Low-Cost Sensor Based Orientation Detection System for Hydrofoil Jet Ski

GENG5512 Final Year Thesis Project

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Abstract

Capturing motion data of a jet ski is crucial for the analysis on its dynamics and stability condition while traveling atop of water. Motion data also provides vital information for any redesign process to take place. To achieve this, instrumentation using sensor components are used to monitor and record vital parameters that dictates the stability of the jet ski. These parameters include, but not limited to, the orientation angle and in the context of hydrofoil jet ski, the submerge depth of the hydrofoil components in the water.

This thesis project focuses on the design and implementation of an Orientation Detection System (ODS) for the REV (Renewable Energy Vehicle) Hydrofoil Jet Ski, also known as the Efoil. As part of the REV initiatives, the Efoil project aims to achieve higher power output and greater speed that are comparable to the common petrol-power jet ski, through the implementation of hydrofoil components on an electrically powered jet ski.

The proposed ODS instrumentation for the Efoil will aim to capture motion data relevant to its operational stability. This includes the orientation angles and the submerge depth of the hydrofoil component. A log of the Efoil's motion data from each drive test will be created as the result of the system implementation and can be utilised for any future design improvements on the Efoil.

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Table of Contents

Table of Figures

Table of Tables

Nomenclature

CAN	Controller Area Network
DOF	Degrees of Freedom
Efoil	REV Hydrofoil Jet Ski
GPIO	General Purpose Input/output
I2C	Inter-Integrated Circuits
IMU	Inertia Measurement Unit
PCB	Printed Circuit Board
SCL	Serial Clock
SDA	Serial Data
SRAM	Static Random-Access Memory
ODS	Orientation Detection System
REV	Renewable Energy Vehicle
UWA	University of Western Australia

1. Introduction

1.1 REV Hydrofoil Jet Ski

The initiative of the Renewable Energy Vehicle (REV) projects at The University of Western Australia (UWA) is to explore, develop, and implement autonomous, electrification designs on commercial transportation vehicles, both for land-based and water-based. From its inception by Professor Thomas Bräunl and Doctor Kamy Cheng in 2008, the REV projects explores the possibilities of electric vehicle conversions by replacing the conventional fossil fuel power source that is dominating the current market with electric based technologies powered by renewable energy sources. And as such, several successful conversions had been done by the REV teams since the inception year, along with other accompanying achievements such as the Electric Charging Stations.

Figure 1 - REV Efoil on drive test

As part of the green initiatives of the REV project, the REV Hydrofoil Jet ski, also referred to as the Efoil project, aims to develop a fully functional electric hydrofoil watercraft. This project was built upon previous REV Electric Jet Ski project works, namely the REV electric Jetski, back in 2015. The Efoil project further explores the possibility of higher speed and a greater power efficiency from green renewable energy source by the implementation of hydrofoil components. A conventional jet ski was modified to integrate battery power source into the hull of the Efoil to provide roughly 30 minutes of operating range. Two hydrofoil fins were installed onto the Efoil with one just below the rider's position and one on the tail of the jet ski to provide greater traveling velocity through water.

1.2 Problem Identification

Although past drive tests had yielded satisfactory results in terms of the functionality of the Efoil towards the end of 2019, the jet ski itself still suffers from instability issues when attempting to perform manoeuvres that changes travel direction while operating on water. As the Efoil's hull is lifted above water when reaching the required speed, thus its vertical profile is significantly higher than other conventional water jet skis and is more prone to off-balancing issues caused by oncoming waves or shifting of rider's mass. A redesign of the hydrofoil components was proposed at the beginning of 2020, to minimise or resolve the said instability issue; however, this meant that more knowledge about the orientation and motion data of the Efoil were required so a reliable redesign could take place.

Furthermore, the Efoil was constructed from the ground up with either customised or off-the-shelf components, thus the vessel was equipped with bare instrumentation system that only monitors the remaining power level, current drawn and voltage information about the on-board battery power source of the Efoil as of the beginning of this thesis project. This was most inconvenient and posed significant risk to the Efoil rider as the limited instrumentation provided no indication about the real time orientation state of the jet ski when it was operated above water, thus no warning was given to the rider if the jet ski was about to tilt off-balance.

To summarise, the design of the Efoil as of the beginning of beginning of this thesis project exhibited balancing issue and called for a potential redesign to the hydrofoil and other components. However, a lack of proper instrumentation on the Efoil prevented any collection of the Efoil's motion data for dynamic analysis to conduct the redesign, and the safety of the Efoil rider was compromised as no indication about the Efoil's orientation state was displayed.

1.3 Scope

From the aforementioned identified problems associated with the Efoil, opportunity arised for the implementation of an Orientation Detection System (ODS) into the Efoil, and such system could provide measurements of the following two parameters of the jet ski which dictated its overall stability:

- Orientation angles of the efoil.
- The submerge depth of the rear hydrofoil fins in the water.

This thesis project aims to assemble the ODS using various low-cost sensors and other required accessory components that are easily sourced from local commercial electronics suppliers. Figure 2 illustrates the scope of the system assembly in dotted red line and demonstrates how the ODS will fit into the instrumentation of the Efoil. The uses of low-cost components are to reduce the overall cost and comply with the budget constraint that is imposed on the REV Hydrofoil Jet Ski project. In conjunction, the project also experimentally designs and determines the feasibility of achieving the aforementioned recording and monitoring functions with relative low-cost instrumentation devices.

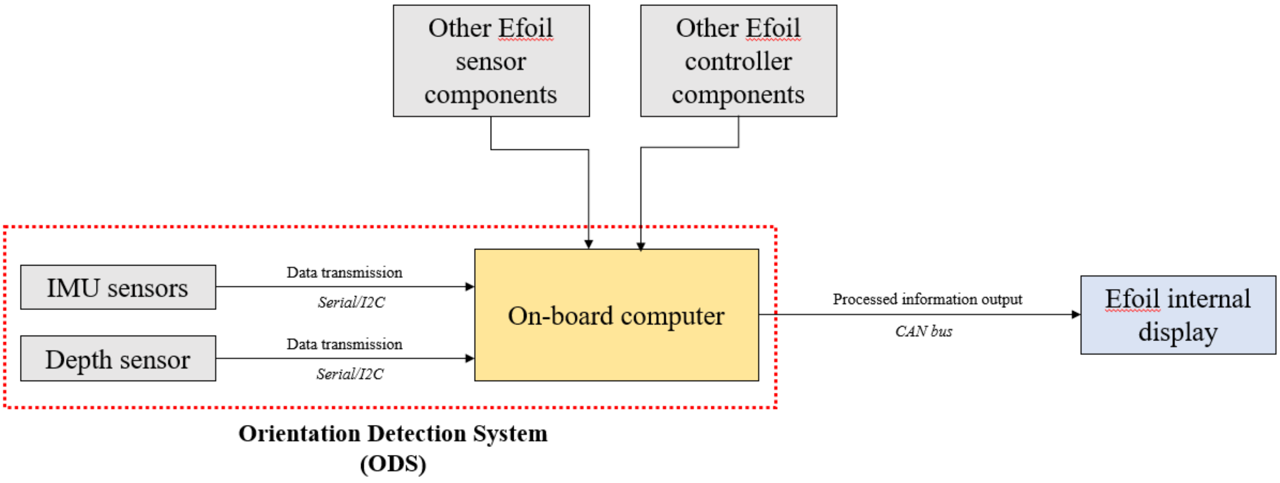

Figure 2 - Block representation of Efoil instrumentation

To assess the ODS, the implementation process and the design of the system must first achieve the function of logging the target parameters that contributes to Efoil's stability from drive tests as these logged data will be valuable to evaluate the Efoil profile design and compare with later design iteration's profile data if the jet ski is to be redesigned for improvements. On top of this, the final assembly of the ODS must also be easy to operate and configure, as well as simple to understand to reduce the complexity of handover process to future project members after this thesis project had finished.

2. Literature Review

2.1 Previous Works

The thesis work done by previous REVski student, Maximilian Woloszyn, focused on the instrumentation of a conventional jet ski after its electric conversion [1]. Woloszyn's work provides an excellent framework for a modular instrumentation design approach whilst utilising sensor components to record and monitor the desired status parameters of the Efoil. The most relevant information provided by his work is the implementation of a single-board computer that function as the storage device for all measurement inputs from sensors, and provides a method to review and reflect on the data obtained on a previous water test of the jet ski.

