GENG5512 MPE Engineering Research Project Part 2

Tuning the Control Systems of an Electric Hydrofoil Watercraft

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Abstract

The electric hydrofoil watercraft (the efoil) entered development in 2018 as part of the Renewable energy vehicles (REV) initiative. The watercraft is modified from the hull of a jetski with a pair of hydrofoils placed under the rider and on the aft of the craft. On the rear foil, a pair of ailerons allow the pitch and roll of the watercraft to be controlled, either by manual input or by onboard control software. The aim of this part of the project was to provide the efoil watercraft with a set of tuned parameters for its onboard control system that will allow the system to automatically stabilise and maintain a desired foiling height above the water without constant manual adjustments from the user. The rationale for this is to improve the safety and ease of use of the overall design. Before this part of the project, already available to be accessed on the craft was log file containing data for the process values and outputs within the control systems. To better utilise this information a logging user interface was created to process the data and allow it to be used for tuning more easily by presenting the user with an intuitive readout and scoring system. Because a model of the system is not available, a heuristic tuning approach was adopted, measuring performance over test runs and improving the control parameters iteratively. This method was implemented using an integral absolute error value to assess how well the system conforms to the desired set points. The pitch and roll control loops conform well to their setpoints after this tuning process, delivering good stabilisation for the craft, with an improvement of 40-70% for each control loop. Continuing to perform tests and iterations should improve the hydro foiling capabilities further. To build on the tuning process, future work could involve different users with varying levels of experience and weight profiles should test the watercraft to validate that the stabilisation performance is not unique to the environment used for testing.

Acknowledgements

I would like to offer my gratitude to a few individuals whose guidance and oversight of this project were critical to its success. To Thomas Bräunl for acting as supervisor and facilitator, the time he takes out of his schedule to keep me on track is greatly appreciated. To Piere-Louis Constant and Eric Metrot for consistent guidance, support, and the work they do on the wider REV hydroski project.

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Nomenclature

REV	*The Renewable Energy Vehicles Lab*
Efoil/Hydroski	*The electric hydrofoil watercraft.*
PID	*Proportional, integral, and derivative*
UWA	*The University of Western Australia*
DMP	*Digital motion processing*
IMU	*Inertial measurement unit*

1. Introduction and Background

1.1 Background

The REV project at UWA was started in 2008 and aims to develop zero emission and autonomous vehicles. In 2015 work was done as part of the REV project to produce an electrically powered jet ski. This craft was modified from a conventional motor driven craft to being full electrically powered. In 2018, work was started on production of a new project that expanded on the lessons learned from this initial electric jet ski project, the REV Hydrofoil Jet Ski, referred to as the efoil project. The rationale for the integration of hydrofoil technology lies in its power efficiency. This is because hydrofoil craft offer relative energy efficiency, with significantly lower surface area touching the water at a given hull weight [1], being able to reach higher speeds with the lower electrical power compared to a conventional motor which improves the battery life of the craft. Other benefits of the foiling behaviour include the craft being quieter, and producing less wake while travelling, both very desirable qualities in a recreational watercraft.

The performance of the efoil was initially dependent on the experience of the rider to a significant degree, as maintaining stabilisation and altitude control requires a combination of constant manual input, adjustment of the riding position and variations of the throttle. Additionally, trying to make a banking turn while foiling was a very difficult manoeuvre, requiring the rider to lean into the turn with by adjusting their body weight. The aim of this projects is to achieve tuning of the control loops of the system such that the watercraft can reliably stabilise itself in real time while foiling without any manual input/adjustment from the user, accounting for turns and different weight profiles. The desired impact is to assist in opening the efoil to a wider market by improving the safety, reliability, and ease of use.

1.2 Prototype Overview

This section will provide an overview of the current iteration of the prototype as context. As a design focused project, this is the primary piece of equipment used in the work performed in this project.

Physical Layout:

The main body of the prototype is a modified jet ski hull fitted to a poly windsurf board. The board and the bottom of the hull are flat, that give the efoil a flat bottom against the surface of the water. The craft also has the rudder assembly component from a foiling sailing yacht, attached mechanically to the handlebars via an internal rod.

Placed in the rudder assembly and midway up the hull of the craft are a pair of T-type foils. The front foil has a positive angle of attack and has a metal mast for stability. The aft foil is entirely fibreglass, (mast included) and houses the main control mechanisms for the craft, the electric thrusters, and a pair of servo-controlled ailerons. These components are positioned at the end of each wing of the T-shaped foil in a custom-made housing. Both foils are retractable for transportation purposes but are secured in place during operation.

The purpose of the windsurf board is to provide additional buoyancy to the craft, however because this buoyancy sits below the weight provided by the user and the internal electronics, a weight is placed in the forward foil to lower the centre of gravity and maintain stability while the efoil is static.

Control Outputs:

Two main control outputs for the efoil are the 5kW electric thrusters and the servo motors. Both components are waterproof as they are submerged perpetually during operation. The servo motors control the angle of a pair of ailerons on each wing of the rear foil, with a zero angle being parallel to the rest of foil. The wired connections between these devices and the internal controller are fully waterproof and are passed up through the centre of the mast.

Steering control is provided by the steering assembly in a twofold manner. It both adjusts the direction of the thrusters, allowing for sharp turns while the craft is moving slowly and acts with a rudder action through the mast that can adjust the yaw.

User Inputs:

The manual inputs on the handlebar setup on the efoil that users can directly interact with are a thumb lever, used as throttle control, a joystick that allows manual control over the ailerons and a latching button for reverse and control tuning. The handlebars themselves provide manual mechanical steering control via a wire passing the steering angle down the length of the craft to a lever.

Power System:

The batteries that are currently used in the prototype are a pair of lithium-ion packs that operate at up to 48V and provide the required 200A needed by the thrusters. Integrated with these are a battery management system and an active balancer to improve discharging profiles. The battery life of the prototype varies significantly depending on operating conditions anywhere between 30 minutes to over an hour. All the internal electrical systems for the control and power are kept in the hull beneath the seat inside a fully waterproof container. This container is strapped down to prevent it from moving within the craft and has full waterproof connections used for integration with the external electronics and the water-cooling system.

1.3 Prototype Control Systems

The current prototype of the efoil can foil up to 400mm above the surface of the water. This places the main hull of the craft in an inherently unstable position, as the concentration of the lifting force is positioned directly under centre of mass of the craft in operation, which is constituted by the rider and the internal electrical components. As a result, constant adjustment is required to keep the craft stable. This adjustment can be provided by the user by shifting their own body weight in a similar manner to a conventional recreational foil board. To mitigate this issue of stabilisation and to provide the watercraft with automatic control over its altitude, a set of control loops are implemented on a BeagleBone Blue single board computer.

