^{38} and as low as $-3.4028235 \times 10^{38}$ [21] so there is no way that any values can wrap in this equation.

3.4 Pi Code

The first step in implementing the higher level logic on the Pi was deciding which operating system and language should be used. ...***

3.4.1 Navigation

Vector fields were chosen as the navigation system. To aid in the implementation of navigation, a class called Location was implemented. This simple class holds latitude and longitude in both radians and degrees. It was decided to implement this class like this so that the conversion only has to be done once, saving on unnecessary repetition of the conversion during calculations. This could have been implemented using a `numpy.array`[22] instead of a new class, but this would have lead to the confusion between latitude and longitude and which way around they are held in the array (which would cause confusion when implementing complicated equations).

Having considered the different ways of implementating vector fields[23; 24], three different vectors types were designed called `Lines`, `Points` and `Planes`. These objects all create a force in a specific direction, which when converted to vectors and added together results in the direction the boat should be travelling.

Line objects represent a line between two Locations, where the force between the Locations acts perpendicular to the lines, and at the ends of the lines the force acts in the direction from the boats current location to the location of the end of the line (see Figure 3.2). Similarly, a Point object represents a point, where the force on the boat acts parallel or anti-parallel to the heading from the boat to the point (as seen in Figure 3.2). A Plane object causes a force of a set strength in a set direction irrespective of location.

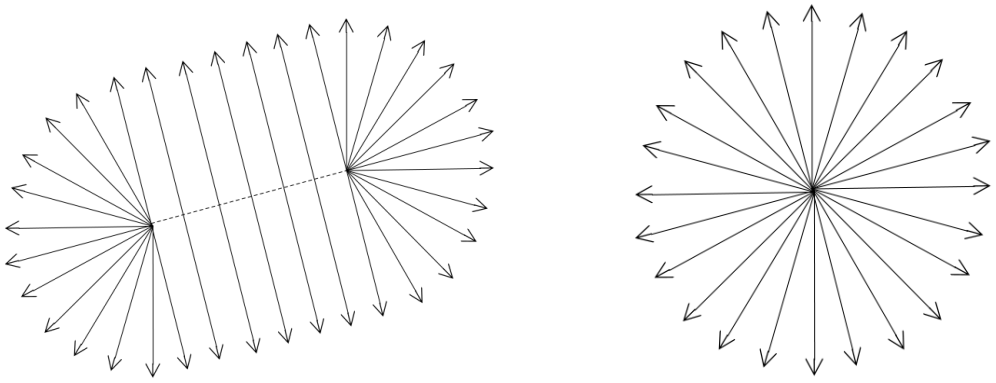


Figure 3.2: Visualisation of the direction forces will act with the Line (left) and Point (right) objects. The arrows represent the direction of a repulsive force; an attractive force would be antiparallel.

The forces on the Lines and Points change with distance to the object. For attractive objects the equation $F = mr^2$ was chosen, where F is the overall force on the boat, m is the weighting of the object and r is the distance from the object. For repulsive forces the equation $F = \frac{1}{mr^2}$ was chosen. These are represented in Figure 3.3.

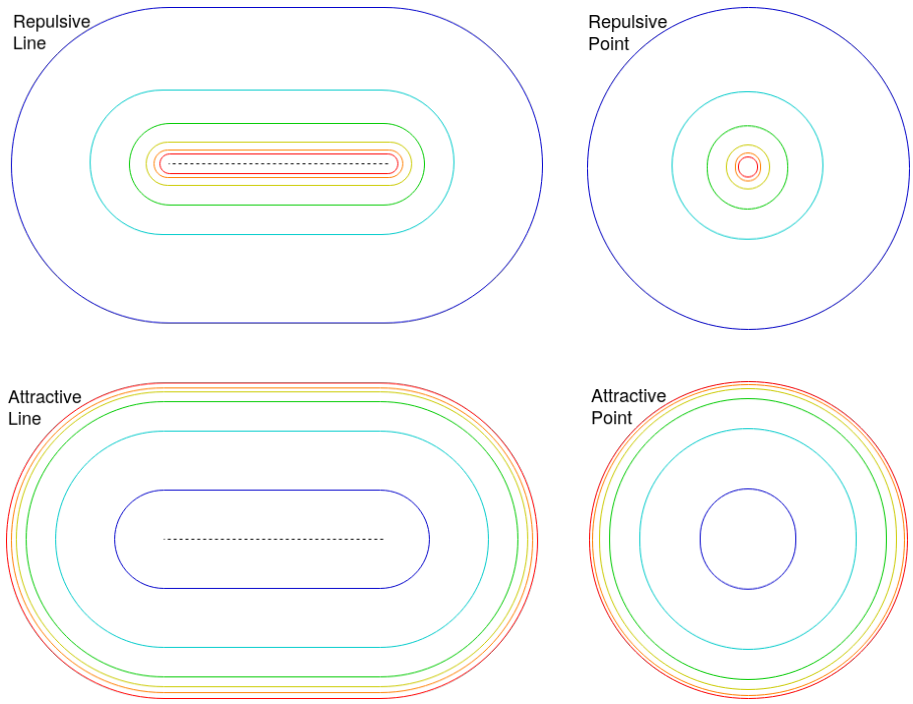


Figure 3.3: Visualisation of the strength of forces acting on the boat with distance from a Line (left) and Point (right). The coloured lines represent equipotential forces, red representing a very high magnitude force force and blue a very low magnitude force.

These lines and points can be added together in different ways at different locations to build a map and make the boat exhibit a desired behaviour.

The input files were formatted as comma-separated values (csv) as this is a common format and python has modules that can be included to read .csv files easily (see Appendix C). Example files from all the tests can be seen in Appendix G.

3.4.2 Behaviours

After exploring several options, a simple algorithm was devised for scanning bodies of water of almost any shape; given the outline of the lake as points defining the perimeter, the two furthest points apart are found. Between these two points, lines perpendicular to the line joining the two points are found at regular intervals (the frequency at which a user would like traces of the water to be taken). The ends of these lines are limited to 5m within the boundary of the water, and attractive Point objects are initialised at these points. The lines between the points are also initialised as Lines. By storing successive waypoints and lines in a list, and iterating over this list, the waypoints can be navigated in a logical order to scan the entire area (the lines would be used to keep the boat on a straight line between the points). See Figure 3.4 for a visualisation of this.

Another strategy explored was the spiral, where points are placed 5 metres in from the points defining the boundaries of the water until the centre is reached, drawing lines between points equidistant from the perimeter, and following those lines. This would be much more complex to implement, and a comparison of these strategies as seen in Figure 3.4, led to the conclusion that the spiral covers more distance than the square-wave strategy, or at best covers the same distance.

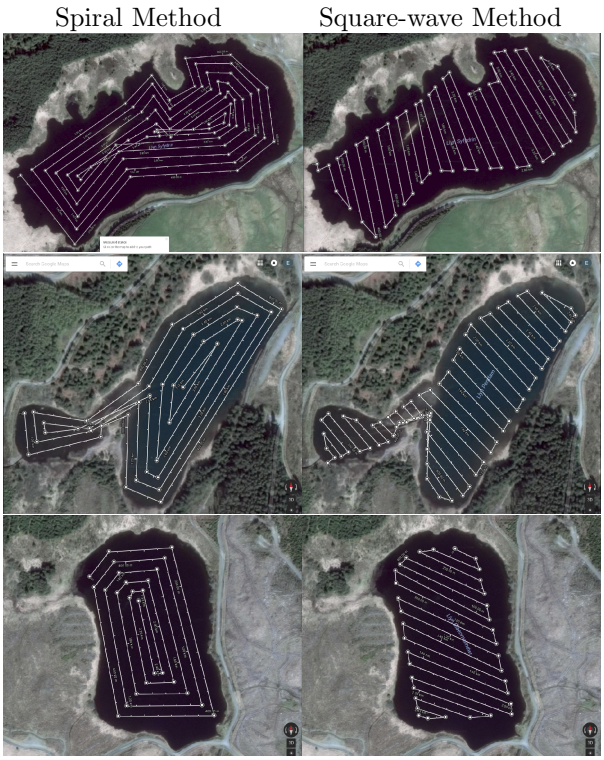


Figure 3.4: A comparison of possible area scanning strategies. The top lake yields a result of 5.96km and 4.31km, the middle 3.12km and 2.82km, and the bottom 2.53km and 2.53km for the spiral and square-wave strategies respectively.

***move this t̂o testing?

The square-wave strategy appears to work in most shaped lakes but there are cases where it will not work; most notably it will not work on an ox-bow lake, nor a meandering river (though it should be noted that this boat should only be used at most very slow moving rivers in order to avoid been dragged downstream – a lake is the preferred environment).

After deciding on a strategy for implementing autonomous strategy planning, it was decided to start with much simpler behaviours that can be more easily tested and debugged (with a complicated algorithm any bugs in the behaviour could be as a result of mistakes in the algorithm or in the rest of the control system). It would also take less time to implement, but would still produce a working control system.

The two behaviours are the `simple_areascan` and `go_to_waypoint` behaviours. The `go_to_waypoint` behaviour takes a target `Location`, makes a `Point` at the `Location`, then

3.4.3 GPS Driver

Implementing the GPS driver was challenging as the GPSD software had to be installed and then investigation had to be done into how to use it. ***

3.4.4 Logs

*** After the first test around the castle (see subsection 4.7.1), it became apparent that the logs recording only location and desired heading were not enough as it was impossible to tell with overlapping tracks what was happening when. Thus it was decided to add as much useful information to the logs as possible.

3.5 Arduino-Pi Communication

Communication between the Arudino and Pi was interesting as Python and arduino C it was hard to find out what encoding the Arduino uses by default over serial. By testing the communications between the two (using `test-comms.py`), it was found that ASCII encoding could be used successfully by the Arduino and UTF8 by the Pi to communicated with eachother.

In order to achieve this, the Python messages need to be encoded calling `.encode('utf-8')` on the desired string, as the defult string sent is not readable by the Arduino.

***Several serial communication libraries were investigated in Arduino C and Python, that claimed to handle easy communication between the two. *** After spike tests it was decided that these libraries were difficult to use and therefore were not used.

With Python, by default the `\n` and `\r` characters were included in the read in string, so if the arduino sent `e` the python code would read and save this as `e\n\r`. This is not ideal for easy comparison of strings, so the `.strip()` function was used to remove these characters.

3.6 Final Integration

The last steps in implementing the system involved writing a script to autonomously run the program. This script starts gpsd, and starts the python code. This was largely unsuccessful as gpsd needs different steps before being deployed, depending on what has been done before (e.g. sockets need disabling the first time round but not every time after that, gpsd must be killed each time the port of the gps changes which could not be done easily in the script). There is also no way of ensuring the gps and Arduino have been assigned the same port every time the pi is restarted (a particular flaw is that when the Arduino is reflashed, the pi will always assign it a new port).

