Autonomous Waverunner – Drive By Wire

Adapting a personal watercraft for remote-controlled application

Bachelor’s thesis at the Department of Electrical Engineering

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Autonomous WaveRunner constitutes a long-standing collaboration between the Swedish Sea Rescue Society (SSRS) and Chalmers University of Technology, founding a series of coherent Bachelor and Master thesis projects.

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Cover: Watercraft being remote controlled using a hand held controller. For more information on the radio link see section 7.

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Abstract

In collaboration with the Swedish Sea Rescue Society, students at Chalmers University of Technology have been working for several years to implement autonomous control of personal watercrafts (PWC) to aid in rescue missions. This project aims to implement the necessary hardware and software for remote-controlling a PWC, thus furthering the development of the autonomous control solution.

The project focuses on designing and implementing a system with emphasis on modularity and robustness. The realised system implementation consists of a centralised bus system connecting several nodes, each responsible for controlling a set of functions in the PWC.

Throttle control was achieved by emulating the control signals sent by the throttle handle. Control over the nozzle thrust vectoring was realised using a stepper motor connected to the steering column via a belt and pulley system. The main benefits of this solution was an adjustable torque and low resistance when controlling the PWC manually.

The solution was tested in the archipelago outside Långedrag and was succesfully remote-controlled, verifying that the system worked as intended with a range exceeding 1 km. The current platform is deemed a robust platform well suited for further developement of the project.

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Dictionary

Other

CAN	Controller Area Network
Drive by Wire(DBW)	A bachelor's thesis at Chalmers University of Technology with the aim to implement the necessary technology to make a personal watercraft remote-controlled.
Electromagnetic log	Rotational sensor using a paddle wheel to measure the speed of the watercraft through the water.
Follow me	Previous bachelor's thesis at Chalmers University of Technology with the aim to make a personal watercraft autonomously follow a leader boat.
Follow the leader	A bachelor's thesis that is working in parallel with Drive-by-Wire and works with the autonomous steering of the personal watercraft.
IP67	Ingress protection for dust and liquid.
PCB	Printed Circuit Board, a unit for mounting electrical circuit components and provide electrical connections between them.
RS422	An electrical specification for a differential serial interface
RR	Rescuerunner, a redesigned personal watercraft used for rescue missions.
SSRS	”Svenska Sällskapet för Räddning af Skeppsbrutne”, also called ”Swedish Sea Rescue Society”. An organisation consisting mostly of volunteers that carry out rescue mission out at sea.
TVS	Transient Voltage Supression
WR	Waverunner, a personal watercraft model from Yamaha.
FMEA	Failure Mode and Effects Analysis, a method to systematically predict the failures that can occur in a system. The method also evaluates the severity of the possible failures.

Drive by wire system

ACU	Acceleration Control Unit
Automatic mode	The mode where the WaveRunner is controlled by external signals through the drive by wire system.
DB1	Data bus 1
DB2	Data bus 2
FMS	Front Mounting System
ICU	Interface Control Unit
Manual mode	The mode of the WaveRunner when it is controlled by a driver through the original system.
NCU	Nozzle Control Unit
OCU	Operator Control Unit

PDU	Power Distribution Unit
RCU	Remote Control Unit
UCU	Utility Control Unit
TCU	Throttle Control Unit

Existing system

APS	Accelerator Position Sensor, a lever that sits on the right side of the steering handlebar and controls the throttle of the jet ski.
ECM	Engine Control Module
Multifunction monitor	The monitor that is located in the front by the steering handle. It shows information such as speed, fuel level, battery voltage and error codes.
RiDE	Reverse with Intuitive Deceleration Electronics, to some extent controls the SCU.
RPS	Ride Position Sensor, a lever that sits on the left side of the steering handlebar and controls the brake and reverse of the jet ski.
SCU	Shift Control Unit, controls the shield that redirects the water jet and makes the WaveRunner brake or reverse.
Shield	A type of cover that can lowered in front of the water jet. This redirects the flow of the water so that it instead of accelerating makes the jet ski brake and reverse.
Trim	Vertical movement of the nozzle

1 Introduction

The Swedish Sea Rescue Society (SSRS) [1] have in recent years in cooperation with Chalmers hosted a few bachelor theses which aim to modify an ordinary jet ski to an autonomous jet ski. This year the project has been divided into two bachelor degree projects, Drive by Wire (DBW) and Follow the Leader. This report is going to be focusing on the Drive by Wire parts.

1.1 Background

SSRS has more than 230 [1] boats that can be used along the Swedish coast. A type of boat that is frequently used is a modified jet ski called Rescuerunner(RR). The Rescuerunner is a specially designed jet ski based on Yamaha's waverunner [2]. SSRS wishes to use the rescuerunner when performing rescue missions because of its many advantages compared to bigger boats. One big advantage is that the RR can be used in really shallow waters [3]. It can also get very close to a person in the water with low risk, which makes it much easier to carry out a rescue mission. The WR is also a very versatile vehicle and it can even be used for towing [4]. One problem with the RR is that it can be very challenging to transport it to the accident scene. Fredrik Falkman, an employee at SSRS, explains that it can be very strenuous to drive the RR to the rescue location. Towing the RR is also an alternative but can be very hard on the equipment, especially when the waters are rough. The space on the main rescue boat is often limited which means that most of the time it is not possible to carry the RR on the leader boat.

To save on both SSRS's equipment and personnel, Chalmers have in cooperation with SSRS started the development of a RR that can autonomously follow the main rescue boat. Earlier projects that have worked with the RR have been called follow me [5]. This year Chalmers has bought a Yamaha Waverunner VX Cruiser HO which will enable the project to be continuously developed as opposed to having to start over each year as earlier. The project has been divided into four parts where two of them will be carried out during the spring of 2019. These two subprojects are called Drive by Wire and Follow the Leader and aims to make the WR remote-controlled and autonomous respectively.

1.2 Purpose

The project aims to implement the technical solutions needed for the WR to be remote-controlled. The solution will be implemented so that the WR can still be driven manually with minimal influence from the remote-controlled system.

The Drive by Wire group has as an internal goal that the project will be sufficiently robust and functional so that there is no need to put any more focus on it. This means that future bachelors will not have to put any focus on the Drive by Wire system and can instead put all their effort into making the WR autonomous.

1.3 Definition of the problem

The purpose was broken down into a number of more concrete technical problems that will be handled during the project:

- Given a control signal the WR should be able to turn, accelerate, brake and reverse.
- The WR should be able to change between manual and automatic control mode.

- The performance and handling of the WR should be minimally affected when in manual mode.
- The project should be sufficiently documented so that it can be built upon by future projects.
- The implementation shall be robust enough that current and future systems can be tested with it.

1.4 Scope

As a consequence of the WR being able to receive radio signals when being remote controlled it can also receive signals from an autonomous system. This system is the system that the Follow the Leader project will develop and can be seen to the left in figure 1.