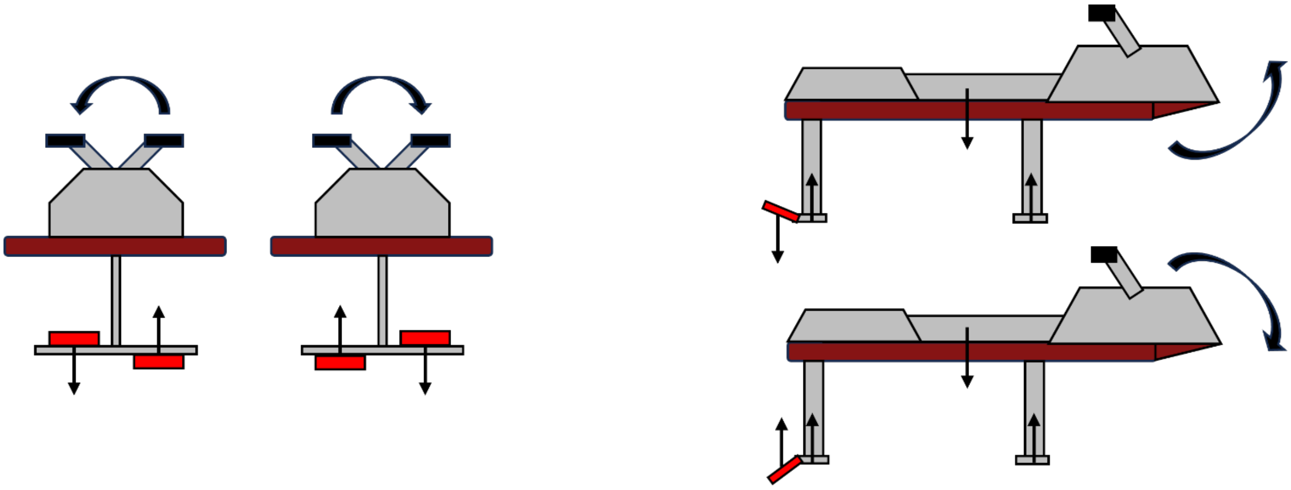

Figure 1.3.1: Action of the Ailerons on the Craft Orientation

Control Principle:
For full control of the watercraft in operation, the three system parameters that need to be controlled for stability are the roll and pitch, in addition to the altitude of the craft while foiling. The roll is defined as the rotation around the axis running from the back of the craft, and the pitch is defined as the rotation around the axis running from the left to right side.

To control these system outputs, the angle of the ailerons is controlled. This, in turn varies the lift force provided by each wing of the rear foil, relative to the constant lift provided by the front foil. To control the roll of the craft, a differential in the angle is introduced, causing a the lift of the wing on one side to be larger than the other, introducing a rotational component to the lift, causing the craft to roll away from the side with the greater lift, as shown in the left of Figure 1.3.1. By adjusting both ailerons by the same amount, the total lift provided by the aft foil can be adjusted relative to the front foil. In effect, this causes the rear of the craft to lower or raise in the water, keeping the middle section at the same height, causing the craft to pitch up or down, shown in the right of Figure 1.3.1. This introduced pitch is also used to control the altitude as the propulsion of the thrusters will cause the craft to incline or decline if it has a non-zero pitch.

Hardware:

Over the lifespan of the efoil project, the craft has had two different iterations of an onboard controller. The current version uses a BeagleBone Blue board, which contains a few pieces of essential functionality. The board has a both Bluetooth and wifi functionality and ports for sensor and control surface integration. Because this board operates at 3.3V input and outputs, any incoming serial data, or analogue signal at 5V are converted down via an external integration board. This runs a program on two separate threads, one which handles the control inputs and output and another that handles the processing and publishing of data.

Control Software:

One of the fundamental assumptions made by the current controller implementation is that the operation of the efoil can be modelled as a linear time invariant system. The design takes the form of a series of cascaded feedback loops. There are three main branches to the control system, the throttle control, altitude/pitch control and the roll control, depicted in block diagram form in Figure 1.3.2.

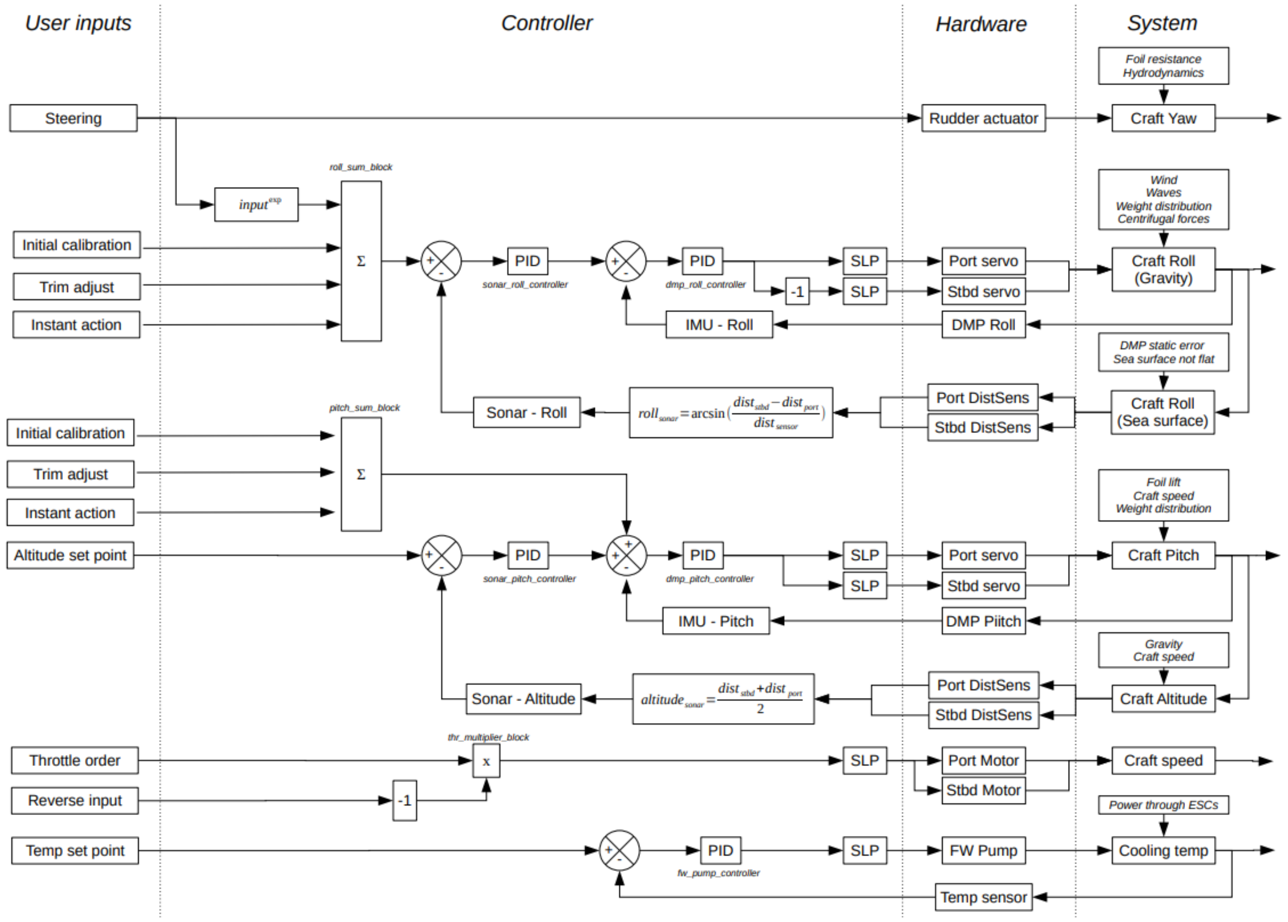

Figure 1.3.2: Diagram of the Onboard Control Loops – PLC REV Documentation [2]

The thrust controller provides the output to the electric thruster and the cooling system. It takes input from the thumb throttle and performs a scalar gain to transform it to an order readable by the speed controllers that send the same variable current to the pair of motors. Although it is not shown in the diagram, currently the throttle order also controls the temperature setpoint for the cooling system control loop. This, in effect, means that while operating the pump will perform active cooling, but will passively regulate the internal temperature of the speed controllers while stationary. When the reverse switch is pressed, the throttle order is inverted and passed to the speed controller.