Similar instrumentation work was also done by Dylan Leong, another previous REVski student who completed his work after Maximilian Woloszyn, Leong's work was an extension that built upon the work foundation completed by Woloszyn [2]. Leong further explored and evaluated the use of an Arduino Mega microcontroller in his thesis work. He concluded that the use of an Arduino based microcontroller lacked sufficient SRAM (static random-access memory) and exhibits slow clock speed which hindered the smoothness of data transmission from external sensors. With his conclusion, Leong also provided valuable improvement suggestion of using Raspberry Pi 3B to replace the Arduino Mega board as the on-board data storage device.

2.2 IMU

2.2.1 IMU Based Orientation Estimation

In almost all motion tracking application, pose information, which includes the orientation and position of an object that is of interest is vitally important in interpreting the dynamics of that object [3]. This set of information can be estimated by inputting the raw outputs from an IMU into a form of filtering algorithm [4]. To be precise, the gyro output (angular velocity of the sensor) is integrated to obtain the orientation, which is often represented by the roll, pitch and yaw angles, and the accelerometer output (external specific forces acting on the sensor) is double integrated to obtain position after first been subtracted by gravity [5,6]. The current time evaluation of the pose information is performed given that the previous pose of the object is known, and this process is often coined as dead reckoning [4,3]. Figure 3 captures the integration processes to perfectly estimate pose information of an object given a known initial pose of the object.

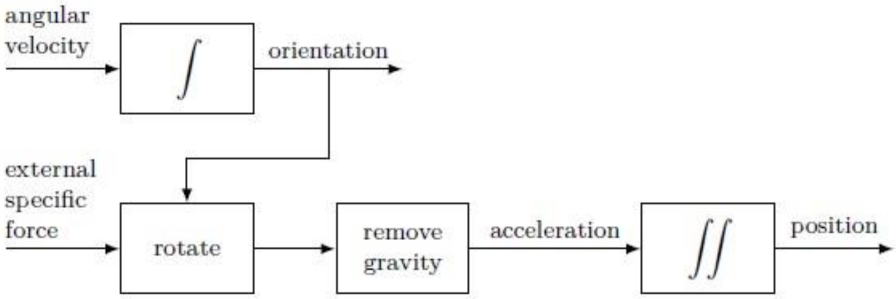

Figure 3 - Block illustration of dead reckoning [3]

Dead reckoning assumes zero presence of measurement errors and biases in IMU output and as such, it estimates the pose information of an object perfectly. However, such perfect estimation is realistically impossible, and measurement errors are an inevitable phenomenon [7]. To obtain a more accurate pose estimation, commercial IMUs are often equipped with sensor fusion or filtering algorithm to reduce the integration drift and errors of the IMU outputs [4]. Figure 4 illustrates a form of estimation process with the implementation of Kalman Filter technique.

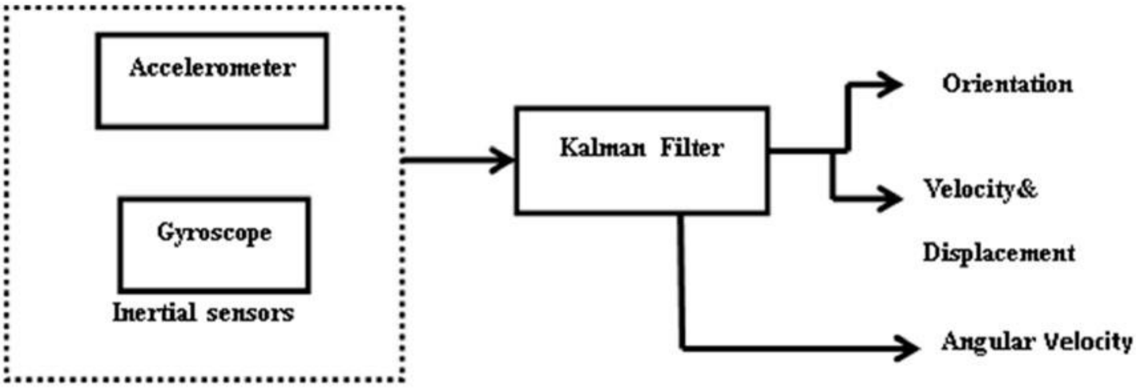

Figure 4 - Block illustration of filtering IMU outputs to obtain pose information [8]

2.2.2 IMU Physical Implementation

Two distinctive physical implementations of the IMU stand, one being the gimballed arrangement, and the other being the strapdown arrangement [4]. The gimballed arrangement ensures the alignment of the accelerometer with the navigation frame. This alignment is achieved by mounting the accelerometer onto a gimballed mechanised platform; thus, the accelerometers are directly integrated to obtain the velocity and position of the navigation frame. On the other hand, the strapdown arrangement is the direct mounting of the accelerometer and gyroscope onto the moving object body [9]. The gyro obtains the rate of rotation of the body, which is then used to refresh the transformation between the body and the navigation frames. The outputs from the accelerometer is then passed through such transformation to evaluate the navigation frame acceleration [4, 9], which in turn evaluates to estimate the orientation of the body.

2.3 Water Vessel Stability

Water vessels suffer from instability caused by oncoming waves while traveling on water. Although occasional, the instability of the jet ski induced by bumpy or heavy waves can prove to be dangerous as the craft can be easily tipped off of its balance by such phenomenon, which result in the jet ski being out of control or the overboard of the rider.

Hydrofoil component plays an important role of dictating the stability of a hydrofoil water vessel. Although similar to aircraft wings, the hydrofoil needs to be fully submerged in water to produce effective lift. This is due to a different density of water to air, the hydrofoil does not require a high velocity to create lift, but the fin must act on an angle to the water or is fully submerged to create sufficient lift force [10,11]. Phenomenon like cavitation, ventilation, planing and other processes created by bumpy water condition can disorient the Efoil, and such disorientation will reduce the submerge level [10,11] of the hydrofoil fins in water. Lift is lost at the end of this domino effect, which can tilt the watercraft fully off its balance.

The stability of a water vessel can also be analysed by planar analysis of the vessel. As such, the jet ski hull exhibits three planes that dictates the overall stability of the vessel. These planes are middle line plane, transverse plane and water plane [12]. The longitudinal stability is controlled by the rotation of the middle line plane, which often can be induced by the rolling motion and in similar fashion, the transverse stability is controlled by the rotation of the transverse plane, and often induced by the pitching motion of the jet ski [12]. From the measurements of the roll and pitch angle change, the stability information about a jet ski can be obtained.

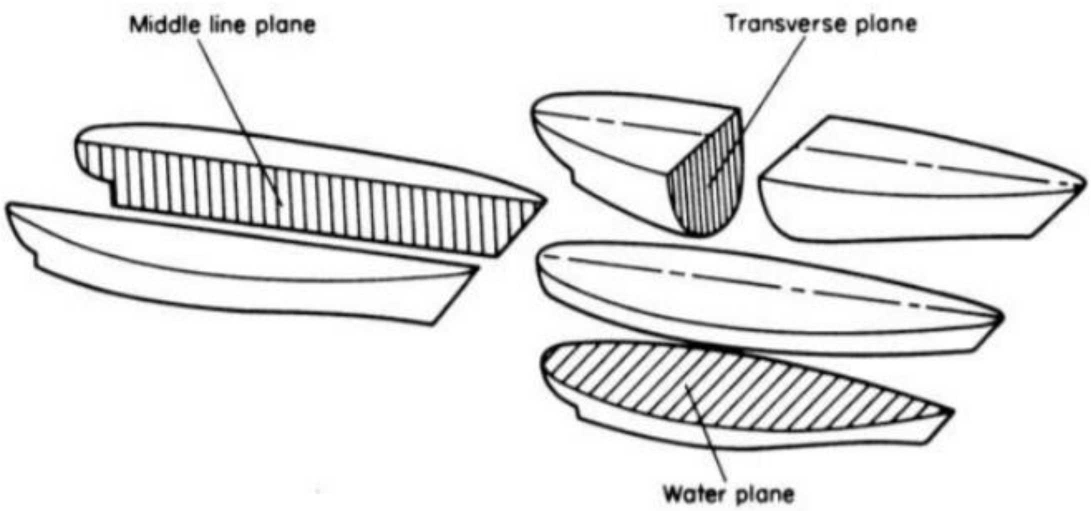

Figure 5 - Planes of a water vessel [12]