Instead, the program should be started by starting gpsd then running the python code from inside the python-code folder. When it starts, text similar to that in Figure 3.5 will appear in the terminal.

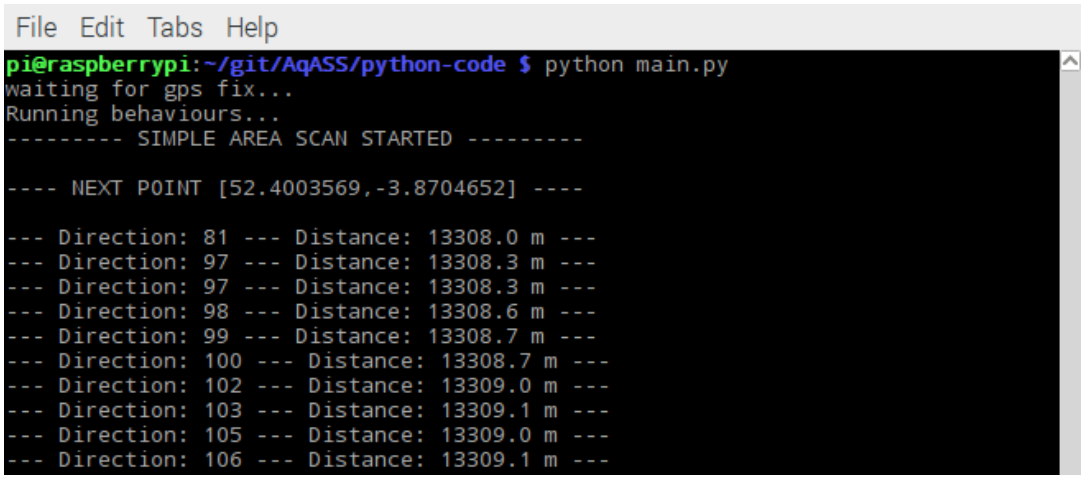


Figure 3.5: Example print out when program is run.

Testing

4.1 Preliminary Tests

At the very start of the project the existing system was tested on the water to see how fast the boat can travel, how fast it is able to turn (and the size of the turning circle) and how much it is affected by external factors (such as waves, currents and wind). This was done by moving the boat under remote control.

Data was recorded by the logging system from the previous, semi-autonomous control system. ***

4.2 Arduino Tests

It would have been ideal to use unit tests to test the individual functions and classes within the Arduino code, but these are not supported by the ArduinoIDE. Unit tests are meant to be supported in PlatformIO, but after trying to get them to work for a very long time, it was decided that they could not be easily used. Instead, alternatives to unit tests had to be used. This mostly involved producing spike work, thoroughly testing this in its own file, then merging this with the main code.

4.2.1 PID Controller

Testing the PID tuning proved difficult, as this must be done on the water, and in order to check the PID tuning, there must be a way of seeing if the boat is oscillating about a heading or not. This is difficult as this cannot be done from shore; one of the main motivations for this project is the impossibility in telling if the boat is travelling in a straight line or not from shore. It would be possible to record the location of the boat according to GPS as it travelled, but GPS is only accurate to 5***meters which is not accurate enough for fine tuning. The added fact that waves and currents will effect the motion of the boat unpredictably means that fine tuning the PID was impossible.

Some tuning of the PID was done during the land tests described in subsection 4.8.1, but the tuning was found to be wrong during the water tests (described in subsection 4.8.2. This is due to an underestimation of the speed of the boat and therefore how fast the boat must move its rudders in order to stay on course.

In the end, the Ziegler-Nichols methods implemented were removed during the lake tests and the manual method was implemented instead (as this is the simplest method) by increasing the value of P until the rudders moved sensibly and proportionately to a change in heading (turning the boat on the spot). The PID was not tuned any further as this was sufficient for the boat to move on the correct heading.

A way to improve the tuning in future would be to enable the PID to be adjusted on the fly (through use of wifi to the Pi and passing messages to the moteino via serial, or through another moteino talking to the boats moteino over radio). By having the PID easily adjustable, and then following the robot in a boat so it can be seen close up how the robot is moving, it should be possible to finely tune the PID. This was not possible in this project as there was not time, and fine tuning was not critical to making the control system functional.

4.2.2 Rudder Driver

***

4.2.3 Motor Driver

***

4.2.4 Compass Driver

The main tests for the compass driver involve testing the calibration, as described in the implementation in subsection 3.3.4.

Looking at Figure 3.1 in subsection 3.3.4, it can be seen that the final equation still does not perfectly calibrate the compass, as there are places where the trend line deviates from the data points; specifically between a compass heading of -20^o and 20^o(which corresponds to an actual heading of 10^o to 50^o). The deviation is at most 10^o, so this should not have too great an impact on the navigation of the boat; the heading may be out by 10^o at some times but the PID*** should compensate for this. The most impact this will have is in making the boat curve towards its target instead of taking a direct course. Further investigation of this problem is discussed in subsection 3.3.4.

Having tested the final equation, it was observed that the compass showed the corrected heading when turned to 90^o, 180^o, 270^o and 0^o. This was a drastic improvement upon the original driver.

4.3 Arduino-Pi Communication

Communication was tested using the main code on the Arduino and python test code on the Pi. The python test code included only bits of code necessary to send messages in order to solely test the functioning of the communications, for these bits of code to be later integrated into the main python code.

4.4 Python Unit Tests

4.4.1 Vector Classes

Some simple unit tests (`vector-test.py`) were created to test the functionality of the different vector classes. These ensured the vector classes were implemented correctly and that the calculations within the vectors worked. When run, these tests all passed after only minor corrections to the code.

Similar unit tests (in `test-locations`) were created for the `Locations` class to test the calculations in the class. Known values were compared to the results of the functions, and compared. Again, these tests were easily made to pass (only needing to correct small bugs).

4.5 GPS Driver

The GPS driver was tested during implementation, by seeing if the data being given was logical. The data showed a correct location when plotted on a map using GPS Visualizer, and so was working as expected.

In later tests it became apparent that the GPS was less accurate than anticipated, but there was nothing that could easily be implemented in the driver to correct for this. In future, to increase accuracy, the main code could be adapted to filter the GPS, or average the readings over time to prevent spurious readings.

4.6 Logs

Testing of the logs was done by running the program and seeing if the logs.csv file had new lines in the correct format. This was done by visual inspection and by passing the file to GPS Visualizer (see Appendix D) and

seeing if the file could be read.

After the testing discussed in subsection 4.7.1, the logs were improved. These were then tested by running the full system (not in a full scale test) and inspecting the log file and using GPS Visualizer again.

4.7 Navigation and Behaviours

In order to test the navigation, the behaviours (which handle navigation) had to be implemented, and were therefore tested together.

For each of the following tests, the specific input files used can be found in Appendix G.

4.7.1 First Castle Grounds Test

4.7.1.1 Method

In order to test the heading resulting from the vector field at different locations, a single point was placed in a field by a known landmark (so the location could easily be identified), in this case the intersection of the paths in front of the memorial. A perimeter was plotted the field, as defined by the paths around the field. The point and the boundary were both given a weighting of 10 and -10 respectively.

The pi was then moved around the field semi-randomly to see how the heading varied in different locations. The heading and distance to the waypoint were printed to the screen, as monitored by a laptop, from which there was an SSH session into the Pi.

4.7.1.2 Results

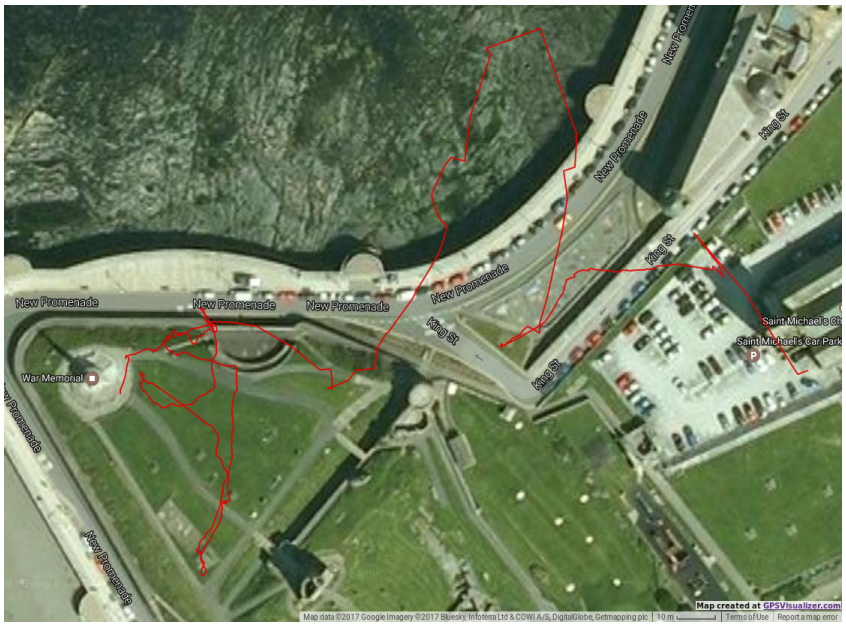


Figure 4.1: Carrying the Pi and GPS around a field to test the heading given by the Pi as given by the single waypoint behaviour. The red line in both images show how the Pi's location changed (according the the GPS), with the zig-zag indicating the desired path. The arrows on the right image show the desired heading at each location.