Both the roll and altitude controller are responsible for manipulating the aileron servos. The -1 gain in the roll controller inverts the signal such that this control loop always outputs opposite angles to each of the servos. Because both loops currently output to the same set of ailerons, there is an additional layer of control that takes an equally weighted average of the two servo output signals and sends that combination to the ailerons.

The setpoint for the altitude controller can be set as desired, but for most previous tests has been set to a value from 200-400mm. If the craft foils above these altitudes, there is an associated risk that the thrusters will partially or fully emerge from the water, which results in cavitation or ventilation and a loss in forward thrust.

The setpoint for the roll control is determined by the steering angle. This is done via the inclusion of a potentiometer adjacent to the steering wire that encodes the rotation of the handlebars as an analogue signal. This value is passed through an exponential function, so the setpoint will not deviate from far from zero at small steering angles but has a strong effect while actively turning. These setpoints are not fixed and can be adjusted by either hardcoding a calibration value, manual adjustment with the thumb joystick or setting a trim value.

There are currently two sets of sensors used to provide feedback for the control loop. A trio of A02YYUW ultrasonic distance sensor modules are placed across the width of the underside that provide altitude readings on the port and starboard sides in addition to a central measurement. To provide the most stable estimate for the altitude feedback, the controller takes the maximum reading as the craft altitude. The other sensor key to the controller feedback is the inbuilt IMU on the processor board. This provides a real-time estimate of the roll, pitch and yaw that is used as feedback for both the roll and altitude controllers. The sonar sensors provide feedback for the first layer of control. The output of this loop provides the setpoint for the loop for which the IMU provides feedback. For the altitude control, this means that the error between the altitude setpoint and the measured altitude is converted to a desired pitch value.

Implemented in each loop is a set of PID control, acting on the error signal from comparing each sensor measurement with the corresponding setpoint using the negative feedback principle with a proportional, integral, and derivative function [3]. The purpose of this is to improve the transient performance of the controller by eliminating steady state error and reducing overshoot. Initially, only the proportional component was nonzero, with the derivative and integral components also changed by adjusting their gain values. A mathematical model for this system is difficult to obtain due to the variations and disturbances present in the dynamics of a marine vehicle while in operation. [4]

1.4 Project Objectives

The objectives/aims for this project are related to a set of desired design outcomes and outputs. For outcomes, the aim of this project is fundamentally to develop tools to be able to tune the parameters of the onboard control systems and a methodology for using these tools for tuning. At the end of the project the control system should ideally be able to perform stabilisation that is not only safe but also reliable independent of any user input. The software should be easily translatable between hardware, as the current prototype may be updated or replaced, and the control systems should be easy to reimplement with minimal retuning necessary. The tuning tools produced should be able to convert the data available on the prototype into a human readable format. Additionally, the tuning method should be easily repeatable, to allow for the tuning of future prototypes. This should act as a step towards pushing the project towards a commercial prototype, which would be beneficial for the REV project and partners. From a technical perspective, the outcomes also include stabilisation while making banking turns. The current approach to this is to alter the setpoint of the roll controller relatively dependant on the steering angle, so it doesn't attempt to counteract the lean that results from this kind of turn. In a final iteration of the control systems, ideally the thumb joystick should not be necessary for adjustment, and the system should stabilise while initially achieving the desired altitude and during foiling irrespective of environmental conditions, different users, and weight profiles.

2. Design Process

2.1 Data Collection

The prototype watercraft has an inbuilt mounted SD card. This is used to store the data values relevant to the control systems and sensor inputs. To initiate the logging process, the throttle is held down until it reaches an amplitude of 0.3. The logging records the data values at a regular frequency of 4 Hz. In past, tshe frequency of the logging process was tied to the interrupts from the sensor inputs, but this has been rectified to facilitate a constant rate instead. Once the throttle is released (or more specifically under an amplitude of 0.1) for twenty readings consecutively, the logging concludes, and the data is saved to a csv file on the SD card. The data is time stamped, with the title of the file taking the general datetime form: *log_DD_MM_ YYYY_HR_MN_SC.csv.* The rationale for this collection method is that it isolates each "trial" as a single run where the throttle is held down and released that can each be processed independently, rather than recording the data constantly while powered on, as the file would be too long to be easily used for analysis. The log files have 33 columns, each representing a different output, input, or process value. With the quality of data in the files, anywhere from a few seconds to a few minutes of data, it's hard for them to be utilized directly and require some degree of post processing. Only 23 of the data columns provide the information relevant to the control systems, these are presented in Table 2.1:

Table 2.1: The available data logged by the efoil.

Time Stamp	The number of seconds from the creation of the log file.
IMU Sensor Readings	The pitch, roll and yaw of the craft in degrees, as measured by the inbuilt IMU on the onboard computer.
Sonar Altitude Measurement	The height of the hull above the surface of the water in millimetres, as measured by the ultrasonic distance sensor.
Altitude Setpoint	The setpoint for the altitude controller in millimetres. This remains constant but is used for visualisation.
User Inputs	- The **throttle input** to the system, provided by the user. The range of this value is between 0 and 1. - The **steering input** to the system. The range is between -1 and 1, representing full turn to the port and starboard sides respectively. - The **joystick input roll and pitch.** These range from -1 to 1 each.
Temperature Measurement	The temperature of the internal speed controllers in degrees.
Roll Controller Signals	The **setpoint, process value** and **output value** for the roll control loop**.** The setpoint and process value are in degrees and the output is given as a value from -1 to 1, in the same manner as the joystick input.
Pitch Controller Signals	The **setpoint, process value** and **output value** for the pitch control loop**.** The units are consistent with the roll controller.

2.2 Tuning Methods

To tune the proportional, derivative, and integral gains on the hydroski, a heuristic tuning method is adopted. This is because, due to the lack of a mathematical model or transfer function for the dynamics of the hydroski (the relationships between the thrust, pitch, and the altitude for example) in operation, rule based tuning methods (methods to automatically tune the parameters based off properties of the transfer function or step response) are less feasible, such as the Ziegler-Nichols method which are based on a delay time and time constant for a clean step response which cannot be generated with this setup [5].

This method is iterative but requires a preliminary step which is the tuning the static gain values and setpoints associated with the user inputs, outputs, and feedback sensors. This includes the initial calibration of the roll and pitch setpoints as shown in the control systems diagram in Figure 1.3.2. This is performed while the craft is not in operation by placing it level on a steady surface and measuring its measured roll and pitch, which vary due to the movement of the IMU during maintenance in the order of up to 5 degrees. This ensures that if the craft is flat on the water during operation, its roll and pitch values will be measured at zero. Other important parameters set in this initial step are the exponential factor for steering input exponent block and the gain for the joystick and steering used as input to the roll controller from the steering. This is used to the effect that the actuation of the steering has a more significant effect on the setpoint when only small adjustments are made, to allow more precise control of the roll during banking manoeuvres.