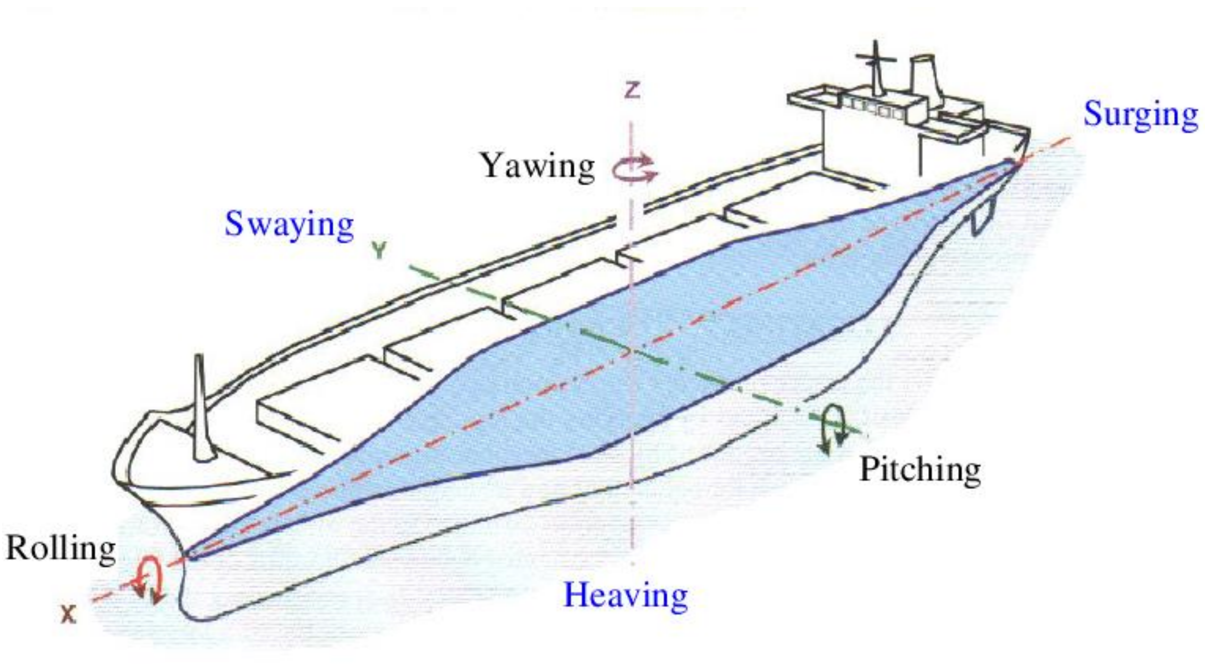

Figure 6 - Notation and sign conventions for water vessel motion description [13]

3. Design Process Overview

The overall design process of the proposed ODS is comprised of the following stages which are illustrated visually as flow chart shown in figure 7 below.

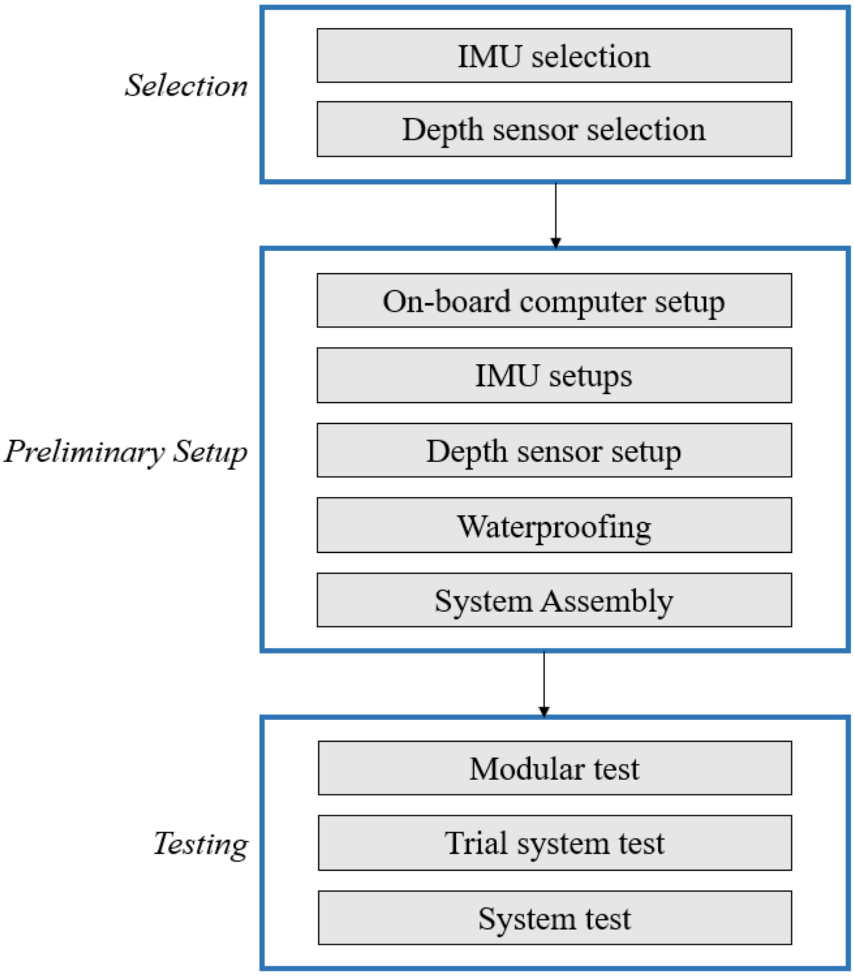

Figure 7 - ODS design process flow chart

The design process is comprised of three main stages, each contains its respective design procedures and is represented by the blue outlines in figure 7. These three main stages are the selection stage for sensor components, the preliminary setup stage to assembly the ODS, and the testing stage to validate the functionality of the proposed system to draw conclusion. Each design stage will be discussed in detail in the upcoming sections of the report.

4. Sensor Selection

Based on the findings from the Literature Review, two target parameters identified that dictates the orientation of the jet ski and consequently its stability are the orientation angles of the Efoil (roll and pitch angles) and the submerge depth of the rear hydrofoil fin of the Efoil in the water. IMUs and depth sensor were chosen to monitor and measure the two stability determining parameters of the Efoil. However, each sensor category contains a wide range of selection that exhibits different performance characteristics, and suitable selection of sensors in each category must be determined to suit the purpose of the ODS for the Efoil.

And as such, a set of selection criteria was constructed to assist in narrowing down the selection range and determine the feasibilities of each sensor type in consideration. The selection criteria are as follows:

Table 1 - Selection criteria for sensor selection process

Selection Criteria	Description
Cost	Will the cost be within the budget of the REV project and be classified as low-cost?
Specification	What is the functionality of the sensor chosen and does it measure the desired measurand?
Ease of integration	How easily can the chosen sensor be integrated with other hardware components and into the Efoil electrical system, both in terms of hardware and software.
Ease of modification	How easily can the chosen sensor be modified to suit the desired purpose?

4.1 IMU Selection

Three different IMU sensors were required for this category so Efoil's orientation angles measurements could be verified by comparing each IMU recordings and to provide backup sensor options if one were to fail.

As the primary sensor type of this thesis project, the choices of sensor in this category must be equipped with output filtering technique or algorithm to reduce the noise and bias present in its orientation estimates. As suggested from Literature Reviews on IMU, the raw orientation estimate outputs from dead-reckoning process performed by IMU exhibits large measurement errors and thus the addition of filtering algorithm is essential. The selected IMU must also exhibit the ability of at least 6-DOF (degrees of freedom) measurements so the roll and pitch angles of the Efoil could be measured. A relatively low pricing is also required for a IMU to be considered. Four sensors were put into consideration. The important specification associated with each sensor is tabulated in table 2.

Table 2 - Specification of each IMU sensor consideration [14,15,16]

	DFRobot BNO055 + BMP280 intelligent 10DOF AHRS	**Adafruit BNO055 Absolute Orientation Sensor**	**PhidgetSpatial Precision 3/3/3 High Resolution**	**Arducopter Mega APM2.5**
Cost	~40 AUD	~50 AUD	~160 AUD	Unknown
Specification	10-DOF orientation measurements	9-DOF orientation measurements	9-DOF orientation measurements	Orientation measurements
Ease of integration	Gravity I2C interface, Arduino compatible	I2C pins and Arduino compatible	Serial connection via USB cable	Serial connection and I2C pins available, already installed on Efoil
Ease of physical modification	Bare PCB, no additional components required	Bare PCB, no additional components required	Encased in hard plastic shell, no additional components required	Encased in hard plastic shell, no additional components required

All IMU under consideration offered similar specification in terms of orientation measurements and could output filtered orientation estimates. It was noted that the DFRobot and Adafruit IMUs both contain a Bosch BNO055 chipset and the same I2C communication protocol that could interface with microcontroller such as Arduino boards or single-board computer such as the Raspberry Pi. However, the option supplied by DFRobot yielded more value for its cost, providing 10-DOF measurements at a price lower than Adafruit's version. And for this reason, DFRobot IMU was chosen as one of the IMUs for the ODS.

