Instrumentation for the REVski; an Electric Personal Watercraft

Final Year Research Project Report

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Abstract

As with any modern vehicle, it is crucial for the operator to be fully aware of the current state of their vehicle and warned about any system failures that may jeopardize their safety. To do this, sensors or instrumentation are used to measure and monitor important parameters such as the speed of the vehicle and is typically displayed to the operator through a dashboard interface. The instrumentation on-board a vehicle depends on several factors but is largely influenced by the type of the vehicle and the environment the vehicle is used in.

This thesis focuses on identifying, designing and installing instrumentation required for the REVski, an electric powered jet ski. The REVski is part of the Renewable Energy Vehicle (REV) project and aims to eliminate noise pollution and emissions while providing the same performance as a conventional petrol-powered jet ski.

The proposed instrumentation for the REVski will aim to measure and display information relevant to an electric vehicle within a marine environment. This includes battery voltage, state-of-charge, temperature and water level. Capturing this data through an on-board computing system will also allow a logbook of the REVski systems to be created, for which can be used for future design improvements.

Acknowledgements

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Acronyms

BMS	Battery Management System
CAN	Controller Area Network
DoT	Department of Transport
ECM	Engine Control Module
EV	Electric Vehicle
EWIS	Electric Watercraft Instrumentation System
GPS	Global Positioning System
IC	Internal Combustion
IOC	Original Information Cluster
NMEA	National Marine Electronics
PWC	Personal Watercraft
REV	Renewable Energy Vehicle
UWA	The University of Western Australia

1.0 Project Background

The term 'jet ski' was first introduced to the public in 1973 as the brand name by Kawasaki Motors for the first commercially successfully personal watercraft (PWC) [1]. Originally invented by Clayton Jacobson II in the early 1960s, jet skis have gradually developed over the years from a simple stand-up recreational vessel, to a more powerful, high performance watercraft used for a variety of practical applications including law enforcement and life guarding [2,3].

PWCs propel through the water by using the thrust produced from a water jet pump. Water is drawn in through an intake grate located on the bottom of the hull and passed through the impeller of the jet pump. Rotational mechanical energy is transferred to the water and then expelled at high pressure to drive the watercraft forward [4,5]. PWCs rely on internal combustion (IC) engines to rotate the driveshaft and power the water jet pump. Exhaust gases containing harmful emissions such as carbon dioxide are released from IC engines and are of a major concern due to their negative impact on the environment and human health.

With global carbon emissions having significantly increased since the 1970s and the transport sector accounting for approximately a quarter of carbon emissions in 2017, there has been a strong focus on the development of renewable energy and electric vehicles to reduce the impact on the environment [6,7]. Automotive manufacturers such as Tesla Motors and Toyota Motor Corporation are pushing the boundaries on reducing the cost of electric vehicles (EV) and hybrid plug-ins in the effort of making them a viable, environmentally-friendly alternative to their petrol-powered counterparts [9]. Educational institutions such as The University of Western Australia (UWA) are also helping the transport sector transition into a more sustainable future by creating initiatives such as the Renewable Energy Vehicle (REV) Project.

The REV project, created by Professor Thomas Bräunl in 2008, is a student-run initiative with the long-term goal of building zero emission electric vehicles that are viable in both performance and commercial markets. Since its formation, the initiative has successfully created a number of EVs including a high-performance Lotus Elise and an autonomous Formula SAE Race Car.

In 2012, the REV project undertook the challenge of converting a 2008 Sea-Doo GTI 130 Jet Ski from a regular IC engine into an all-electric, battery powered PWC (Figure 1.1). Formally known as the REVski, the project aimed to eliminate carbon emissions and noise pollution while still retaining a comparable on-water experience.

Figure 1-1: Original Seadoo GTI 130 [16]

2.0 Project Scope

2.1 Previous Work

Following the successful conversion from the IC engine to a fully submersible 50 kW AC induction motor powered by Lithium Iron Phosphate ($LiFePO_4$) batteries [11], the REVski project shifted its focus on reaching the same performance of the original PWC. In addition to this, the safety and thermal management systems were upgraded to include various other components such as the bender module and motor controller cooling plate respectively.

In 2015, the REV Team carried out modifications to the positioning and arrangement of the batteries to optimise the space in the hull while low voltage and extra low voltage safety protection systems were implemented to ensure the REVski remained compliant to Australian Standards [1].

Following a yearlong break in 2016, the REVski project restarted at the beginning of 2017 with the focus to (1) continue optimising the space within the hull to accommodate a greater number of batteries, (2) reorganise the installation and wiring of specific safety components and (3) to monitor the charging process of the batteries to prevent damage occurring through over or under-charging.

The first objective was achieved through redesigning the mounting system for the auxiliary components and reconfiguring the batteries to be housed in hollow tubes. The second objective being fulfilled by the installation of the battery management system (BMS) in its standalone water proof box and the third through the construction of an apparatus measuring individual battery voltages.

2.2 Problem Identification

As with any modern vehicle, instrumentation systems are installed to measure and monitor parameters of interest to the driver. Depending on what sensors are installed, collecting and measuring key vehicle parameters has a number of benefits with the most advantageous being [1] it allows the driver to be fully aware of the current state of their machine and warned of any system failures, [2] it eases the troubleshooting process through the ability to diagnose system faults, and [3] it enables performance characteristics to be optimised and improvements be made to future designs.

Prior to its electric conversion, the REVski was installed with sensors specifically relevant to that of an IC engine. This included instrumentation measuring the position of the camshaft, pressure of the intake manifold and temperatures of the exhaust gas and lubricants. This information along with various other parameters were captured and processed through the Engine Control Module (ECM) and then communicated to the rider through the Original Information Cluster (OIC) (Figures 2.1 & 2.2).

Figure 2-2: Engine Control Module of the original PWC

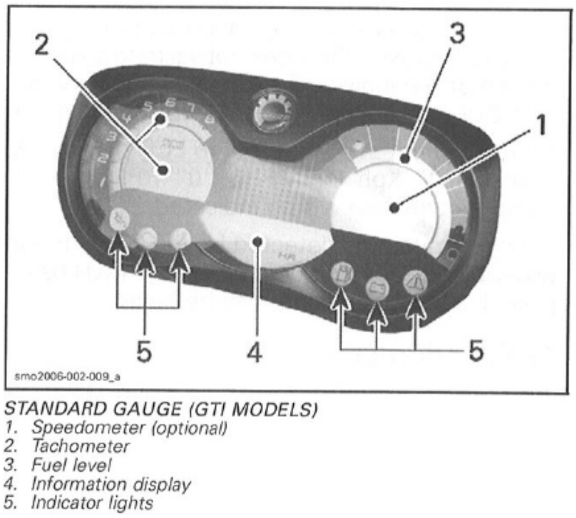

Figure 2-1: Original Information Cluster of the original PWC [16]

The removal of the IC engine let to the loss of these sensors and also the function of the OIC. Although, many of the instrumentation associated with IC engines are not applicable to an EV, they both share an interest in basic vehicle parameters such as speed and revolutions per minute. Since the REVski's conversion, there has been no system installed that measures and displays any parameters to the rider. This poses significant issues when operating the REVski, as this may lead to a compromise of the rider's safety, delays in the troubleshooting process or inefficiencies in system functions.