After this step, the iterative process of heuristic tuning is as follows. First a change is made to the proportional, integral, or derivative gains and a trial run is performed, testing both an extended straight foil and a turning manoeuvre. Then, the performance is evaluated by the user and any observers on how well the system conforms to the altitude setpoint and stabilises. This evaluation uses the set of a pre-established heuristics listed in section 2.3 as success criteria which are used to determine if a change made to the gain values has increased or decreased performance. Then, if the change made decreased performance, they are reverted, and if they improved performance they are kept. The iteration then continues by making another change and repeating the process. The general approach for which parameters to change on each iteration is to begin with the derivative and integral gains at zero. Then, first increase the proportional control until the system response is fast enough to adapt to changes in the setpoint. Following this, introduce an integral component to eliminate the steady state error and finally set the derivative gain to a non-zero value to limit the overshoot introduced as a side effect of the integral control [6].

2.3 Tuning Heuristics

When analysing the logs made available by the hydroski metrics for success were established. Given the format of the available data is, with independent trial runs, the score system used is the integral absolute error (IAE) or the integral square error (ISE), calculated and averaged over the length of the full trial. These scores take the form:

$$ISE = \int error(t)^2 dt$$

$$IAE = \int |error(t)| dt$$

The error in these formulas is the difference between the input (measured from the sensors) and its corresponding setpoint. This gives an approximation of how well the craft conformed to the setpoint over the run. The issue with averaging over the course of a trial is that there may be times where the craft is floating on the water's surface. The control system has no control over the craft when it is not in motion, and the roll and pitch present at these instances may cause a high average integral error despite the system stabilising well during foiling.

Other numerical scores for determining the performance of a trial run are the maximum overshoot, steady state error, rise time oscillation frequency [7]. The maximum overshoot is critical for the roll controller as the setpoint is dynamic with to the steering, and an excess overshoot will cause the craft to lean too far and could result in the balance becoming unrecoverable by the control systems. The steady state error is a success criteria used for the altitude control, as the setpoint is a constant, and if the system had steady state error it would not foil at the correct height. The rise time and oscillations frequency are relevant to the roll and pitch stabilisation controllers. A high oscillation frequency, with a significant amplitude can represent instability in the system, especially if it causes the output to the servos to saturate at their maximum. The rise time is a critical criterion for the dynamic setpoints of the roll and pitch controllers, which need to respond quickly to counteract any variations in the balance. As described, some heuristics are more important for some outcomes than others, and the variation between trial runs may cause some runs to be deemed successful through a false positive, but with sufficient iterations, this method should produce a satisfactory set of control gain values. In designing analysis tools for the data produced by the hydroski, these heuristics should be calculated automatically, rather than manually for each trial, to improve the speed at which the tuning described in section 2.2 can be performed.

3. Final Design, Results and Discussion

3.1 Finalised Log Processing Tools

Part of the process for tuning the control loops necessitates the post processing of the data logs produced by the efoil during operation into a format that can be easily analysed, as described in the tuning methodology. The key factors that were considered when producing an analysis methodology are the readability of any outputs and the relevancy of the data used for analysis to the specific task. Over the duration of the project tools for this were developed, with additional features integrated when required for the tuning process.

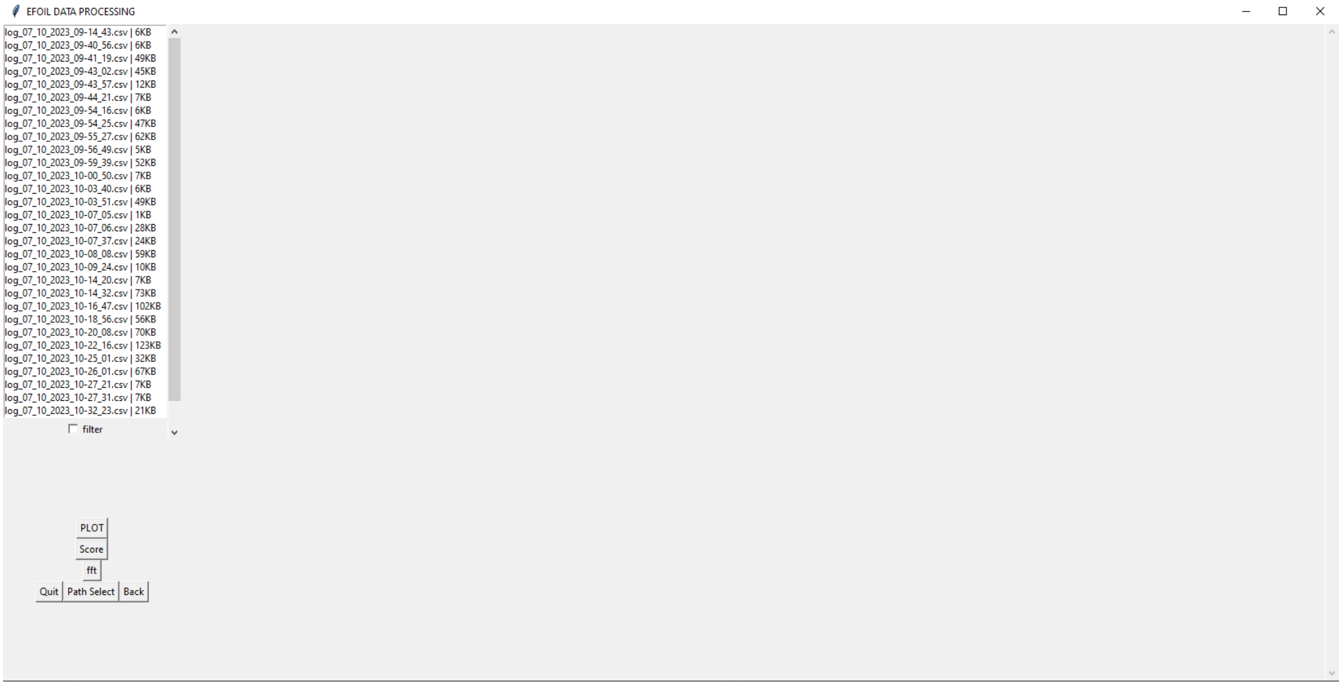

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Figure 2.2.1: The python user interface for data visualization

A program with a user interface (UI) was created using the Tkinter package for python. This UI was integrated with interaction elements that allow an individual working on the efoil project to interact with the data analysis and visualization methods. Because of the large quantities of log files present, it was necessary for usability that a file explorer was included in the UI, on the far left. This allowed a user to organise their log files in any manner they choose and use the "Path Select" and "Back" buttons to select their desired working directory. Once the directory is chosen, all the csv files that match the naming conventions described in section 2.1 are displayed in a list box on the top left, along with their file sizes. The file sizes of the log files can be a good representation of the duration of the trial, as longer trials have more data points. This is useful information as longer trials tend to be more useful in the tuning process as they can provide a more compete overview of the behaviour of the system. A "filter" checkbox is included in the UI that sorts the logs by their file size for this purpose.