A second IMU option was required for the aforementioned purpose of IMU recording verification and backup, and for this reason, the Phidget IMU was also chosen to be included in the proposed orientation estimation system. It was expected that this IMU would yield a better performance in orientation estimates than the DFRobot IMU to justify the steep price difference between the two.

The third choice of IMU, the Arducopter Mega APM2.5, was already installed onto the Efoil prior to this thesis project. It had already functioned as the stabilisation tool of the Efoil but lacked any orientation measurement output, thus it was logical to include this sensor choice into the ODS so its functioning outputs could be recorded and monitored.

4.2 Depth Sensor Selection

The depth sensor measures how far the hydrofoil fin of the Efoil is submerged in the water while in operation, and is required to measure a depth of at least 10 metres below the water surface as well as a quick sampling time to capture swift changes in the submerge level of the Efoil's hydrofoil fin.

Table 3 - Specification of each IMU sensor consideration [17,18]

	Bluerobotics Bar30 High-Resolution 300m Depth/Pressure Sensor	**Bluerobotics PCB for Bar02 Ultra High Resolution 10m Depth/Pressure Sensor**
Cost	~100 AUD	~80 AUD
Specification	Up to 30 bar absolute pressure (300m depth)	Up to 2 bar absolute pressure (10m depth)
Ease of integration	3.3V I2C communication. Arduino and Raspberry Pi compatible	3.3V I2C communication. Arduino and Raspberry Pi compatible
Ease of physical modification	Protective aluminium casing	Bare PCB ready for soldering

The PCB bar02 depth sensor from Bluerobotics was evaluated as the most optimal choice due to its pricing was much lower than its counterpart, the Bar30 variant. While each consideration offered high resolution depth/pressure measurement, the bar30’s measurement range was simply an overkill for the intended purpose of submerge tracking of hydrofoil in the water, whereas bar02 offers a more appropriate measurement range of 10 metres. The bare PCB construction of bar02 option also offered customisability to the sensor so custom casing could be constructed to house the depth sensor depending on the situation requirement.

5. Preliminary Setup

This section of the thesis report details the process of preliminary setup of the ODS into the Efoil, which directly follows the selection process. This stage of the design was consisted of establishing hardware connections between the chosen sensors and its accompanying microcontroller as well as introducing the single-board computer into the assembly. Other design considerations such as waterproofing of the final assembly was also done during this design stage and will be further discussed in this section of the report.

5.1 On-board Computer

To assemble the IMU's and depth setup together, a single-board computer, Raspberry Pi 4 was introduced to provide the functionality of sensor measurements logging and storage, it also functioned as the on-board computer of the Efoil for later CAN bus installation so the sensor measurements could be relayed to the internal display of the Efoil. The Raspberry Pi 4 Model was chosen due to its cost-effectiveness and simple to configure for novice programmer. From the recommendations made by Dylan Leong in his thesis work. The Raspberry Pi 4 has the advantage of providing a better data transmission due to its increased SRAM size when compared to other microcontroller device that performs similar function [2].

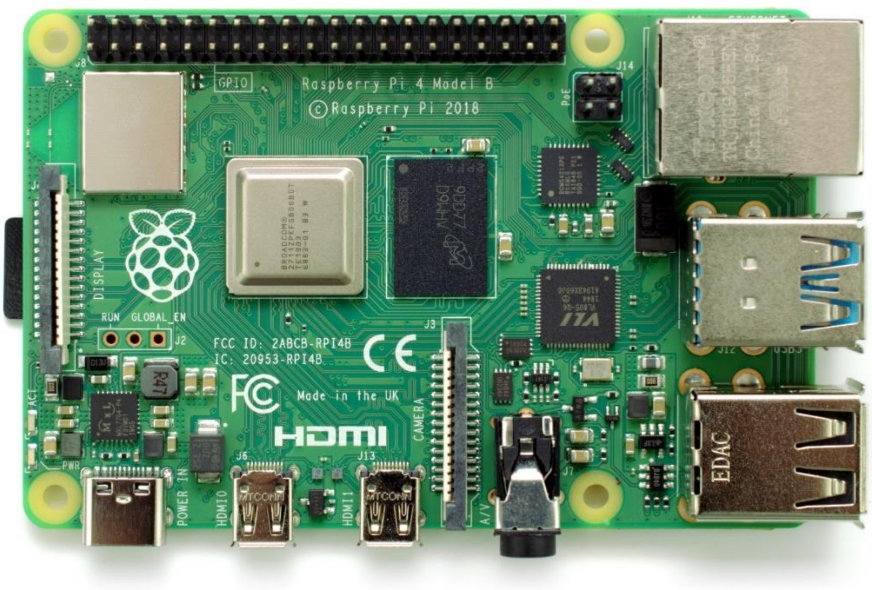

Figure 8 - Topview of the Raspberry Pi 4 Model B board

To power the Raspberry Pi, a USB connection from the Pi to the Arducopter Mega APM2.5 board was first established. The Arducopter was linked directly to the battery power source of the jet ski, so the initial connection was setup in a way that the Raspberry Pi could draw power from the Efoil battery via the Arducopter board. However, it was found that this connection was not practical as the serial connection of the two devices hindered the power transmission from the battery to the Raspberry Pi, and caused insufficient power supply to the Pi. To resolve this issue, new split wire connection was introduced so the Raspberry Pi could draw power directly from the Efoil batteries, bypassing the Arducopter board.

5.2 IMU Setups

The three IMUs were directly connected to the Raspberry Pi via USB connection so serial outputs from each individual sensor can be recorded and stored onto the Raspberry Pi. This section of the report will detail how the hardware connections were setup for the three chosen IMUs of DFRobot BNO055, PhidgetSpatial and the Arducopter.

DFRobot BNO055

Different to the other two IMUs, this bare PCB IMU requires an external microcontroller to interpret the readings and measurements output. As this IMU was able to measure either raw accelerometer, gyroscope and magnometer or orientation angle, an external microcontroller was required to functions as the tool to select which output the IMU was measuring.

An Arduino Uno board was chosen as the microcontroller for the DFRobot BNO055 IMU and the reasoning behind were its simple setup process and was easy to configure for people with beginner to novice level of coding skills.

Table 4 - Pin connection table for DFRobot IMU [19]

DFRobot BNO055 IMU Pinout (wire colour)	Functionality	Corresponding Arduino Uno Pin
VCC (red)	Positive pole	GND
GND (black)	Negative pole	3.3V
C (green)	I2C-SCL	A4
D (blue)	I2C-SDA	A5

For the Arduino Uno to receive data from IMU, the baud rate was set to 115200 using the Arduino IDE, the red and black wires from the IMU were jumped to the 3.3 volt and ground pins respectively on the Uno board, and to enable data transmission, the green and blue wires were jumped to A4 and A5 pins respectively on the Uno board. The Arduino Uno board was then connected to one of the serial ports on Raspberry Pi board using USB cable so the data received by the Uno board can and saved onto the on-board computer.

PhidgetSpatial

The PhidgetSpatial IMU required a much less complex physical connection process when compared to the DFRobot BNO055 connection. The IMU is simply connected to the one of the Raspberry Pi's serial port via USB cable.

Arducopter

A similar connection setup was used on the Arducopter as the PhidgetSpatial IMU. A micro-USB cable was used for the physical connection as the Arducopter board contained a micro-USB port for serial data transmission into other device such as the Raspberry Pi.

5.3 Depth Sensor Setup

The depth sensor was installed and sealed inside of left motor cover located on the rear hydrofoil fin as illustrated in figure 9 below. The depth sensor sat within the small circular opening of the cover so only the ceramic pressure gauge of the sensor was exposed to water when the fin submerged in the water. The rest of the sensor PCB was attached onto the inside of the cover, and since the cover was not waterproof, waterproofing rubber seals were applied on top of the depth sensor and around the general area where it was situated so the entire sensor PCB became waterproof.