4.7.1.3 Results

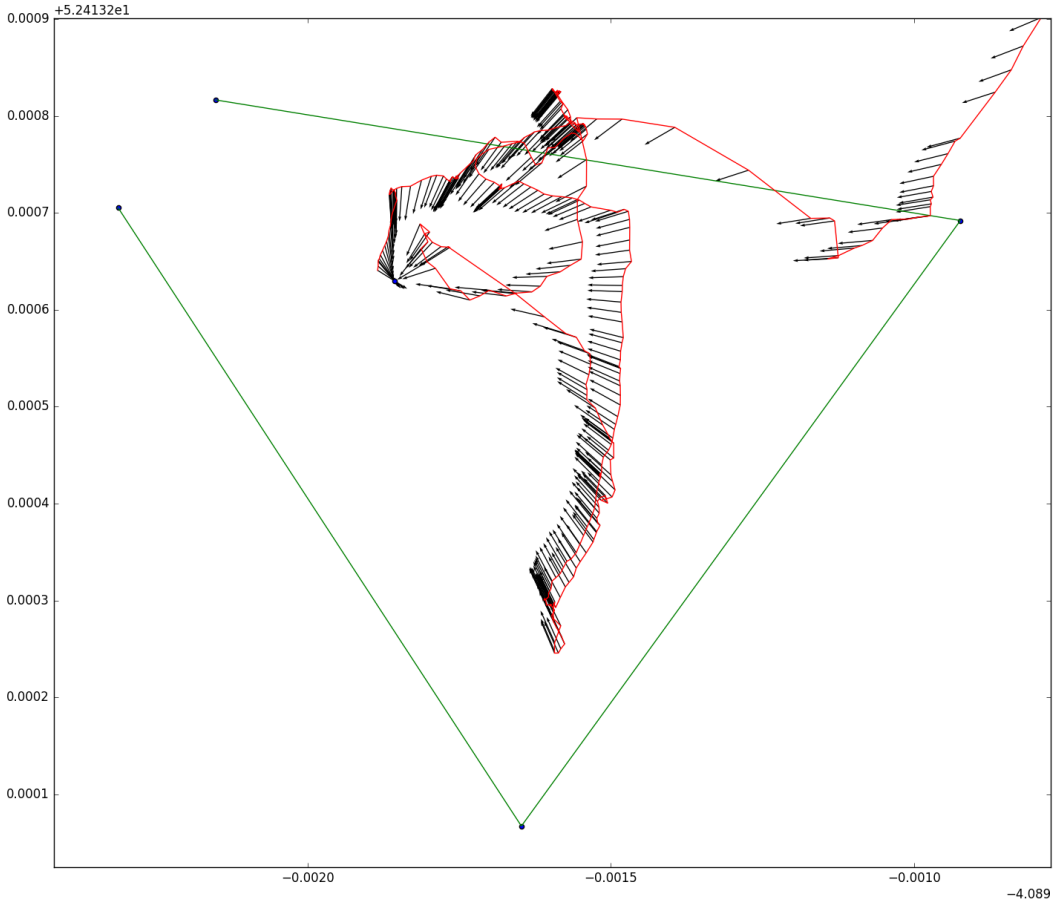


Figure 4.2: Carrying the Pi and GPS around a field to test the heading given by the Pi as given by the single waypoint behaviour. The red line in both images show how the Pi's location changed (according the the GPS), with the zig-zag indicating the desired path. The arrows on the right image show the desired heading at each location.

4.7.1.4 Analysis

It was found that the vector field was not responding correctly to the boundary of the field. It was expected that near the boundary the heading would become perpendicular to the boundary (in order to steer the boat away from it), especially as the force would tend to infinity the closer to the boundary it was.

This is most likely because there was no limit on the attractive force of the point, so when the current location is far from the waypoint, the force tends to infinity. This means that for the boundary force to become significant, it too would have to tend to infinity, which would require being extremely close to the line. Looking at the results of the plotted vector, it can be seen that specific points were in fact directly on the line but were still not pointing in the correct direction.

To solve this problem of attractive objects overpowering repulsive objects, a limit was placed on the size of the attractive vectors. This means that the boat will always tend to head towards attractive objects, except where there is an obstacle, and avoiding obstacles takes priority.

4.7.2 Second Castle Grounds Test

4.7.2.1 Method

Testing of the single waypoint behaviour (`go_to_waypoint()`) was done using the Raspberry Pi with only a GPS attached. Every new desired heading was saved along side a the current GPS location, and in later tests the time stamp. GPS co-ordinates outlining a field and waypoints within the field were found using GPS Visualizer and were passed to the code as further discussed in subsection 3.4.1. To test the algorithm, the Pi was moved around the field in a zig-zig shape to cover the whole field, including right up to the field boundaries and beyond.

4.7.2.2 Results

The logged locations can be seen in Figure 4.3 for the castle field tests.

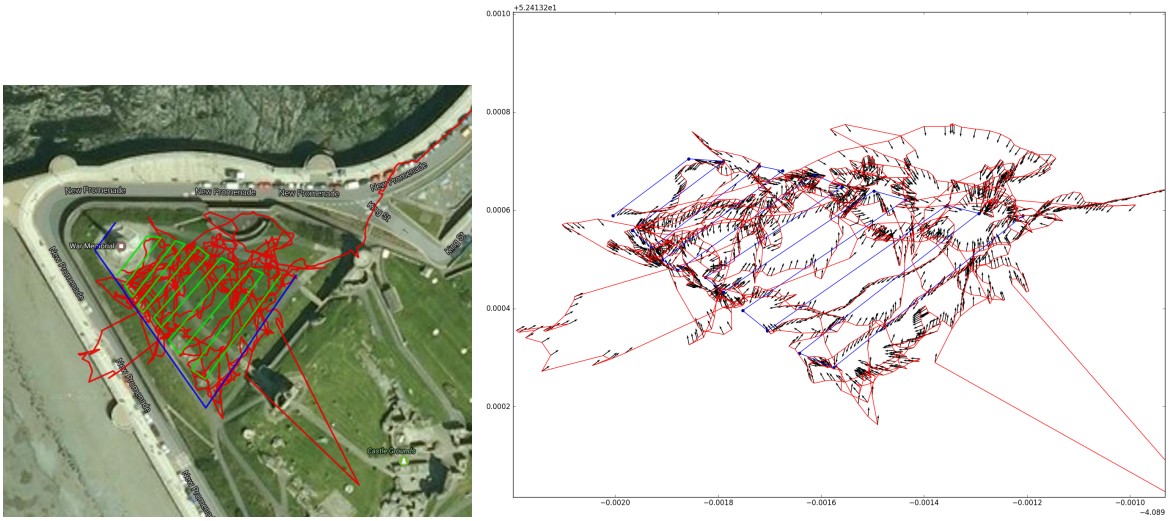


Figure 4.3: Carrying the Pi and GPS around a field to follow the waypoints (as planned by the simplescan behaviour), resulted in unreadable data being logged, but feedback during the tests confirmed that the behaviours were acting correctly. The red line in both images show how the Pi's location changed (according the the GPS), with the zig-zag indicating the desired path. The arrows on the right image show the desired heading at each location.

4.7.2.3 Analysis

It was found by looking at the desired heading on when at each location within the field, the algorithm was working correctly. The logged data for these tests is very hard to interpret (see Figure 4.3), but for these tests logging was to serve as a potential supplement to the test and as a record of the test, rather than being an integral part of the test.

4.7.3 Large Field Test

After seeing the field by the castle was too small for accurate readings, it was decided to move to a bigger field with less structures around to block the GPS signal. The bigger field also better replicates the size of a lake or body of water likely to be used with the boat.

Another advantage to using this field is that it is a football pitch with markings so it could be easily seen

while carrying out the test where the Pi was in relation to where it should be navigating to (i.e. the long legs of the course should result in the Pi giving a heading to move parallel with the width of the pitch). This made the test much easier to carry out.

4.7.3.1 Method

Again, a series of waypoints were plotted in the field with the outside edge of the field as the 'water' boundary.

For this test a magnetic orienteering compass was used to find the exact direction the Pi was saying to move in. It was then attempted to move in that direction to test how well the navigation worked.

4.7.3.2 Results

The results can be seen in Figure 4.4 and Figure 4.5.

Figure 4.4: Carrying the Pi and GPS around a field to follow the waypoints (as planned by the simple_areascan behaviour) The red line shows how the Pi's location changed (according the the GPS), with the zig-zag indicating the desired path.

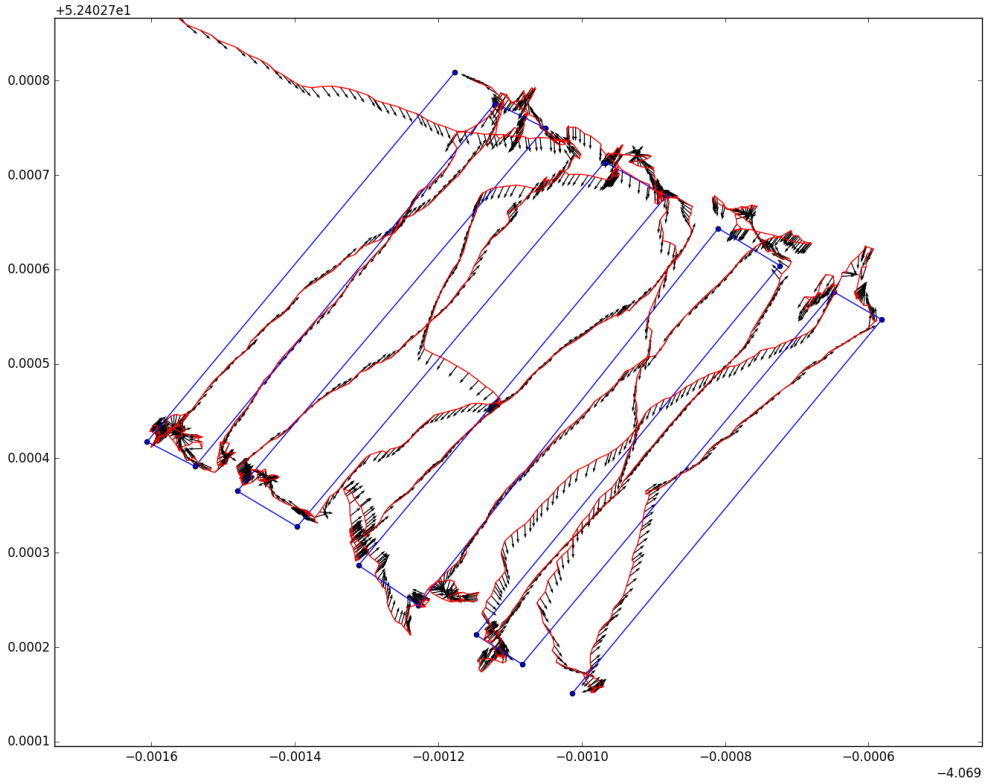


Figure 4.5: Carrying the Pi and GPS around a field to follow the waypoints (as planned by the simplescan behaviour), resulted in unreadable data being logged, but feedback during the tests confirmed that the behaviours were acting correctly. The red line shows how the Pi's location changed (according the the GPS), with the zig-zag indicating the desired path. The arrows show the desired heading at each location.

4.7.3.3 Analysis

***need to analyse these results The results all together are largely unreadable, but feedback during the tests confirmed that the behaviours were acting correctly.

4.8 Overall Functionality

To test the functionality of the overall control system two different types of test were used; land tests and water tests.

4.8.1 Land Tests

Firstly, the boat needed to be tested on the land, as testing a control system on the water when it has not been tested all together before could result in losing the boat.

4.8.1.1 Method

Therefore so called "Car park tests" were carried out on the boat; this involves loading the full program as though it is about to go out on the water, but instead carrying it or placing it on a trolley (see Figure 4.6) to be wheeled around a field or large open space (such as a car park). By watching the rudders and adjusting the boats heading according to the rudders, it is possible to simulate how it would move on the water.