The technical solution is limited by that it will be developed for a specific personal watercraft, Yamaha Waverunner VX Cruiser HO. This means that the solution will not necessarily work for other personal watercrafts.

The solution is also limited by that it needs to be compatible with the autonomous system that is developed by the Follow the Leader project. Specifically this means that the communication between the systems needs to work according to agreement with the parallel group. The work distribution with the parallel group also means that Drive by Wire will not be implement any position feedback or autonomous steering of the WR. A simplified overview of the technical scope of the project and its relation with the Follow the Leader project and the Waverunner system can be seen in figure 1. A more detailed specification of the interfaces between the systems is presented in section 2.3 and the sections referenced from it.

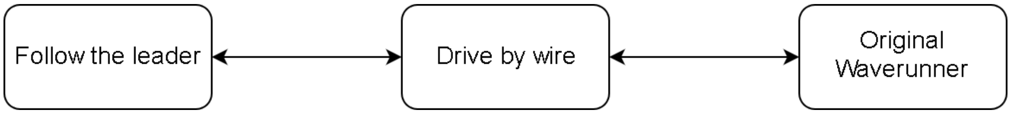


Figure 1: System overview

2 System description and overview

This section of the report serves to give a technical overview of the entire combined remote-controlled Waverunner (WR). The first subsection will introduce the WR as designed by Yamaha, while the rest of this section aims to give an overview of the implemented drive-by-wire system.

2.1 Waverunner overview

The existing platform, the WR, is a high speed water craft power by a water-jet. It's equipped with a 4 stroke combustion engine and a mechanical handlebar in combination with both analogue and digital electronics to perform it's properties[6].

The WR can be divided in different technical systems. In this study the electric and electromechanical systems will be the main perspective. The engine's mechanical properties will therefore not be the main focus [7].

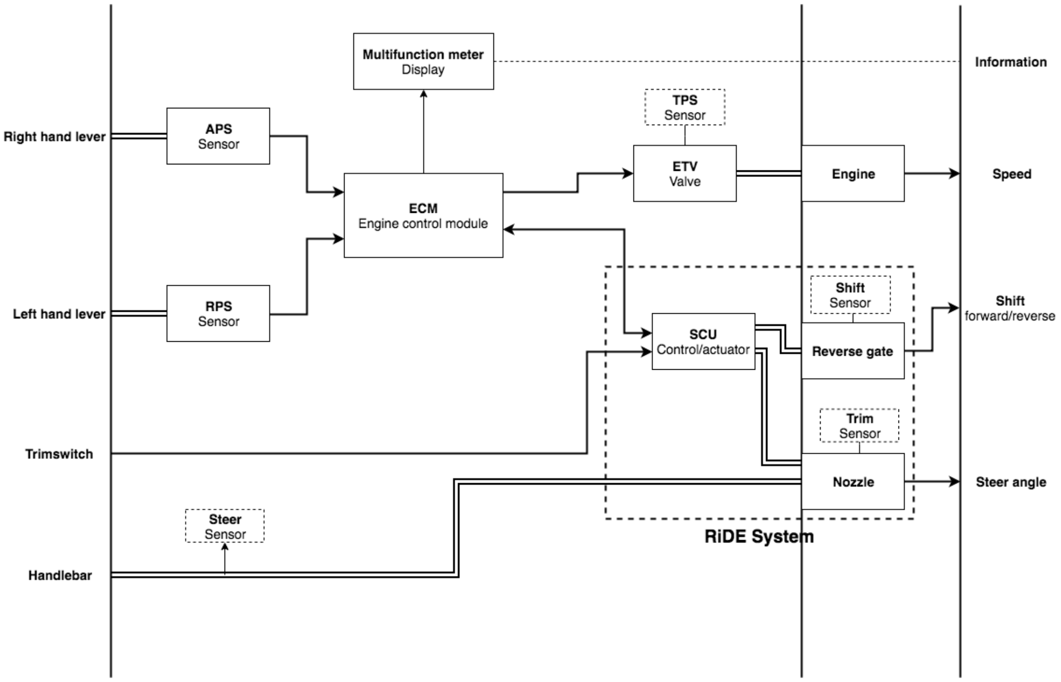


Figure 2: System overview - Original system

In figure 2 the existing electromechanical system is described in a high level perspective, which is derived from research in the Yamaha service manual [7]. All the sensors in the WR are not considered and some system are not treated. Mechanical linkages are represented by double lines and electric signals are represented by a single line and an arrow. The arrow describes the main direction of communication.

The Accelerator Position Sensor (APS) and the Ride Position Sensor (RPS) are components in the handle bar lever to generate signals representing user input. The Engine Control Module (ECM) controls the throttle after signals from APS, RPS and other sensors. The ECM is also connected with the Reverse with Intuitive Deceleration Electronics (RiDE) and thereby affects the control of the nozzle and shifting from forward to reverse. The handlebar is moved by the operator and uses mechanical linkage to steer the nozzle. [7]. More detailed explanation can be found under subsections regarding specific subsystems.

2.2 General system requirements

The project and development of the implemented system must follow directions from the SSRS as mentioned in the introduction. Those directions result in the system requirements regarding shifting between manual and automatic control. The manual mode must not be noticeable affected to retain full manoeuvrability for the SSRS operators when shitfing from automatic control. Requirements regarding a specific subsystem is described under the corresponding subsection.

Table 2: General system requirements

Criteria	**Control method**	**Goal value**	**Priority**
Shifting manual and automatic control	Stress test	Functional	Requirement
Retain functionality in manual mode	Stress test	Min. affected	Requirement
Usable in costal environment	Design review	IP67	Requirement
Controllability of throttle and steer angle	Measurement	>95%	Requirement
Controllability of breake and reverse	Measurement	>95%	Request
Emergency stop functionality	Stress test	Functional	Requirement
Range of radio control	User Test	>250 m	Requirement

Stress testing refers to repeateadly actuating the function multiple times while verifying that the system works as expected. Certain criteria are difficult to test without compromising the system performance, for example the ingress protection rating. In these cases design review has been used as a control methodology. Design review is based on the concept of critically analysing the design and making sure that individual components are qualified for the set requirements and that manufacturer recommendations are followed.

The requirement of an emergency stop functionality will be met by utilising the built in dead man's switch on the WR with an operator present at all times. Care must be taken for this operator to remain alert and prepared to stop the PWC should any fault scenario occur while testing.

2.3 Implemented system design architecture

Based on the problem definition and given external requirements, the task of controlling the WR was divided into multiple modules or nodes. Each specific problem in controlling the WR was thus given its own solution. To facilitate communication between the different modules, they were assigned to one of two Controller Area Network (CAN) data buses.