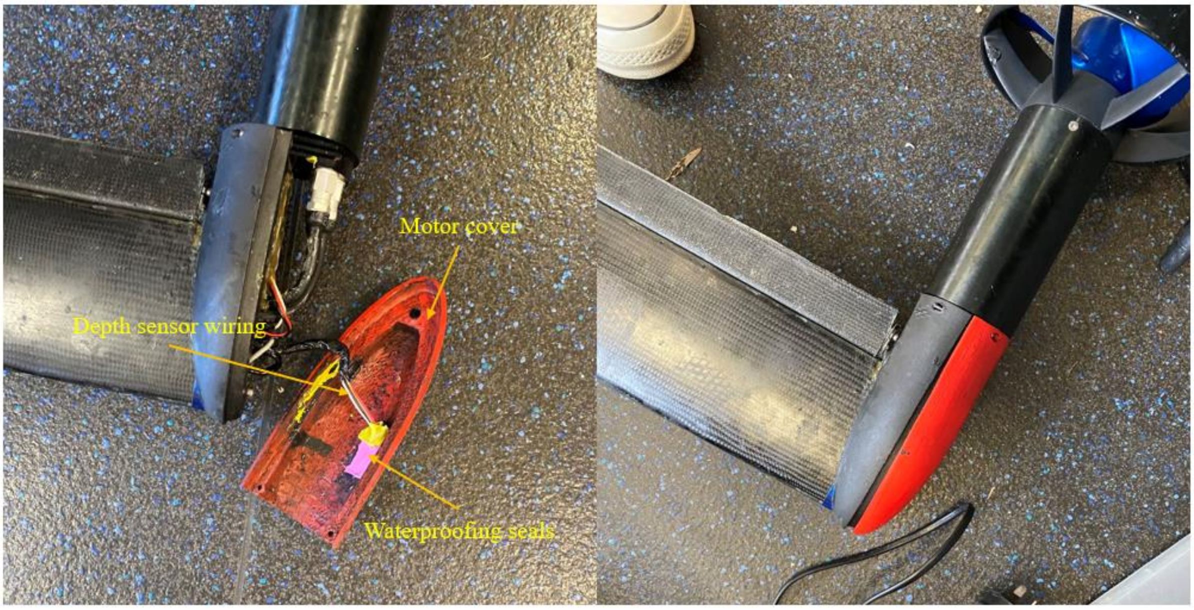

Figure 9 - Left, depth sensor setup within the Efoil motor cover. Right, reinstalled motor cover

The depth sensor was originally intended to be physically connected to the Arducopter board so the water depth data can be printed and stored alongside the orientation angle outputs from the Arducopter to the Raspberry Pi. However, the idea was scratched later due to the issues associated with Arducopter configuration and programming. Because the international border closure caused by the 2019 novel Coronavirus outbreak, the code author for Arducopter, Luis-Pierre Constant, was unable to reach Western Australia in time to configure the Arducopter to include depth sensor data, a new plan was developed for the physical connection of the depth sensor.

The depth sensor wires were directly jumped to the GPIO pins on the Raspberry Pi so Raspberry Pi can directly receive depth data without the need to modifying the software of the Arducopter.

Table 5 - Pin connection table for Bluerobotics Bar02 depth sensor [20]

Bluerobotics Bar02 Depth Sensor Pinout (wire colour)	Functionality	Corresponding Raspberry Pi 4 GPIO Pin
VCC (red)	Positive pole	Any 3.3V
GND (black)	Negative pole	Any GND
C (green)	I2C-SCL	GPIO 3
D (blue)	I2C-SDA	GPIO 2

For the Arduino Uno to receive data from the depth sensor, the red and black wires from the IMU were jumped to the 3.3 volt and ground GPIO pins respectively on the Raspberry Pi, and to enable data transmission, the green and blue wires were jumped to GPIO 3 and GPIO 2 pins respectively on the Pi board.

5.4 Waterproof Consideration

Considering that the Efoil was to operate over water environment and most likely would encounter water splash due to its hull crashing onto oncoming waves, it was paramount that the whole assembly of the ODS was isolated from any water source to prevent any water damage to the ODS and to reduce the risk of electrocuting the Efoil rider. Based on the guideline set out by Clause 7.3.2 in Australian Standard of AS/NZS 3004.2-2014, a minimum rating of IP55 was required for electrical equipments to be in a similar operational environment as the Efoil [38]. And as such, a waterproof enclosure of IP65 rating was used to house the whole system assembly. The enclosure option also provides protection to the assembly from dust ingress [38].

5.5 Final System Assembly

Based on the findings from Literature Review, to effectively measure and truthfully capture the orientation change of the Efoil induced by the roll, pitch and yaw motions, the IMU sensors must sit on the axes of rotation of its middle line plane and transverse plane so an equal amount of roll and pitch motion could be detected by the sensors. Thus, the final orientation estimation system assembly was setup within the hull compartment of the Efoil, on top of the battery box and directly below the rider. This was to position the IMU on where Efoil's centre of mass was located and approximately where the axes of middle line plane and transverse plane rotation met. Figure 10 presents a visual illustration of the plane axes of rotation and where ODS assembly is located within the Efoil with respect to the two axes.

Figure 10 - ODS assembly location. Left, side view of the Efoil. Right, front view of the Efoil

As mentioned in the previous section, a waterproof compartment was introduced to provide a method of waterproofing the final assembly, and as such, the majority of the assembly components were housed within the waterproof box compartment and placed within the Efoil hull. However this was with the exception of the depth sensor, which sits inside of the motor cover and is connected to the main assembly via cable that ran from the hydrofoil fin all the way into the hull of the Efoil.

Figure 11 - Depth sensor wire connection within the Efoil

The main components of the final ODS assembly are summarised in table 6 below.

Table 6 - Final ODS assembly components overview

Assembly Component	Component Name	Component Description
IMU sensor 1	DFRobot BNO055 + BMP280 intelligent 10DOF AHRS	Estimates and records the orientation angles of the Efoil
IMU sensor 2	PhidgetSpatial Precision 3/3/3 High Resolution	Estimates and records the orientation angles of the Efoil
IMU sensor 3	Arducopter Mega APM2.5	Estimates and record the orientation angles of the Efoil
Depth sensor	Bluerobotics PCB for Bar02 Ultra High Resolution 10m Depth/Pressure Sensor	Estimates and record the submerge level of the tail hydrofoil fin
On-board computer	Raspberry Pi 4 Model B	Sensor data storage
IMU microcontroller	Arduino Uno	Dictates what parameter will be measured by DFRobot BNO055 IMU

Figure 12 below illustrates a block diagram representation of the flow of information from sensors and how it is collected within the final system assembly. The diagram also details the corresponding pins on the Arduino Uno and Raspberry Pi boards that the sensor data flow into.

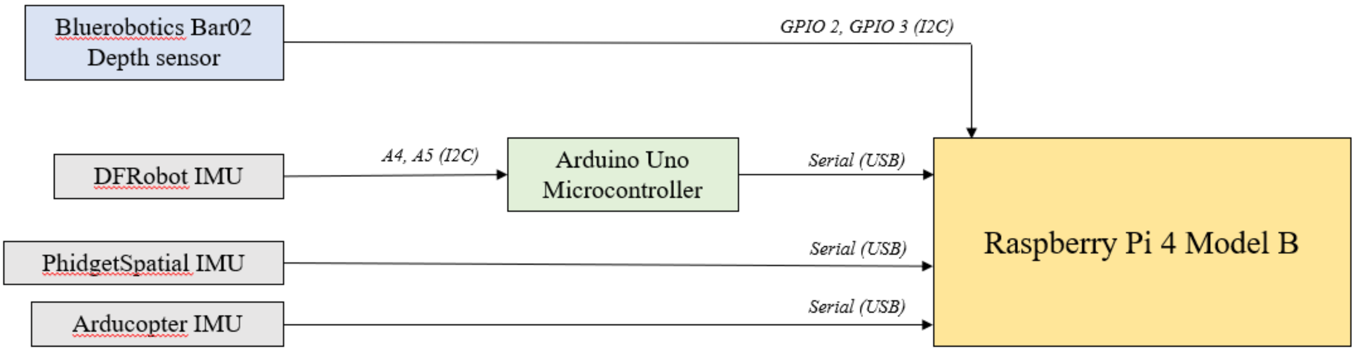

Figure 12 - Connection of the final ODS assembly

Figure 13 and 14 shows the final assembly of the orientation estimation system within the waterproof compartment box.