With this technique it is possible to tell if the final behaviour of the boat is correct, and it is possible to tell if it is safe enough to place on the water (e.g. it doesn't try to move in the completely wrong direction at any point, the system doesn't unexpectedly crash at any point).

4.8.1.2 Results

Figure 4.6: Testing boat in a field on a trolley. The right hand picture shows the route the GPS recorded. The purple zig-zag shows the most efficient route between the waypoints chosen (with waypoints at each turn in the purple line). The boat started at the top of the red line, and ended at the dark purple line on the right. The different colours indicate a change in which waypoint is trying to be reached.

4.8.1.3 Analysis

With the first land test, the boat seemed to move in large loops rather than directly between the waypoints, though this could be as a result of the GPS inaccuracies (this will make the boat want to go on a different heading as it appears to be in a different location to where it is in reality).

The GPS location results for this test are shown in Figure 4.6 . It can be seen that there is a lot of variation with the GPS readings, as expected with this type*** of GPS, and in a somewhat built up location. The bright green line and dark blue line are particularly inaccurate, but this was the case only for a short amount of time.

As the GPS was jumping so much, it was hard to tell how well the control system was working so it was decided to test it on land again using points further spread out (***

4.8.1.4 Second Method

***

4.8.1.5 Results

***

4.8.1.6 Analysis

*** At this point it was decided that the system works enough for a water test to be carried out.

4.8.2 Water Tests

4.8.2.1 Method

*** This test was designed to test the overall function of the system in the environment it is designed for. Way points were plotted in a simple course around the lake. These were spread out and evenly spaced so that results could be easily interpreted.

4.8.2.2 Results

On first observation, the results of the water test looked very promising. As can be seen in Figure 4.8, during both runs of the test the boat followed the northward and southward sides of the route almost perfectly both times. The general direction for the rest of the route was correct, except at the start of the run both times where the boat was moving on a bearing that was roughly 30^o clockwise of where it should have been moving. This was thought to be a result of an error in heading difference calculations in section 3.3, but this could not be fully fixed between tests, only after both tests.

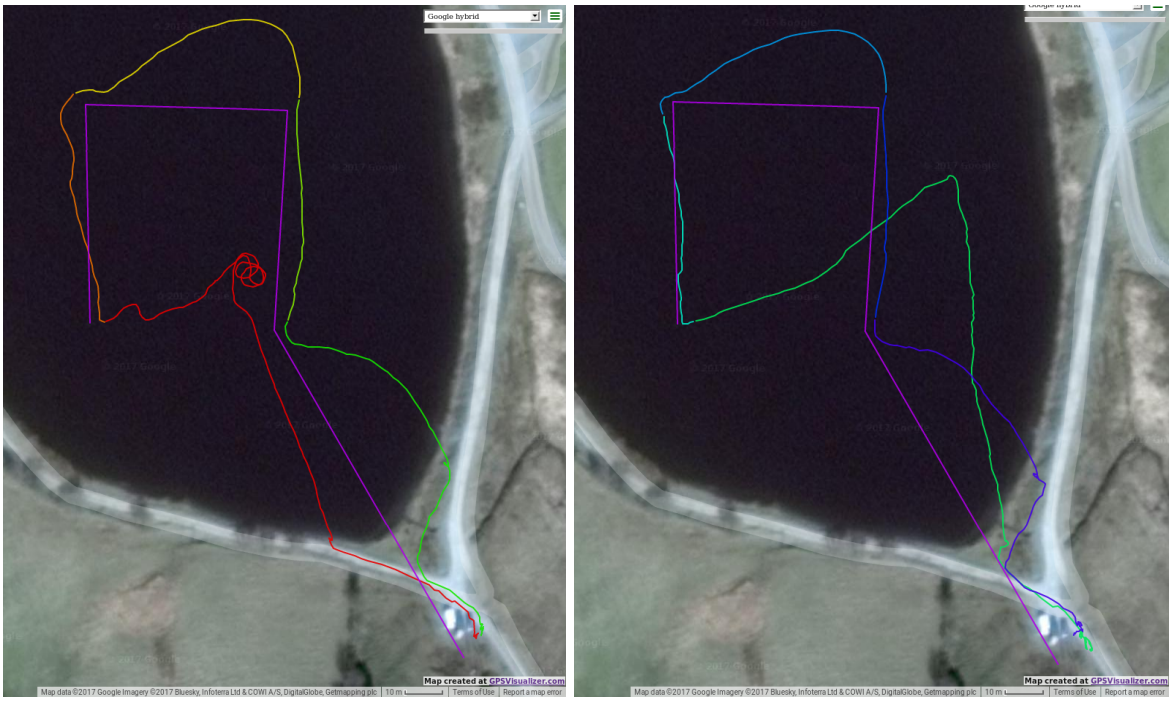


Figure 4.7: The results from the lake tests. The GPS track has been plotted over a satellite image of the lake for visualisation.

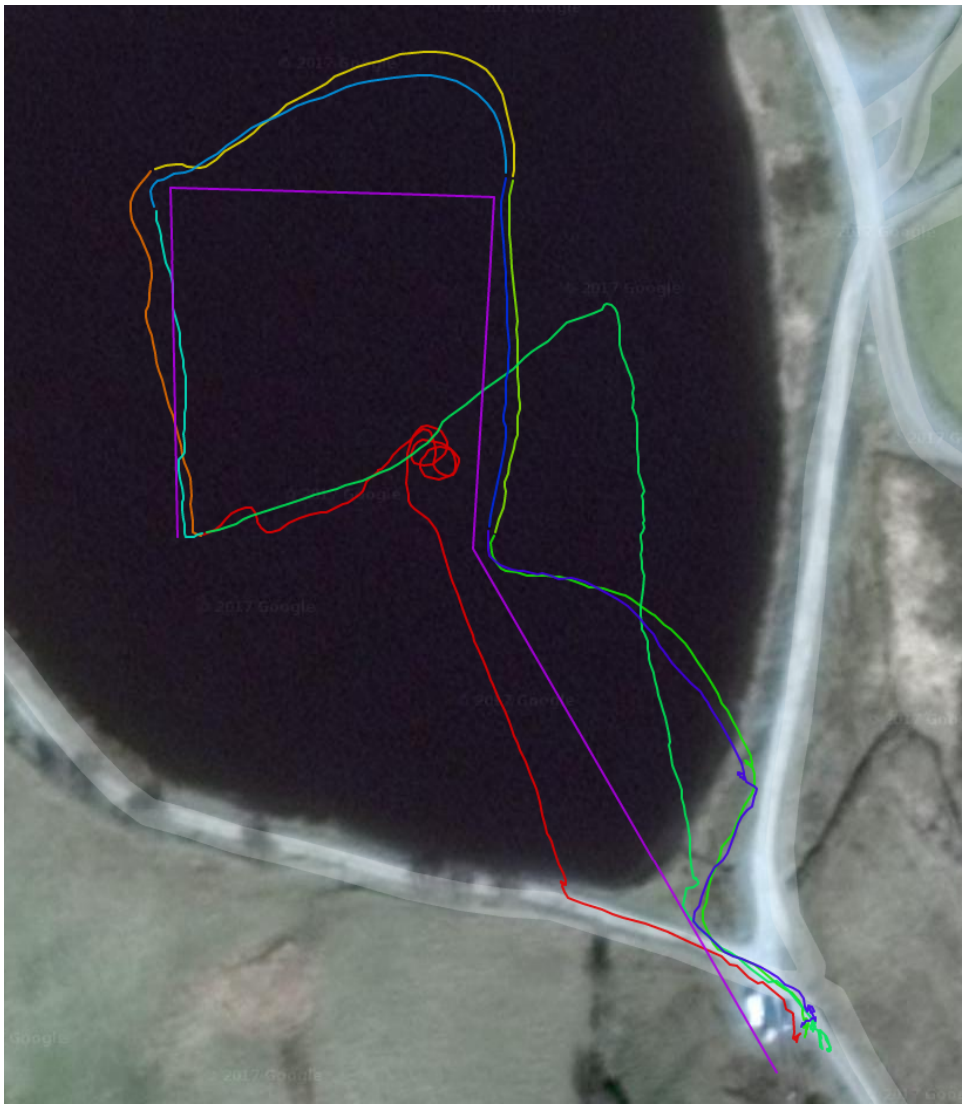


Figure 4.8: Both traces from lake tests. The first test is the trace that starts turquoise and goes to purple as the trace moves clockwise. The second test is the trace that starts red and fades through orange, yellow, green.