2.3 Objectives

This report aims to document the process of ensuring the rider of the REVski is aware of the current state of the vessel and is able to use the information collected for future design improvements.

This process can be separated into the following objectives;

1. To identify vehicle parameters most critical for an electric PWC;
2. To design an electric watercraft instrumentation system (EWIS) that captures and processes incoming information from various sensors;
3. To log and display the information collected to the rider of the REVski.

2.4 Acceptance Criteria

To assess the success of the design the follow assessment criteria is proposed:

1. The proposed instrumentation system captures parameters of interest and is able to record data in an easy to use format.
2. The functionality and operability of the proposed instrumentation system is easy to use and simple to understand.

3.0 Literature Review

3.1 Desired Parameters

Although EVs are relatively new to the transport industry and feature many new and unconventional technologies, the vehicle parameters most critical to the driver are similar to traditional motor vehicles [11]. According to Pham [12], the essential parameters required to be measured in any modern motor vehicle to ensure the operator is aware of the vehicle's state are as follows;

- Speed of the vehicle;
- Revolutions of the driveshaft;
- Fuel remaining;

These basic parameters above are also desired in the REVski and thus will form the basis of the instrumentation system. It must be noted that the fuel remaining is not applicable for the EVs and will be replaced with an instrument used to measure the charge remaining in the batteries. In addition to these, White [13] recommends measuring parameters related to the safety system of the REVski. This includes the ability to detect water leaks within the hull and also monitoring the temperatures of the battery tubes, motor controller and electric motor from over-heating. Burden [14] also suggests that instruments measuring water depth and wind speed are also important in a marine environment however are not essential. The following literature review will expand on the parameters above and explore different methods of obtaining the desired parameter in the REVski.

3.2 Speed

As with any mode of transport, speed limits are enforced to protect other individuals and prevent damage to the surrounding environment. In Western Australia, an 8-knot (15 km) speed limit is enforced by the Department of Transport (DoT) in particular areas [15]. This includes going through an arch of a bridge or passing within 15 metres of another vessel. To abide by the rules and regulations of the DoT, an instrument measuring the speed of the REVski is required.

3.2.1 Paddlewheel Sensor

From the Sea Doo Shop Manual [16], the speed of the REVski prior to the conversion was measured by utilising a paddlewheel sensor mounted on the rear of the hull. Paddlewheel sensors operate by reading voltage signals generated by a freely rotating wheel embedded with magnets. These voltage pulses range from 5.9-10.6 V and are directly proportional to the flow rate. The signals are then transmitted to the ECM and interpreted to give a speed reading of the vessel. There are some limitations associated with paddlewheel sensors and their operation, mainly due to the need to be completely submerged in a relatively stable fluid velocity profile to produce accurate readings and to operate in a clean, low viscous environment to ensure to the proper function of the spinning mechanism [17].

3.2.2 Global Positioning System

The Global Positioning System (GPS) provides another mean of measuring the speed of an object [18]. GPS measures ground speed by taking the geolocation of two points to calculate distance and then dividing by the given timestamp. This is represented by the following formula (Eq. 1);

$$Speed = \frac{Distance}{Time} \qquad \text{Eq. 1}$$

The GPS satellites transmit signals to receivers using the National Marine Electronics Association (NMEA) 0183 standard [19]. The NMEA protocol consists of strings which contain data on various other parameters such as time, date, longitude and latitude.

3.3 RPM

According to Ovens [20], measuring the revolutions of the drive shaft is of high importance as it allows the efficiency and performance characteristics of the vehicle to be determined. The RPM of the original PWC was measured using a position sensor that recorded signals generated from the crankshaft rotating within a magnetic field. These signals were then sent to the ECM and used to calculate RPM [16]. Typically, these sensors are located internally with the IC engine and hence was removed during the electric conversion of the REVski.

3.3.1 Rotary Encoders

One method of measuring RPM of the driveshaft is through quadrature encoders. Most commercially available quadrature encoders contain two channels (A and B) to sense position. These channels produce square wave outputs 90 degrees out of phase and indicate the position and direction of rotation of the shaft [21]. By measuring the relative position and number of pulses generated, RPM can be calculated using the following formula (Eq. 2).

$$RPM = Pulse\ Count \times \frac{60 \times updates\ per\ second}{\#\ of\ pulses\ per\ revolution} \qquad \text{Eq. 2}$$

The updates per second and the number of pulses per revolution are specific parameters unique to the quadrature encoder.

3.3.2 Hall Effect Sensor

Similar to quadrature encoders, Hall Effect sensors generate voltage pulses of varying frequencies to measure RPM. These sensors consist of a Hall Element and a permanent magnet attached to the driveshaft. As the driveshaft rotates, a small potential difference is produced when the magnetic field generated from the magnet passes a flow of current perpendicularly (Hall Element) [20]. Depending on the number of magnets, multiple voltage pulses can be produced for every revolution of the driveshaft.

3.4 Battery Charge Remaining

To replicate the same function as the fuel gauge and indicate to the operator the amount of charge remaining in the battery tubes, the state-of-charge (SoC) of the batteries is considered sufficient. SoC is defined as a measure of the amount of electrical energy stored in the battery and is expressed as a percentage [22]. Calculating the SoC of a battery pack is a complex task and often an estimation of variables rather than a direct measurement as it relies on a number of factors such as the battery’s chemistry and condition [23]. Methods that measure SoC include:

1) Voltage Method – Where the discharge curve of a battery illustrates the relationship of voltage (V) against capacity remaining (Ah). This method depends on knowing temperature and current draw for accuracy [24].
2) Coulomb Counting – Involves integrating current over time to the number of discharged amp hours under load. This method requires frequent recalibration due to long-term drift and lack of a reference point [20].

4.0 Design Process

The process for designing and implementing the EWIS on-board the REVski can be summarised through the following flowchart (Figure 4.1).