The first CAN bus, called "Data bus 1" or "DB1" connects high level nodes in the system which are nodes not directly connected to any of the original systems of the WR. The data sent on data bus 1 is primarily commands given from either the autonomous control unit (ACU) of the Follow-the-leader project or the remote control unit (RCU). The other CAN bus, named "Data bus 2" or "DB2" connects all the low-level nodes in the system, i.e, those nodes which are directly responsible for controlling the WR.

The arrived upon system architecture is displayed in figure 3. A brief introduction to each node will be given here, followed by a thorough explanation in each modules respective section of the report. A topological map demonstrating the physical placement of each module in the WR is presented in figure 4

The interface control unit (ICU) is the main controller of the drive by wire system. The primary task of

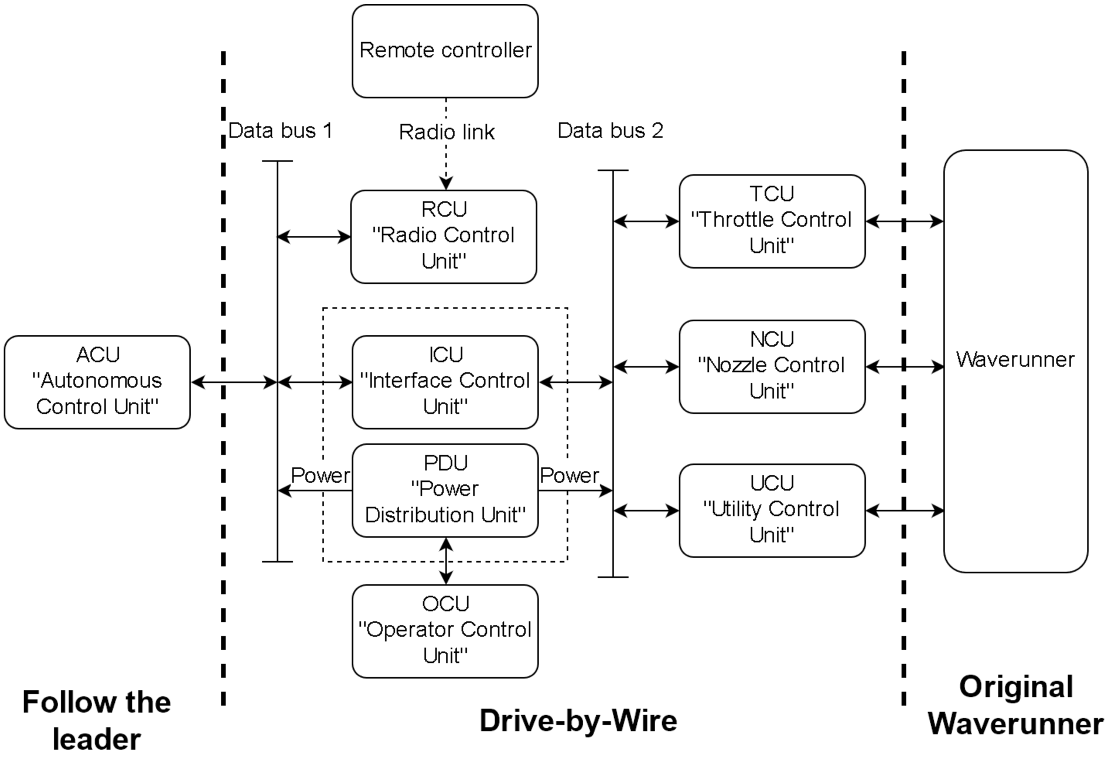


Figure 3: System overview of implemented solution

the ICU is to connect the two data buses to allow messages to be passed between nodes, most importantly steering angle and throttle commands from either the ACU or RCU which are then sent to the appropriate low-level node.

The power distribution unit (PDU) acts as the central node in the power system of the drive by wire system. The PDU connects to the electrical system of the WR at the battery poles and provides multiple separately fused as well as undervoltage and overvoltage protected power lines to the rest of the system. The PDU outputs three main power lines, each with different purposes. A regulated 5 V output is provided as a logic power supply to power the microcontrollers of the nodes on DB2. A 12 V output that is only turned on when the system is in automatic mode is used to switch the nodes into automatic mode. At last, an always on 12 V supply is provided to the high-level nodes on DB1.

The operator control unit (OCU) is directly connected to the PDU and provides a method for the operator of the WR to switch between the manual and automatic modes of the drive-by-wire system. In manual mode, all control of the WR is granted to the operator, while in automatic mode, the control is granted to the RCU or ACU. The OCU also indicates to the operator which mode is currently active via one green and one white led. Furthermore, the OCU is prepared with a usb port and a bi-directional RS422 serial interface to the ICU to be used as a diagnostics and logging port. As the functionality of the OCU is limited and directly connected to the PDU they will both be examined further in the PDU section of the report.

The remote control unit (RCU) adds the ability to control the WR remotely with a radio remote control. The unit interfaces to a radio receiver that is paired to the remote controller and sends any received commands to the ICU on DB1.

The autonomous control unit (ACU) is outside of this project's scope but is described here as a means to

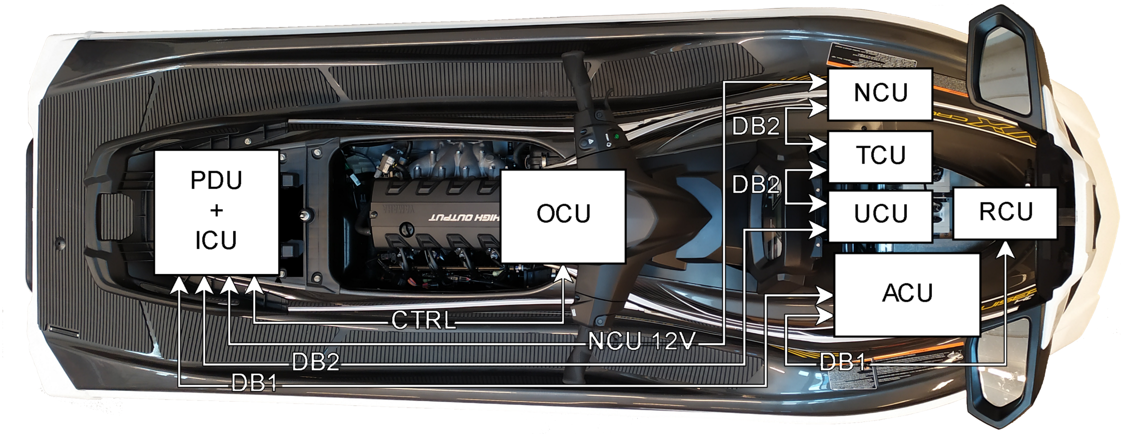


Figure 4: Physical placement and cable routing within the WR

better understand the functional principle of the drive-by-wire system. The ACU will send steering angle and throttle commands to the ICU, much like the RCU, although based on sensor data and gps positions in order to autonomously guide the WR.