Once a file is selected from the list, the "PLOT" button will invoke the data visualization program using the python Matplotlib library. This library is used for its easy customisation for simple reconfiguration [8]. which This will automatically read in the csv and split the data into a set of subplots on a single page figure. The resulting figure will appear in the blank space on the right side of the user interface, with a vertical scroll bar to view the whole output at a sufficient size in a limited space. An example of the matplotlib configuration using one of the latest trial runs during the tuning process is given in Figure 2.2.2.

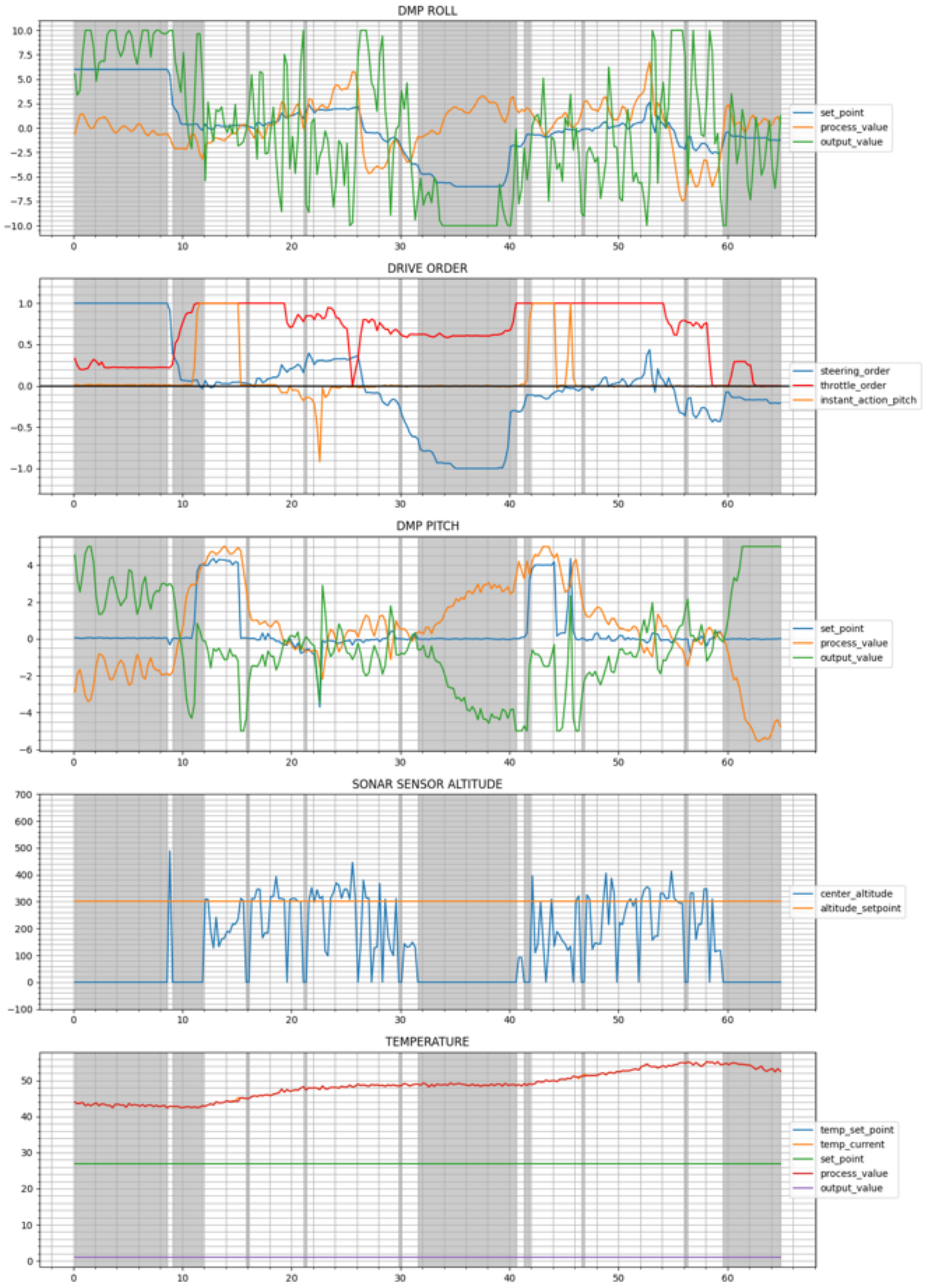

Figure 2.2.2: Example of the visualization printout

The subplots are structured such that they isolate the values relevant to each control loop within the system. The two stabilisation plots, showing the pitch and roll controllers, are placed either side of the "DRIVE ORDER" subplot, which shows all the user inputs, including the throttle, steering and joystick. Because all the plots use the time stamp included in the data logs as their shared axis in seconds, this subplot of user inputs can be used to assess the context under which the behaviours seen in the other plots have occurred. This is the reason the subplots are stacked vertically, so drawing a vertical line from one plot to the other will show the data at the same instance in time.

For each of the controller plots (DMP Roll and DMP Pitch), the subplots show the setpoint, process value and output overlayed. The output is the signal sent to the servos for control of the ailerons. This value is limited to between -1 and 1 in the data logs but is scaled up by a factor of 10 for the roll control and 5 for the pitch control, so that the output can be viewed on a similar scale to the reading from the sensors.

When analysing the data, it is important to be able to interpret when the craft is undergoing foiling, and when it just simply traversing on the surface of the water. The "SONAR SENSOR ALTITUDE" plot shows the desired setpoint for the altitude and the measurement of the altitude of the course of the trial. The axis for the altitude sensor is in millimetres, to make the incoming data. By identifying areas where the altitude takes a zero value for multiple consecutive data points, the times when the craft is not foiling are identified. Points where the data drops to zero for a single data point are not counted for this, as this is common with the ultrasonic distance sensor if droplet of water lands on the sensor during operation, so these points are still counted as part of the foiling. These times are marked on each plot as a greyed-out area, showing that they are not areas of interest for the specific use case of tuning the stabilisation and altitude control.

As described in section 2.3 for tuning, the data visualizations needed to be supplemented with quantifiable success metrics. To accommodate this in the final design, an extra program was integrated, the "Score" button on the left-hand panel. When pressed, this button would process the data of the currently selected and produce a readout to the python instance containing the relevant scores. These scores are the total integral absolute error for the roll, pitch, and altitude control loops in addition to the median altitude measurement. These scores all include both the raw score and a filtered score. The filtered score incorporates an additional factor within the calculation, using the same system for determining when the craft is foiling, to only factor the signal into the calculation for a trial when it occurs during the set of time stamps where the craft is exhibiting foiling behaviour. This estimate worked better once the craft was able to achieve this behaviour consistently, but otherwise, the unfiltered score a larger percentage of the data points for each trial. The median altitude function is used to determine the steady state error associated with the altitude control loop by taking the difference with the current setpoint. The median is used instead of the average to mitigate the effect of outlier errors on the sensor signal.