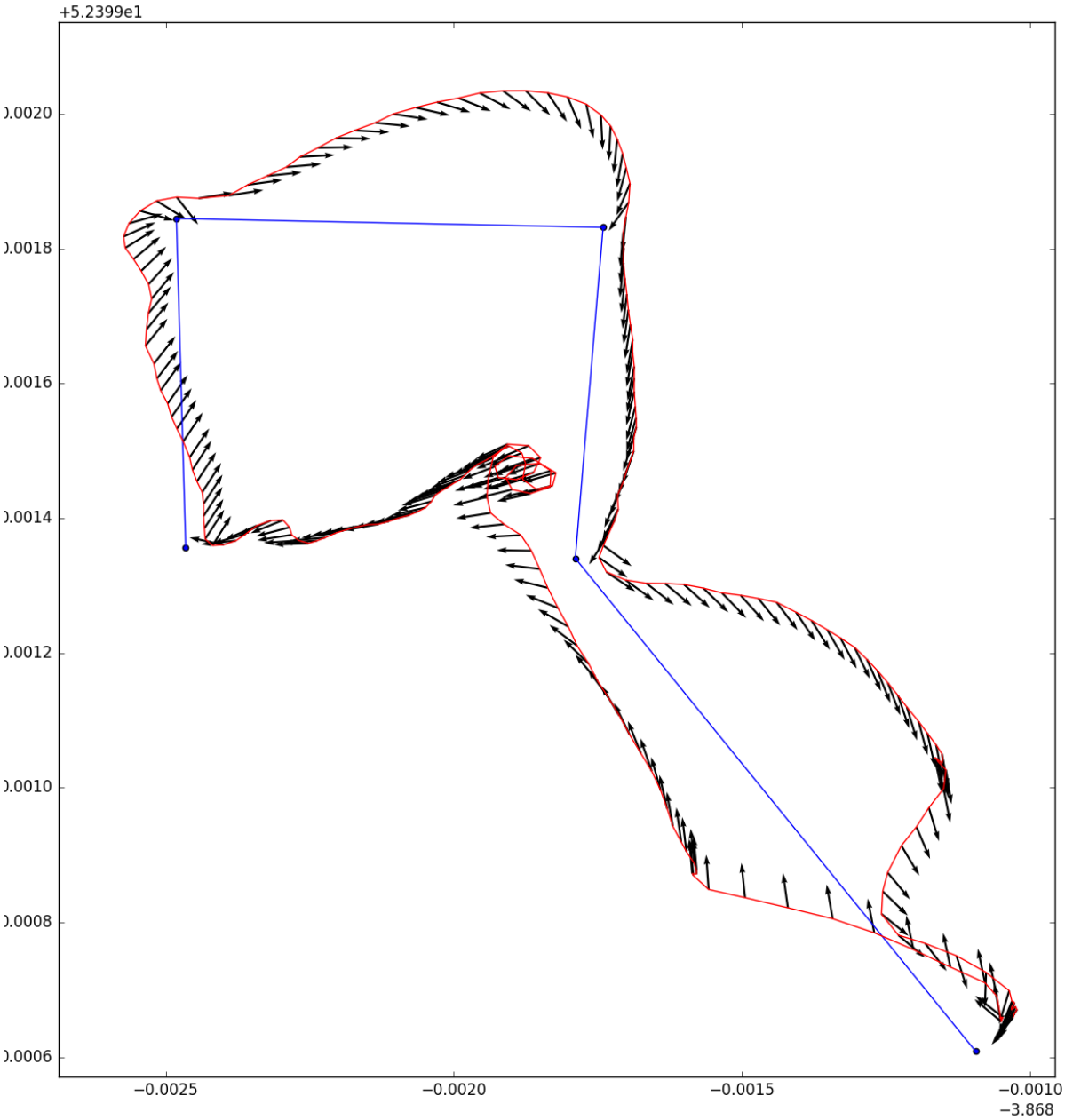


Figure 4.9: Plot of latitude vs. longitude of the boat during the first lake test (red line) with arrows at every 3rd point indicating the Pi's desired heading. A plot with arrows at every point resulted in arrows too small be seen here (a .svg file is included in the code submission). The arrows direction is adjusted in accordance with the scale of the x and y axis, so absolute angle may not be accurate here, the relative angle is (an arrow pointing directly at a waypoint will always do so no matter the change in scale).

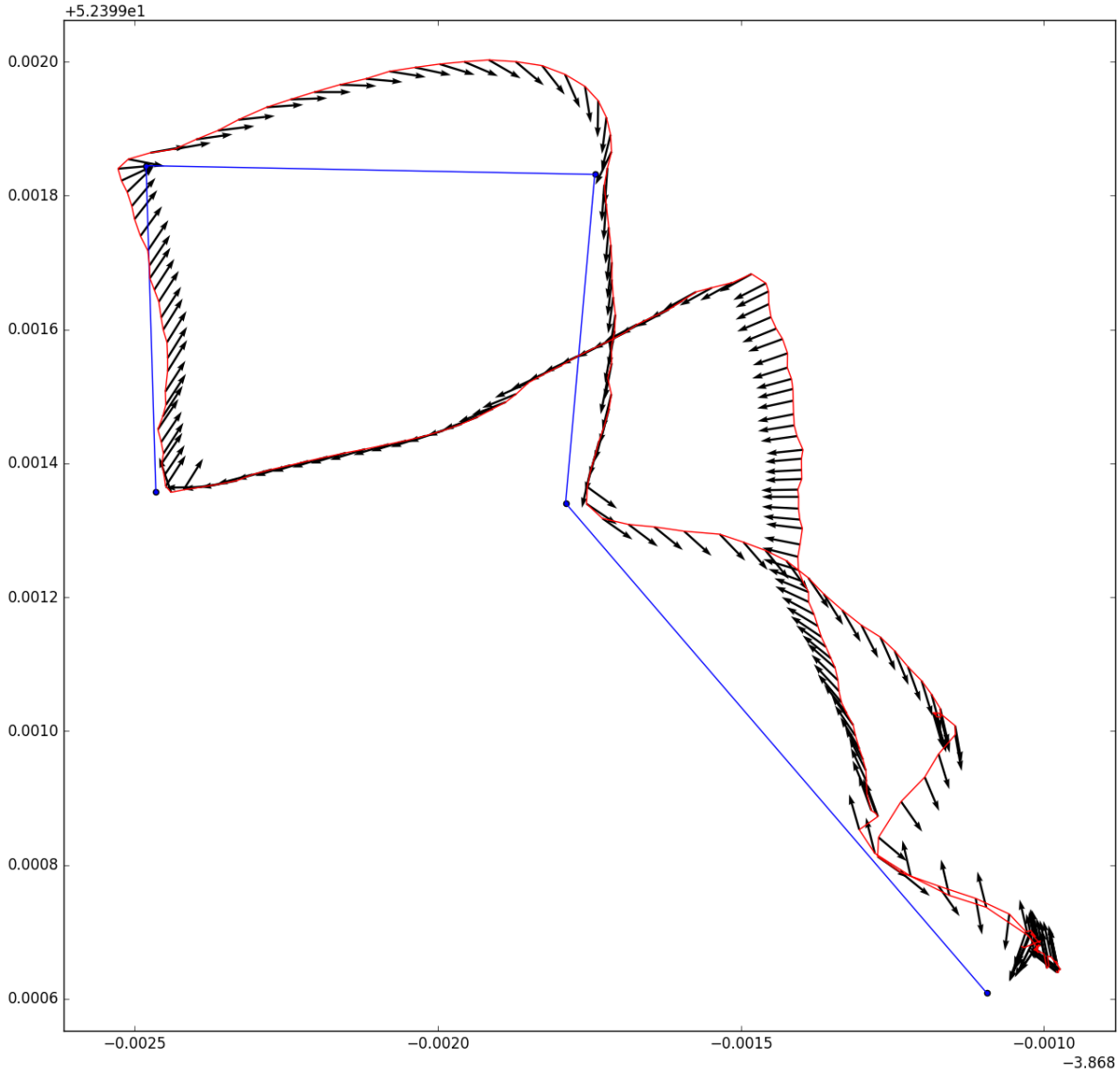


Figure 4.10: Plot of latitude vs. longitude of the boat during the second lake test (red line) with arrows at every 3rd point indicating the Pi's desired heading. A plot with arrows at every point resulted in arrows too small be seen here (a .svg file is included in the code submission). The arrows direction is adjusted in accordance with the scale of the x and y axis, so absolute angle may not be accurate here, the relative angle is (an arrow pointing directly at a waypoint will always do so no matter the change in scale).

4.8.2.3 Analysis

Further processing of these results, plotting the desire heading at each location narrowed down whether the python code or the Arduino code was at fault for the detours at the start and the looping behaviour at the north-most leg of the course.

As can be seen in Figure 4.9 and Figure 4.10 , during the second half of detour at the start of both tests the python code was not at fault as it was saying to move almost directly towards the first waypoint. Initially Pi's desired heading was slightly too clockwise but became correct after the first half of the detour.

Between the first and second waypoints, the boat managed to move in the correct direction but this is not in fact the route the Pi was saying to take. The desired headings from the python code were around 50^o clockwise of where they should have been.

The northward drift between the second and third points was most likely due to the wind and waves (as they were generally blowing east or north east). This drift should have been corrected by the python code (as discussed in subsection 3.4.1) but was not (the expected result would be seeing the arrows pointing more southward as the drift got larger, around a third of the way along this leg).

Looking closer at the code to see if there were any obvious mistakes in the implementation of the vector fields that could cause the wrong heading to be given, it was found that the way the vector force for attractive objects was limited (as discussed in subsubsection 4.7.1.4)was implemented incorrectly. The way

In `get_vector()` in the `Vector` class Figure 4.11:

```
23          if self.weight >= 0: # This is attractive, so takes form f=mr**2
24              force = self.weight*(dist**2)
25
26              # fy = fcos(bearing), fx = fsin(bearing)
27              y_force = np.around(force*np.cos(np.radians(bearing)), ROUNDING)
28              x_force = np.around(force*np.sin(np.radians(bearing)), ROUNDING)
29
30              # Prevent the attractive force overpowering obstacles/boundaries
31              x_force,y_force = constrain_vector(x_force,y_force,100)
```

```
47  def constrain_vector(x_force,y_force,limit):
48      if x_force >limit:
49          y_force = (limit/x_force) * y_force
50          x_force = limit
51
52      if y_force >limit:
53          x_force = (limit/y_force) * x_force
54          y_force = limit
55
56      return x_force,y_force
```

Figure 4.11: Snippets of code that show the mistake in constraining the force of attractive vectors.

As can be seen from Figure 4.11, the vector is constrained by testing if the vector in the x or y direction (corresponding to latitude and longitude) is greater than the limit, and if it is scaling down the x and y axis so neither axis is greater than the limit. This is not good, as a force acting a 45^o to the x and y axis could have an x component of the limit and a y component of the limit, which would be stronger than a force of the same magnitude but only in the direction of one of the axes.

The correct way to limit the vectors is to limit the force before the vector components are calculated, as this means the overall force is limited rather than individual components, resulting in forces in all directions having the same impact on the calculations for heading.

Putting this mistake in the context of two attractive objects, where the boat is located where the two have reached the force limit, it can be seen that the overall direction of the boat is greatly different from the intended behaviour. With the simple area scan behaviour, an attractive `Point` is placed at the waypoint and an attractive `Line` is placed between the this point and the previous waypoint (or the boats location when the behaviour started if there was no previous waypoint). This means the force from the line and point when maxed out should be pointing towards the line with an angle of just under 45^o. But if the line is parallel to the x or y axis (directly North to South, South to North, East to West or West to East), then the force from

the point becomes stronger than from the line (as it is not parallel to an axis) so the resulting force pulls more toward the point than the line.

Another problem that was discovered is that, even if the force sizes were correct, and all the calculations were correct, the force of the line is the same as that of the point when the limit on both is reached.

Firstly, this means that if the limit for the line is not reached, the point will always overpower the line, causing the overall heading to be negligibly tended towards the line rather than causing a significant pull towards the line.

Secondly, this means for the force of the line to overpower that of the point, to force the boat back on to the line, the distance away from the line must be large. The distances at which the point and line have the same force was not properly investigated, and so it may be that the line has no affect on the overall heading as the force is too weak.

To solve this, the line could be made to have a much higher limit, and therefore will overpower the point if both have reached their limits. The line could also be made to have a much larger weighting so that its force is stronger at smaller divergences from the line, making it head back towards the line if the cross track error becomes significant.

Another change that should be considered is with the type of equation used for the attractive point. In its current implementation the force on the point is always at its limit until the boat gets close to it, at which point the force starts to become small (it currently uses a the $F = mr^2$ relation, which means as the distance halves, the force quarters – see subsection 3.4.1). This means the force is overpowering at a distance, but potentially too small in close proximity (anything strongly repulsive, or with a greater attraction, near the point could result in the waypoint never being reached). If the force,F, was instead directly proportional to the distance,r, instead of to the distance squared, then these issues would be resolved; the force would be the same at all distances.

