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Final Year Thesis Project

System Architecture & Instrumentation for Electric Jet Ski Project

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Abstract

The Renewable Energy Vehicle Project is a long-running project with the goal of revolutionising personal transport by building a zero-emission solution for the future. The REV project plans include exploring electric propulsion technology, powered through renewable energy sources, to replace the current fossil fuel-dominated transport system. The REVski is an experimental project to convert a petrol Jet Ski to an electric propulsion system with a 50kW AC motor and 80Ah of battery capacity. The REVski project aims to develop a Jet Ski alternative that is environmentally friendly, produces less noise, and greatly reduces running costs compared to conventional combustion motors. During the conversion the existing Electronic Control Unit (ECU) was removed along with the motor assembly, requiring the development of a new ECU that is specialised to run with electric vehicles. The Electronic Control Unit in development needs to facilitate running a CAN communication network, fault checking, running the user display, collecting data from outboard water sensor cluster, along with position tracking through GPS. Additionally, the ECU will log data to send status updates to the REV project database using 3G communication from the GPS. This thesis documents the development of an ECU, the corresponding system architecture, and instrumentation for electric conversion vehicles - with the goal of developing a flexible system for use within future REV projects.

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Acronyms

Acronym	Definition
UWA	University of Western Australia
REV	Renewable Energy Vehicle (Project)
RPM	Revolutions Per Minute
ICE	Internal Combustion Engine
REVski	REV Electric Jet ski
SCM	Single Chip Microprocessor
GPS	Global Positioning System
ECU	Electronic Control Unit
SoC	Stage of Charge
OCV	Open Circuit Voltage
ESR	Equivalent Series Resistance
CAN	Controller Area Network
MC	Motor Controller
HV Contactor	High Voltage (B+) Contactor
LV Contactor	Low Voltage (B-) Contactor
UV	Under Voltage
OV	Over Voltage
ZEVA	Zero Emissions Vehicles Australia
IC	Integrated Circuit
DCDC	Direct Current Voltage Converter
VCL	Vehicle Control Language

1. Project Introduction

1.1 REV Introduction

The Renewable Energy Vehicle Project is a long running project with the goal of revolutionising personal transport though building a zero emission solution for the future. The REV project plans include exploring electric motors technology powered through renewable energy sources to replace the current fossil fuel dominated transport system. The REV Project was started by Professor Thomas Braunl & Dr Kamy Cheng in 2008 after the viability of electrical vehicles as the next big competitor to combustion engines became evident. Following the projects inception the team has been responsible for several successful Electric Vehicle conversions, along with Electric Charging Stations, and a web portal providing statistics on the usage of the REV project systems.

Included in the list of projects that the REV team have undertaken is the REV Electric Jet Ski, referred to as the REVski, an ICE Jet Ski which was retrofitted with an electric drivetrain. The REVski project goal to provide all the fun of a conventional Jet Ski with significantly less noise and pollution. The REVski started as a SeaDoo 4-TEC Jet Ski which was purchased with a broken motor; the motor was stripped and replaced with a custom built water cooled 50kW three phase Electric motor from SME. In addition to the Electric Motor a 7.6kWh battery system utilising the Headway 38120 cells was packaged into the hull to provide approximately 26 minutes of range.

Figure 1 - Marti James Leven on the REVski

Starting in the second semester of 2018 four new REV project team members commenced their work on continuing the REVski project through Professor Thomas Braunl's Thesis Program. The four new team members include Marti James Leven, Dylan Leong, Ze Lin, and Amos Ran. The REVski platform allows the development of the team's experience with working on a complicated real-world application of their electrical engineering skills, in addition to furthering the REV projects development of Marine Electric Vehicles to further the goal of a zero emission future.

1.2 Previous Work:

The two most recent contributors to the Instrumentation and Safety systems include Maximilian Woloszyn [1], and Jayden Dadleh [2]. Dadleh was responsible for updating the BMS system during 2017 and worked extensively on removing damaged cells caused by storage of under voltage cells, the 2017 thesis group concluded with a successful water tests albeit significant BMS cut-out issues due to damaged cells were noted. In 2018 Woloszyn was responsible for integration of the instrumentation system, as previously no instrumentation was provided to present the speed or required information to the user. Woloszyn's group had success in characterising how to run the display and an EWIS system was built that could display the craft's speed, although was the team was only able to dry test the REVski.

1.3 Problem Identification:

Between 2017 and the commencement of the 2019 semester 2 REVski team, only a single successful water test had been completed as the previous teams had struggled with significant amounts of battery, battery management, and instrumentation issues. As part of the thesis problem identification to get the REVski working the team spent a total in excess of 1000 man hours between commencement of the project to the first water test. A total of six water tests were run allowing the identification of the following list of system faults:

PI.1.0: Battery Management System, and Battery Faults

- **PI.1.1:** BMS Safety System cutting out during high load, with increasing frequency during high load or low charge.
- **PI.1.2:** Several Batteries show signs of severe degradation; characterised by rapidly dropping open circuit voltage and inability to charge to higher voltage levels.

PI.2.0: Instrumentation displayed to user insufficient

- **PI.2.1:** While the previous group had successfully demonstrated the EWIS running the display to Professor Thomas Braunl, the system was not integrated into the REVski after the finalisation of the 2018 project.
- **PI.2.2:** Instrumentation display was lacking speed, RPM, remaining capacity, and warning readout.
- **PI.2.3:** EWIS system developed was not suitable for use within the REVski during operation.

PI.3.0: Quality of wiring and connectors not meeting operational standards

- **PI.3.1:** Spade connectors carrying power and signal had significant reliability issues, resulting in cables disconnecting under high vibrations situations.
- **PI.3.2:** Failure of LTW panel mount connectors; there was large amount incorrectly soldered connectors resulting in intermittent failures, additionally several panel mount connectors were used as inline connectors causing reliability issues.

PI.4.0: Safety Circuitry and Charging Design Flaws

- **PI.4.1:** The deadman circuit was found to be highly unreliable, cutting out if the deadman connector had its angle changed or was rotated around the receptacle.
- **PI.4.2:** The charging circuit required a momentary switch to be held down for the duration of charging.
- **PI.4.3:** The safety system logic was not safely deactivating all contactors while in fault states, meaning that fault states did not have sufficient risk mitigation for the users and craft.

1.4 Objectives

Based on the problem identification three major directives were developed to be solved, with the overarching goal of getting the REVski into a fully operational state. The three major directives are as follows:

1. Replace BMS system with system that provides tracking and active management of cells to mitigate the effects of cell degradation.
2. Redevelop previous EWIS system into a full ECU, with full integration of the BMS and Motor Controller System, along with improvements to instrumentation displayed on the SeaDoo display.
3. Update Safety System and wiring to satisfy reliability and engineering standards.

The goal of the finalisation of this project includes a fully operation REVski that is able to inform the user of different safety aspects, reducing the barrier to entry for Marine EVs such that the public could use and maintain the craft without specialist knowledge, furthering the goal of the REV project of enabling zero emission vehicles to power the transport needs of the world.

2. Design Considerations

2.1 LiFePo4 Batteries

Compared to other lithium technologies LiFePO4 cells have popular in early EVs due to their large voltage tolerance, tolerance of high depth of discharge, and safety. In particular the Headway 38120L cells used in the REVski are known for being one of the safest lithium battery technologies and are quite tolerant to abuse. Headway 38120L cells have a nominal voltage of 3.2V and capacity of 10Ah, and are able to discharge 5C continuous (50A) and 10C peak (100A) [3]. This made the cells an attractive choice during the development of the REVski due to their high discharge capacity, and safety. Below is a tabulated specifications for the headway cells:

Table 1 - Headway 38120L Specifications [3] [4]

Capacity		10Ah
Voltage	Minimum	2.0V
	Nominal	3.2V
	Maximum	3.8V
Discharge Capability	Continuous	5C (50A)
	Peak	10C (100A)
Weight		348g
Energy Density		92 Wh/kg
Cost		$26.50 AUD

2.1.1 Cell Characterisation

For the purposes of tracking and managing the cells within the REVski, a model must be developed that allows the health of the cells to be characterised by a set of extractable variables. The three relevant characterising variables used for cells within the REVski includes **E**quivalent **S**eries **R**esistance (**ESR**), **O**pen **C**ircuit **V**oltage (**OCV**), and **S**tate **o**f **C**harge (**SoC**). The variables are used as part of the Lumped Model for a cell, shown below in figure 2, which represents the differences between an idealised voltage source and a the real output provided by a battery.

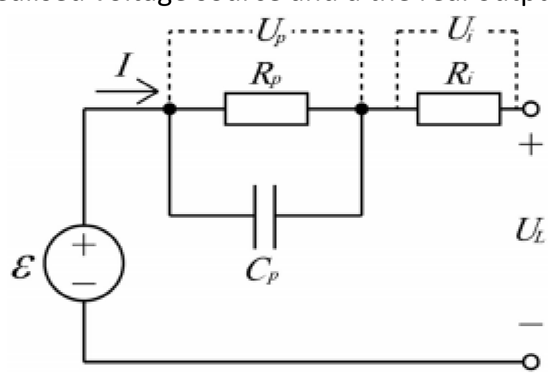

Figure 2 - Lumped Model of Cell [5]

An important note is that the parallel capacitor resistor part of the circuit cannot be easily characterised with the planned system; as the polling rate is too slow to provide reliable insight into the time constant of U_p without specialised cell testing units. The three characteristics have a complex set of inter-relations based on the physical construction, chemical interaction, usage of the battery, and other external factors, though they provided a basis that allows the tracking of cell health. The final goal of the cell characterisation is the ability to use an extended Kalman Filter [5] model - allowing high accuracy state estimation, although implementation of a Kalman filter is outside of the scope of the project.

2.1.1.1 Equivalent Series Resistance

The ESR is the resistance between terminals of the battery, and is used as part as the lumped model of the cell. In the figure 2 a model is shown of a lumped model for a battery, with the ESR represented by R_i. As the ESR is a series resistance in line with the voltage source, when current passes through this resistance there is a corresponding Ohmic voltage drop across the terminals. The ESR varies greatly depending on temperature and SoC, and therefore requires second order models [6] or Kalman Filters [5] to track effectively. In the case of battery packs; each cell in series increases the packs resistance, while each cell in parallel reduces the pack resistance due to parallel resistance paths. One of the weaknesses of the REVski battery system is that it uses a 30S8P (30 series 8 parallel) pack configuration, running the LiFePo4 cells at extremely high C ratings compared to most other lithium chemistries. In comparison if the system was built using more conventional 18650 cells, the lower discharge capability would require the system to be build using significantly more parallel strings; consequently reducing output resistance, and therefore potential drop under load.

2.1.1.2 Open Circuit Voltage

OCV is the voltage between terminals measured while open circuit, meaning that there is no current draw causing voltage drop through the ESR. The OCV is useful because the cell voltage limitations should only be considered under open circuit conditions, as the safety limits are based on the ideal source portion of the lumped model without the parasitic components. The OCV of a cell changes depending on what state of charge the cell is at based off a known OCV/SoC curve, and therefore provides an individual measure of each cells SoC. Figure 3 provides an OCV/SoC curves of a Li-ion battery.