The throttle control unit (TCU) is one of nodes interfacing the drive-by-wire system to the WR and is designed to control the forward and reverse throttle. Specifically, the TCU is connected between the two throttle handles and the engine control module (ECM) and can generate its own signals to the ECM based on commands sent over data bus 2. A relay switches the throttle control between the TCU and the two handles based on wether the system is in automatic or manual mode.

The nozzle control unit (NCU) interfaces with the steering mechanism of the WR to provide control of the nozzle in the horizontal plane. A stepper motor coupled with a belt to the steering column axis provides the actuation and an absolute rotary position sensor directly mounted to the steering column provides position feedback. While in manual mode, the power to the motor is disabled, leaving the motor in a freewheeling state where it does not interfere with manual operation.

The utility control unit (UCU) is responsible for the control of several of the WR's peripheral functions, some of which are yet to be implemented. The UCU interfaces to the buzzer of the WR which provides a method to notify the operator of certain events like when the system is switched between automatic and manual modes. The node is also prepared to start and stop the engine of the WR and read out the speed through water as reported by the WR's electromagnetic log.

The front mounting system (FMS), is a modular solution to mount several of the previously mentioned modules in the WR. It is constructed with extruded aluminium profiles which provide a flexible mounting system for the NCU, TCU, UCU and ACU.

2.3.1 Wiring and connectors

The entire finished drive by wire system will involve many different components to function as intended. This requires some foresight when planning out how to design wiring harnesses to connect everything together. Additional challenges are also created from the tough operating conditions with elevated temperatures, humidity and corrosion from salt water.

The circular Lumberg connectors from the 02 series [8] were chosen as the main connector for the wiring in the WR. The circular form factor makes it easy to drill holes for mounting them on different enclosures. Different sizes are used when possible to prevent the user from accidentally swapping the connectors between different functions and systems which should not be connected to each other. Another benefit with this connector lineup is that it is IP67 rated when mated. There are also several different sizes available to meet the entire range of different currents required in the project.

The selection of wires to be used was somewhat limited by the chosen connectors. On DB2 the largest wire size that would fit was 0.5 mm^2 but the current requirements are quite high. To handle the increased self heating, polytetrafluoreten isolated wire was used on all wires with a cross sectional area of 0.5 mm^2 or smaller [9]. PTFE is also useful for having good chemical and abrasive resistance.

A complete list of the wiring between systems is available in table 3. All wires are in twisted pairs except for the power cables going to the NCU. Cable and panel indicates the connector type used from the Lumberg 02 series [8].

Table 3: List of signals in wiring harness

Pin nr.	**Signal**	**Colour**	**Area**	**Fuse**	**Cabel**	**Panel**
AUX - Auxiliary power for future use					0251 02	0271 02
1.	AUX_12V	Red	0.5 mm^2	8 A		
2.	AUX_GND	Black	0.5 mm^2			
NCU 12V					0252 02	0272 02
1.	NCU_12V_AUTO	Red	2.5 mm^2	15 A		
2.	NCU_GND	Black	2.5 mm^2			
DB1 - CAN and power					0251 04	0271 04
1.	DB1_CANH	Blue	0.5 mm^2			
2.	DB1_CANL	White	0.5 mm^2			
3.	DB1_12V	Red	0.5 mm^2	7.5 A		
4.	DB1_GND	Black	0.5 mm^2			
DB2 - CAN and power					0250 06	0270 06
1.	DB2_CANH	Blue	0.5 mm^2			
2.	DB2_CANL	White	0.5 mm^2			
3.	DB2_12V_AUTO	Red	0.5 mm^2	4 A		
4.	DB2_GND_12V_AUTO	Black	0.5 mm^2			
5.	DB2_5V	Yellow	0.5 mm^2	4 A		
6.	DB2_GND_5V	Black	0.5 mm^2			
CTRL - OCU control signals					0250 08	0270 08
1.	CTRL_12V	Red	0.5 mm^2	0.2 A		
2.	CTRL_GND	Black	0.5 mm^2			
3.	CTRL_AUTO_12V	Yellow	0.5 mm^2	0.2 A		
4.	CTRL_RLY_MAN/AUTO	White	0.5 mm^2			
5.	CTRL_TXD+	Blue	0.25 mm^2			
6.	CTRL_TXD-	White	0.25 mm^2			
7.	CTRL_RXD+	Yellow	0.25 mm^2			
8.	CTRL_RXD-	White	0.25 mm^2			

2.3.2 Controller Area Network architecture

The communication between the nodes of the drive by wire system as well as the communication with the Follow The Leader project uses Controller Area Network (CAN) bus systems. There are several reasons that make CAN a suitable communication standard in this case. First and foremost, the CAN bus provides a flexible communication where additional nodes can be added as needed in the future to accomodate additional needs that may arise. Secondly, CAN provides a data link layer that handles payload encapsulation, acknowledge signals, checksums as well as a bus access method with the ability to prioritize messages based on their ID[10]. Finally, CAN uses differential signaling which provides a high common mode rejection ratio which is necessary for robust communication in rugged environments [10].

CAN hardware architecture

The CAN standard specifies a maximum bit rate of 1 Mbps, called high speed, for bus systems with lengths not exceeding 30 m [10]. As the combined length of each databus in the WR is approximately 5 meters, far less than the maximum length, the maximum bit rate was chosen.

Furthermore, the use of high speed CAN requires the use of 120 Ω termination between the differential pair at each end of the bus to minimise reflections [10]. This is implemented in one end of both data bus 1 and data bus 2 with resistors on the ICU circuit board. For data bus 1, the other termination is connected at the RCU circuit board. As can be seen in figure 4, any additional nodes on data bus 1 should thus be placed between the ICU and ACU or between the ACU or RCU. Data bus 2 is terminated using a spare connector with only a resistor. As each node on data bus 2 except the ICU has two bus connectors connected in parallell, adding an additional node only requires an additional bus cable and that the termination connector is placed at the output of the last node.

CAN message architecture

Each command or dataset that is sent over CAN has its own CAN message identification (ID). A message ID allocation plan has been created to coordinate the use of message IDs between different nodes. The plan was created to enable simple use of hardware CAN filters on the nodes which filter out any messages that are not relevant to that node. For node number $i = 0, 1, ..., 15$ only messages with id $i + n \cdot 16, n \in \mathbb{N}$. are received. For example, as can be seen in table 4, the UCU is only interested in messages 2, 18, 34 and 66. This is achieved by setting a can filter id in the node to 0b0000000010 (2) and the filter mask to 0b0000001111. This way, the four least significant bits (LSB) of an incoming message id are compared to the four LSB of the can filter id by the can controller, and only if these match will the message be handled in the software of the node.

An additional point of interest regarding the CAN messages is the transmission of larger than 8 bit values. As a CAN message is divided into multiple 8 bit words [10]., data with a longer word length has to be split into multiple parts. This can be seen in table 5 where ”Data [0]” and ”Data [1]” of message id 49 are combined to form a 16 bit uint. In all such cases, the most significant byte is transferred in the byte with the lower number to make sure that all nodes receive and transmit these values in the same way.