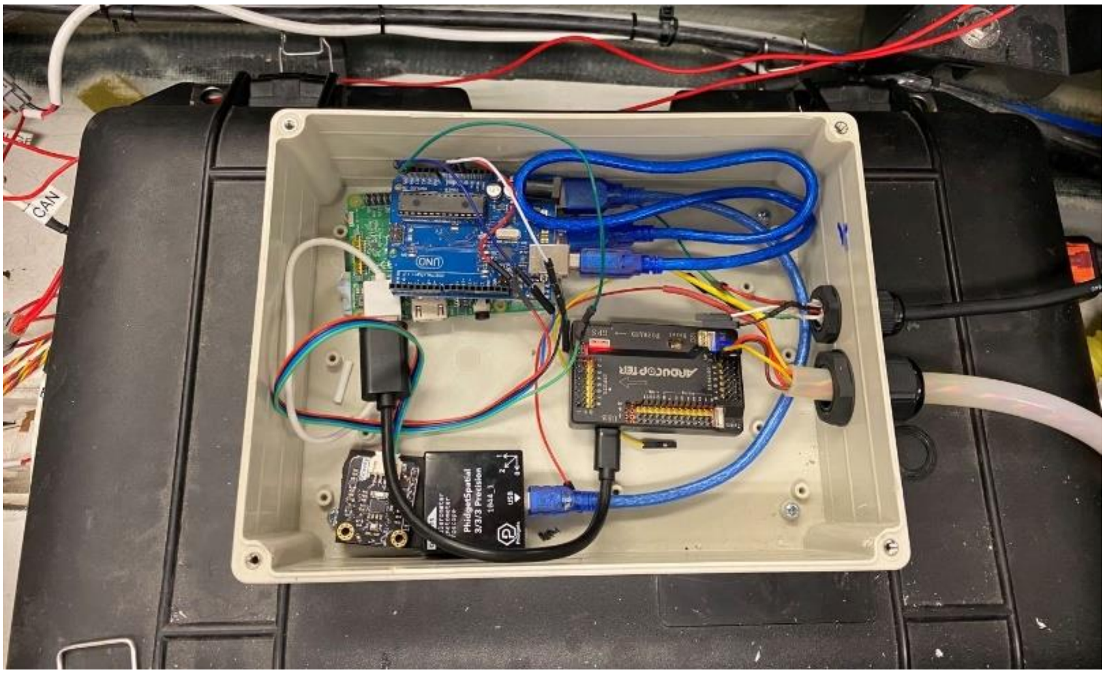

Figure 13 - Final assembly of ODS with cover off

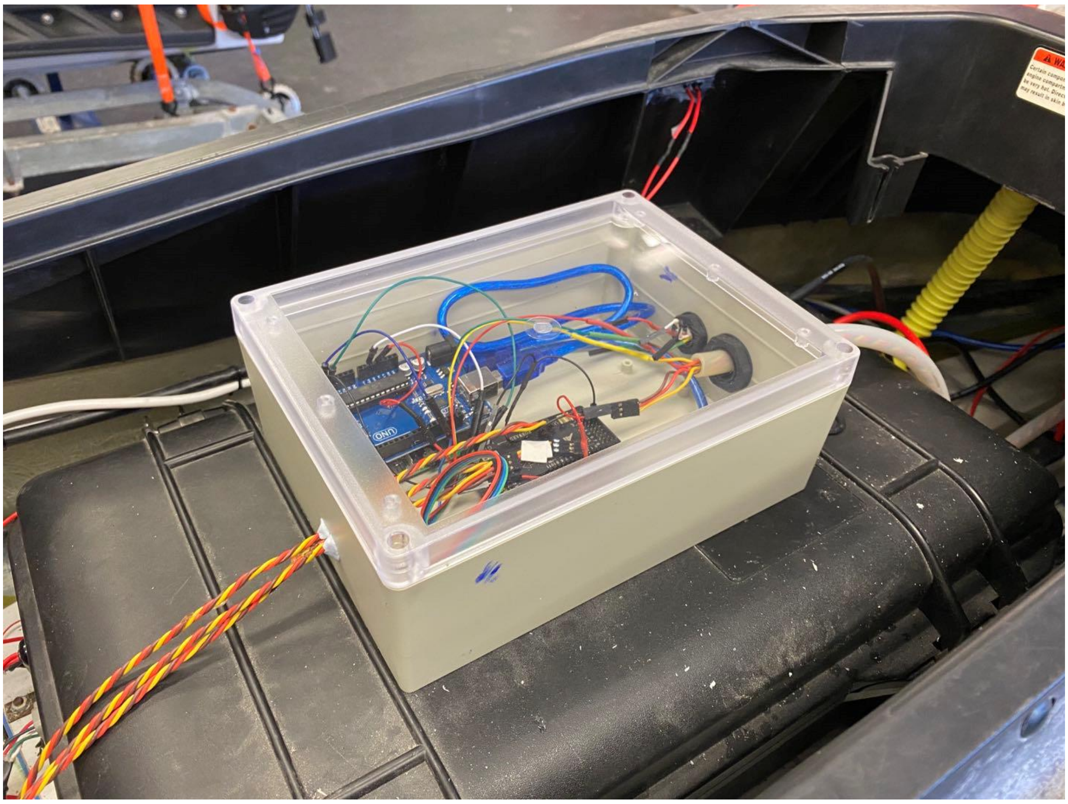

Figure 14 - Final assembly of ODS with cover on

6. Testing of System Setup

The testing of the proposed system is divided into three different phases and these are modular testing, trial system testing and finally system testing. The segmented testing approach was done for a better control measures for the testing of the system and to familiarise myself with each individual component and how well they function within the final assembly. This approach was used also to validate the entire setup in a systematic fashion so any issues could be easily identified and isolated for treatments.

6.1 Modular Testing

This part of the testing procedure was aimed to validate the connection and setup for each individual sensor component within the final assembly. The modular testing was done by connecting each sensor component to the Raspberry Pi individually and conduct a trial data logging session to see whether or not the sensors were outputting the right parameter measurements and if the Raspberry Pi was collecting and logging the sensor outputs in the desired fashion. And as such, it was easy to verify the code written to setup each sensor component and the on-board computer.

6.2 Trial System Testing

After conducting the modular testing, all components were assembled together, and all sensor components were connected to the Raspberry Pi via the pre-determined connection method. The aim of this testing phase was to identify any issues with the final assembly by conducting simultaneous data collection by the Raspberry Pi from all the sensors in a controlled and static environment. A secondary aim for this testing phase was also to check whether the Raspberry Pi will execute properly when powered by Efoil’s power source.

6.3 System Testing

System testing posed as the final testing phase of the system. This part of the testing was done whenever the Efoil was mobilised for a drive test, so each sensor component could perform in a real jet ski operating environment. The measurements from each sensor in this test could also be compared to and validate the trial data collected from the trial system tests, and as such, the functionality and operability of the proposed orientation estimation system could be validated.

However, due to the outbreak of the Novel Coronavirus in 2020 that restricted social gathering event such as the drive test, only a limited number of system testing was conducted during the period of this thesis project. Although issues associated with the final assembly were identified, no solid conclusion could be made regarding the validity of the proposed system setup as not enough system testing were done.

7. Results and Discussion

7.1 Trial System Test Results

As introduced in previous section, the trial system testing was conducted after the assembly and installation of the ODS within the Efoil hull and trial data logging session was performed to capture test sensor data from each IMU and the depth sensor using Raspberry Pi..

Sample sensor recordings were collected for a period of 120 seconds in static condition and the data collected on the Raspberry Pi was later graphed for visualisation using Excel. The graphed results of trial system test can be found in the Appendix A for IMUs and Appendix B for depth sensor.

As shown from the results of the trial system test, each target parameter was successfully measured by its respective sensor and the measurement data was stored onto the Raspberry Pi. The stored data could be further analysed. Since the testing was performed in a controlled static environment with zero motion input from the Efoil all sensor outputting almost zero values with minor offsets observed.

7.2 System Testing Results

Although system testings were performed on a limited occasion due to the reasons as discussed before, no meaningful sensor data was collected by the Raspberry Pi as various issues were encountered with the setup during this testing phase. The limitations of the current proposed system setup were exposed and will be further discussed in the next section.