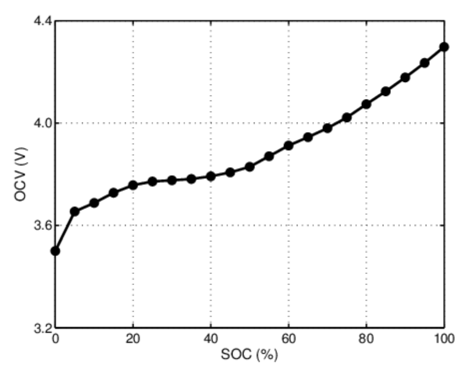

Figure 3 - OCV/SoC of a Li-ion Battery [6]

2.1.1.3 State of Charge

In the case of the REVski the State of Charge (**SoC**) is being used as a measure of total Amps the battery pack has output since last full charge. The total discharge current can be compared to the expected OCV/SoC curves which shows the differences in discharge between each cell. The SoC of the system also provides insight into the real capacity of the cells, which is expected to degrade over time due to chemistry changes.

2.1.2 Cell Degradation

Cell degradation in batteries happens for multitude of reasons; including temperature, age, being outside safe voltage limits, and the load of the cells. Cell degradation in Lithium Cells is typically characterised by increasing ESR and reduced discharge capability, a cell with high ESR causes a resistive voltage drop when the battery is under load - reducing the output voltage and wasting a proportion of the energy capacity as waste heat.

2.2 Battery Management System:

Despite the REVski using headway cells that are highly tolerant of abuse, several years of student (mis)management has allowed significant degradation in the original battery cells. In addition some of the cells have been replaced by new cells, causing a large variance in ESR between cells due to differing levels of degradation. The ESR difference has caused a large amount issues with varying SoC between cells, which contributes to addition cell degradation when other cells in the pack are then forced to pick up the slack. To avoid further damage and to maintain the pack in acceptable condition, without unacceptable time investments into individual balancing, the system had to be updated.

2.2.1 Previous BMS8 Installation

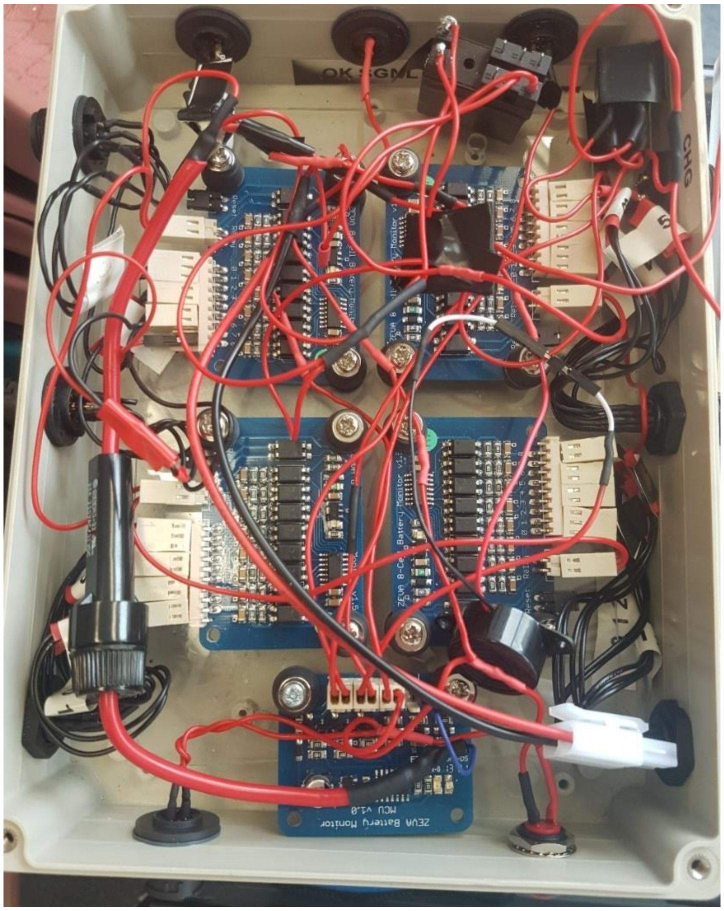

Figure 4 - Previous BMS8 Installation

The BMS8 battery management system previously installed on the REVski uses a hysteresis model to keep the cells within safe voltage limits, using dual solid state relays to signal to a master module that no cells are outside the voltage range. As the BMS8 has no shunt resistors it does not provide balancing capability, and disables the contactor in cases when cell voltages are outside the safe limits. Without shunts the BMS8 does not have balancing capability and alongside using a cheap constant current charger; the ESR voltage drop of the cells directly results into a difference in cell voltages after charging - resulting in an unbalanced pack. Previously to get a sufficiently balanced pack post charging requires manual balancing to be done by the user to equalise the SoC between the cells. Additionally the only method of balancing cells is individually shunting directly through the balance leads, putting severe limits on the shunting current. Manually balancing is incredibly time consuming (estimated 40 hours) and requires constant user input due to the electrical and fire risks involved. The extreme time investment and risks involved with manually balancing has contributed to insufficient balancing done on the craft, a big contributing factor to the cell degradation over time. A major focus of the system upgrades includes the ability to directly manage the pack balance by updating the battery management system.

In addition to all the engineering faults, there were additionally significant architecture and wiring faults present in the BMS8 system; including the fact that the BMS8 master module did not properly latch into the charging state. The inability for the BMS8 master module to latch into charging state required the charge switch to be held down constantly during charging; resulting in the system just closing the charging relays but not resetting the charger enable once the cells were high, causing the charger to continue attempting charging even if the charge relays were disabled.

2.2.2 Updated BMS System

Figure 5 - BMS12 module from ZEVA [7]

The battery management system chosen was the BMS12 produced by ZEVA, the BMS12 does not directly provide **U**nder **V**oltage (**UV**) and **O**ver **V**oltage (**OV**) cutoffs, and instead reports cell voltages to a master module and conditionally uses shunt resistors to discharge over voltage cells. The difference in pack management strategy allows the system to track cell voltages, while the master module is able to provide the OV/UV protection without directly requiring active relay signals to be passed between the modules. Due to the ZEVA BMS12's reporting the cell voltages over CAN, the ECU is able to piggyback onto the CANbus and read in the reported cell voltages - allowing the data basing of the cell voltages in real time.

2.3 Previous System Architecture

2.3.1 Previous Electrical Schematic

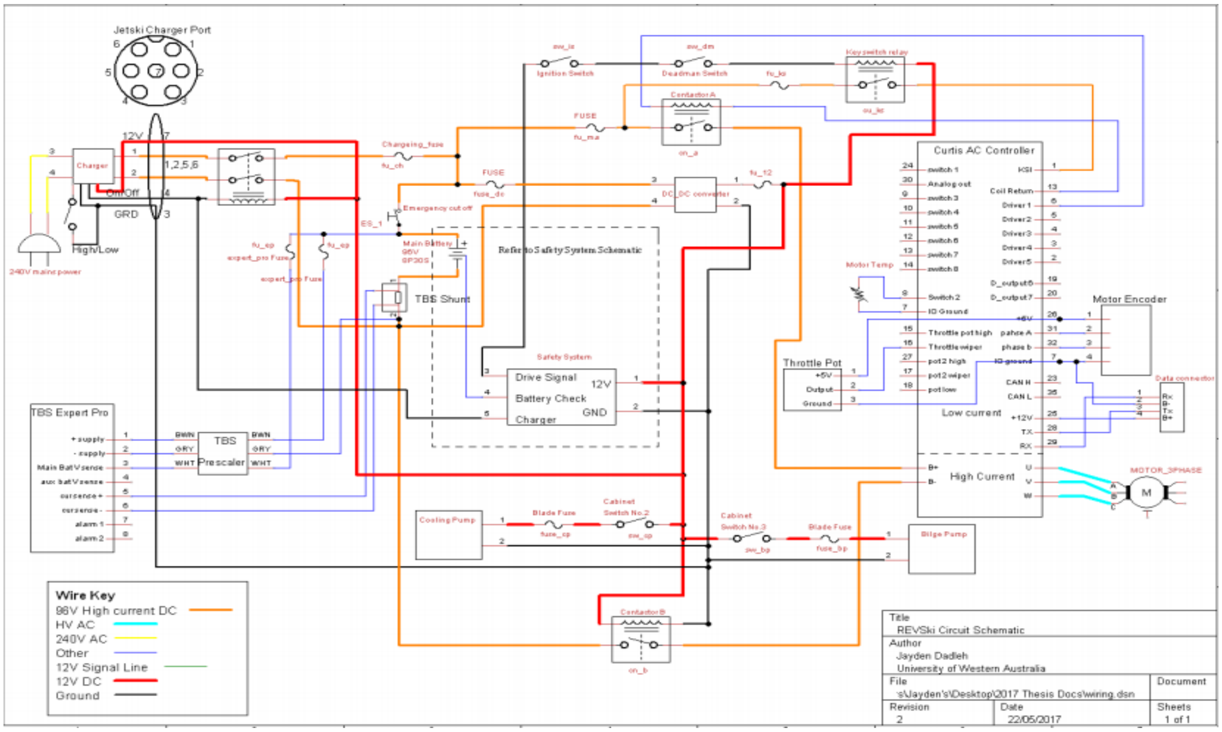

Figure 6 - Previous Electrical Schematic [2]