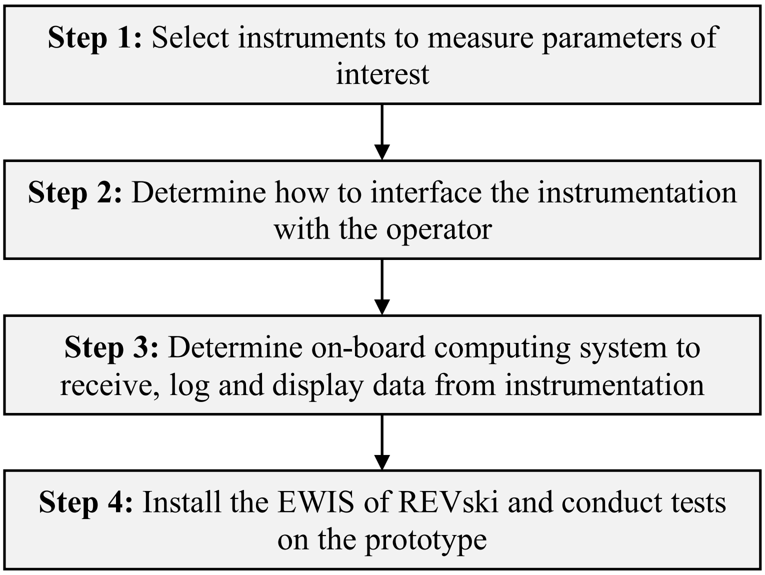

Figure 4-1: Design Process Flow Chart for developing the EWIS

Each step of the design process is described in further detail below.

4.1 Instrumentation Selection

As outlined in the literature review, there are many ways to measure each parameter of interest to the rider of the REVski. To determine which instrumentation should capture each parameter, selection criteria was developed to assess the instrument's ability to meet key areas or constraints that are thought to impact the feasibility of the instrumentation system. The key areas/constraints are listed below;

1) **Specification** – Does the instrument measure the desired parameter for the REVski with sufficient accuracy?[1]
2) **Instrument Simplicity** – Is the instrument a simple device that is easily understood and does not require many additional resources or components to obtain the desired parameter on the REVski?
3) **System Integration** – Can the instrument be easily integrated/installed into the instrumentation of the REVski? (E.g. communication protocol)
4) **Cost** – Is the cost of the instrument reasonable and within the budget of the REVski?

Using these criteria, each instrument for a given parameter was given a rating from 1 to 4 based on its ability to satisfy the key areas or constraints above. An explanation of each rating score can be found in Appendix 11.1. The instrumentation considered below was selected based on their commercial availability. It should be noted that some instruments are already

[1] The required specification is different for each parameter and is listed when assessing against selection criteria. An instruments rating against the specification criteria was determined using the instrument's data sheet.

installed on the REVski. For the purpose of the design process, these instruments are still assessed against the selection criteria to determine if they remain the instrument of choice.

4.1.1 Speed Sensor

The speed sensor must be able to measure speeds of up to 100 km/h as this is the maximum specified speed of the original IC engine PWC.

Table 4-1: Assessment of Speed Sensors against Selection Criteria

Key Area	**Instrumentation**		
	Original Paddlewheel Sensor [16]	Keyes Studio GPS Shield with SD Slot and Aerial [25]	Columbus V-800 GPS Data Logger [26]
Specification	(4) Analogue voltage readings	(4) NMEA comm. protocol	(4) NMEA comm. protocol
Simplicity	(1) Requires ECM to be reinstalled	(4) No additional components	(4) No additional components
Integration	(4) Already installed in the REVski	(3) Requires installation	(3) Requires installation
Cost	(2) ~$200 for replacement if damaged	(4) ~$25	(3) ~$70
Overall Rating	11	**15**	14

Discussion: Both the GPS Shield and the V-800 score well in simplicity being a single component while the original paddlewheel sensor would require the reinstallation of the ECM. The differentiating factor between the GPS Shield and the V-800 is the cost of the module with the V-800 being twice the price. In addition to the GPS Shield being the favoured sensor, it also houses an integrated micro SD port which can be used for data logging.

Selection: Keyes Studio GPS Shield with SD Slot and Aerial

4.1.2 Battery Charge Remaining

The instrument used to monitor the SoC of the batteries must be able to sense voltage from 0 -110 V. This is due to the batteries having a total system voltage of 96 V.

Table 4-2: Assessment of SoC instruments against Selection Criteria

Key Area	**Instrumentation**		
	Voltage Method using Voltage Divider Circuit	TBS Monitor E-Xpert Pro [27]	ZEVA EVMS V3 [28]
Specification	(2) Inaccurate representation; depends on no. of factors	(4) Accurately represents SoC	(4) Accurately represents SoC using CAN Bus

Simplicity	(2) Requires additional pieces of equipment	(3) Requires pre-scalar box and shunt	(4) Same no. of components as BMS
Integration	(3) Integrated through BMS	(4) Already installed in the REVski	(4) Replaces BMS
Cost	(4) ~$30	(2) ~$300	(2) ~$350
Overall Rating	11	13	**14**

Discussion: The ZEVA EVMS V3 is the ideal instrument in terms of being able to collect battery parameters. It has the ability to be easily integrated into the current battery management system of the REVski and uses the CAN Bus communication protocol to send messages. However this technology has only recently entered the commercial market and so during the electric conversion the REVski, a TBS Monitor E-Xpert Pro was installed to measure the SoC of the batteries. Due to this constraint and the cost of implementing the ZEVA system, the TBS will be considered further in the development of the EWIS.

Selection: TBS Monitor E-Xpert Pro

4.1.3 Revolutions per Minute

According to Beckley [8], the AC induction motor installed in the REVski operates between 0 to 8000 RPM. Thus, the selected instrument must operate within this range.

Table 4-3: Assessment of RPM measuring sensors against Selection Criteria

Key Area	**Instrumentation**	
	Hall Effect Sensor (UGN3503UA) [29]	LARM Incremental Encoder MIRC 325/64 PB) [30]
Specification	(2) Sensitive to surroundings	(4) Accurate readings through digital signals
Simplicity	(4) No additional components	(4) No additional components
Integration	(1) Requires apparatus stand and magnet attached to shaft	(4) Already installed in the REVski
Cost	(4) ~$5	(2) N/A
Overall Rating	11	**14**

Discussion: Based on the selection criteria, the incremental encoder outperforms a Hall Effect sensor in all criteria except for cost. Since the incremental encoder was installed during the electric conversion of the REVski, this does not impact the budget of the EWIS. Readings from a Hall Effect sensor are highly influenced by surrounding components and would require an apparatus connected to the driveshaft, hence for the low specification and integration rating.

Selection: LARM Incremental Encoder MIRC 325/64 PB

4.1.4 *Temperature Sensors*

As mentioned in the literature review, the temperature of the main components of the REVski should be monitored to ensure that driver is aware of any system that may be overheating. To determine the specification of the temperature sensors, the maximum operating range between all main components must first be calculated.

Table 4-4: Operating Temperature Ranges for Main Components of REVski

Component	Operating Temperature Range
$LiFePO_4$ batteries	-20°C to 65°C [31]
AC Curtis Motor Controller	-40°C to 50°C [32]
AC Induction Motor	65°C to 75°C [8]

Based on Table 4.4, the maximum operating range is -40°C – 75°C, however considering the local climate conditions, a specification range of 0°C – 70°C is deemed reasonable.