CAN software architecture

As the task of reading and writing to the CAN bus is a common central function of all nodes, a CAN software template was developed in order to significantly reduce the time needed for the programming of each node. The basic structure of this template can be seen in figure 5 which also depicts the flow of can messages to and from the ICU. In the main program, the CAN bus is started and an interrupt routine is attached to the CAN receive interrupt vector, causing any incoming messages to run the CAN interrupt

Table 4: Overview of implemented can messages on data bus 2. Note that 16 bit values span two 8 bit data objects.

Message	**ID**	**Nodes**	**Data[0]**	**Data[1]**	**Data[2]**	**Data[3]**
Reqeust status	0	ICU to TCU	uint8 (5)	-	-	-
Request status	1	ICU to NCU	uint8 (5)	-	-	-
Request status	2	ICU to UCU	uint8 (5)	-	-	-
Status response	16	TCU to ICU	uint8 (1=ready)	-	-	-
Status response	17	NCU to ICU	uint8 (1=ready)	-	-	-
Status response	18	UCU to ICU	uint8 (1=ready)	-	-	-
Command throttle	32	ICU to TCU	uint16 APS (0.01 %)		uint16 RPS (0.01%)	
Command position	33	ICU to NCU	int16 angle (0.01 °)		-	-
Command horn	34	ICU to UCU	uint16 duration (ms)		-	-
Engine on/off	50	ICU to UCU	uint8 (1/0)	-	-	-
Request log speed	66	to UCU	uint8 (5)	-	-	-

Table 5: Overview of implemented can messages on data bus 1. Note that 16 bit values span two 8 bit data objects.

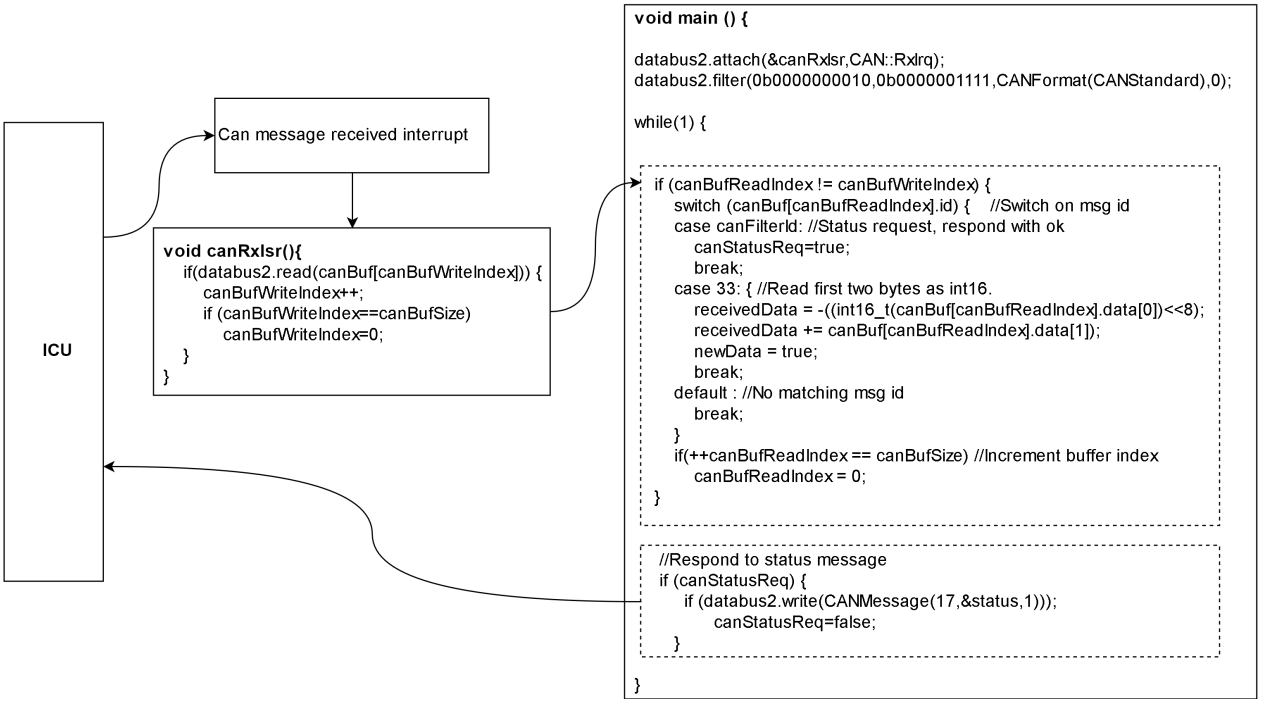
Message	**ID**	**Nodes**	**Data[0]**	**Data[1]**	**Data[2]**	**Data[3]**
Request status	0	ICU to RCU	uint8 (5)	-	-	-
Request status	1	ICU to ACU	uint8 (5)	-	-	-
Status response	16	RCU to ICU	uint8 (1=ready)	-	-	-
Status response	17	ACU to ICU	uint8 (1=ready)	-	-	-
Command throttle	32	RCU to ICU	uint16 APS (0.01 %)		uint16 RSP (0.01 %)	
Command throttle	33	ACU to ICU	uint16 APS (0.01 %)		uint16 RSP (0.01 %)	
Command angle	48	RCU to ICU	uint16 Angle (0.01 °)		-	-
Command angle	49	ACU to ICU	uint16 Angle (0.01 °)		-	-

service routine. Additionally, a filter is activated, making sure that the software only has to handle relevant messages. The rest of the template is structured as a state machine as this makes it possible to fully test how the software handles all scenarios [11]. Another advantage of the state machine is that it's inherently non-blocking, meaning that the node will always be ready to handle incoming data or other tasks assigned to it with low latency.

When a message is received in the interrupt routine it is stored to a buffer and a global buffer index is incremented. Meanwhile, in the main program, this buffer index is monitored for changes which means that a new message has been received. As all messages are uniquely identified by their ID, the software then uses the ID to decide what should be done with the data in a switch-case block. Some messages, like the status request message, warrant a response from the node. This is handled using the state machine logic by setting a status request flag high, which will be reset when the status response has been successfully sent. This approach makes sure that the node does not wait for the response message to be sent in case the bus is written to by another node, which can cause latency. Instead, the node is free to handle other tasks until the bus becomes available.