3.2 Limitations on the Results

There are a few problems that manifested as roadblocks to the development of tuning tools and the tuning process itself. The most significant of these limitations was the issue of the altitude sensors. Two different methods were attempted at implementing altitude feedback over the duration of this project. The first was the ultrasonic sensors, which had been inoperable for a large part of the development process. The sensors worked when tested in isolation, and when integrated onto the craft while it was static for maintenance, but they would cease to provide altitude information to the controller when the craft was tested in the field. This issue has since been resolved, but many of the test logs produced by the hydroski for early trials do not have altitude data available. To test the sensor, a hardware bridge was developed as part of this project to acts as an intermediary between the sensor and the controller that measures the sensor output and calculates the number of errors that occurs by counting the number of instances that the sensor sends message of the incorrect format. This hardware bridge was developed on an ESP8266 development board, using the microcontroller capabilities to control a small organic light-emitting diode display screen for a visualisation that can be interpreted during field tests without accessing the onboard software. An example of the display is shown in Figure 3.2.1.

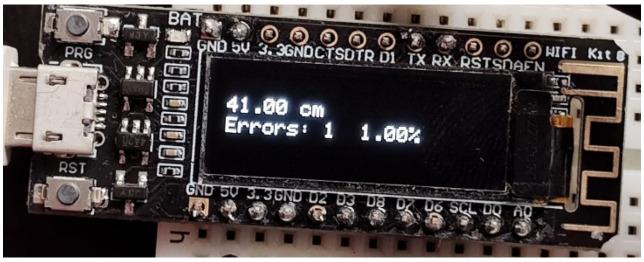

Figure 3.2.1: Altitude Sensor Testing Bridge

The thrusters on this prototype also caused some disruption to the data collection. Initially, there were placed at the ends of each wing on the rear foil, but this resulted in undesirable behaviour where if one thruster failed, the steering assembly would jerk sharply to one side and cause the rider to potentially be thrown off. To mitigate this, the architecture was rearranged, placing the thrusters vertically on rear foil, one above and one below the wings. This however introduced an additional limitation by limiting the maximum foiling height because of the top thruster losing power if a path for the air to reach the thruster was created by the motion of the watercraft.

For gathering of results, a significant limitation to any testing or trials is the limited battery capacity present on the watercraft. The battery capacity of the prototype allows for around 45 minutes to an hour of continuous testing, after which, the power provided by the thrusters drops significantly. This varies given the power requirements of the testing being performed but should last longer the more effectively the craft performs. This means that each test run can only contain a limited number of individual trials, generally around 30-50, before the available power becomes too low, and the thrusters stop operating.

3.3 Pre-Tuning Trials

An initial set of trails were performed at the beginning of the tuning process, with only the static gains and setpoints adjusted. These function as control tests, the scores for which can be calculated retroactively and used to determine both the effectiveness of the designed data analysis tools and the heuristic tuning process. The PID gain values in the control systems for these trails were all initially zero, except the proportional. Using the visualisation tools described in section 3.1, as an example of the performance of the watercraft prior to tuning, the subplots in figure 3.3.1 were generated from a control trial.

In this trial, the distance sensor was working, and demonstrates that the craft was capable of foiling for at least 10 to 15 seconds consecutively. The drive order plot shows that the craft user did not engage a turn, as the steering is not at an extreme, except for when the craft is not foiling at times from 20 to 30 seconds. The small actuations of the "instant_action_pitch" shown in the drive order represent the user manually pitching up the craft using the joystick, to initially cause it to increase in altitude to engage the controller, which is why it occurs at the beginning of each instance of foiling.

There are several strong signs from the visualisation in figure 3.3.1 alone that the stabilisation and altitude control was not functioning as intended. The first is that the altitude does not conform well to the setpoint, varying between a height of 100mm to 500mm despite the setpoint at 200mm, with regular fluctuating behaviour in places. The readings for the roll and pitch controller (the "process value" shown in the DMP Roll and DMP Pitch subplots) do not conform well to the setpoint shown in blue. This causes the output signal to the servos to reach its maximum, shown in green, reaching an amplitude of 10 degrees. The oscillatory, almost sinusoidal behaviour in the roll controller likely means that the user was manually balancing with their body weight, or that the overshoot on the controller was too significant and causing the craft to become unstable by being unable to settle to a level position. There is also a level of oscillation in the process value of the pitch controller, which could be the cause of the frequent variations in the altitude, or an effect, as the setpoint of the pitch controller is cascaded from the error in the altitude.

3.4 Post-Tuning Trials

In contrast to the behaviour of the system discussed, the behaviour of the system after tuning can be observed subplots as part of the visualization shown in Figure 3.4.1. This trial takes a similar general structure to the pre-tuning trial, with two periods of foiling around 15 to 20 seconds.

The clearest indicator of improved performance is that in this case, the outputs angles to the ailerons, shown as "output_value" on the pitch and roll controller subplots, do not reach their saturation value (5 for pitch and 10 for roll, which are scaled up for display from their maximum of 1 amplitude) during the foiling, keeping the system within a state where any deviations in the roll or pitch can be recovered from by the controller.

The altitude controller conforms very well to the output setpoint, with slight deviations resulting from the inconsistencies with the sensor feedback and does not exhibit the oscillatory behaviour in the pre-tuned case.

This is also true for the roll and pitch controllers, for which the process values visibly conform to the setpoint. This is especially for the pitch controller, which settles to approximately zero during the main duration of the foiling around 4-5 seconds after the initial pitching to increase the altitude of the watercraft to initiate the foiling behaviour. In both trials depicted, the steering is close to zero, representing the user driving the watercraft in a straight-line during foiling, so the setpoint for the roll controller tends to stay around zero. In the untuned case, the process value measured by the internal IMU for the roll measured oscillations to angles of at least 10 degrees. The tuned case did not measure roll values more than 5 degrees, which represented a significant improvement with the addition of the tuned PID parameters. The oscillation that was present in the untuned case is also absent or greatly reduced after the tuning process. As with the untuned case, while the watercraft is not foiling (the greyed-out areas), the controller does not operate, as the action of the ailerons has little effect on the stability when compared to the buoyancy provided by the hull.