Table 4-5: Assessment of Temperature Sensors against Selection Criteria

Key Area	Instrumentation	
	DS18B20 Digital Temperature Sensor [33]	LM335A Analogue Temperature Sensor [34]
Specification	(4) Digital signal measures within range	(2) Analogue signal measures within range
Simplicity	(4) No additional components	(4) No additional components
Integration	(3) Modifications to main components required	(3) Modifications to main components required
Cost	(2) ~$15	(4) ~$4
Overall Rating	13	**13**

Discussion: After assessing the two temperatures against the selection criteria, a clear decision was not evident as both received the same rating. It can be seen that the quality of the signal was directly related to the cost of the sensor. The deciding factor was the number of temperature sensors required. A total of seven sensors (five for the battery tubes, one for the motor controller and one for the motor) were needed and thus the cost associated with purchasing seven DS18B20 outweighed the benefits.

Selection: LM335A Analogue Temperature Sensor

4.1.5 *Water Level Sensors*

Monitoring the presence of water within the hull of the REVski is paramount to ensure the safety of the rider and reduce the possibility of electric shock and/or fire. It is desirable to measure minute amounts of water to such that a leak will be alerted to the rider. Thus, the specification of the water level sensors is the ability to detect a 1 cm droplet of water.

Table 4-6: Assessment of Water Level Sensors against Selection Criteria

Key Area	Instrumentation	
	Keyes Analogue Water Level Sensor [35]	Wireless Water Presence Sensor – 108R [36]
Specification	(2) Analogue signal measures within range	(4) Digital signal measures within range
Simplicity	(4) No additional components	(2) Requires modules to send signals
Integration	(4) Already installed in the REVski	(1) Requires installation of modules into REVski
Cost	(4) ~$6	(1) ~$60
Overall Rating	**14**	8

Discussion: It is clear from Table 4.6 that the Keyes Analogue Water Level Sensor is the superior choice particularly in integration and cost. Although the quality of the signal from the 108R is better than the analogue sensor, this did not make much of a difference. In addition to this, the 108R requires a sender and receiver module for communication which increases the difficulty of implementation

Selection: Keyes Analogue Water Level Sensor

4.2 Display Selection

The second step of the design process involved determining how to interface the information collected from the instrumentation to the rider. Two options were available;

1) Use the original Seadoo information cluster, or
2) Design a new dashboard display tailored towards the REVski.

To determine which interface to use, the advantages and disadvantages of each were identified and summarised in Table 4.7.

Table 4-7: Advantages and Disadvantages of the OIC and designing a new dashboard display

	Original Information Cluster	New Dashboard Display
Advantages	- Pre-existing and already integrated with REVski - Contains gauges for desired parameters - Compliance with standards and regulations	- Tailored towards REVski to include desired parameters - Able to customise features (E.g. communication protocol) - Opportunity to be more interactive and aesthetically pleasing
Disadvantages	- Communication protocol and message format unknown - Dated technology	- Resource heavy - Costly - Time-consuming - Subject to standards and

		regulatory approval

Discussion: Both options present strong arguments for their own respective case. In order to differentiate between the two, the amount of work required to implement each display into the EWIS must be assessed. Given that the OIC is already installed in the REVski, the amount of resources needed is much less than a new dashboard. The only remaining step for the OIC be integrated with the EWIS is to understand how to activate the display gauges. For these reasons, the OIC is the preferred interface between the rider and the EWIS.

Selection: OIC

4.3 Computing System Selection

Following the determination of the outputs for both the instrumentation and OIC the third step of the design process required the selection of an on-board computing system to receive, log and display the incoming data. Similar to the instrumentation selection process, there are a number or requirements the computing system must satisfy. This includes;

1) Being lightweight and compact to fit within the small confines of the hull;
2) Contain the necessary hardware to receive and transmit information from the sensors;
3) Be compatible with the OIC;
4) Simple and easy to use;
5) Cost-effective.

A Raspberry Pi 2 and Arduino Mega 2560 R3 both provide suitable options for capturing and processing data of the EWIS and are assessed against the selection criteria in Table 4.8. The same rating table in Appendix 11.1 applies to the computing system selection.

Table 4-8: Assessment of Computing Systems against Selection Criteria

Key Area	**Instrumentation**	
	Raspberry Pi 2 Model B	Arduino Mega 2560 R3
Size	(4) 85 mm x 56 mm x 13.5mm	(4) 102 mm x 53 mm x 10 mm
Hardware	(3) - Broadcom BCM2836 chip - 40 GPIO pins - Micro SD port	(4) - ATmega2560 chip - 54 Digital I/O pins - 16 Analogue Input pins
Compatibility with OIC	(2) CAN Bus shield required	(2) CAN Bus shield required
Simplicity	(3) - Linux OS - Programming knowledge required	(4) Suitable for beginners - Open source libraries readily available online
Cost	(3) ~ $50	(3) ~ $50
Overall Rating	15	**17**

Discussion: Overall, the Raspberry Pi 2 and the Arduino Mega scored fairly similar results in meeting the above requirements. The main difference being the Pi not having the analogue pins to receive data from the temperature and water level sensors. This does not pose an issue if the digital water level and temperature sensors where selected. However, this would increase the cost of the overall instrumentation system and thus not ideal for this project. Another difference between the two computing systems is that the Pi is slightly more complex to use than the Mega as it requires knowledge in both Linux and programming. For this given instrumentation system, the Mega suffices however depending on the future use of the REVski instrumentation system, the simplicity of the Mega may cause potential issues.

It should be noted that although the Raspberry Pi contains a SD card slot for data logging, the selected speed sensor also contains are integrated SD card slot and thus the ability to log data was not a requirement for the computing system.

Selection: Arduino Mega 2560 R3

5.0 Implementation

This section focuses on the fourth step of the design process and describes how each component is implemented in EWIS.

5.1 GPS Module

The integration of the Keyes Studio GPS Shield with the Mega is simple as the module is stacked directly upon the header pins of the Mega. A voltage input of 5V is supplied from the Mega to power the module.

To initialise communication with the Mega, the GPS baud rate was set to 9600 bps and the RX and TX pins of the module jumped to pins 18 and 19 on the Mega. Once a satellite fix was obtained, the open-sourced library TinyGPS++ was used to deconstruct the NMEA data into a more desirable format. The speed of the REVski corresponded to the 7^{th} element of the $GPVTG string.

In order to enable data logging using the micro SD port, pins 53, 51, 50, 52 from the Mega are jumped to pins 10, 11, 12, 13 on the GPS Module respectively. This was required as the SD card slot uses serial peripheral interface (SPI) lines to receive and log data.

5.2 RPM

Given that the communication wires of the incremental encoder are already connected to the motor controller through pins 31 and 32, the RPM of the driveshaft is simply measured through the extension of these wires into pins 20 and 21 of the Mega. As outlined in the literature review, an incremental encoder outputs two square wave signals 90 degrees out of phase for which can be decoded to produce a pulse count. By setting 'updatespersec' equal to 2 and pulses per revolutions to 64, the RPM of the driveshaft can be computed using Eq. 2.