Evaluation

5.1 Acheivement of Aims

Further testing needs to be carried out before this system completely satisfies the aims of this project (in its current state the boat will make it to the waypoints but will not necessarily take the most efficient route).

The aims of this project (as set out in section 1.2) were achieved to the following extents:

- develop code to make the boat travel in a straight line towards a selected location on a body of water; acheived
- boat travel to a series of way-points ; acheived
- develop an algorithm for automatically selecting the most efficient course for boat to take to scan a selected area ; semiacheived
- telemetry and the design of a user interface that allows the user to communicate with the boat while it is on the water, and easily select the route the user wishes the robot to take; not acheived
- semi-autonomous functions that can be used on the boat before and after starting the area scanning, such as heading holding, station keeping or return home functions, to aid in deployment of the system.; made redundant

5.2 What went well

Feature driven development was suitable...

Time management at the end of the project was good enough that multiple large tests could be carried out.

In some ways this project has succeeded, as the boat is now able to scan a body of water autonomously, even if it is somewhat inefficient.

5.3 What went not so well

Better understanding of methodologies would have aided the understanding of how work was meant to be distributed in the project.

Time management was extremely poor at the start of this project. The amount of time taken for each feature was underestimated and did not leave room for set-backs.

This project did not initially identify the full aims of this project correctly, simply stating the aim of working control system code. Having worked through this project it is evident that there are different levels of 'working' and that it is not as simple as working or not working. The control system in its current state does work, and the boat is able to navigate to the required waypoints, but this requires manual input of waypoints in the correct order into the correct files, and the course the boat takes is not efficient.

5.4 What would change if were to do again

I would pay closer attention to the time plan, adjusting it more frequently to reflect what has happened so far.

Better identification and detailed design of features when each feature is started.

Kept a detailed diary and evaluation of the project so far, constantly reflecting on what could be improved.

5.5 What i have learnt

I have learnt a lot from this project, particularly increasing my programming skills, my knowledge of vector fields and knowledge of project structures.

5.6 What could be done in the future

If there was me time to do more with this project, I would definitely take the boat to do more tests on the lake to find out why exactly it was not following the lines correctly. Once complete, I would then look at implementing the strategy planning algorithm.

I would also refactor some of the code to be even more modular and to have better structure; so far there is still a lot of code in the main files of the Python code.

I would also implement more tests for the individual parts of the code, as many of the tests have become outdated or unable to run with this code.

Appendix A: Ethics Questionnaire

AU Status
Undergraduate or PG Taught

Your aber.ac.uk email address
eas12@aber.ac.uk

Full Name
Elizabeth Stone

Please enter the name of the person responsible for reviewing your assessment.
Reyer Zwiggelaar

Please enter the aber.ac.uk email address of the person responsible for reviewing your assessment
rrz@aber.ac.uk

Supervisor or Institute Director of Research Department
cs

Module code (Only enter if you have been asked to do so)
CS39440

Proposed Study Title
MMP Backpackable Robot Boats for Sonar Surveys

Proposed Start Date
30/01/2017

Proposed Completion Date
08/05/2017

Are you conducting a quantitative or qualitative research project?
Mixed Methods

Does your research require external ethical approval under the Health Research Authority?
No

Does your research involve animals?
No

Are you completing this form for your own research?
Yes

Does your research involve human participants?
No

Institute
IMPACS

Please provide a brief summary of your project (150 word max)
Develop a control system for a small light-weight motor boat in order to scan a body of water autonomously.

Where appropriate, do you have consent for the publication, reproduction or use of any unpublished material?
Not applicable

Will appropriate measures be put in place for the secure and confidential storage of data?
Yes

Does the research pose more than minimal and predictable risk to the researcher?
No

Will you be travelling, as a foreign national, in to any areas that the UK Foreign and Commonwealth Office advise against travel to?
No

Please include any further relevant information for this section here:

If you are to be working alone with vulnerable people or children, you may need a DBS (CRB) check. Tick to confirm that you will ensure you comply with this requirement should you identify that you require one.
Yes

Declaration: Please tick to confirm that you have completed this form to the best of your knowledge and that you will inform your department should the proposal significantly change.
Yes

Please include any further relevant information for this section here:

Appendix B: Project Organisation

The resulting to-do list at the end of the projct.

```
To do:
- [ ] Sonar driver
- [ ] create simple vector feild visualiser that prints all vectors in given area under set of criterea
- [ ] Find vector field simulator (so dont have to write own)

Done:
- [x] Decide on methodology
- [x] Acquire basic hardware
- [x] Start research into best language and operating system to use
- [x] More research into/experimentation with language and OS to use
- [x] More research into how to use ROS
- [x] Decide on type of navigation system to use
- [x] Decide on control system architecture
- [x] Compass driver
- [x] Motor driver
- [x] Servo driver
- [x] Investigate how to split area up (gps -> distance desired -> gps)
- [x] decide on final strategic plan for navigating area
- [x] set up pi
- [x] GPS driver
- [x] deside on comms protocal between arduino and pi
- [x] Find exact equations for vector field implementation
- [x] Compass calibration
- [x] Arduino-pi comms
- [x] Servo calibration
- [x] Motor Calibration
- [x] PID tuning
```

The plan at the start of the project:

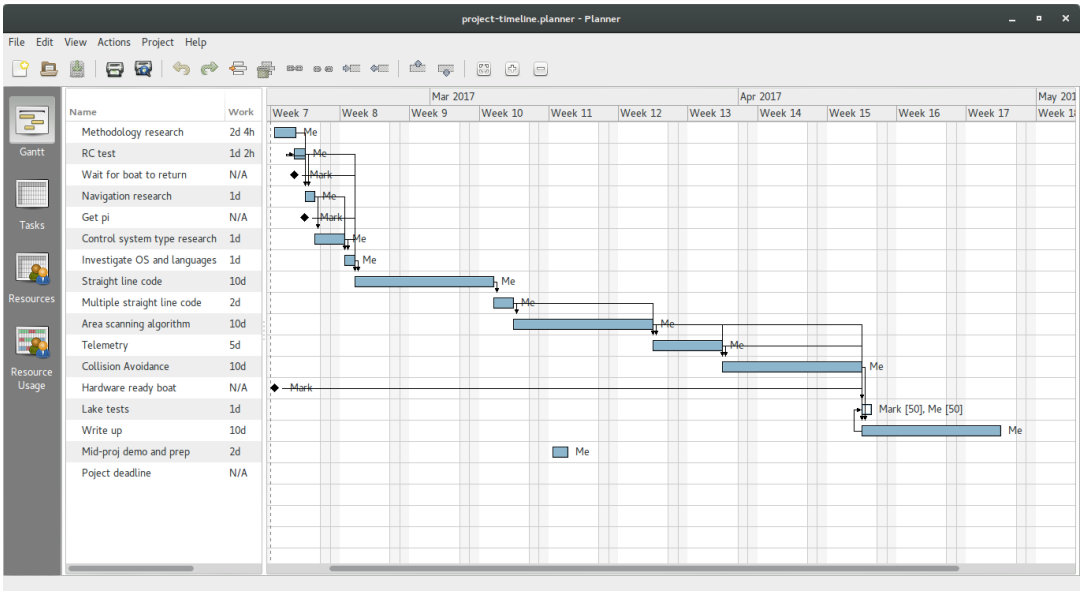


Figure B.1: Original timeline of the project.

The new plan just before the mid-project demonstration:

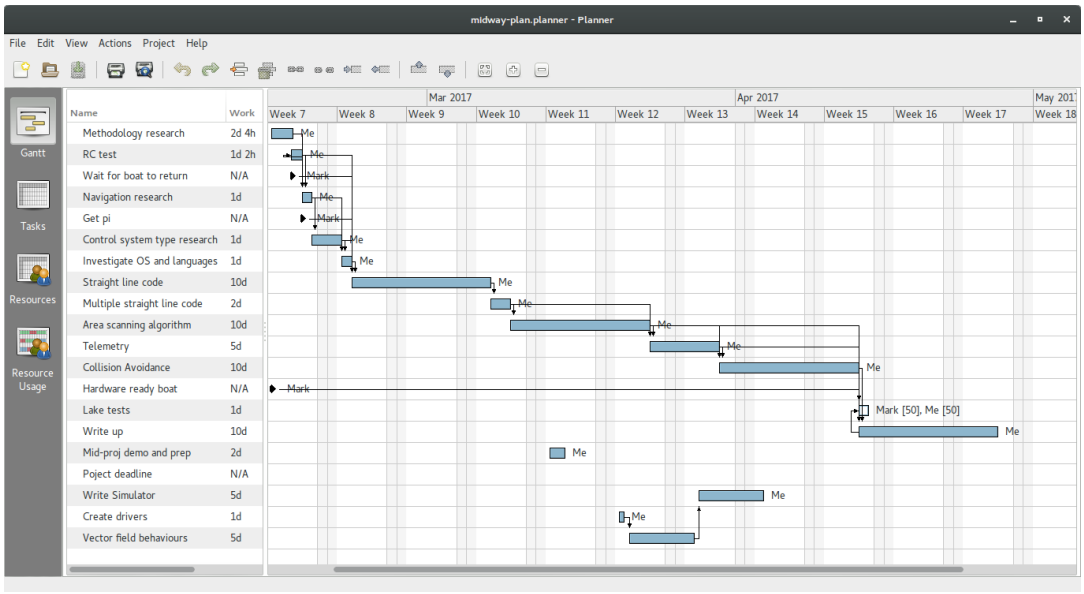


Figure B.2: Timeline halfway through of the project.