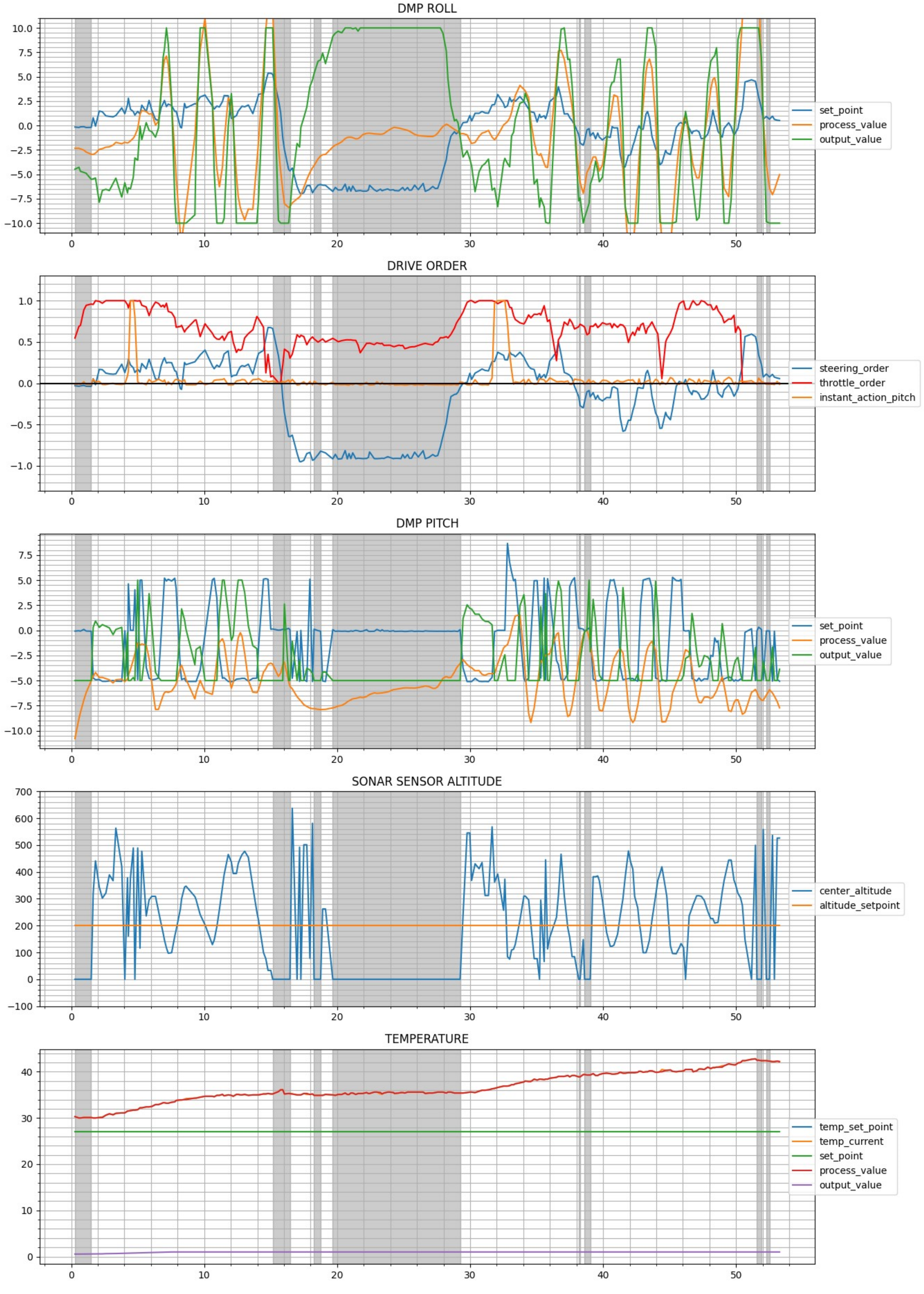

Figure 3.3.1: Pre-tuning readout for the control systems

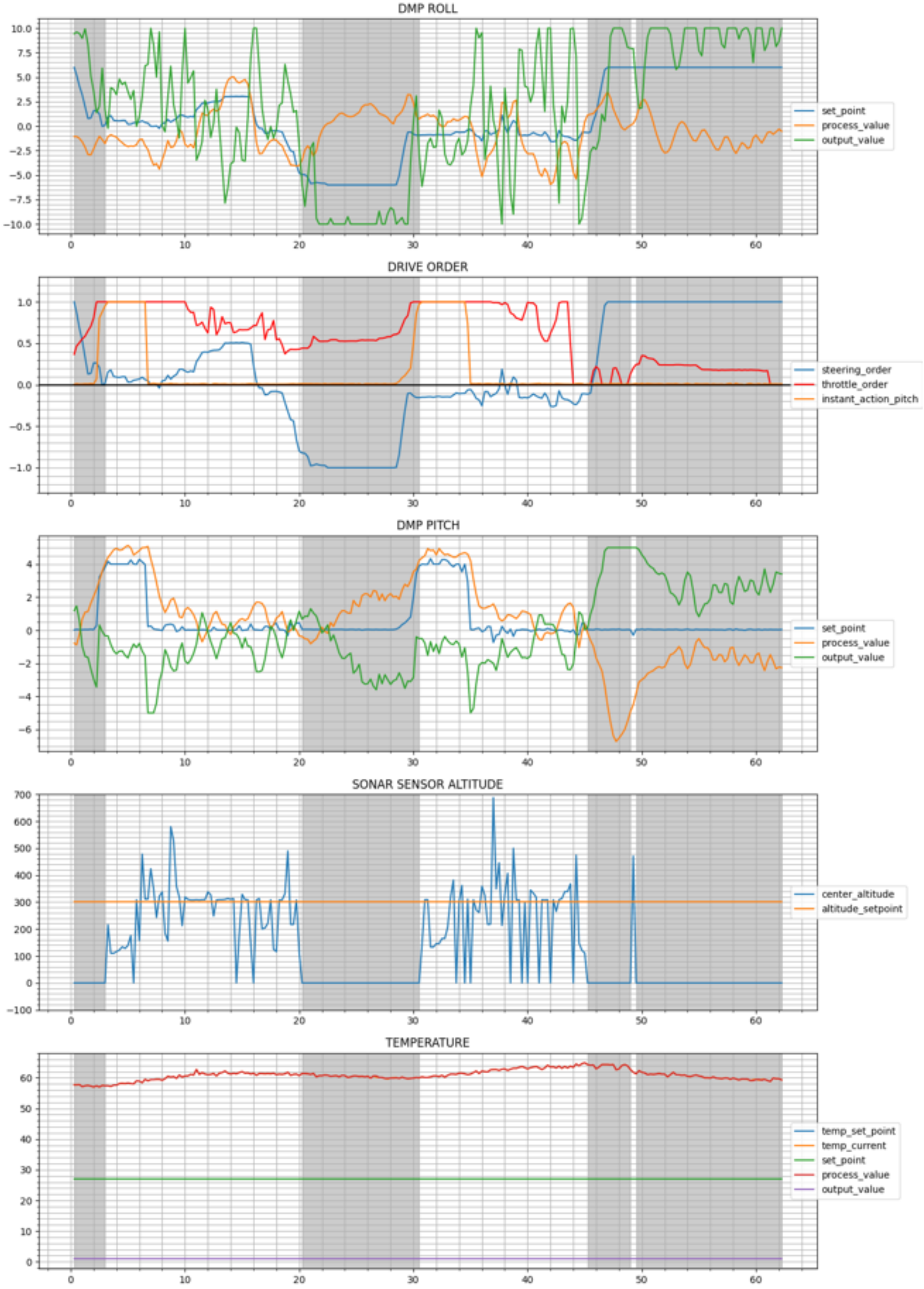

Figure 3.4.1: Post-tuning readout for the control systems

3.5 Evaluation of Tuning Performance

Using the scoring functionality of the user interface design outlined in section 3.1 to calculate success criteria for the pre and post tuned cases offers a more quantifiable representation of the increase in performance offered by this tuning method. Because both these cases have altitude sensor data, the weighted methods can be used to only utilise the data from when the watercraft is foiling.

For the untuned case, the average integral absolute error for the roll controller is 13.02 degrees and for the pitch controller is 13.04 degrees. The average integral absolute error for the altitude controller is 135.17mm. The median altitude for this case is 289.70mm, which given that the altitude setpoint for this trial was set at 200mm represents an increase in the steady state value of 89.70mm, or a percentage of 44%.

For the case of the tuned trial, the average IAE is 3.52 degrees for the roll controller and 1.77 degrees for the pitch controller. Comparing this to the untuned case, using these metrics, the tuning process has resulted in a trial for which the performance of the stability control has significantly increased. The median altitude, taken over the lengths of non-zero altitude of the trial, is 283.29mm. The setpoint for this case was established as 300mm, so the difference in the steady state is approximated as 16.71mm or a percentage of 6%.