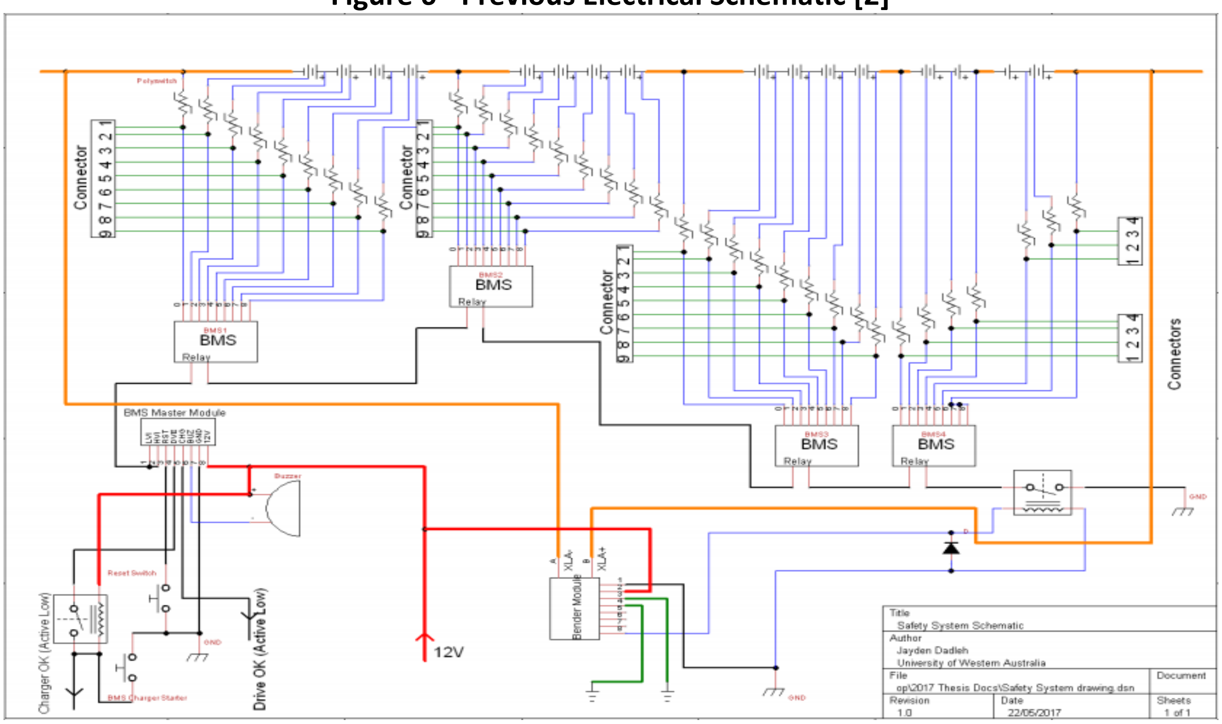

Figure 7 - Previous Safety System Architecture [2]

As can be seen from the above two schematics, there is significant wiring complexity between modules, in addition to poor choices in connectors has caused a large set of reliability issues where often inconsistent faults were caused by loose or damaged connectors within the mess of cables. Additionally the layout means that fault detection requires rigorously checking each connection and connector for faults which greatly extends the troubleshooting cycle beyond reasonable limits. The next iteration should enable quick fault checking and improve wiring reliability.

2.4 EWIS to ECU update

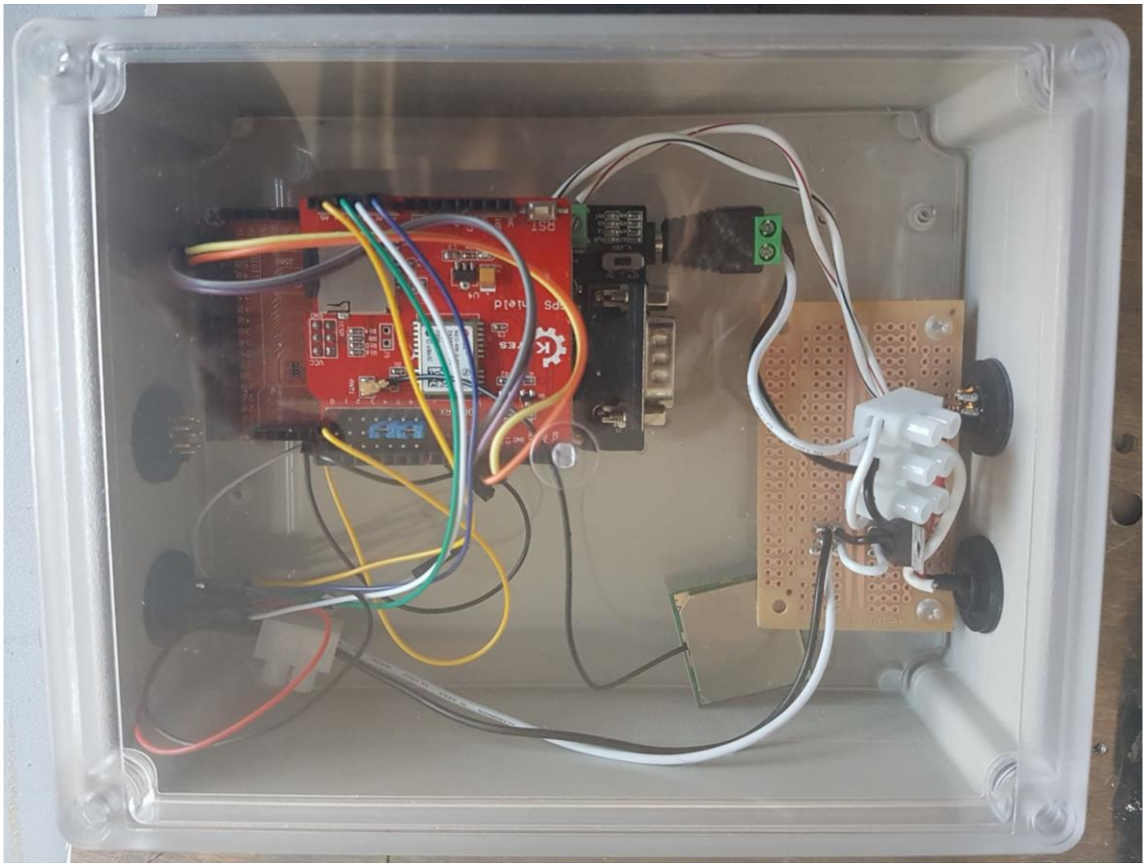

Figure 8 - Previous EWIS system

Upon the commencement of the 2018 semester two thesis group, the only integrated information on the display was the speed; which was captured by the EWIS using a Keyes GPS shield [8]. The **E**lectric **W**atercraft **I**nstrumentation **S**ystem (**EWIS**), pictured in figure 8, had numerous engineering and quality faults including; insufficient location accuracy, not engineered to withstand vibrations, and inappropriate use of DuPont connectors. As the design did not have any particular merits the entire system was redesigned from the Arduino Mega up.

2.5 SeaDoo Display

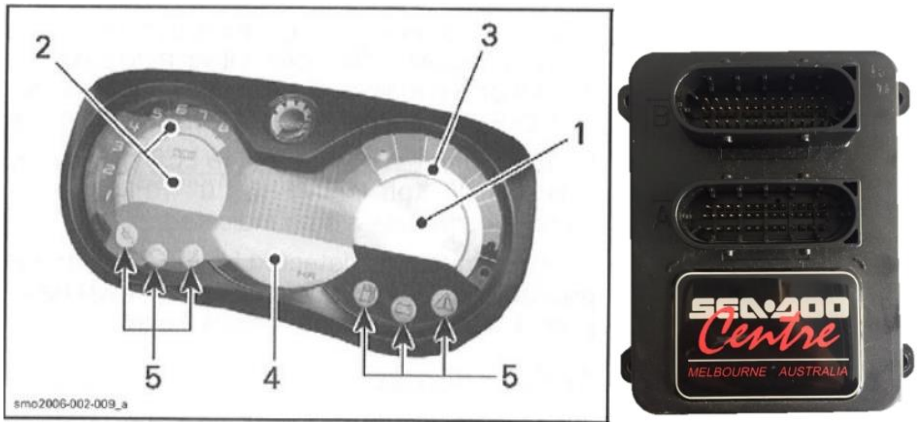

Figure 9 - SeaDoo CANbus display cluster & SeaDoo petrol engine ECU [1]

As outlined in the introduction; the original SeaDoo display cluster had previously been run by the petrol motor ECU, which was removed as part of the retrofit. As part of updating the user display system the team needed a way to update the SeaDoo display. Due to the proprietary nature of using a SeaDoo branded display cluster there is no official documentation or specification sheets released for this product, meaning that the specifications for running the display are not available online. Thanks to the work by Maximilian Woloszyn the CANbus standard to run the display was decoded, preventing the display from being replaced.

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						

Figure 10 - CAN specifications of the SeaDoo display cluster

Thanks to the planned upgrades on the GPS and ZEVA systems, the important state variables of the craft are able to be updated on the display by the ECU, providing the user the critical information needed for safe travel in the craft.

2.6 Motor Controller:

The REVski drive train uses a Curtis 1238 motor controller that powers the SME 3 phase induction motor, providing the power to the jet pump. The Curtis 1238 is able to output 550A for two minutes, giving it a peak power rating of 52kW at 96V. The Curtis controller required reprogramming to characterise the motor, as it was found that the motor was running backwards and changing the poles produced mistiming errors on the motor controller. Due to the OEM level programmer costing nearly 600 AUD [9], the programmer was loaned from EVworks [10] which allowed the team to enable the correct direction at full power. In addition the use of the OEM level programmer allowed the team to enable several settings, such as enabling the CAN node and setting the timeout response. Unfortunately the team was not able to fully access the **V**ehicle **C**ontrol **L**anguage (**VCL**) due to the limited software provided and therefore could not override several settings such as the CAN PDO timeout.

Figure 11 - Curtis 1238 Motor

2.6.1 CANopen Integration:

CANopen is an application level communication protocol used for managing CANbus networks [11], the communication between nodes is actively managed through setting the state of different nodes via several commands. The CANopen node id of the Curtis 1238 is 0x038 which was found by decoding the heartbeat 0x738, allowing the ECU communicate with the Curtis MC. As the Curtis Motor Controller is CANopen enabled we are able to do several interactions with the node as specified by the CANopen standard, including NMT, PDO requests, SYNC, as part of the CANopen integration on the Curtis 1238, the following state tree was developed from the interactions from different commands.

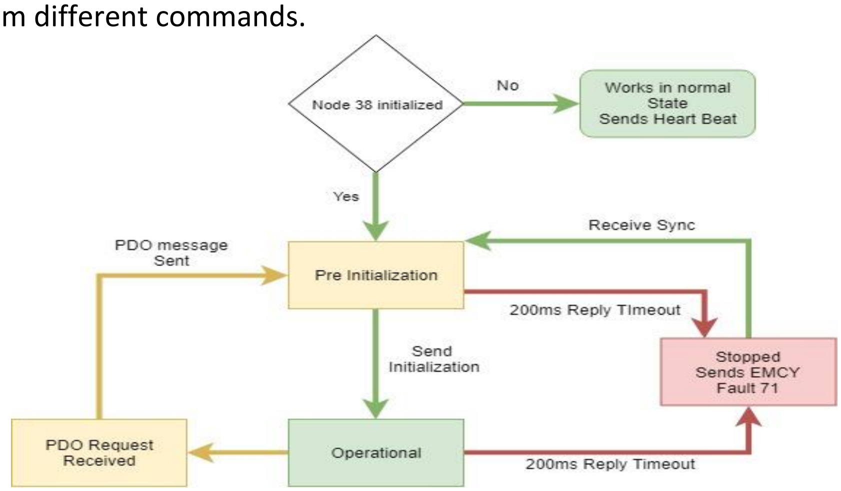

Figure 12 - CANopen implementation for Curtis Motor Controller

As can be seen from the figure 12, constant network commands must be sent via the CANbus to stop the MC falling into the PDO timeout state, which throws an error message and locks the motor controller until another update is sent. The PDO timeout error means that the ECU is required to be highly reliable to prevent the motor controller constantly entering timeout faults.