5.3 TBS E-Xpert Pro

Although the TBS was originally installed during the electronic conversion of the REVski, in an ideal world and completeness of the EWIS, the SoC of the batteries would be displayed through the OIC using the fuel gauge. This is further supported by the fact that the TBS display is covered by the lid of the switchbox and so the SoC of the batteries is unknown to the rider unless he or she compromises their safety by attempting to open the lid.

To do integrate the SoC with the fuel gauge, the relevant data is extracted from the TBS by using the RS232 Communication Interface Kit provided by the manufacturer. As seen in Figure 5.1, data is sent from the TBS to the interface box via a RJ12 cable and communicated to a PC using a RS232 serial to USB cable. Since the Mega is unable to communicate using USB, a RS232 to TTL convertor is used to send data to pins 16 and 17 of the Mega.

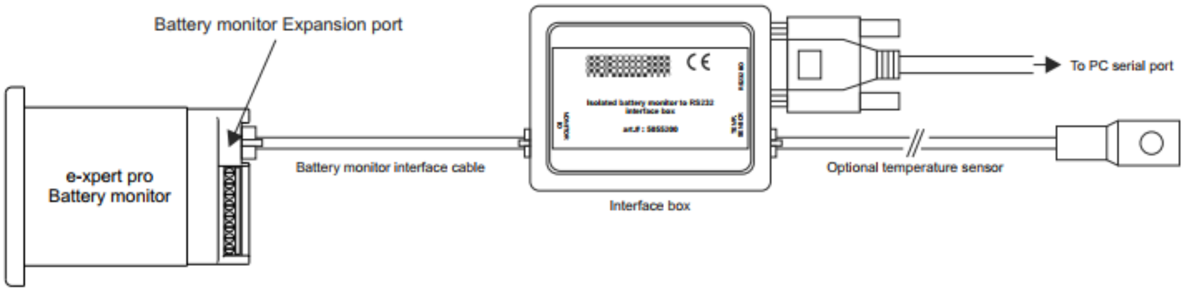

Figure 5-1: TBS Monitor RS232 Communication Interface [27]

Due to unforeseen issues and time constraints, the code to collect data from the TBS is not completed at the time of writing and thus prevented the desired information from being obtained. As a result, the SoC is unable to be displayed to the rider of the REVski during operation.

5.4 Temperature and Water Level Sensors

With the installation of the temperature and water level sensors completed by previous students, the only task remaining was to connect the sensors to the analogue input pins on the Mega Tables 5.1 and 5.2 defines the input pin assignments of both temperature and water level sensors respectively.

Table 5-1: Water Level Sensor analogue pin assignment to the Mega

Water Level Sensor	Location in Hull	Assigned Input
1	Middle Left	A0
2	Middle Right	A1
3	Bottom Left	A2
4	Bottom Right	A3
5	Motor Controller	A4

Table 5-2: Temperature sensors analogue pin assignment to the Mega

Temperature Sensor	Component	Assigned Input
1	Motor	A9
2	AC Motor Controller	A10
3	T1	A11
4	T2	A12
5	T3	A13
6	B1	A14
7	B2	A15

For the safety instrumentation to be effective, calibration factors and threshold limits must be imposed onto the temperature and water level sensors. This is to ensure an accurate reading is obtained and that once a sensor reaches an undesirable condition, the instrumentation system is able to alert the rider through a warning light on the OIC.

In order to provide an accurate reading of the surrounding temperature, the temperature sensors were subject to a calibration test. Appendix 11.2 outlines the procedure followed to obtain a calibration factor for the temperature sensors. The procedure was conducted for all temperature sensors and a calibration factor of approximately 5.08 was observed for all sensors.

Given the purpose of the temperature sensors in the instrumentation system, a threshold limit must be imposed to alert the rider of the REVski if a component is overheating. This threshold value, or triggering point will vary for each component due to different operating ranges. Thus, the maximum operating temperature for each component was selected as the threshold limit

Given the function of the water level sensors, only a threshold limit is required. Although they were installed by a previous REV Team, no documentation was found regarding a threshold limit or the triggering of the sensors. Thus, a threshold limit was experimentally obtained using a simple testing procedure. The test procedure followed is outlined in Appendix 11.3. The procedure determined the output values of the sensor when subject to varying levels of water. A reading of 0 reflects no water, while being completely submerged returns a value of 1024. It was decided that a threshold limit of 200 would be imposed as this correlated to a 1 cm droplet and provided a good indication if a leak was to be present.

5.5 OIC

In order to use the OIC as the display interface for the EWIS, the internal workings of the display first required to be understood. From the Seadoo Shop Manual, the OIC communicated with the ECM using the Controller Area Network (CAN Bus) communication protocol. As seen in Figure 5.2, a CAN Bus message is made up of 8 components of either

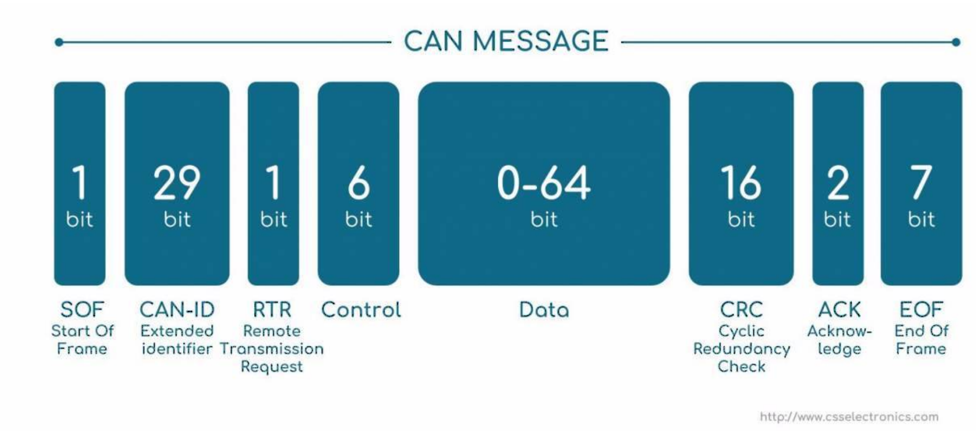

Figure 5-2: Structure of a CAN Bus Message [37]

11-bit or 29-bit identifiers [37].

Of the 8 components, the CAN-ID and the Data field are the most important. The CAN-ID contains the message identifier that activates particular sections of the OIC (E.g. speedometer, tachometer etc.) and the data field consists of byte packets that contain encrypted values corresponding to actual sensor readings [37]. To use the OIC as the interface for the EWIS, these CAN-Bus messages were logged, analysed and deciphered. Using an Arduino Uno and a CAN-Bus shield, the CAN-IDs and structure of the data fields for each display gauge was determined. The results are summarised in Table 5.3 and a complete analysis of the Seadoo CAN-Bus protocol is presented in Appendix 11.4. Figure 5.3 demonstrates the ability to manipulate the display once these CAN-Bus components are known.