2.3.3 Micrcontroller board

The microcontroller used in all modules except for the ICU is the Nucleo-F303K8. It is an STM Nucleo-32 which uses an STM32F303K8T6 microcontroller unit. This is an Arm Cortex-M4 with an operation frequency of 72 MHz, floating point unit, 64 kbytes of flash memory, 3x DAC outputs and CAN support[12].



```
void canRxIsr(){
    if(databus2.read(canBuf[canBufWriteIndex])) {
        canBufWriteIndex++;
        if (canBufWriteIndex==canBufSize)
            canBufWriteIndex=0;
    }
}
```

```
void main () {

databus2.attach(&canRxIsr,CAN::RxIrq);
databus2.filter(0b0000000010,0b0000001111,CANFormat(CANStandard),0);

while(1) {

  if (canBufReadIndex != canBufWriteIndex) {
      switch (canBuf[canBufReadIndex].id) {    //Switch on msg id
      case canFilterId: //Status request, respond with ok
          canStatusReq=true;
          break;
      case 33: { //Read first two bytes as int16.
          receivedData = -((int16_t(canBuf[canBufReadIndex].data[0])<<8);
          receivedData += canBuf[canBufReadIndex].data[1]);
          newData = true;
          break;
      default : //No matching msg id
          break;
      }
      if(++canBufReadIndex == canBufSize) //Increment buffer index
          canBufReadIndex = 0;
  }

   //Respond to status message
   if (canStatusReq) {
       if (databus2.write(CANMessage(17,&status,1)));
            canStatusReq=false;
      }

}
```

Figure 5: Logic flow of can messages from ICU to a node and from a node to the ICU.

It should be more than enough for most of the modules in the drive by wire system. It also uses the same footprint as the Arduino Nano. There are several reasons for not choosing the more popular Arduino line of microcontrollers. STM provides several development boards that are cheaper, more powerful and features in a compact size than most Arduinos. It is also possible to not use a development board in the future but for this project is has several advantages. The STM Nucleo-32 comes with an on board debugger and programmer, this allows programming and debugging software by just connecting a USB cable. It can of course be replaced by just the microcontroller unit and the necessary circuit around, but then it would need an external programming unit. However if the drive by wire system is to be used in a RR in the future, then the development boards needs to be replaced since it is not allowed to use Nucleo boards in commercial products[13].

2.3.4 Enclosure

By recommendation from Fredrik Falkman from SSRS all of the hardware should be enclosed in hardware meeting the IP67 standard. This to withstand dust and temporary immersion [14]. An increased internal pressure due to temperature differences can also damage the seal of the enclosures which can render it unusable. This can then damage the internal electronics in the box. The solution for this is to have a Gore vent which is also recommended by Falkman[15].

3 Interface control unit

The main task of the ICU is to act as an interface between the higher level follow the leader system and the drive by wire implementation. From a hardware perspective the ICU is quite simple as it's based on a Nucleo-F446RE development board with an additional circuit board connected to the expansion header. The expansion board connects the ICU to DB1, DB2, PDU control signals and to the OCU via a serial connection over RS422. There is also a USB connector available on the enclosure for updating the firmware and accessing a serial console to read debug messages and issue commands to the system. The system is provided standby power from a separate 5 V linear regulator on the PDU. A complete schematic can be found in the appendix 54.

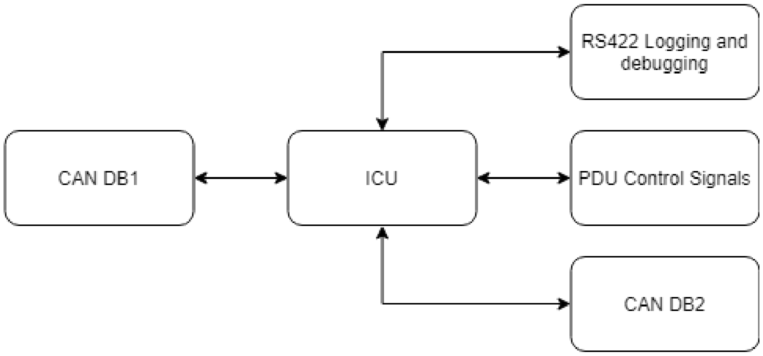


Figure 6: Simplified block diagram of ICU hardware

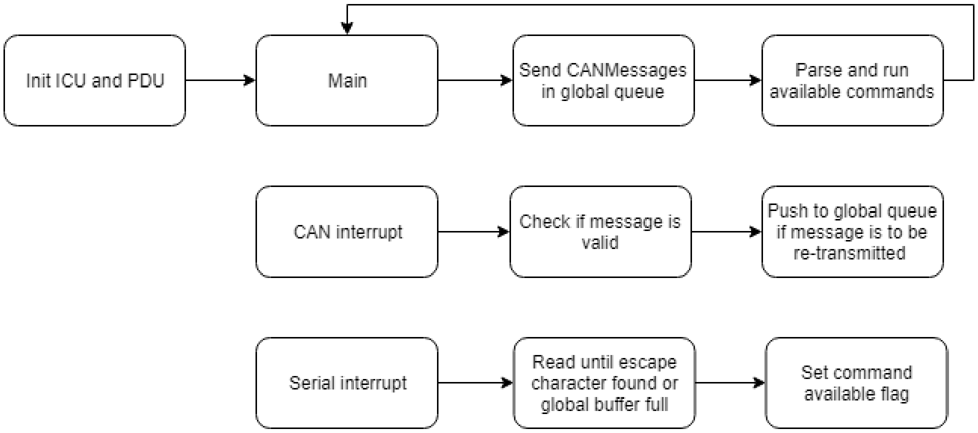


Figure 7: Software flowchart for ICU

The program structure is based around a main loop that polls different tasks and runs them if required. Interrupts are used to update status flags for the tasks in the main loop. An attempt has been made to design the code in a modular way with replaceable interfaces to simplify future changes in the firmware.[16]

The serial port is configured with a baud rate of 115200 bits per second, 8 data bits, 1 stop bit and no parity. The current configuration doesn't have any functionality for editing commands as they are typed and doesn't echo the input back so it's recommended to enable local echo in the serial terminal. Additional commands can be added but the current code is not designed to parse any other arguments than an unsigned int follow by eight hex bytes. The command string also need to be three characters long to be considered valid.

If new subsystems need to be added to either DB1 or DB2 the ICU software implements a canNode class

Table 6: List of available commands from ICU serial port

Cmd	Description	Example
DB1	Adds message with ID and Data (bytes hex) to send queue	DB1 5 FF AA
DB2	Adds message with ID and Data (bytes hex) to send queue	DB2 5 FF AA
PD1	Enables (1) or disables (0) printing of received messages on DB1	PD1 1
PWR	Enables (1) or disables (0) power from PDU	PWR 1

that allows for simple additions of additional nodes. Adding another node is done by calling the constructor for the canNode class and specifying which ID:s should be sent to the node. The added canNode will then continuously check the output queue associated with it and output any matching messages on the CAN bus.

The ICU is currently functional enough to enable testing of the other subsystems. Features that are planned in the future are more advanced logging functionality and a flexible way to implements actions based on the activity on either DB1 or DB2. One suggestion is to add a list of callback functions associated with each canNode object.