2.6.2 CANopen PDO format

Process **D**ata **O**bject (**PDO**) is a CANopen implementation that enables nodes to pass critical data to the CANbus, PDOs require the receiver to have a decoding dictionary that allows the required information to be extracted from the message frame. Based on online documentation from HPevs [12] a PDO decoding table was found for the Curtis Motor Controller, shown in Figure 13. By using a CANopen implementation the team was able to successfully request both PDO1 and PDO2 from the motor controller, although due to a difference in setup the majority of variables did not match the decoding table; the matching values included Motor RPM, Temperatures, and Fault Primary/Secondary. Despite attempts of matching user inputs to changes in the CAN PDO output the team did not manage to discover the reason for the differences, or a way to restructure the PDO requests with the Vehicle Control Language using the Curtis OEM Programmer.

	ADDRESS ID					
	CAN ADDRESS 0x601	Units	Scale	**CAN ADDRESS 0x602**	Units	Scale
Byte0	Motor RPM high byte	RPM	1	Stator Frequency high byte	Hz	1
Byte1	Motor RPM low byte			Stator Frequency low byte		
Byte2	Motor Temp	Deg C	-40 to 200	Controller Fault Primary		
Byte3	Controller Temp			Controller Fault Secondary		
Byte4	RMS Current high byte	Amps	0.1	Throttle Input	%	1
Byte5	RMS Current low byte			Brake Input		
Byte6	Capacitor Voltage high byte	Volts	0.1	**System Bits***		
Byte7	Capacitor Voltage low byte			Not used		

Figure 13 - CANopen PDO decoding table for Curtis 1238 by HPevs [12]

3. Updates to REVski System Architecture

The following section documents the changes made to the REVski architecture:

3.1 Updated Electrical Schematic

As shown in 2.3, the wiring complexity and number of safety critical signals that are required to pass between modules greatly degraded system reliability. Using the EVMS as a central safety manager node greatly simplifies the safety and electrical schematic, additionally greatly reducing the number of cables and connectors between modules within the system. Due to the reduced amount of connections, the team was also able to untangle and cable manage the remaining cables into bundles – improving access and maintainability greatly.

3.1.1 Updated Electrical Schematic

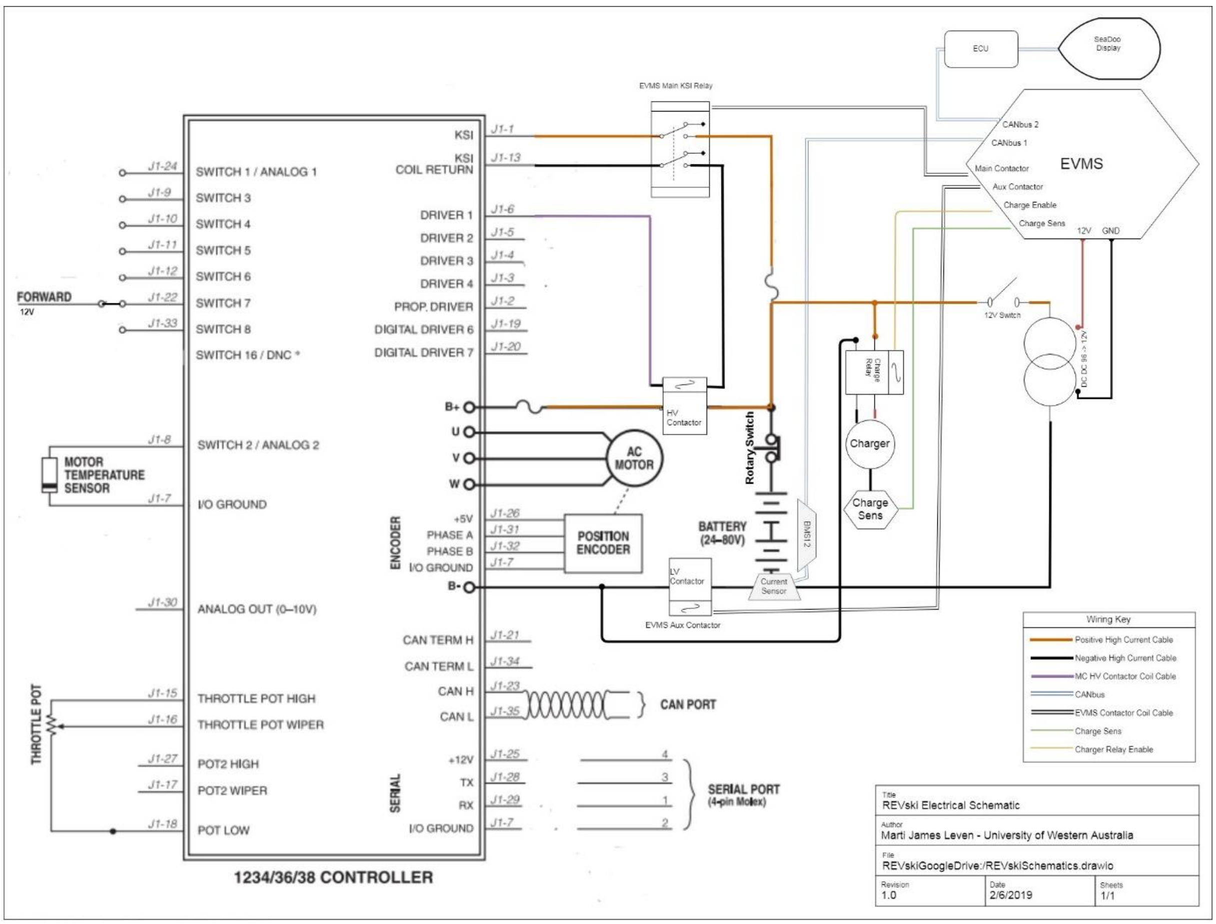

Figure 14 - Updated Electrical Schematic

3.1.2 CANbus schematic

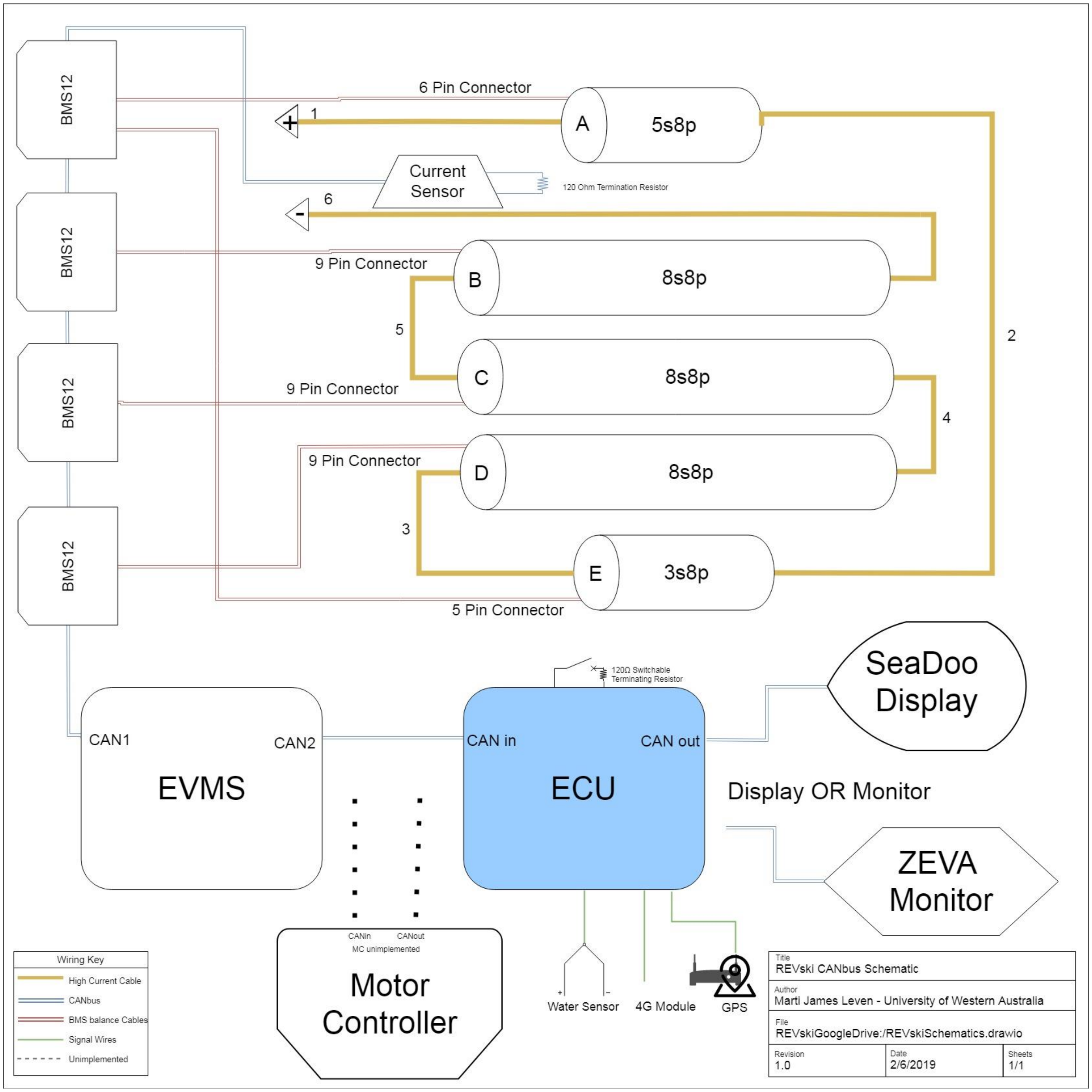

Figure 15 - CANbus schematic

Compared to the previous build of the REVski using the BMS8 and BENDER safety system, the BMS12 CANbus system has all the same safety systems, while just passing a CANbus cable through the units. Additionally, as the safety system is functionally a Bus, fault checking can be executed by testing the end to end resistance from the bus, allowing faults to be isolated significantly faster. By using high quality connections between modules the reliability of the safety system is again greatly improved.

3.1.3 Main Contactor Updates

AC motor controllers have a low resistive and incredibly high capacitive load, upon connecting a battery across a motor controller a large inrush current is created that can easily be several times the rated current of the contactors, which has the potential to fuse contacts and blow fuses [13]. The inrush current from motor controllers can be mitigated by using a high power pre-charge resistor between the motor controller B+ and the contactor. The pre-charge resistor gradually equalises the potential difference across the contacts, allowing the contactor to close without risk of arcing or damage. The Curtis 1238 motor controller has a large capacitor bank, requiring the motor controller to control the pre-charge and main coil driver. Prior to startup the Curtis motor controller **K**ey **S**witch **I**ndicator (**KSI**) is connected directly to the Battery + terminal, allowing the motor controller to charge the capacitor bank before closing the main contactor safely [14].