Table 5-3: Summary of CAN-Bus protocol used on the REVski

Parameter	CAN-ID	Byte Used
Speed	0x208	0,1,6
RPM	0x310	0,1
Fuel Gauge	0x210	0
Warning Indicators	0x308	All

Figure 5-3: Manipulation of OIC to display maximum values

To send messages to the OIC from the Mega, a CAN-BUS Shield V1.2 from Seeed Studio is used. Similar to the GPS module, the shield is directly compatible with the Mega and is able to be stacked and thus was easily integrated into the design of the EWIS.

The OIC is powered using a 12V input sourced from the DC-DC convertor of the REVski. The CAN-HIGH and CAN-LOW signal wires from the OIC are connected to the CAN Bus shield using the screw terminals located on the shield.

5.6 Arduino Mega

The Mega can be powered via the USB connection or with an external power supply. To reduce the need for a voltage regulator, 12V is supplied from the REVski's DC-DC convertor to the Mega using the board's power jack.

Given the nature of the operating environment, the enclosure for which the Mega is housed and the connections into the enclosure from the instrumentation and IOC must be waterproof. As defined by AS/NZS 3004.2-2014 Clause 7.3.2, for electrical equipment within an environment similar to that of the inside of the REVski, the minimum IP rating is 55 [38]. Since the purpose of the project is important and impacts the safety of the rider, it was decided to house the Mega in an IP65 rated enclosure. An IP65 rating protects the Mega and the stacked shield from total dust ingress and low pressure water jets from any direction [38].

5.7 Final Assembly

The main components of the EWIS are summarised in Table 5.4.

Table 5-4: Main components of the EWIS

Function	Instrument
GPS Module	KS0253 Keyes Studio GPS Shield with SD Slot and Aerial
Incremental Encoder	LARM Magnetic Incremental Encoder MIRC 325/64 PB
State of Charge	TBS Monitor E-Xpert Pro
Temperature Sensor	LM335AZ Voltage Mode Temperature Sensor
Water Level Sensor	K-0135 Keyes Water Level Sensor
Computing System	Arduino Mega 2560 R3
CAN Bus Shield	Seeed Studio CAN-BUS Shield V1.2
Dashboard Display	Original Seadoo Information Cluster

A block flow diagram representing the final assembly of the EWIS is presented in Figure 5.4. From the diagram, it can be easily understood how information from the instrumentation is collected, processed and displayed to the rider. Figure 5.5 shows the assembled EWIS inside its enclosure.

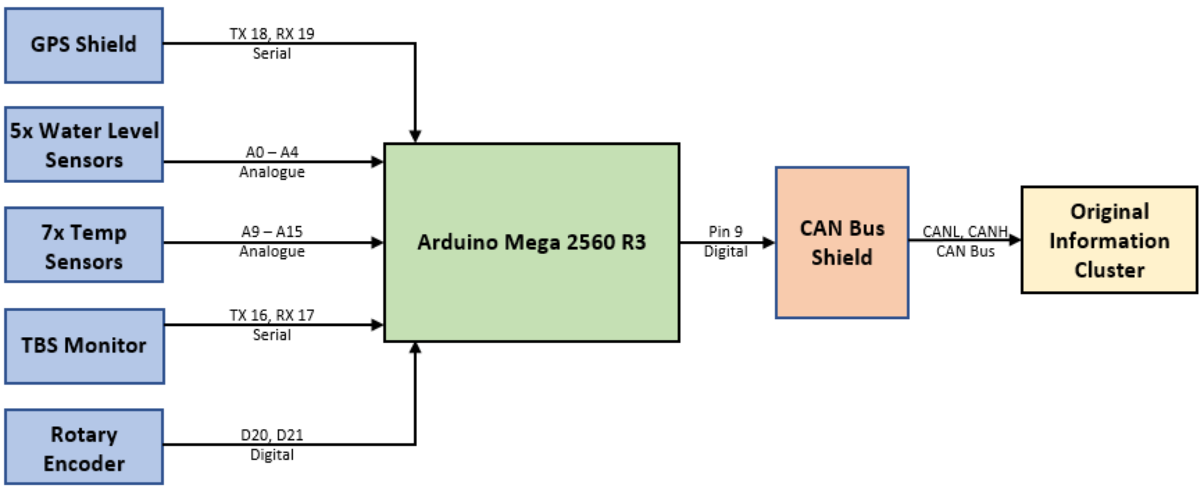

Figure 5-4: Block flow diagram of the EWIS

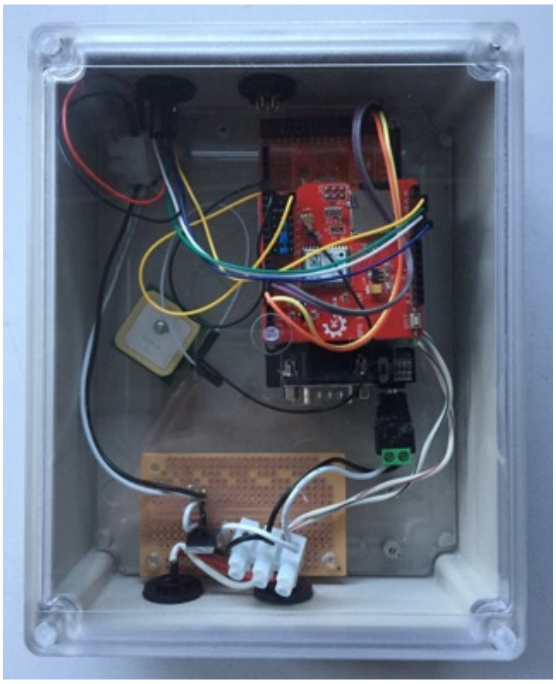

Figure 5-5: Assembled EWIS in Enclosure

A schematic drawing of the pin configuration for the EWIS is presented in Figure 5.6.