7.3 Issues Encountered

Several issues associated with the final ODS setup were encountered from system testing. The initialisation of the sensors was spurious and unpredictable during all the system testing as the on-board computer failed to initialise the sensors to begin measuring the target parameters. Because of this, no meaningful data was collected from the system tests. This was most prominent on the DFRobot IMU and the depth sensor as observed from the trial system testing phase. For DFRobot, it was suspected that lose jumper wire connection caused the issue as this produced unstable connections between the Raspberry Pi and the IMU itself. For the depth sensor, the rusting of the sensor PCB board was determined as the reason behind the failed sensor initialisation as green coloured rust could be spotted on the depth sensor PCB after removing the waterproof seals post system tests, this was caused by salt water from drive tests had observably weakened the connection between the wire and the sensor board itself.

7.4 Discussion

From the results obtained from the trial system test, it was obvious that the ODS was able to collect the orientation angle information and the submerge depth of the hydrofoil fin of the Efoil in real time, which met the desired purpose of function as outlined in the thesis project scope. Although the desired function could be performed by the ODS, the system testing and the subsequent issues encountered revealed that refinements were needed to improve the current system design so the desired function could be performed in a real time operational environment.

As the system will most likely see an upgrade or re-design in the future, one of the objective for the design of the proposed system was to keep the entire assembly as simple and intuitive as possible so handover process to future designer could be conveniently and easily performed. The assembly of the proposed system was segmented so each component could be easily identified. The choices of sensors and other accompanying accessories were kept simple so each component of the system could be easily understood and operated by another person with novice electrical work and programming knowledge, and as such, the ODS setup was kept as simple as possible. The design process was also divided into segments so it could be easily interpreted and reproduced by future project students.

Overall, the implementation of the Orientation Estimation System on the Efoil was of great significance as it provided a method of obtaining the motion data of the jet ski when in real time operating environment. The captured motion data can be used to assist in the redesign of the Efoil or any future modification of Efoil parts. This also enables the ability to monitor the orientation status of the Efoil while travelling through water with further implementation of a CAN bus connection, so rider can be visually warned whenever the Efoil is off balance and mitigation action can be immediately performed.

7.5 Future works

Calibration of the sensors

As observed from the results of trial system test, the sensor outputs exhibited small amounts of offset. This indicated calibration was required for the sensors to output the most accurate estimation about the orientation angles and submerge depth of the Efoil's hydrofoil fin. A proper output zeroing process would be required for each IMU before future drive tests. This is to ensure that IMUs are set to output orientation angles of zero degree when no roll and pitch motion is performed by the Efoil, and the motion data of the Efoil can be accurately obtained.

Sensor Data Output Streamline

The current design of the system stores each sensor data in separate files within the Raspberry Pi, this makes the sensor data inspection exhausting as the files are accessed individually, reducing the clarity in the connections between measured data. This also creates unwanted confusion when interpreting the sensor data as each sensor time stamp is slightly different from each other and cannot be easily matched together for further analysis. The data output could be streamlined so all sensor data are recorded onto a single file on the Raspberry Pi. This improves the visualisation of the data and gives the viewer a clear picture of how the stability varies with the target measured parameters.

Controlled System Startup

Due to the time and resource constraint imposed by the COVID-19 situation, the current system is not equipped with any form of power switch to toggle the sensors or the whole system on and off at will. The current system begins to record as soon as the on-board computer is connected to the Efoil power source via jumper wires underneath the rider’s seat, to prevent unwanted startup of the system, the wires must be manually disconnected from the power source. This method of manual startup limits the flexibility of the ODS as riders cannot access to the physical power connection to the system without the need to remove the Efoil seat cover and manually disconnect the wires. This creates safety concerns for the riders and increases the risk of riders falling overboard when trying to adjust the system. And because of this, a physical or remote power toggle could be implemented to the current design so the system can be accessed remotely without need to access the internal hull of the Efoil.

On-board Computer Improvements

Although the current on-board computer contains enough processing power to execute tasks such as sensor data reception from sensor components and the subsequent storage of these data, the physical layout of the board was limiting at times. To be more specific, the Raspberry Pi 4 is only equipped with four USB ports for serial connections, this was insufficient as most ports were occupied by the IMU connections, leaving only one port for external accessories such as mice and keyboard or other sensor components. Modification to the Raspberry Pi 4 could be made in the future to improve its physical layout so more serial connections could be made.

8. Conclusions

To achieve the purpose of monitoring the REV Hydrofoil Jet Ski's orientation while in operation and the collection of its motion data such as the roll, pitch angles and hydrofoil fin submerge depth, the proposed Orientation Estimation System was designed and setup during the span of this thesis project. This was carried out following four distinctive design phases which included:

1. **Sensor components selection** – to select the appropriate IMUs and depth sensor to achieve the afore-mentioned goal of Efoil orientation estimation.
2. **Preliminary setup** – the physical connection and setup of each sensor component and the eventual assembly of the final system.
3. **Testing** – to test and evaluate the performance and functionality of the current system design by subject the system and sensor components to three testing conditions of modular testing, trial system testing and system testing.

This thesis project marks the initial step carried out to measure and collect the Efoil's motion data in the hopes of providing useful dynamic information about the Efoil to assist in future re-design or upgrade. As demonstrated in the pre-system-testing phase, the proposed system has achieved the desired functionality and met the design criteria. However, the current system design leaves much room for future upgrades and can be redesigned to suit other purposes depending on the future goals of the REV Hydrofoil Jet Ski project.

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Appendix A – IMU Trial System Testing Results

DFRobot BNO055

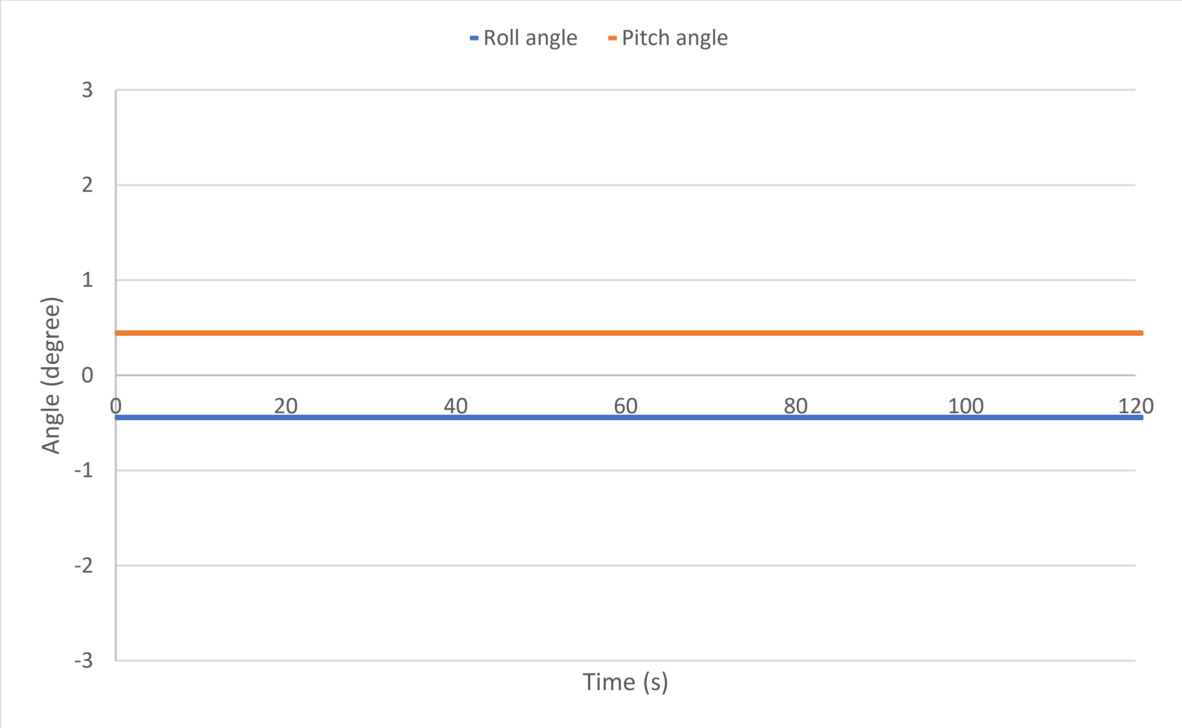

Figure 15 - DFRobot roll and pitch angle measurements of 120 seconds for trial system test