One of the critical safety oversights that was found in the previous system stemmed from a misunderstanding of how the Curtis motor controller drives the main contactor. Previously the BMS signal only toggled the KSI relay which only disconnected the pre-charge KSI voltage; the lack of KSI voltage only prevents the motor controller from closing the contactor, and does not directly open the contactor during a fault. This causes a significant safety risk, as the previous system BMS tripping only opened the auxiliary contactor (LV) and not the main contactor (HV). This issue has caused no significant faults, although greatly increases the risk of a contactor welding from incorrect use. Welding contactors causes a massive safety risk as someone servicing may inadvertently cause short circuits to normally disconnected parts of the circuit, in future care should be taken to confirm that pre-charging and fault states for contactors are correctly engineered. The issue was fixed by replacing the **KSI** relay with a similar double pole double throw relay that disconnects the main coil driver on the motor controller as shown in the updated system architecture in figure 14. This change additionally allows the EVMS to disconnect the motor controller from the battery during charging, which improves the charging safety.

3.2 ECU Upgrade

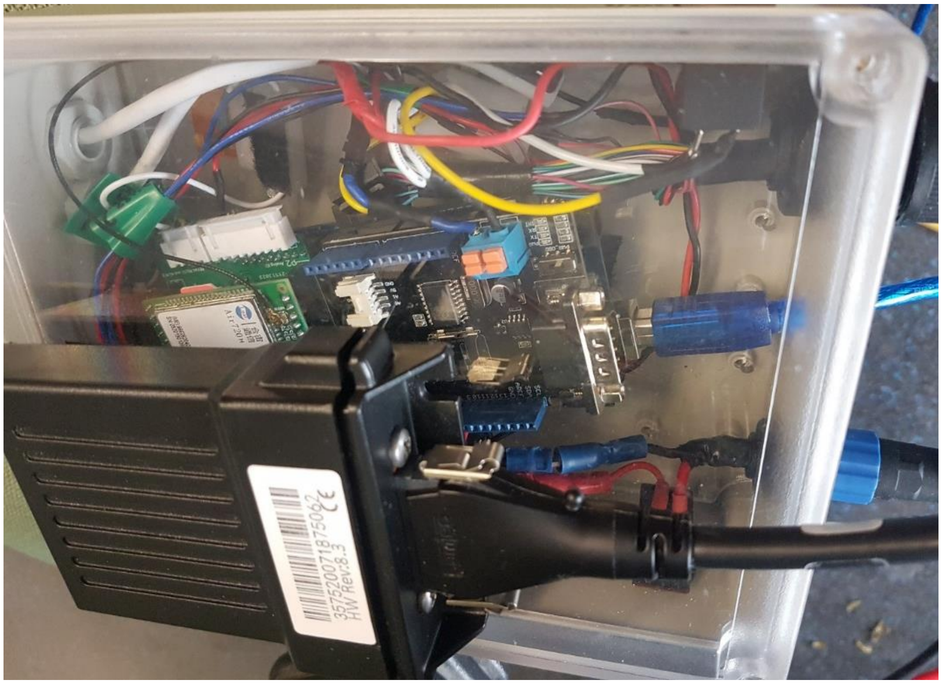

Figure 16 - Upgraded ECU

As part of upgrading the overall infrastructure of the craft the EWIS system was rebuilt using higher quality components; including an Astra AT240 Fleet Management **GPS**, a **DCDC** regulated power supply, an updated CANbus shield from Seeed Studio, and a custom ordered RS232 and 4g Modem breakout shield. The updated system was renamed the **E**lectronic **C**ontrol **U**nit (**ECU**) in reference to the increased scope of work done by the unit.

3.2.1 Astra AT240

The Astra AT240 GPS intended use involves fleet management and logistics applications [15]. Due to the use of the AT240 within fleet management it has been developed to be automotive grade, using an impact resistant case with an ip67 rating - suitable for use outside of the ECU box within the REVski. As the GPS had sufficient ingress protection, it was decided to mount the unit above the ECU box to improve signal quality. The GPS performance was significantly improved compared to the Keyes Studio GPS, though it struggles to maintain a GPS lock while inside the REVlab due to the signal interference from the surrounding building. The GPS lock is required when updating the webserver due to the database requiring an accurate timestamp from the NMEA data [16].

3.2.2 4G Luat Air720

The REVski project was not able to use the AT240 module's integrated 3G TCP connection to send data to the webserver due to security concerns from the UWA IT department. Due to the Astra not functioning as an internet gateway an additional 4G modem was required to allow the ECU to update the webserver, a Luat 4G modem implemented by Dylan Leong [17] and connected to the custom RS232 board created by team member Ze Lin. Due to the 4G modem using a completely custom made HTTP format compiled within the Arduino, there is a significant processing, character concatenating, and serial communication delay caused when sending data over 4G. As parts of the 4G sending sequence is blocking, which prevents the microprocessor from operating on any other functions, during the time taken to send via 4G the ECU is locked out of any other of the critical processes that it is responsible for.

Figure 17 - CPT 12-5V DCDC

3.2.3 DC Converter & Power Smoothing

Previously the Arduino's onboard dc regulator was used to convert the 12V supply to 5V for the microprocessor and shields, although it was found that the onboard regulator did not provide sufficient smoothing during operation of the craft. A Car Power Technology 15W DC-DC converter; which both converts the 12V auxiliary power into 5V for the Arduino mega, and provides regulation on the output to protect the electronics. Prior to this upgrade the reliability of the ECU during testing compared to on the bench were significantly different, causing major delays in the development of the ECU from transient errors. In future REV projects it is recommended that battery to 12V DCDC is mounted with the contactors rather than alongside the motor controller to avoid EMI, and decoupling capacitance and Zener diodes should be included surrounding sensitive electronics for additional power smoothing [18].

3.2.4 ECU state diagram

The ECU's main job is to run the CANbus, with secondary priorities of gathering water data, saving to SD card, and sending data to the server. When the Arduino is sending via modem to the server several large processes have to take place; including concatenating the variables into a HTML message body, building the HTML header, sending the HTML via Modem, and listening for the server response after sending. The team has previously experienced is CANopen timeouts due to the length of time that the Mega takes doing some of these secondary tasks. Due to these timeouts causing the motor controller to enter the PDO timeout fault which causes the interlock to trigger - the CANopen implementation for the motor controller was abandoned due to the risk out lockout.

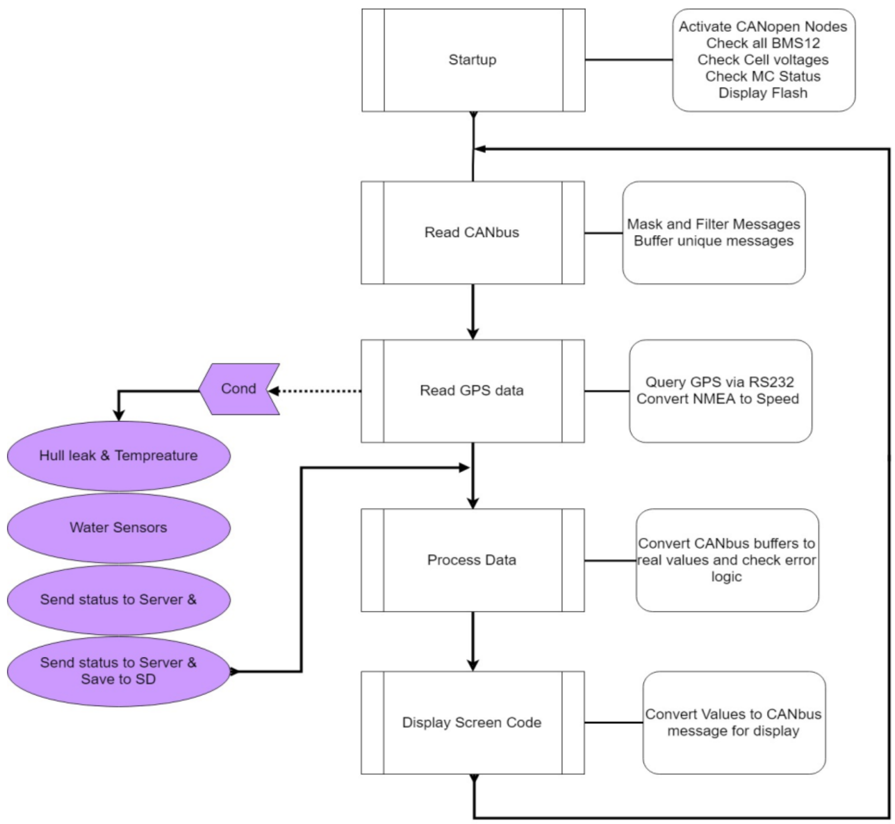

Figure 18 - ECU state machine diagram

Figure 18 presents the state diagram of the code that the ECU Arduino runs, focusing on the CANbus code that runs every loop. It should be noted significant input was provided by the other thesis team members into the conditional elements of the code, as detailed in their respective theses.

3.2.5 ECU CANopen and CAN Filtering

The Arduino Mega 2560 has a relatively slow processor clock speed at only 16Mhz which is suitable for hobby microelectronics projects. The Arduino Mega is able to fulfill the requirements of CANbus processing, although it struggles managing CANopen nodes in addition to processing the HTML packages for the 4G modem. A major part of the future work includes moving to another processor with faster clock speed to greatly reduce the delay allowing the ECU to successfully control the CANopen node without lockouts. One of the optimisations done to greatly reduce lockouts was the use of hardware filtering provided by the MCP2515 CAN **IC**, allowing the hardware itself to pre-filter the CANids prior to interrupting the Arduino with the receive check flag. The introduction of hardware filtering improved the time between updates on the Arduino, as previously the buffer would often be overwritten by ids that the ECU did not use.

Table 2 - CANbus ids of each Module

Node	bit0	bit1	bit2	bit3	bit4	bit5	bit6	bit7	bit8	bit9	b10	DEC	HEX
EVMS	0	1	1	1	1	0	0	0	0	0	0	30	0x01E
Current Monitor	0	0	0	1	0	1	0	0	0	0	0	40	0x028
BMS0a	1	0	1	1	0	1	0	0	1	0	0	301	0x12D
BMS0b	0	1	1	1	0	1	0	0	1	0	0	302	0x12E
BMS1a	1	1	1	0	1	1	0	0	1	0	0	311	0x137
BMS1b	0	0	0	1	1	1	0	0	1	0	0	312	0x138
BMS2a	1	0	0	0	0	0	1	0	1	0	0	321	0x141
BMS2b	0	1	0	0	0	0	1	0	1	0	0	322	0x142
BMS3a	1	1	0	1	0	0	1	0	1	0	0	331	0x14B
BMS3b	0	0	1	1	0	0	1	0	1	0	0	332	0x14C

To create the filters the binary CANids required by the ECU are noted down, then a mask is applied such that there are 6 or less variations in the addresses, and each remainder become a filter. As can be seen from the table above the first four bits were chosen to be ignored, and the subsequent binary strings are categorised into 5 filters. The MCP2515 CAN board uses the following masks and filters for the CANbus:

Table 3 - MCP2515 CAN Filters and Masks for REVski

	bit0	bit1	bit2	bit3	bit4	bit5	bit6	bit7	bit8	bit9	b10	DEC	HEX	Purpose
Mask	0	0	0	0	1	1	1	1	1	1	1	2032	0x7F0	Mask
Filter 1					1							16	0x10	EVMS
Filter 2						1						32	0x20	Current
Filter 3						1			1			288	0x120	BMS0
Filter 4					1	1			1			304	0x130	BMS1
Filter 5							1		1			320	0x140	BMS2,3
Filter 6												0	0x0	Unused

The Bitmask indicates to the filter that the first four bits are to be ignored, and the following 6 bits must exactly match one of the filters. This filter setup reduces the number of addresses the ECU accepts by an order of 27 times, greatly reducing the amount of superfluous CAN messages being loaded into the buffer.