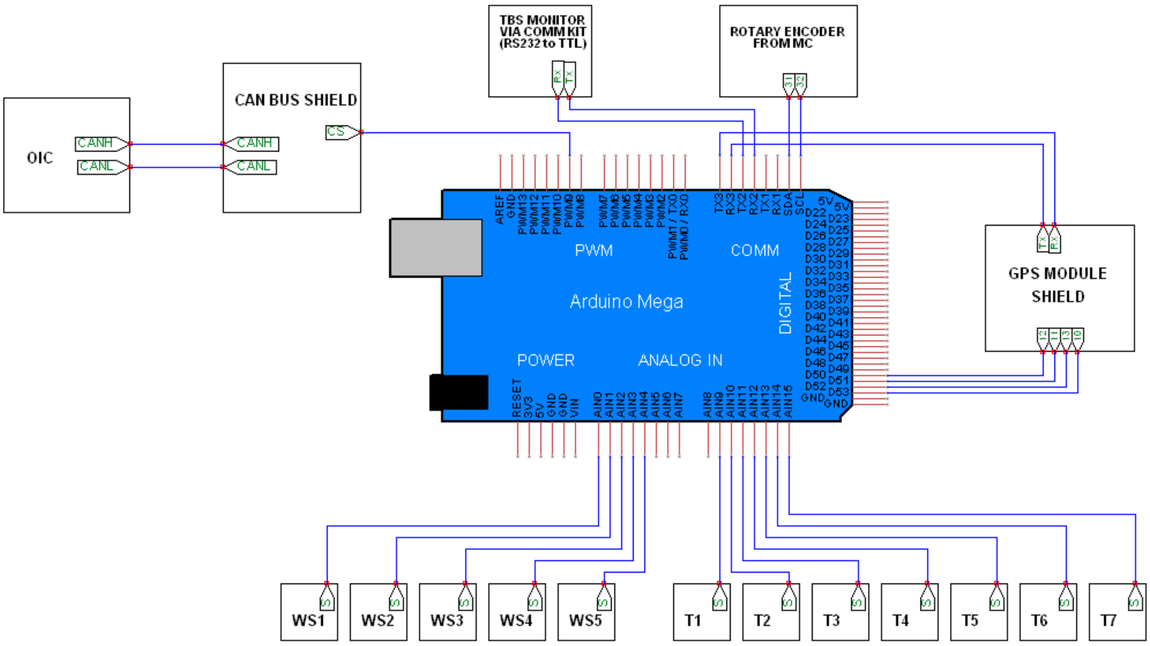

Figure 5-6: Schematic Diagram of the EWIS

6.0 Testing

To achieve the objective of creating an effective system that captures, processes, records and displays information from the desired instrumentation, the testing of the EWIS was broken down into two stages;

1) Modular testing;
2) System testing in both dry and water environments.

Modular testing involved the testing of individual components with the Arduino Mega and the OIC. The primary aim of testing each of the modules individually was to firstly, validate the link between each EWIS stage and secondly, to verify the code written was able to receive information from the instrument and transmit the data to the OIC. It was assumed that the instruments were able to accurately measure their corresponding parameters and thus did not require the need to undergo testing.

Once each of modules had successfully passed their individual tests, the EWIS was installed in the REVski. Once installed, the system was connected together and the code from each module compiled into a single script. The main objective of a dry test was to check if the EWIS was able to execute and log the desired functions of each instrument and display the information through the OIC as a whole system whilst in a controlled environment. This allowed any issues to be quickly identified and fixed. This test was verified through visually inspecting the OIC and analysing the .csv file generated from data logging.

At present, modular testing and dry system testing of the EWIS has been completed. Ideally, a water test should be conducted to confirm the results obtained through the dry test and validate the functionality and operability of the EWIS in a real operating environment. However, due to issues with damaged battery cells and a faulty jet pump, water tests have not been able to be conducted.

7.0 Results

Following the installation of the EWIS into the REVski, a dry test was conducted to test the functionality and operability of the system within a controlled environment. This test was captured via the micro SD card and an extract of the results are presented below in Table 7.1.

Table 7-1: Results obtained from Dry System Test 31/05/18

Date	Time	Lat	Long	Spd	RPM	T1	T2	T3	T4	T5	T6	T7	W1	W2	W3	W4	W5
0/0/2000	0:00:00	0.00	0.00	0	0	23.2	23.5	23.2	23.4	23.0	23.2	23.3	0	0	0	0	0
0/0/2000	0:00:00	0.00	0.00	0	0	23.2	23.5	23.1	23.4	23.0	23.2	23.3	0	0	0	0	0
0/0/2000	0:00:00	0.00	0.00	0	0	23.2	23.5	23.1	23.4	23.1	23.2	23.4	0	0	0	0	0
31/05/18	6:35:41	-31.98	115.82	0	0	23.2	23.5	23.1	23.4	23.2	23.2	23.4	0	0	0	0	0
31/05/18	6:35:42	-31.98	115.82	0	0	23.3	23.5	23.1	23.4	23.2	23.3	23.4	0	0	0	0	0
31/05/18	6:35:43	-31.98	115.82	0	0	23.3	23.5	23.2	23.4	23.2	23.3	23.3	0	0	0	0	0
31/05/18	6:35:44	-31.98	115.82	0	0	23.3	23.5	23.2	23.4	23.1	23.2	23.3	0	0	0	0	0
31/05/18	6:35:45	-31.98	115.82	0	0	23.3	23.5	23.2	23.4	23.0	23.2	23.3	0	0	0	0	0
31/05/18	6:35:46	-31.98	115.82	0	0	23.3	23.5	23.2	23.4	23.0	23.2	23.3	0	0	0	0	0
31/05/18	6:35:47	-31.98	115.82	0	0	23.3	23.5	23.2	23.4	23.0	23.2	23.3	0	0	0	0	0
31/05/18	6:35:48	-31.98	115.82	0	0	23.3	23.5	23.2	23.4	23.0	23.2	23.3	0	0	0	0	0
31/05/18	6:35:49	-31.98	115.82	0	0	23.3	23.5	23.2	23.4	23.0	23.2	23.3	0	0	0	0	0

The latitude and longitude coordinates recorded correspond to the location of the REVski lab (Figure 7.1).

Figure 7-1: Satellite location of coordinates obtained from the GPS Module

Discussion: From the results of the dry test, it is observed that each parameter of interest is being recorded using the integrated card slot of the GPS Module and verifies that each module functions correctly. Given that the dry test is in a controlled environment, the null values for the speed, rpm and leak detection sensors are expected as the REVski is stationary and no water was observed to be in the hull at the time. The temperatures of the battery packs, motor controller and motor represent the ambient temperature with the REVski lab and this is justified as the REVski was not in operation. The accuracy of the GPS module can also be observed based on the location given by the latitude and longitude coordinates. The null values for date and time in the first three rows is explained by the GPS searching for a satellite fix. It should be noted that since the information from the TBS is still in the process of being obtained, it was not recorded during the data logging process.

8.0 Discussion

8.1 Acceptance Criteria 1

As determined in the literature review, the speed, rpm, battery charge remaining and status of the auxiliary systems are essential parameters that are required to be monitored for an EV for a variety of reasons. These parameters formed the basis of Objective 1 of the project and thus was the main focus of the EWIS. During the design process, it was quickly realised that not all ideal instruments could be obtained due to a number of limitations and thus concessions had to be made to the overall design. Although this did not have a major impact on the functionality of the system, other parameters such as individual batteries voltages were conceded and the reliability of analogue signals was questioned. Nonetheless, all parameters identified were able to be captured by the EWIS and logged as per Objective 2. The format of the logged data was given particular attention to ensure it was comprehensible and followed a logical process

Assessment: Achieved

8.2 Acceptance Criteria 2

Given that the EWIS is the first instrumentation system installed on the REVski, it was a constant consideration to keep the design as simple as possible to allow the handover and development of future work be easily carried out. This is reflected in the three segments of data collection, processing and visualisation that make up the foundation of the EWIS. Having the ability to clearly differentiate between each section enables the functionality and operability of the entire system be easily understood. Simplicity and ease of integration was also factored into instrumentation selection as part of the selection criteria.