4 Power distribution unit

The PDU is the system responsible for delivering power to all other subsystems that this project has added to the WR. A system with corresponding functionality has not been included in previous work done in earlier projects so a solution had to be developed from the ground up. This section will cover the main considerations that drove the design, an overview of the system and what needs to be taken into consideration if future subsystems are to be added to the WR from an electrical power perspective.

4.1 Requirements

The main requirement for the PDU is to supply all other subsystems with reliable power. As a lot of expensive equipment will be connected to the power system originating from the PDU it is also important to provide them with solid electrical protection. ISO 7637-2 [17] is a standard for 12 V vehicle system that has been used as a reference when designing transient and overvoltage protection. Multiple of the tests specified in ISO 7637-2 are time consuming and require specialised test equipment. When possible, similar test will be performed to evaluate the system. It is also useful to look at application notes with reference designs and components that are already qualified for requirements specified in ISO 7637-2 to minimise the risk of design errors.

Table 7: Requirement specification for PDU

Criteria	**Control method**	**Goal value**	**Priority**
Transient protection	Design review	ISO 7637-2	Requirement
Overvoltage protection	Design review/test	ISO 7637-2	Requirement
Reverse polarity protection	Design review/test	ISO 7673-2	Requirement
Supply current subsystems	Test	Pass/fail	Requirement
Power margin for future additions	Test	150 %	Request
Switch power off for manual mode	Design review/test	Pass/fail	Requirement

4.2 System overview

The functionality described in the criteria above can be implemented with a few different functional blocks that can be seen in figure 8. Splitting the implementation into different blocks simplifies the design process as the blocks can be tested and verified separately.

The protection circuitry is based around an LTC4365 [18] with two back-to-back n-channel mosfets as the series pass element. This provides under- and overvoltage protection but an additional transient voltage suppression (TVS) diode is needed to protect the mosfets from fast voltage spikes. [19] The TVS diode needs to be sufficiently large to absorb the energy generated during a load dump scenario, where the energy of the alternator is applied to the supply rail in an uncontrolled way, so that the main fuse breaks before the diode overheats. The demands are somewhat alleviated by choosing a high clamping voltage that will reduce the current.

A latching relay circuit, seen in figure 9, has been constructed to enable switching from manual to automatic mode. Not shown in the schematic is a logic level mosfet connected to the low side of the relay coil that can enable and disable relay operation. A TVS diode has been used to protect the relay coil from arcing and the mosfet from exceeding the maximum allowed drain to source voltage [20].

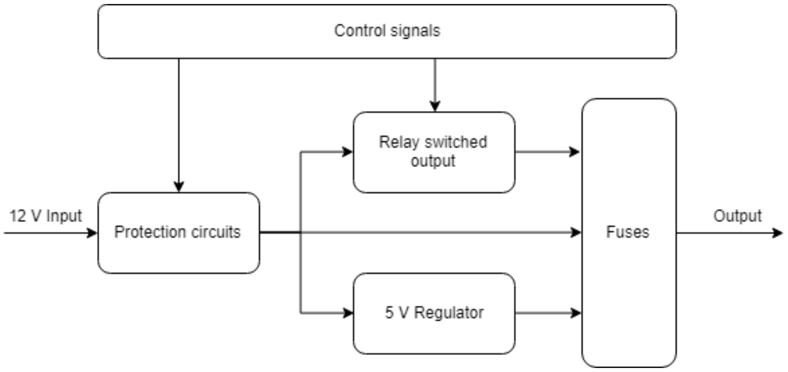


Figure 8: Simplified block diagram

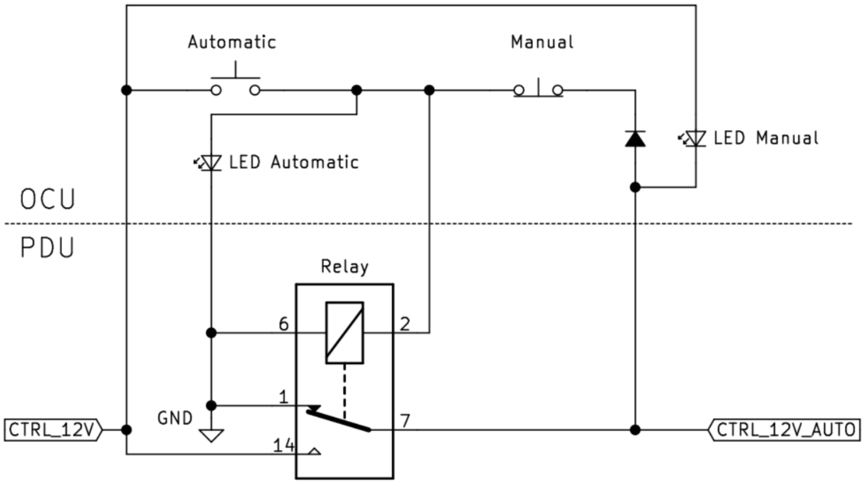


Figure 9: Latching relay circuit for control of switching between manual and automatic mode

Also implemented is a hall effect current sensor and a voltage divider with zener diode clamping to allow simple measurement of total current and input voltage respectively.

4.3 Designing for high current

The dimensioning of the PDU was based on a rough estimation of the maximum current the system could use. This has been compiled in table 9 and adding the current consumed result in a net current of 30 A. It is probably not realistic that all systems will consume their maximum current continuously at the same time but 30 A was selected as a design target to provide some margin.

The main limiting factors on how much power the PDU can provide to existing and future systems are thermal, both the circuit board substrate and components will get damaged from getting to hot. Initial testing with a resistive load inside the PDU enclosure gave a thermal resistance from case to ambient of approximately 2.2 $°C/W$. With the losses specified in table 10 this would result in an enclosure temperature at least 31 $°C$ above the surrounding ambient. The ambient temperature in the WR with the engine running has not been measured but an estimate of 50 $°C$ would put the inside of the enclosure at over 80 $°C$. The circuit board itself would also have hot spots that reach even higher temperatures.

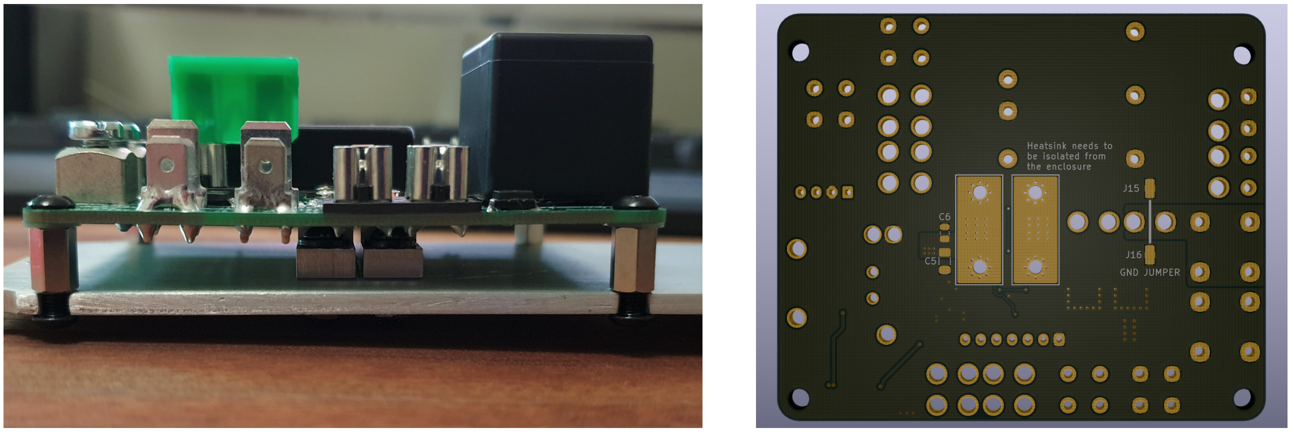
Table 8: List of control signals connected to PDU