PhidgetSpatial

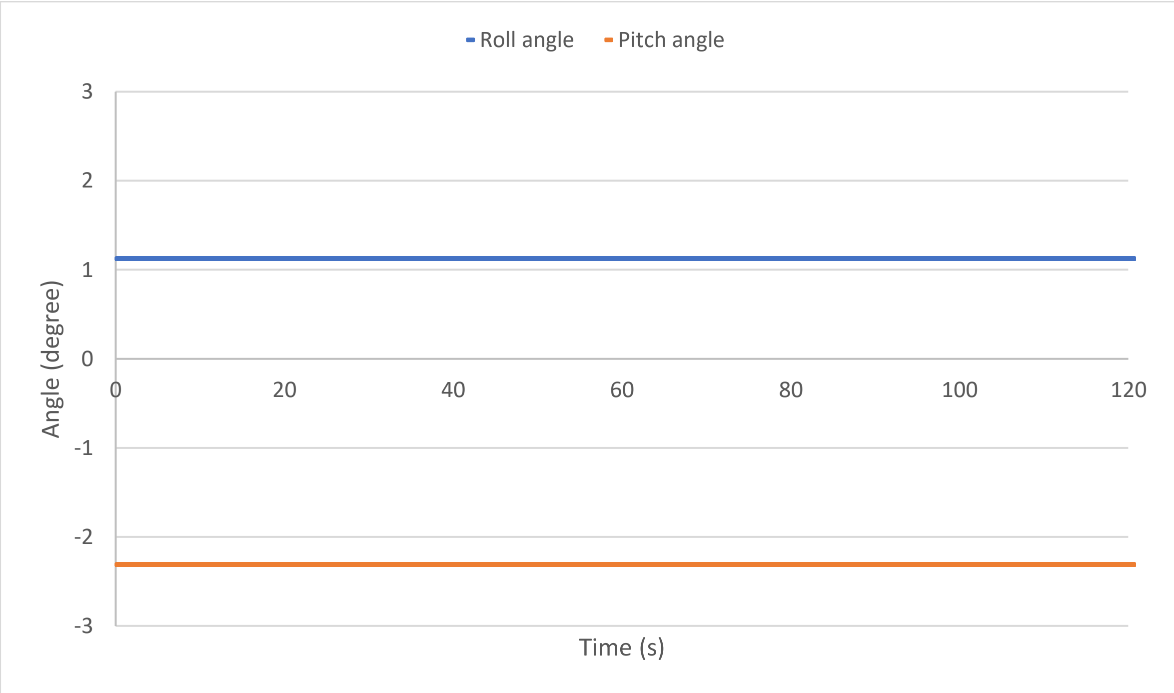

Figure 16 - PhidgetSpatial roll and pitch angle measurements of 120 seconds for trial system test

Arducopter

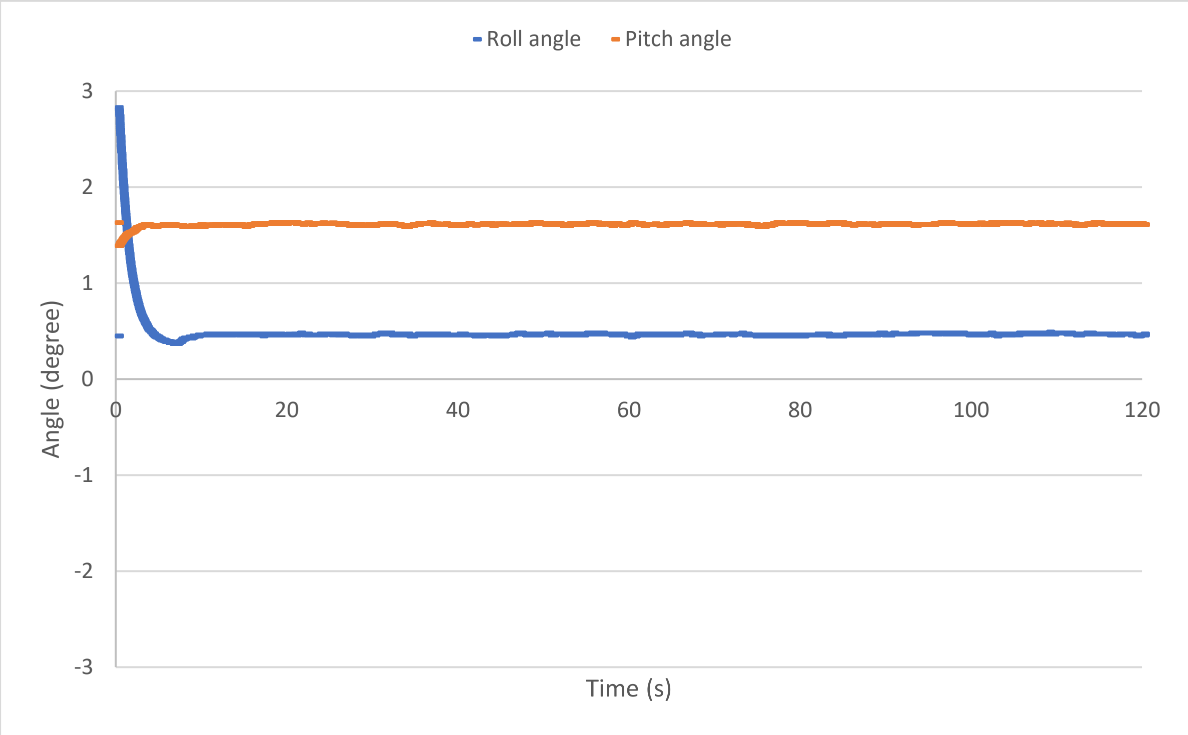

Figure 17 - PhidgetSpatial roll and pitch angle measurements of 120 seconds for trial system test

Appendix B – Depth Sensor Trial System Test Result

Bluerobotics Bar02 Depth Sensor

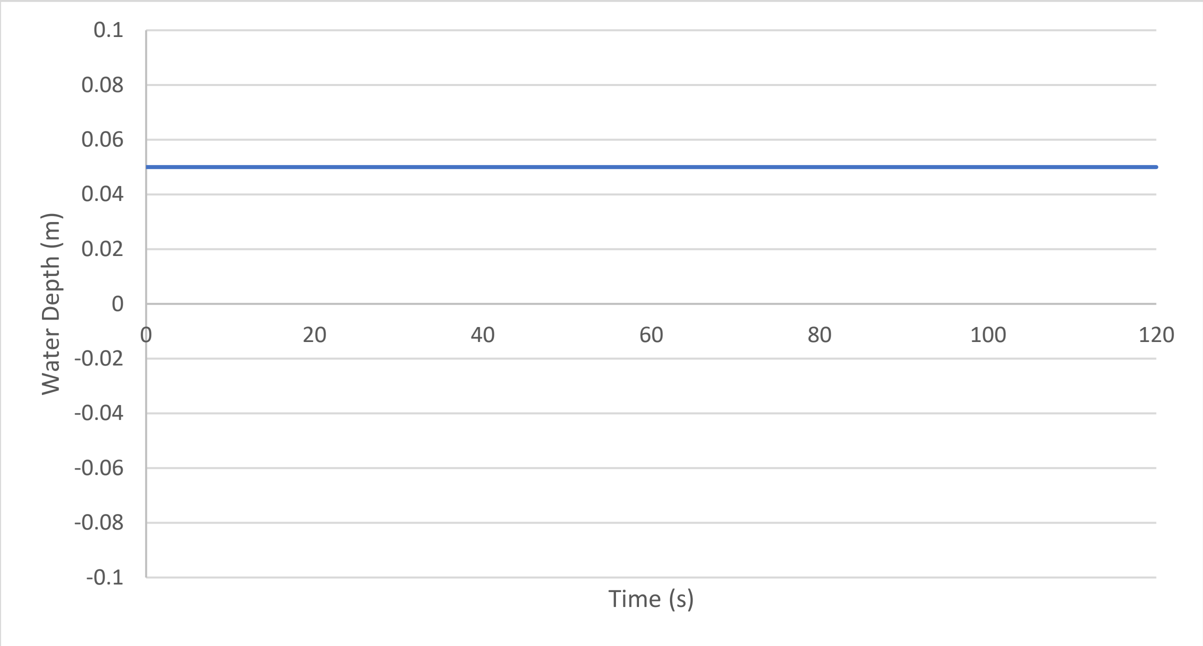

Figure 18 - Bar02 depth sensor water depth measurements of 120 seconds for trial system test