Appendix C: Additional Libraries

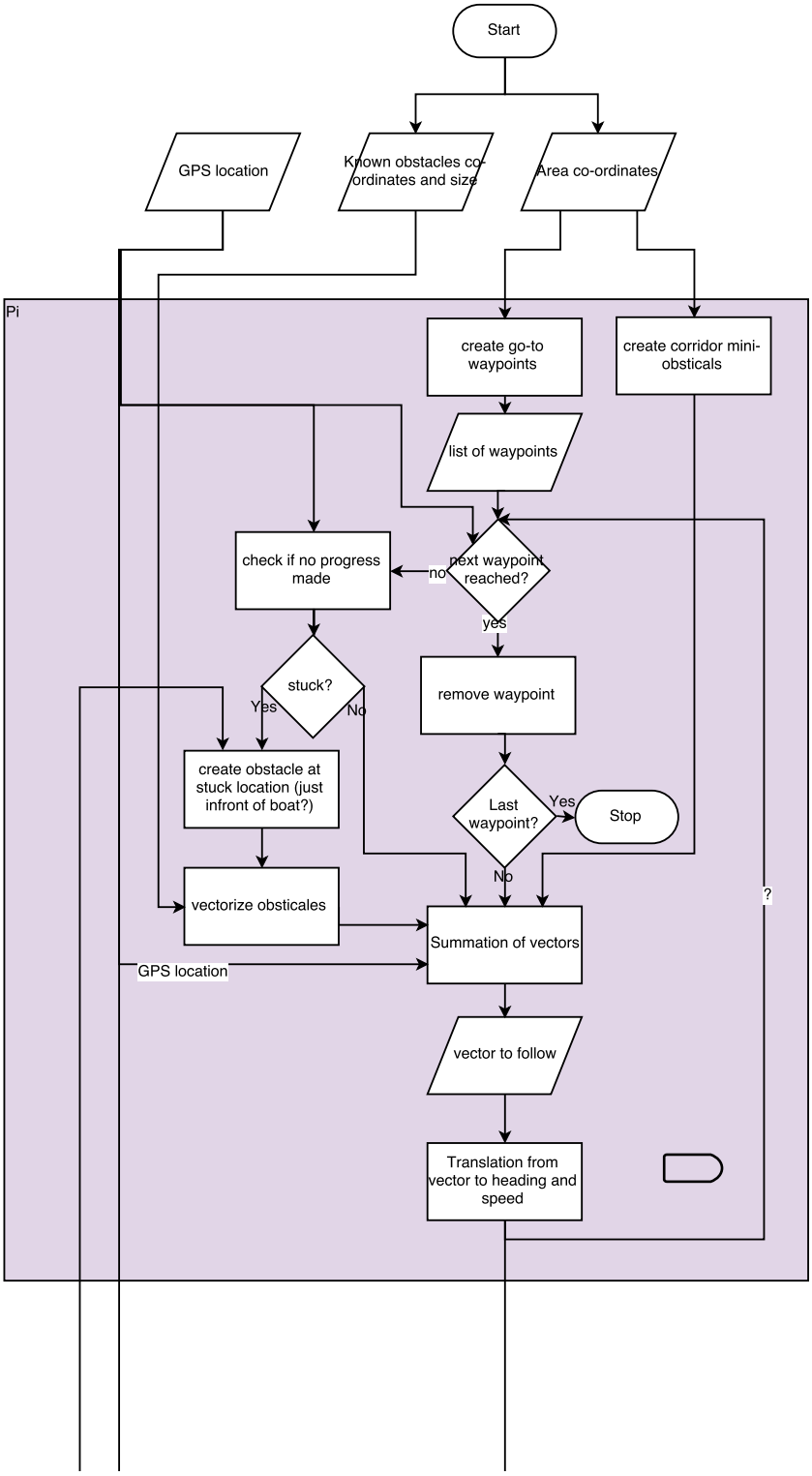
The following libraries, or code, were used or built upon in this project.

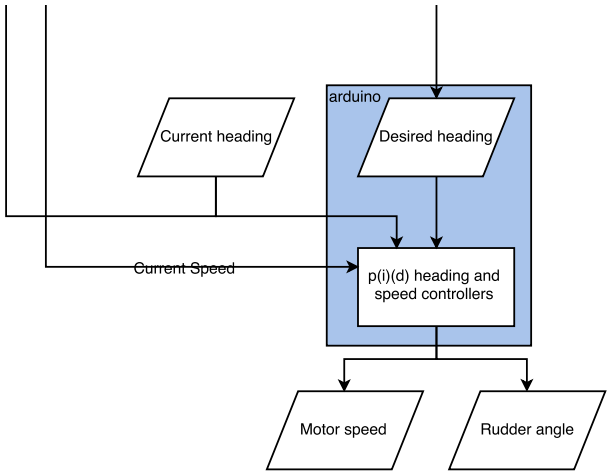
- **Arduino, avr/sleep, Wire, Servo** Come as standard with the ArduinoIDE. These libraries were used without modification.
- **Adafruit_HMC5883_U** and **Adafruit_Sensor** are libraries developed by Adafruit for use with the HMC5883 compass. They are released under the BSD license and Apache License, Version 2.0 respectively. Both can be downloaded from `https://learn.adafruit.com/adafruit-hmc5883l-breakout-triple-axis-magnetometer-compass-sensor/wiring-and-test` .
- **numpy, unittest, csv, time, threading,serial** are modules included by default with Python.***
- **gpsd** can be found at `http://www.catb.org/gpsd/`, or can be installed on a Debian based system using `sudo apt-get install gpsd`

Appendix D: Tools

- **GitHub** and **git** *** were used for version control. More information can be found at `https://github.com/`. Repositories specific to this project can be found at `https://github.com/Tebazil12/AqASS` .
- **PlatformIO and Atom** PlatformIO is an integrated development environment (IDE) that can be used for the development of arduino code, and is a plugin for the Atom IDE. More information and downloads can be found at `http://platformio.org/`
- **ArduinoIDE** was used in the later part of Arduino code development. It can be installed using `sudo apt-get install arduino` on a Debian based system or from `https://www.arduino.cc/en/main/software`.
- **gedit** was used to write the Python code. This can be installed on a Debian based system using `sudo apt-get install gedit` or can be downloaded from `https://software.opensuse.org/package/gedit`
- **python** ***command was used to run the Python code on the commandline. No IDE was used for Python development or deployment.
- **GPS Visualizer** at `http://www.gpsvisualizer.com/` was used to plot GPS co-ordinates for planning a course, and for interpreting the logs after a test.
- **Google Maps** at `https://www.google.co.uk/maps/` (full version) was used for the comparison of navigation strategies.
- **draw.io** at `https://www.draw.io/` was used to create diagrams and drawings in this report, and throughout this project.
- **LibreOffice Calc** was used to plot the compass calibration graphs in subsection 3.3.4. It can be found at `https://www.libreoffice.org/`.

Appendix E: Initial Design Flow Diagram




arduino
Current heading
Desired heading
Current Speed
p(i)(d) heading and speed controllers
Motor speed
Rudder angle

Appendix F:Compass Test Results

Compass heading/^{o}	Actual heading/^{o}	Compass Error/^{o}
0	30	-30
20	50	-30
40	80	-40
60	111	-51
80	144	-64
100	181	-81
120	213	-93
140	248	-108
160	275	-115
180	297	-117
200	311	-111
220	320	-100
240	328	-88
260	335	-75
280	341	-61
300	346	-46
320	356	-36
330	0	-30
340	10	-30

Appendix G: Test Specific Input

G.1 Castle grounds Test

`water.csv` file input:

***

`object.csv` file input:

G.2 Second Castle grounds Test

`water.csv` file input:

```
52.4139445,-4.0910125
52.4138627,-4.0911117
52.4133948,-4.0905726
52.4137874,-4.0901327
```

`waypoints.csv` file input:

```
52.4137891,-4.0902078
52.4134799,-4.0905753
52.4135093,-4.0906423
52.4137940,-4.0902936
52.4138103,-4.0903553
52.4135551,-4.0907040
52.4135960,-4.0907523
52.4138218,-4.0904358
52.4138398,-4.0904975
52.4136337,-4.0907899
52.4136631,-4.0908247
52.4138480,-4.0905592
52.4138725,-4.0906128
52.4136778,-4.0908784
52.4136991,-4.0909079
52.4138807,-4.0906745
52.4138905,-4.0907201
52.4137236,-4.0909293
52.4137596,-4.0909669
52.4139003,-4.0907899
52.4139052,-4.0908569
52.4137891,-4.0910044
```

G.3 Large Field Test

`water.csv` file input:

```
52.4033860,-4.0713331
52.4038949,-4.0707806
```

```
52.4032584,-4.0694529
52.4027625,-4.0699840
```

`waypoints.csv` file input:

```
52.4028509,-4.0700135
52.4032469,-4.0695816
52.4032764,-4.0696487
52.4028820,-4.0700832
52.4029131,-4.0701476
52.4033042,-4.0697238
52.4033435,-4.0698096
52.4029442,-4.0702280
52.4029867,-4.0703112
52.4033778,-4.0698820
52.4034138,-4.0699679
52.4030276,-4.0703970
52.4030653,-4.0704802
52.4034498,-4.0700510
52.4034760,-4.0701208
52.4030914,-4.0705392
52.4031176,-4.0706062
52.4035087,-4.0701771
```

G.4 First Astro Test

`water.csv` file input:

```
52.4143535,-4.0656334
52.4145204,-4.0648770
52.4141392,-4.0646598
52.4139723,-4.0654054
```

`waypoints.csv` file input:

```
52.4143322,-4.0655449
52.4140181,-4.0653062
52.4143584,-4.0654349
52.4140525,-4.0651855
52.4143895,-4.0652928
52.4140787,-4.0650567
52.4144157,-4.0651560
52.4141130,-4.0649226
52.4144386,-4.0650433
52.4141425,-4.0647992
52.4144598,-4.0649334
```

G.5 Second Astro Test

`water.csv` file input:

```
52.4147805,-4.0662798
52.4150979,-4.0649012
52.4141081,-4.0644291
52.4137662,-4.0659446
```

`waypoints.csv` file input:

```
52.4147232,-4.0657943
52.4140181,-4.0653840
52.4148639,-4.0651372
```

G.6 Lake Tests

`water.csv` file input:

```
52.4016465,-3.8711625
52.4023469,-3.8699180
52.4021865,-3.8687432
52.3994372,-3.8685071
52.3996532,-3.8706315
52.4001998,-3.8721818
```

`waypoints.csv` file input:

```
52.4003569,-3.8704652
52.4008446,-3.8704813
52.4008315,-3.8697410
52.4003405,-3.8697892
52.3996090,-3.8690946
```

Appendix H: Previous Code

The following code segments from the file pCont_Correction.ino were studied, and reproduced here, with permission. This code was studied to find the previous pins and calibration values for the servos as a starting point for my own calibration. This code is owned by Aled Davies, and was made to control previous systems on the same boat as used in this project. ***The full version will be included in the code submission for further reference.

```
15 Servo servo;  //this is the servo for turning
16 Servo esc;  //the esc obviously
17
18 #define speedesc 110  //this is the speed you will drive, choose what you want
19
20 SoftwareSerial ss(RXPin, TXPin);
21
22 void setup()
23 {
24   Wire.begin();
25   Serial.begin(115200); //braud rate for serial monitor
26   ss.begin(GPSBaud);
27   esc.attach(9);  //esc is attached to pin 9
28   servo.attach(8); // servo is attached to pin 8
29   esc.write(80); //this is the value that will arm the ESC (needs tinkering)
30
31 delay(1000);
32 }
```

```
184   if(turn==8)
185   {
186     if(abs(x4) > 2)
187     {
188       servo.write(90 - (abs(P * x4))); //turn right in proportion to the difference
189     }
190     else
191     {
192       servo.write(90); //set the rudders to straight
193     }
194     delay(60);
195     return;
196   }
197
198   if(turn==5)
199   {
200     if(abs(x4) > 2)
201     {
202       servo.write(90 + (abs(P * x4))); //turn right in proportion to the difference
203     }
204     else
205     {
206       servo.write(90); //set the rudders to straight
207     }
208     delay(60);
209     return;
210   }
211
212   if(turn==3);
213   {
214      servo.write(90);  //set the rudders to straight
215      delay(60);
216      return;
217   }
218 }
```

Appendix I: Built Upon-On Code

The following code segments were copied from their respective sources, and built upon in my code.