To validate this result further, multiple trials from the same test run can be considered, to ensure that the results presented in sections 3.3 and 3.4 are not simply outliers. By taking the average over 15 individual trials of varying lengths, each with at least one section where foiling behaviour was observed, a generalised performance estimate for the pre and post tuned system is derived. The standard deviation of the trial runs is used a measure of the disparity in the trial runs to evaluate the consistency of the performance.

Table 3.5.1: Average integral absolute error for the **Roll** Controller over 15 trials

	Untuned System	Tuned System
Average	13.10°	4.93°
Standard Deviation	7.91°	1.49°

Table 3.5.2: Average integral absolute error for the **Pitch** Controller over 15 trials

	Untuned System	Tuned System
Average	8.99°	2.67°
Standard Deviation	2.49°	0.72°

Table 3.5.3: Average integral absolute error for the **Altitude** Controller over 15 trials

	Untuned System	Tuned System
Average	142mm	80mm
Standard Deviation	28mm	11mm

From table 3.5.1, which shows the roll controller values, there is a 62.3% improvement in the integral absolute error values after the tuning process. The improvement in the pitch controller stability, shown in the table 3.5.2 is 70.3%, with a lower integral error in both the tuned and untuned cases compared to that of the roll controller. The standard deviation for the tuned systems for all three metrics is significantly lower, indicating a more deterministic system that operates with the desire behaviour more frequently with fewer outliers. For the altitude control, shown in table 3.5.3, the system conforms to the setpoint more strongly in the tuned system with an improvement from the untuned system of 43.6%. For the altitude measurement, the average steady state altitude during foiling is shown in Table 3.5.4. The important metric from this table is the average difference, the difference between the measured value and the setpoint. The tuned case exhibits an average 61% improvement on the untuned case.

Table 3.5.4: Median measured altitude over 15 trials

	Untuned System	Tuned System
Average Altitude	300mm	261mm
Desired Setpoint	200mm	200mm
Average Difference	100mm	-39mm
Standard Deviation	41mm	17mm

4. Conclusions and Future Work

The design outcomes for the designing of the tuning tools were to produce a system to convert the data provided by the watercraft into a human readable format that presents the information in a clear and succinct manner. The visualisation user interface produced satisfies these criteria by separating out the logged data into a set of isolated data loops, with individual measurements, setpoint and error values. The scoring output of the interface allows a user to process the data easily and automatically generate the success metrics to evaluate the performance of the systems. This program can be utilized for data visualization for future work on this project, and can be easily modified and tweaked as needed, as it is written in python code. Using the developed tools and tuning method, after several iterations, the control system for the watercraft has seen a significant improvement in its performance, with the average of the IAE improving by 62.3% for the roll, 70.3% for the pitch and 43.6% for the altitude control. This indicates an improvement in both the stabilisation and the automatic altitude control. The validation tests were performed without using manual setpoint control with the joystick, so these improvements allow the craft to perform the foiling behaviour well independent of user input.

The tuning process for this prototype was performed under consistent environmental conditions, often in the same location, with the same few users. Future work could involve continuing the iterative tuning process but validating that the system still performs well under different conditions, with different weights and number of riders. Alternatively, investigation of alternative control architectures could be explored, implementing a simplified hysteresis controller for example, could lower the number of parameters that need to be changed in each iteration compared to the current setup. Integration of additional sensors for altitude, roll and pitch measurements to improve the reliability of the feedback information to the control systems would be necessary for more accurate altitude control. A second prototype is being developed for the watercraft, using a new modified jet ski hull and propulsion setup. Consequently, implementation of the control hardware on the new system, followed by either retuning of the control systems or using the performance metrics to create a system that can automatically tune the system in real time could be potential avenues for future work.

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Appendices

Appendix A – Raw performance metrics for the 15 validation trials

Roll Controller IAE	
Untuned	Tuned
5.63	4.18
10.28	5.90
7.41	6.49
10.07	5.26
13.02	3.52
5.83	5.45
27.99	5.91
11.85	3.37
31.74	8.78
16.25	4.34
13.49	4.52
8.51	4.68
3.51	4.00
17.90	2.66

Pitch Controller IAE	
Untuned	Tuned
6.19	2.79
7.71	2.98
9.80	4.05
9.03	2.24
13.05	1.77
7.56	2.55
15.28	3.63
8.59	1.79
11.25	3.96
6.60	2.10
6.97	2.36
7.94	2.57
7.58	2.11
8.28	2.44

Altitude Control IAE	
Untuned	Tuned
93.82	69.75
113.67	84.43
160.99	69.15
124.15	79.86
135.17	76.35
142.44	78.01
116.45	98.16
135.38	79.03
148.85	100.67
154.36	63.80
145.80	67.40
150.85	75.12
217.69	93.24
154.14	91.46

Average	Average
13.11	4.93
std dev	std dev
7.91	1.49

Average	Average
8.99	2.67
std dev	std dev
2.49	0.72

Average	Average
142.41	80.46
std dev	std dev
27.66	11.23

Median Altitude			
Untuned	Setpoint	Difference	Percentage
214	200	14	7%
246	200	46	21%
282	200	82	34%
289	200	89	36%
290	200	90	37%
264	200	64	28%
278	200	78	33%
319	200	119	46%
321	200	121	47%
347	200	147	54%
334	200	134	50%
337	200	137	51%
373	200	173	60%
309	200	109	43%

Tuned	Setpoint	Difference	Percentage
278	300	-22	8%
280	300	-20	7%
268	300	-32	11%
276	300	-24	8%
283	300	-17	6%
266	300	-34	12%
228	300	-72	27%
255	300	-45	16%
224	300	-76	29%
272	300	-28	10%
266	300	-34	12%
249	300	-51	19%
258	300	-42	15%
252	300	-48	17%

Average
300
std dev
41

Average	Average
100	39%
std dev	
41	

Average
261
std dev
17

Average	Average
-39	14%
std dev	
17	

Appendix B – Code for derivation of performance criteria

```
    def point_error(self, input, setpoint, time):
        return input[time] - setpoint[time]

    def median_alt(self, alt, times):
        alt_points = 0
        alt_values = []
        n = len(times)
        for i in range(n):
            # Altitude Error
            if alt[i] != 0:
                alt_points += 1
                alt_values.append(alt[i])s
        alt_median = statistics.mean(alt_values)
        return alt_median

    def weighted_integral_error(self, input, setpoint, alt, alt_sp, times):
        weighted_error = 0
        total_error = 0
        altitude_error = 0
        alt_points = 0
        self.error_vector = []
        n = len(times)
        for i in range(n):
            error = abs(self.point_error(input, setpoint, i))
            alt_error = self.point_error(alt, alt_sp, i)

            total_error += (error)

            # Altitude Error
            if alt[i] != 0:
                alt_points += 1
                altitude_error += abs(alt_error)
                weighted_error += (error)
            else:
                altitude_error += 0

        weighted_error /= times[n-1]
        total_error /= times[n-1]
        altitude_error /= alt_points
        return [total_error, weighted_error, altitude_error]
```