3.3 Display Implementation:

3.3.1 Fuel State Display

One of the limitations of the display was that the fuel gauge was found to be highly quantized - having a total of only 8 states, this meant that the maximum quantization error on the fuel meter is 12.5%. The large quantization error present on the display significantly restricts the low end usability of the fuel meter as a measure of remaining capacity. Due to the limitations of the fuel meter range the fuel level displayed was remapped to show the lowest fuel level at 20% remaining capacity to avoid the user risking total loss of capacity. Once the SoC falls below 20% the display will begin flashing a battery warning error, indicating that the user must either return to shore, if able, or otherwise take emergency precautions. In the case of emergencies where returning to shore isn't possible, the 20% reserve capacity accounts for 16 Amp hours of nominal capacity, which is able to power the DCDC, EVMS, ECU and Bilge pump for a total of 10 hours, exceeding the NSCV standard for emergency reserves of class 1D vessels of 3 hours [19].

3.3.2 RPM Gauge displaying Current

Due to the issues present between the MC CANopen and the ECU; retrieving the motor RPM variable caused additional reliability issues in the craft, thus as a compromise the current draw from the batteries was chosen to be displayed in the RPM gauge. Displaying the current draw provided the user insight into how hard the motor is working, which was found to be an appropriate alternative measure of work to RPM for electric vehicles. Due to the display range of RPM and accuracy of the ZEVA current meter; 0.1A was chosen as the unit measurement to be displayed on the meter, as it maximised viewing range while keeping within the bounds of sensor accuracy and avoided complicating the user's intuition of the metric through more complex calculations. Below are two figures displaying a dry run of the craft drawing 136 Amps, and simulated situation where the EVMS reports below 20% **SoC**.

Figure 19 - RPM Meter displaying 136 Amp Draw, and low SoC warnings presented on display

3.4 ZEVA System

Figure 20 - ZEVA System

Zero Emission Vehicles Australia provides an all in one solution to the safety management of the contactors, charging, and battery management within an electric vehicle. The ZEVA system includes four BMS12 modules, an **E**lectric **V**ehicle **M**anagement **S**ystem (**EVMS**) V3, a 600A Hall Effect current sensor, and an EVMS monitor. The system was purchased an installed within the REVski; with the goals of providing improved cell management, simplifying the safety circuitry, improving the charging method, and improving the consistency and reliability of the systems within the craft. The EVMS functions as a master unit for the BMS12, manages the contactors

3.4.1 EVMS installation

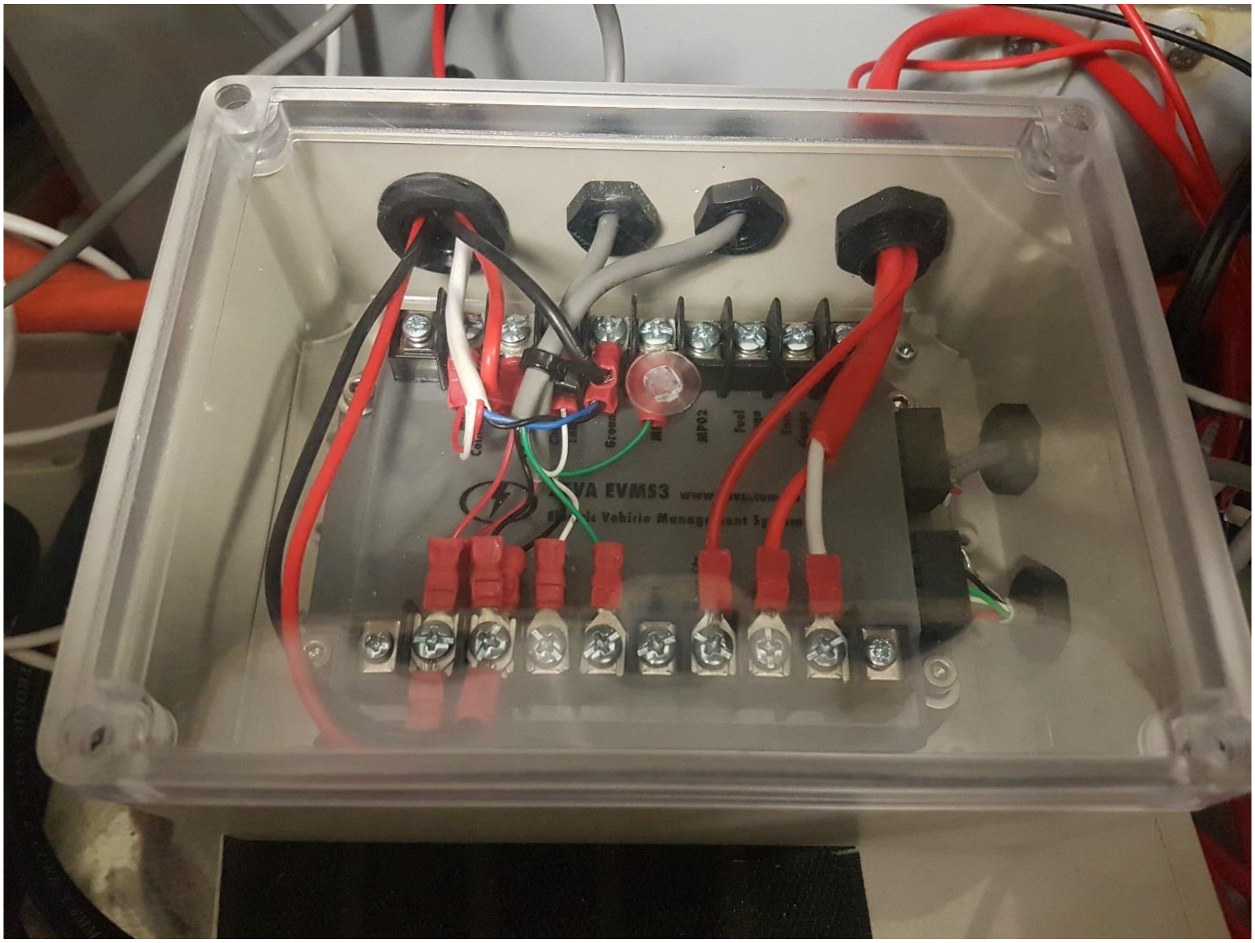

Figure 21 - Mounted EVMS within system

Figure 21 displays the EVMS mounted within a waterproof box within the REVski. The EVMS checks the cell voltages and current reading from the CAN1 port, and relays the CANbus over CAN2 to the EVMS Monitor. Using the current measurements the EVMS is able to integrate the discharged current to estimate SoC, providing information on the total output of the pack since charging, additionally the EVMS monitors the traction circuit to check that the contactors are functioning correctly.

3.4.1.1 EVMS Key & Deadman

As the REVski operates a high powered jet pump the use of an overboard or deadman switch is required for the safety of the user. The EVMS requires a 12V input to signal that the 'key' is in the vehicle, and additionally has an MPO signal that goes to 12V in the case of a fault. A buzzer is also used to signal if the deadman switch is disconnected, or if there is an EVMS fault. The system to handle the EVMS Key and the buzzer is built using two SPDT relays, as shown in figure 22.

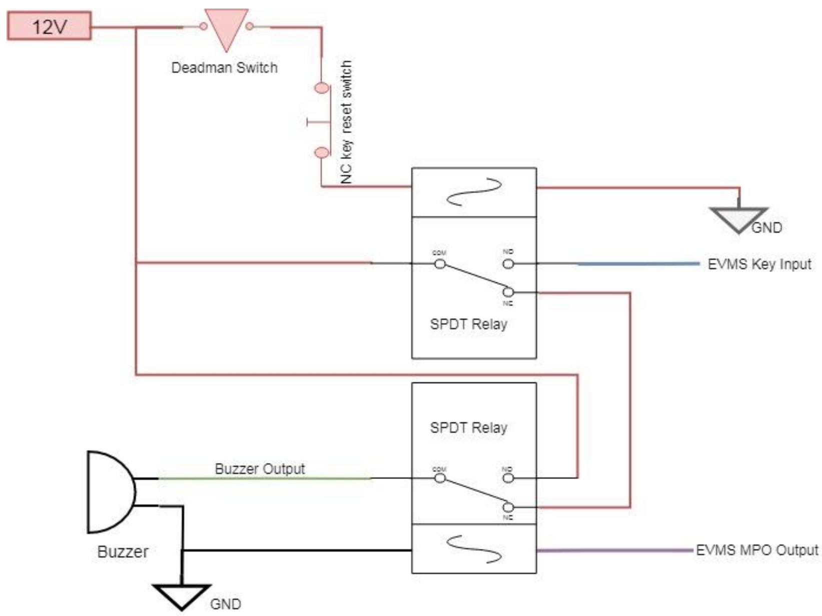

Figure 22 - Deadman Key Relays

As when clearing EVMS errors or entering charging state requires the key to be temporarily disconnected, a normally closed key switch was added on the BMS box to enable the user to easily reset the state without removing the deadman switch.

3.4.2 BMS12 Installation

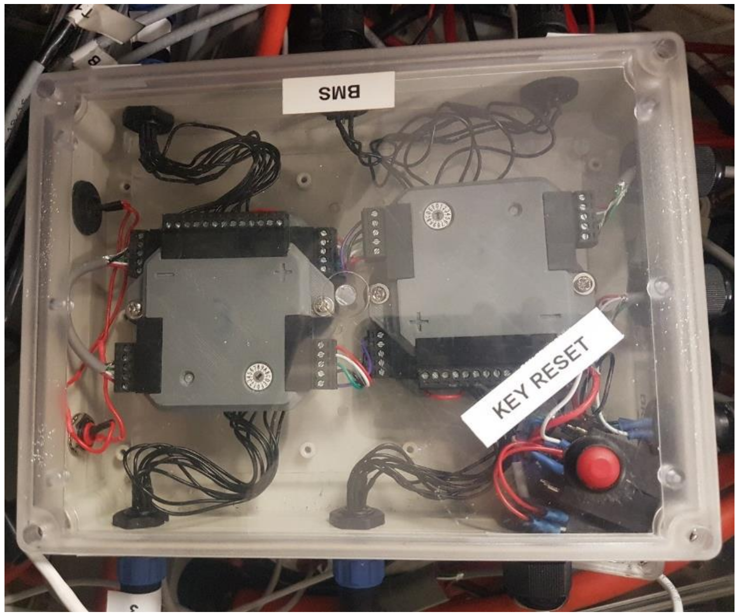

Figure 23 - BMS12 installation inside the REVski

As can be seen from figure 23, the BMS12 installation was done in the previous BMS waterproof box, reusing the balance lead connectors. The BMS12 are mounted in a stacked configuration with rubber grommets providing shock absorption between the units. The CANbus lines are wired in series allowing the CANbus to enter and exit the module without creating branches to the main bus. Additionally the Deadman relay system was included in the BMS box to use the charge reset switch.