GPSD Code from `http://www.danmandle.com/blog/getting-gpsd-to-work-with-python/` was adapted and used in `GpsPoller()` class in `gps_driver.py`.

```
#! /usr/bin/python
# Written by Dan Mandle http://dan.mandle.me September 2012
# License: GPL 2.0

import os
from gps import *
from time import *
import time
import threading

gpsd = None #seting the global variable

os.system('clear') #clear the terminal (optional)

class GpsPoller(threading.Thread):
  def __init__(self):
    threading.Thread.__init__(self)
    global gpsd #bring it in scope
    gpsd = gps(mode=WATCH_ENABLE) #starting the stream of info
    self.current_value = None
    self.running = True #setting the thread running to true

  def run(self):
    global gpsd
    while gpsp.running:
      gpsd.next() #this will continue to loop and grab EACH set of gpsd info to clear the buffer

if __name__ == '__main__':
  gpsp = GpsPoller() # create the thread
  try:
    gpsp.start() # start it up
    while True:
      #It may take a second or two to get good data
      #print gpsd.fix.latitude,', ',gpsd.fix.longitude,'  Time: ',gpsd.utc

      os.system('clear')

      print
      print ' GPS reading'
      print '----------------------------------------'
      print 'latitude    ' , gpsd.fix.latitude
      print 'longitude   ' , gpsd.fix.longitude
      print 'time utc    ' , gpsd.utc,' + ', gpsd.fix.time
      print 'altitude (m)' , gpsd.fix.altitude
      print 'eps         ' , gpsd.fix.eps
      print 'epx         ' , gpsd.fix.epx
      print 'epv         ' , gpsd.fix.epv
      print 'ept         ' , gpsd.fix.ept
      print 'speed (m/s) ' , gpsd.fix.speed
      print 'climb       ' , gpsd.fix.climb
      print 'track       ' , gpsd.fix.track
      print 'mode        ' , gpsd.fix.mode
      print
      print 'sats        ' , gpsd.satellites

      time.sleep(5) #set to whatever

```

```
  except (KeyboardInterrupt, SystemExit): #when you press ctrl+c
    print "\nKilling Thread..."
    gpsp.running = False
    gpsp.join() # wait for the thread to finish what it's doing
  print "Done.\nExiting."
```

Shortest Distance to a Line Code from `https://blackboard.aber.ac.uk/webapps/blackboard/content/listContent.jsp?course_id=_17289_1&content_id=_768895_1&mode=reset` was adapted and used in `closest_point()` in `vectors.py`.

```
# -*- coding: utf-8 -*-
"""
Title:  'Minimum Distance From A Point To A Line Segment' Assignment Solutions

Author: Dr Tom Knight
Date:   Nov 2016
"""

# Using numpy rather than math provides element-wise efficiencies
import numpy as np
```

```
# Best version that also returns the nearest point on the line segment
def efficientAndPoint(A, B, P):
    """
    Computes the minimum euclidian distance from some point, P, to a finite
        line segment, AB, drawn between two points A and B.

    Input:    A, B, P (1D numpy.array's of the same length and dtype=float)

    Returns : Minimum distance as a float

    Uses numpy.linalg.norm to compute length of vectors.

    Similar to __main__.efficient but also returns the nearest point on
        the line segment
    """
    u, v = B-A, P-A
    c1 = u.dot(v)
    if c1<0:
        return np.linalg.norm(v), A
    c2 = u.dot(u)
    if c1>c2:
        return np.linalg.norm(P-B), B
    I = A+(c1/c2)*u
    return np.linalg.norm(P-I), I
```

Angle between Bearnings Code from Bearing section of `http://www.movable-type.co.uk/scripts/latlong.html` was adapted and used in `bearing_to()` in `locations.py`.

JavaScript: *(all angles in radians)*

```
var y = Math.sin(λ2-λ1) * Math.cos(φ2);
var x = Math.cos(φ1)*Math.sin(φ2) -
        Math.sin(φ1)*Math.cos(φ2)*Math.cos(λ2-λ1);
var brng = Math.atan2(y, x).toDegrees();
```

Haversine Formula Code from `https://rosettacode.org/wiki/Haversine_formula#Python` was adapted and used in `dist_between()` in `locations.py`.

```
from math import radians, sin, cos, sqrt, asin

def haversine(lat1, lon1, lat2, lon2):

  R = 6372.8 # Earth radius in kilometers

  dLat = radians(lat2 - lat1)
  dLon = radians(lon2 - lon1)
  lat1 = radians(lat1)
  lat2 = radians(lat2)

  a = sin(dLat/2)**2 + cos(lat1)*cos(lat2)*sin(dLon/2)**2
  c = 2*asin(sqrt(a))

  return R * c

>>> haversine(36.12, -86.67, 33.94, -118.40)
2887.2599506071106
>>>
```

Python CSV Reader Code from `http://www.pythonforbeginners.com/systems-programming/using-the-csv-module-in-python/` was adapted and used in `read_locations()` in `main.py`.

```
import csv

ifile = open('test.csv', "rb")
reader = csv.reader(ifile)

rownum = 0
for row in reader:
# Save header row.
if rownum ==0:
header = row
else:
colnum = 0
for col in row:
print '%-8s: %s' % (header[colnum], col)
colnum + = 1

rownum + = 1

ifile.close()
```

Python Serial Code from `http://pyserial.readthedocs.io/en/latest/shortintro.html` was adapted and used in `main.py`.

```
>>> import serial
>>> ser = serial.Serial('/dev/ttyUSB0')  # open serial port
>>> print(ser.name)         # check which port was really used
>>> ser.write(b'hello')     # write a string
>>> ser.close()             # close port
```

Arduino Communications Code from https://github.com/abersailbot/dewi-arduino/blob/master/src/dewi.ino was adapted and used in serial_comms.ino and src.ino.

```
void read_line(char* line) {
    // read characters from serial into line until a newline character
    char c;
    int index;
    for (index = 0; index < 5; index++) {
        // wait until there is a character
        while (Serial.available() == 0);
        // read a character
        c = Serial.read();
        if (c == '\n' || c== '\r') {
            line[index]='\0';
            break;
        }
        else {
            line[index] = c;
        }
    }
    // terminate the string
    line[index+1] = '\0';
}
```

```
    switch (current_line[0]) {
        case 'c':
            bearing = read_compass() - COMPASS_OFFSET;  // compensate for offset
            bearing = mod(bearing);  // wrap around
            log_json_float("compass", bearing);
            break;
        case 'w':
            wind_angle = read_wind_sensor() - offset;  // compensate for offset
            wind_angle = mod(wind_angle);  // wrap around
            log_json_int("wind", wind_angle);
            break;
        case 'r':
            set_rudder(get_amount(current_line));
            break;
        case 's':
            set_sail(get_amount(current_line));
            break;
        case 'o':
            store_offset(read_wind_sensor());
            offset = get_stored_offset();
            break;
}
```

PID Pseudo-Code from https://en.wikipedia.org/wiki/PID_controller was adapted and used in src.ino.

```
previous_error = 0
integral = 0
loop:
  error = setpoint - measured_value
  integral = integral + error*dt
  derivative = (error - previous_error)/dt
  output = Kp*error + Ki*integral + Kd*derivative
  previous_error = error
  wait(dt)
  goto loop
```

Vector-field Graphing Code from `http://www.scipy-lectures.org/intro/matplotlib/auto_examples/plot_quiver_ex.html` was adapted and used in `plotresults.py`.

```
import numpy as np
import matplotlib.pyplot as plt

n = 8
X, Y = np.mgrid[0:n, 0:n]
T = np.arctan2(Y - n / 2., X - n/2.)
R = 10 + np.sqrt((Y - n / 2.0) ** 2 + (X - n / 2.0) ** 2)
U, V = R * np.cos(T), R * np.sin(T)

plt.axes([0.025, 0.025, 0.95, 0.95])
plt.quiver(X, Y, U, V, R, alpha=.5)
plt.quiver(X, Y, U, V, edgecolor='k', facecolor='None', linewidth=.5)

plt.xlim(-1, n)
plt.xticks(())
plt.ylim(-1, n)
plt.yticks(())

plt.show()
```

Additional Vector-field Graphing Code from `http://matplotlib.org/examples/pylab_examples/quiver_demo.html` was adapted and used in `plotresults.py`.

```
'''
=======================================================
Demonstration of advanced quiver and quiverkey functions
=======================================================

Known problem: the plot autoscaling does not take into account
the arrows, so those on the boundaries are often out of the picture.
This is *not* an easy problem to solve in a perfectly general way.
The workaround is to manually expand the axes.
'''
import matplotlib.pyplot as plt
import numpy as np
from numpy import ma

X, Y = np.meshgrid(np.arange(0, 2 * np.pi, .2), np.arange(0, 2 * np.pi, .2))
U = np.cos(X)
V = np.sin(Y)

plt.figure()
plt.title('Arrows scale with plot width, not view')
Q = plt.quiver(X, Y, U, V, units='width')
qk = plt.quiverkey(Q, 0.9, 0.9, 2, r'$2 \frac{m}{s}$', labelpos='E',
                   coordinates='figure')

plt.figure()
plt.title("pivot='mid'; every third arrow; units='inches'")
Q = plt.quiver(X[::3, ::3], Y[::3, ::3], U[::3, ::3], V[::3, ::3],
               pivot='mid', units='inches')
qk = plt.quiverkey(Q, 0.9, 0.9, 1, r'$1 \frac{m}{s}$', labelpos='E',
                   coordinates='figure')
plt.scatter(X[::3, ::3], Y[::3, ::3], color='r', s=5)

plt.figure()
plt.title("pivot='tip'; scales with x view")
M = np.hypot(U, V)
Q = plt.quiver(X, Y, U, V, M, units='x', pivot='tip', width=0.022,
               scale=1 / 0.15)
qk = plt.quiverkey(Q, 0.9, 0.9, 1, r'$1 \frac{m}{s}$', labelpos='E',
```

```
                    coordinates='figure')
plt.scatter(X, Y, color='k', s=5)

plt.show()
```

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