Assessment: Achieved

8.3 Significance of Design

The significance of installing the EWIS on the REVski is large when compared to the vessel's condition just after its electric conversion. Prior to the installation, the rider was unaware of the current state of the vessel and the troubleshooting was a long and laborious process. The EWIS puts the REVski in a better position to optimise its current systems and assist in the design of any future modifications. When comparing the EWIS to the instrumentation installed on the original IC engine PWC, the EWIS can be seen as elementary and relatively basic due to the number of parameters captured. Attempting to capture the same number of parameters as the original instrumentation system would not have been feasible and more than likely have resulted in the failure to meet the acceptance criteria.

8.4 Limitations

During the design process, a number of limitations were encountered which inhibited the optimal design of the EWIS. These included;

1) Budget constraint and previously installed instrumentation

Being unable to purchase the desired instrumentation (E.g. ZEVA EVMS V3, digitised sensors) lead to a negative effect on the quality of the EWIS. However the next best alternative was selected in an attempt to reduce the impact posed by the budget constraint.

2) Unable to conduct water testing due to external factors

Water tests could not be conducted due to issues with the battery cells, motor controller and jet pump. These factors prevented the EWIS from completing a test in real-test environment. Although the results from the controlled test were satisfactory, a water test would have solidified the validity of the EWIS.

8.5 Future Work

8.5.1 Additional Parameters

Depending on the future use of the REVski, additional instrumentation can be installed on the REVski to measure other parameters that may be of interest to the rider. This may include measuring water depth, throttle position or time left to full charge. The accommodation of additional sensors was considered during the design process of the EWIS and thus can be implemented. Being able to measure additional parameters will assist in future design improvements and also increase the ability to detect faults or issues in a timelier manner.

8.5.2 Redesign of the OIC

Most modern day EVs have information clusters that are suited to their application and display parameters that are relevant for EV components. The OIC of the REVski can be redesigned to include additional gauges to display all the parameters captured by the EWIS. This may include individual battery voltages, battery current, SoC etc.

8.5.3 Cruise Control Mode

With the design of the EWIS being able to accurately measure the speed of the REVski using the GPS module, a cruise control mode can be implemented. This would require a feedback loop between the GPS module and the throttle position to be created and the installation of a cruise control button. Potential application of this feature could be during water quality sampling of a waterway where a constant speed is required to obtain reliable results.

9.0 Conclusion

The purpose of this project was to design an instrumentation system that was able to capture key parameters of interest and display this information to the rider of the REVski. This was achieved by following a four step design process; This involved (1) assessing selected instrumentation against a set of design criteria, (2) determining how to interface the information to the rider, (3) selecting a computing system to capture and process the data and, (4) installing and testing the EWIS in the REVski.

A summary of the EWIS design includes:

- Key parameters such as speed, rpm, battery charge, component temperatures and water leaks are captured through instrumentation and sent to an Arduino Mega.
- The Arduino Mega processes records the incoming data onto a micro SD card which can later be used for design improvements or troubleshooting.
- The data is converted into a CAN Bus message using a shield stacked on the Arduino Mega and transmitted to the OIC. This informs the rider of the current state of the REVski.

This project presents the first steps of recording basic vehicle parameters on an electric PWC. Based on the proposed assessment criteria, the design of the EWIS provides satisfactory results and meets the desired objectives. Depending on the future use of the REVski, the EWIS has the capacity to be further developed to include other parameters such as water depth or throttle position. Incorporating additional parameters will not only improve the functionality of the EWIS but also build on the benefits gained from having an on-board instrumentation system.

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11.0 Appendix

Appendix 11.1: Rating Classification

Rating	Description
1	Instrument does not meet key area/constraint and likely to severely impact the feasibility of the instrumentation system.
2	Some aspects of the instrument falls within the key area/constraint and will have a slight negative impact on the feasibility of the instrumentation system.
3	Majority of the instrument aspects fall within the key area/constraint and will not impact the feasibility of the instrumentation system.
4	All aspects of the instrument falls within the key area/constraint and supports the feasibility of implemented the instrumentation system.

Appendix 11.2: Temperature Sensor Calibration Procedure

The objective of this test to calibrate the sensors to provide an accurate reading of the actual surrounding temperature.

Note: The procedure must be conducted for each temperature sensor

1) Connect the LM335 sensor to the Arduino. Refer to data sheet for pin configuration.
2) Read output values from the temperature using the Serial Monitor of the Arduino.
    a. Values range from 0 – 1024.
3) Convert the output values into degrees Celsius using the following conversion factor.

$$T_{\circ C} = \frac{\left(\frac{Output}{1024}\right)}{0.01} - 273.15$$

4) Measure the actual temperature of the sensor using a proven, high precision thermometer.
5) Determine the calibration factor required for the sensors to reflect an accurate temperature reading.
6) Repeat steps 1 - 4 to verify the correct calibration factor has been calculated.

Appendix 11.3: Water Level Sensor Threshold Procedure

1) Connect the sensor to the Arduino. Refer to data sheet for pin configuration and set up
2) Read output values from the sensor using the Serial Monitor of the Arduino.
    a. Values range from 0 – 1024.
3) Slowly submerge the sensor into water.
4) Record the output value for different water depth levels.
5) Determine threshold limit based on the above results.

Appendix 11.4: Summary of CAN-Bus Communication Protocol for Seadoo

CAN ID	BYTE 0	BYTE 1	BYTE 2	BYTE 3	BYTE 4	BYTE 5	BYTE 6	BYTE 7
0x208	0x$$ - Speed > 25km (Max speed: 113 km/h)	0x$$ - Speed < 25km			0x01 - Fuel Warning Light flashing; "Fuel Lo" 0x03 - Fuel Warning Light flashing; "Present 1"		0x01 - Speed only 0x02 - Temperature only 0x03 - Speed and Temperature	
0x210	0x$$ - Fuel Gauge level (0-100%)							
0x308	0x02 - Battery Warning Light flashing; "12V Hi" 0x05 - Battery Warning Light flashing; "12V Low" 0x0A - Battery + Eng Warning Lights flashing; "12V Hi + Chk Eng" 0x0B - Battery + Eng Warning Lights flashing; "12V Low + Chk Eng" 0x0C - Eng Warning Light flashing; "Chk Eng" 0x10 - Temp Warning Light; "Engine" 0x15 - Temp + Battery Warning Lights flashing 0x1A - Battery, Temp + Eng Warning Lights flashing 0x24 - Temp Warning Light flashing; "Exhaust" 0x44 - Oil Warning Light flashing; "Oil" 0x90 - Temp Warning Light flashing; "Engine" 0xE2 - Temp, Oil + Battery Warning Lights flashing	0xFF - Limp Home Mode; "L Home"						
0x310	0x$$ - RPM > 240 (Max RPM: 9980)	0x$$ - RPM < 240						