The BMS12 modules were mounted using bolts to an acrylic plate, with shock absorbing rubber feet preloading the modules to prevent vibration. The BMS12 units use Molex Eurostyle pluggable screw terminals [20] which have proven to provide reliable connections when properly tightened. This BMS12 configuration has been a significant improvement to the safety and wiring reliability compared to the previous BMS8 installation.

3.4.2.1 BMS12 Battery Installation

The BMS12 modules were installed into the previous BMS box as the balance leads were already broken out allowing the units to be installed easily, though fully use the capability of the BMS12 the units should be installed directly inside the battery tubes. Installing the BMS12 units next to the batteries would greatly decrease the balance lead length, in addition to allowing the units to measure the temperature of the batteries using thermocouples. Installation into the battery tubes initially was rejected due to the time required to access the tubes and the worry of the BMS units draining the battery.

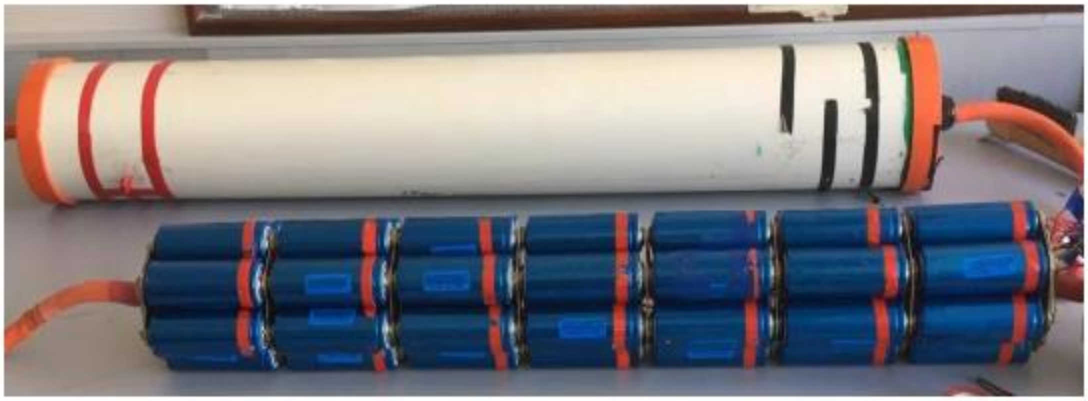

Figure 24 - 38120L Batteries, and Battery Pack Tube [2]

Through discussion with Ian Hooper [21] the total current draw of each unit was found to be only 1Ah over a month while in standby mode, and disconnecting the highest potential balance lead removes the voltage drain entirely. The low voltage drain means that the BMS12 units would take close to 40 months to drain the batteries from the nominal storage voltage [22] to the minimum safe voltage – meaning that the installation of the BMS modules with the batteries would not result in cell damage in a reasonable timeframe.

3.4.3 EVMS Current Sensor

As a part of the ZEVA EVMS state of charge estimation - a current sensor is required; the ZEVA 600A Hall Effect sensor was chosen as the range most closely matched the current draw of the Curtis 1238 Motor Controller. There is a significant safety benefit in using a hall effect sensor over a shunt; as the Hall Effect sensor is contactless there is no chance of voltage transients or current surges damaging the sensor, assuring reliable current sensor measurements. As a trade off from the increased safety compared to current shunts, Hall Effect sensors have a theoretically decreased precision at low current [23], although through observations during charging the accuracy has been within 0.3A or 1.2% compared to the charger readout. The unit was mounted inside the Contactor box; allowing the unit to measure directly from the B- terminal which enables measurement during both running and charging.

Figure 25 - EVMS Current Monitor [33]

3.4.4 EVMS Monitor

The ZEVA EVMS Monitor is not intended to be left inside the craft, as the risk of damaging the screen is considered too high, instead the unit is designed for assisting the user in the setup of ZEVA products, charging, and maintenance. The EVMS Monitor is able to display all the cell voltages and temperatures, in addition to allowing the user access to a setup screen which allows management of BMS and EVMS settings. As a precautionary measure any changes in the EVMS settings should be updated in the ECU code, allowing the ECU to retrieve the settings from the EVMS and check for disparities.

Figure 26 - EVMS Monitor by ZEVA [21]

3.4.5 EVMS Ground Isolation

One of the features included on the EVMS is a chassis ground isolation measurement. The system uses a 200kΩ resistor connected between chassis and the HV circuit, allowing the measurement of isolation. This provides the craft with addition protection against isolation faults which include; damaged wire insulation, a human touching HV rail, or salt water ingress. This functionality replaces the previous BENDER safety module, which for the purposes of the upgraded system architecture has been made redundant by the EVMS.

3.5 Wiring and Safety Standards

In terms of wiring standards AS NZS 3000 is the typically the most comprehensive and relevant standard, providing a generalised best practice wiring guide for most engineering undertakings. Within the REVski project, the AS NZS 3000 does not provide enough specificity and must be expanded and specialised to ensure consistent wiring standards are upheld within the craft. As the majority of issues and faults stem from inconsistency in wiring; a specified and easy to follow best case practice must be reinstated, allowing future work on the REVski to continue with consistent practices in place.

3.5.1 Connector Standards Update:

One of the major updates to the best case safety practices within the REVski includes moving away from the LTW panel mount connectors used previously. Despite finding the LTW connectors to be sufficiently waterproof at IP67, the construction and the usage of these connectors have caused the connectors to be ruled unsuitable for usage in the REVski. The major limitations that make LTW connectors unsuitable are caused by insufficient strain relief on the cables, difficulty in soldering the connector causing bad connections, difficulty in examining solder joints causing delay in fault detection, and the strength and stiffness of the pins was found to be lacking causing bent shorted pins when improperly inserted.

As the issues inherent in the use of LTW connectors within the REVski have caused such large delays due to intermittent faults, an executive decision was made to start replacing any fault involving LTW connectors with a new IP67 connector that was more suitable for the environment within the REVski. Through discussion with both the lab supervisor Marcus Pham and an Altronics store clerk, the waterproof connector solution that the team decided upon included discarding panel mount connectors in favor of passing short cables using ip68 glands [24], and then using inline ip67 connectors with higher build quality to connect between waterproof boxes; the inline connector that was decided upon was the Deutsch brand [25], a comparison between LTW and Deutsch connectors is below:

Table 4 - LTW vs Deutsch Connector Comparison

	LTW	Deutsch
Connector Type	Panel Mount	Inline
Pins	2,3,4,5,6,7,8,(9)[1],18	2,3,4,6, (8,10,12)[1]
Ingress Protection	ip67	ip67
Cost	$26.20 - 42.45 AUD [26]	$7.95 - 18.95 AUD [27]

[1] Available outside Altronics

The connector change is in line with the changes in the updated BMS & ECU system, as the majority of new connections are CANbus connections or relay connections where the 4 pin Deutsch connector are less than half the cost of LTW connectors, additionally providing significant ease of use and reliability benefits. A standard was developed for the Deutsch connectors that specified the order of wires, signals and colours to minimise the risk of using incorrect connectors causing short circuit faults. Below is the tabulated Standard which suits the W3032 shielded twisted pair [28] and W2341 unshielded security cable [29] which are the two common Altronics cables used in the REVski:

Table 5 - Deutsch Connector Standard

Deutsch Connector Standard for REVski		
Pin	Colour	Standard Connection
Pin 1	Red	12V
Pin 2	Black	Ground
Pin 3	Green, (Blue)[1]	CAN Low, Relay Low, (N Low Signals)[1]
Pin 4	White, (Yellow)[1]	CAN Hi, Relay Hi, (N High Signals)[1]
Outer Heat Shrink	White, Blue, Green, Red	CAN1, CAN2 Relay/Signal, Power [2]

[1] Alternative [2] Respective to colour

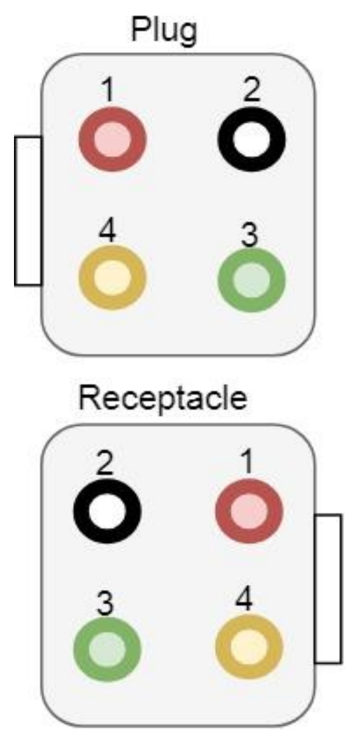

Figure 27 - Cable Standard: Back of Deutsch Connector

Figure 28 shows the standard for a pair of Deutsch connectors; with two forms of cable identification (label and written), and blue outer heat shrink indicating that they are CAN2 cables.

Figure 28 - Standard for CAN2 using Deutsch Inline connectors

3.5.2 Wiring Certification:

In addition to the connector standards changing, an improvement in the quality and accountability of wiring changes should be upheld within the REVski. Part of the reason the craft took so long to get into working order was a range of terrible wiring and soldering practices that resulting in a range of issues including unexpected shorts, broken solder joints, improperly crimped wires causing large resistance, and incorrect pinout between connectors. An example showing the shocking lack of technical skills (or care) in the REVski left by previous years includes the deadman with an LTW panel mount connector, used as an inline connector, with a complete pinout mismatch - meaning the deadman switch only operated by incidental contact with the correct pin due to an excessive length of uninsulated wire.

To prevent such dangerous wiring faults, any future wiring changes undertaken on the REVski should be certified by an appropriate supervisor; in the case for the current REV project Thomas Braunl, Marcus Pham, or Ivan Neubronner. For certification a visual inspection, end to end connectivity test, isolation to ground and power rails, strain relief test, and an updated diagram of changed systems should be submitted, in person or video format to the appropriate supervisor and documented in the REVski drive.

4. Results

4.1 ZEVA system upgrade

The ZEVA EVMS installation was highly successful; greatly simplifying the layout of the craft while providing enhanced safety and reliability. The ability to quickly retrieve the cell voltages and power output from the EVMS Monitor enables improved fault detection and allows the users to track the state of the craft.

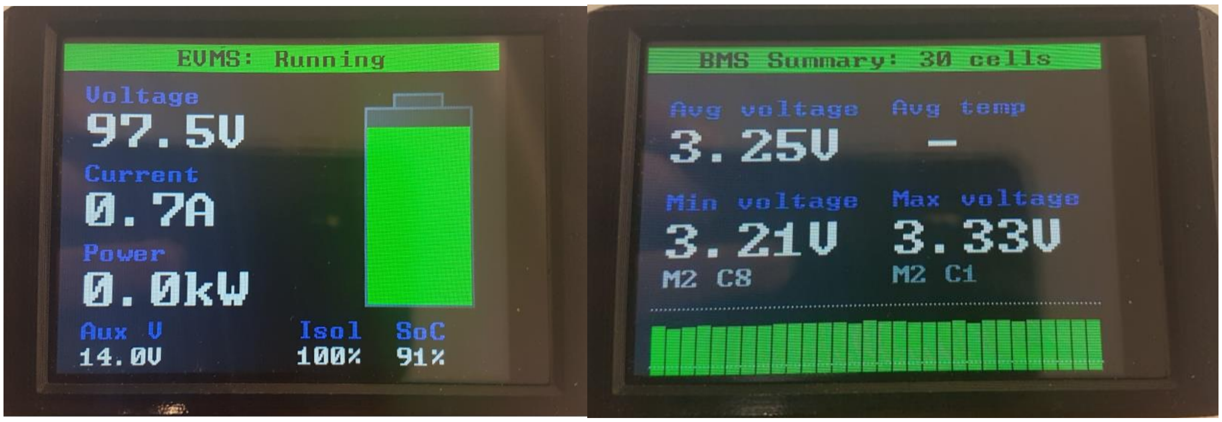

Figure 29 - ZEVA Monitor displaying REVski pack voltages and outputs

The ZEVA EVMS system has additionally proven itself to safely charge the cells by managing both the charger relays and the charger enable and is able to disable the charger, a significant improvement over the BMS8 master module.

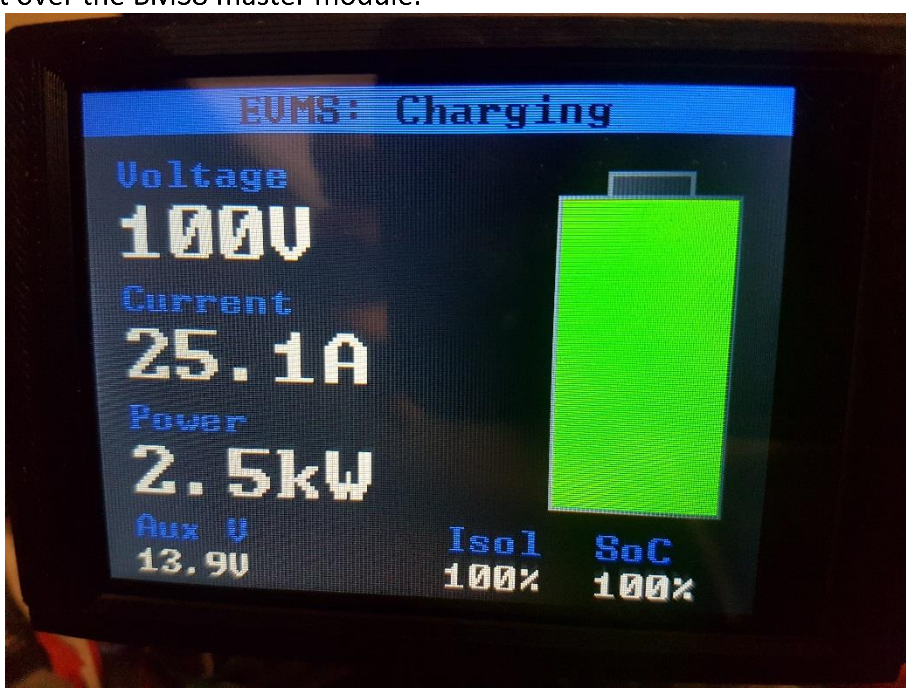

Figure 30 - EVMS monitor during 25A charging

4.2 ECU and Display

The SeaDoo display showing the current draw on the RPM gauge was highly successful, matching the TBS current meter to an accuracy of 1A. The display has a sufficiently high CANbus refresh rate to not cause stuttering or blanking out the screen without the 4G updates, and works with a minor stutter when the 4G module uploads data - blocking the ECU. The EVMS integration to the ECU was highly successful, with the ECU able to read and report on the important variables coming from the EVMS system including cell voltages and the status of the craft directly to the REV project database. Several error states were built into the ECU code that alert the user of faults via the display, such as the low SoC.

4.3 System Reliability & First Water Test

Due to the new ZEVA EVMS system and simplification in the electrical systems in the REVski the reliability of the REVski was found to be greatly improved in a water test. The first test with the ZEVA system was not tracked due to the 4G integration not being up to date with the newly installed EVMS. During the test the GPS speedometer functioned adequately, although provided erroneous readings occasionally. The current reading on the RPM Gauge closely matched the TBS current monitor, confirming that the current reading is sufficiently accurate for use on the SeaDoo display.

4.4 Damaged Cells

It should be noted that throughout the project Cells 22 and Cell 2 were found to drop significantly faster than the rest of the pack, and almost all tests ended when cells 22 and 2 reached the low voltage limit set by the BMS system. The BMS12 system provided the ability to set the safety limit on the EVMS monitor at a lower voltage, accounting for the voltage drop caused by ESR, allowing significantly improved time on the water. Compared to water tests using the BMS8, the time on the water is significantly improved due to the ability to update the low voltage cutoff, as previously the damaged cells would trigger the BMS UV cutout from the nominal pack voltage due to high ESR causing large voltage drops. The results of the ZEVA system in the water test were satisfactory, although the previously damaged cells continue to be a limitation of the craft and thus are required to be replaced in the future.

4.5 Cell Tracking Results:

By reading in the CANbus messages from the ZEVA systems the ECU is able to track a range of variables as the craft is both running and charging, updating the REV project website with the status over the 4g modem. Two charging rates were tested over a short period from the GWL 96V Constant Current charger [30], with the raw data extracted from the REV project website [31] allowing the results to be plotted.

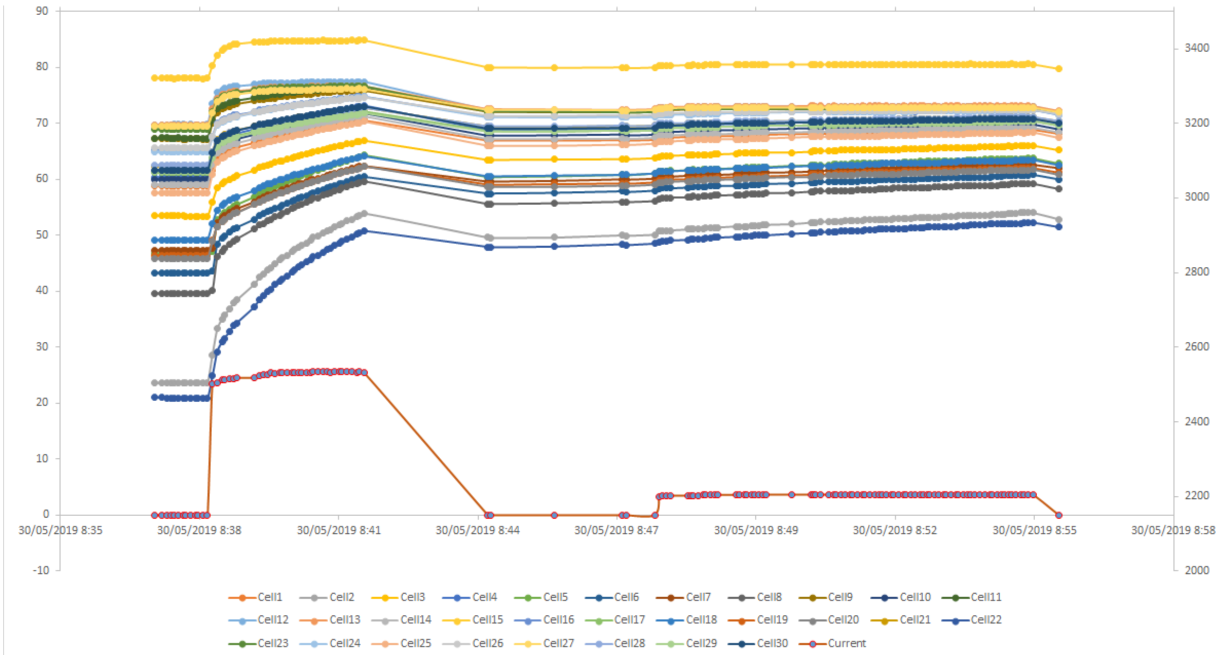

Figure 31 - Cell Voltages (mV) during continuous current charging, at 25A and 3.5A modes

The databased cell voltages provide significant insight into the pack health, by back calculating the voltage drop from OCV due to the current output, we are able to estimate the ESR of the cells. Additionally as the ZEVA system tracks total capacity discharged by integrating the current discharge we are also able to decouple SoC from the previous results which enables a full health report to be generated from the data. Due to the time limitations the scope of this aspect was limited to installing the BMS12 system and sending the data to the database; and future work must be done to extrapolate the results using an extended Kalman filter to extract the required cell health metrics from the database.

5. Conclusion

The REVski BMS upgrades have enabled individual cell tracking, allowing active management of the cells with shunt balancing. The BMS system additionally reports the cell voltages to the REV Webserver, allowing cell health to be extrapolated from the data. The ECU system was greatly improved with new modules and design, allowing the ZEVA EVMS systems to provide a fuel and current reading for the display. Additionally the safety system was improved which greatly reduced the amount of maintenance required between trips. In conclusion the system changes for the REVski have largely fulfilled the desired objectives set out within the objectives at the start of the project; with the REVski functioning far closer to a real product, compared to the disorganised project it started as. The updated architecture of the REVski also provides lessons of the development of future marine vehicles, enabling the REVski to function as a platform for future REV project development into marine electric vehicles.

6. Future Recommendations

6.1 Updated ECU Microprocessor

The Arduino Mega currently running the ECU is highly underpowered for the purposes of real time CANbus and HTML processing, and a microprocessor with significantly higher clock speed should be implemented. Barriers to improving the microprocessor include the requirement of redesigning a custom PCB shield to break out the pins back into the Arduino Mega format, or redesigning a custom interface to the required IC's for controlling different aspects of the system.

6.2 4G update GPS Limitation

The AT240 GPS still does not provide a consistent GPS lock inside the REV lab, causing inconsistent database periods due to the ECU update requiring an accurate timestamp. Based on the limited GPS data available during charging, the ECU should read in the EVMS status and remove the requirement of GPS updates if the EVMS reports it is charging, allowing the cell reporting to be done in combination with the Arduino timekeeping when the GPS is unavailable.

6.3 Implementing a Kalman filter

Implementing an extended Kalman filter was the goal of the data basing of the cell voltages throughout charging and running. While the database already allows rudimentary cell health analysis based on the graphs, a Kalman filter would provide an analytic method directly producing cell health metrics from the data.

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