Signal	**Type**	**Purpose**
I_SENSE	Analogue output	Voltage proportional to current through PDU
V_SENSE	Analogue output	Voltage proportional to PDU input voltage
$\overline{\text{FAULT}}$	Digital output	Indicates voltage out of range and output disabled
$\overline{\text{SHDN}}$	Digital input	Disables output when pulled low (not to be driven high)
ENABLE	Digital input	Connected to mosfet that enables relay operation
CTRL_RLY_MAN/AUTO	Input	Return from OCU connected to relay coil
CTRL_AUTO_12V	Output	Connected to NC switch in OCU
CTRL_12V	Output	Connected to NO switch in OCU

Table 9: List of estimated current consumption and resulting losses

Subsystem	**Power**	**Current at 12 V**
NCU	120 W	10 A
DB1	120 W	10 A
DB2	60 W	5 A
AUX	60 W	5 A

A number of actions were taken to improve the thermal performance. 70 μm copper was chosen to decrease resistive losses and improve the thermal conduction through the pcb. The two mosfets produce a lot of heat in a small area so an attempt has been made to conduct the heat away from the board using thermal spacers made from aluminium. The thermal spacers are placed directly under the two mosefets and heat is conducted through the board using a grid of thermal vias[21] as can be seen in figure 10b. The thermal spacers are connected to the enclosure mounting plate but are electrically isolated using thermal washers to prevent the mosfets from shorting out. The mounting plate helps to both conduct the heat through the enclosure and to distribute the heat for an more even dissipation.



(a) Circuit board with thermal spacer, view from the side

(b) Bottom side of circuit board

Figure 10: PDU Thermal solution

Table 10: List of estimated losses at 30 A current consumption

Type	**Power lost**	**Assumptions**
Resistive	9 W	Assumes 10 mΩ
Linear regulator	1 W	
Switching regulator	1 W	
Mosfet on resistance	3 W	Assumes a total of 3.2 mΩ

4.4 Testing and consideration for future additions

The full assembly of both the PDU and ICU can be seen in figure 11. The design of the PDU was mostly error free except for two incorrect footprints that could be fixed by reworking the board, see PDU schematic in the appendix 71 for details. An extra fuse and connector has been left unused to allow for extra power for a future subsystem outside the envelope of DB1 and DB2.

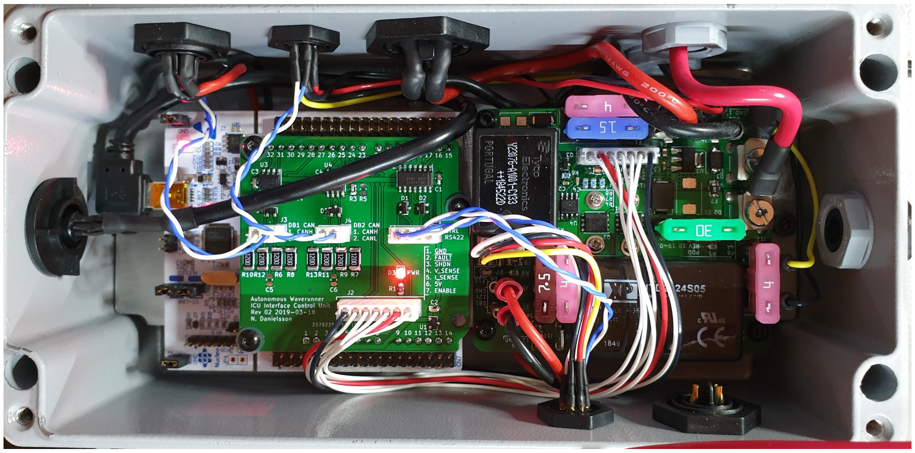


Figure 11: PDU and ICU assembled together

The LTC4365 protection circuit has been tested for both undervoltage and overvoltage conditions. The yellow trace is the input signal and the LTC4365 is only enabled within the interval of 5 V to 15 V. No testing has been performed on reverse polarity or transient suppression but the PDU has operated without problems during multiple test connected to the entire system.

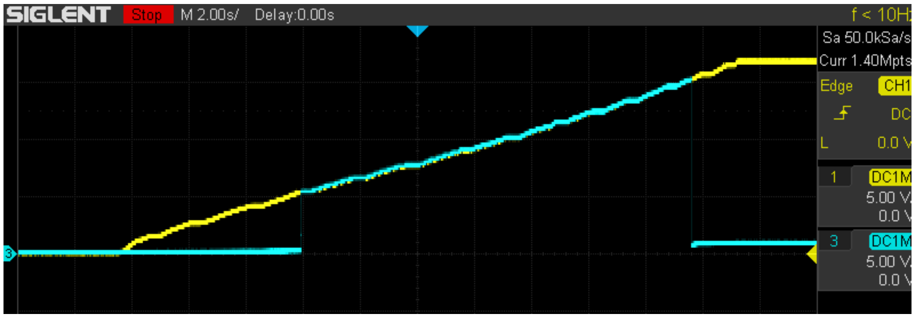


Figure 12: Testing of LTC4365, 5 V per division

The main considerations moving forward is that the thermal performance of the system still is not fully evaluated. It is also a possibility that the WR battery and generator could be a limitation if additional loads need to be added to the system. Another concern with sharing battery with the WR is that to high of a standby power consumption quickly discharges the battery. Possible solutions to this problem include utilising the LTC4365 soft switch function or adding a physical battery disconnect switch.

5 Nozzle control unit

The WR is equipped with a water-jet located in the far back of the craft. This type of water-jet uses a nozzle for both steering and accelerating. By turning the steering handlebar the nozzle will be angled differently and will work as a thrust vector control for the WR. Unlike a rudder the nozzle can't turn the WR without being powered up which means that the whole vehicle will accelerate while it is turning.

5.1 Original system

The original steering in the WR uses mechanical solution to transfer steering angle between the steering handlebar and the nozzle. In this case a steering wire is connected to the steering shaft which is then connected to the steering handlebar itself. The other end of the steering wire is connected to the nozzle.

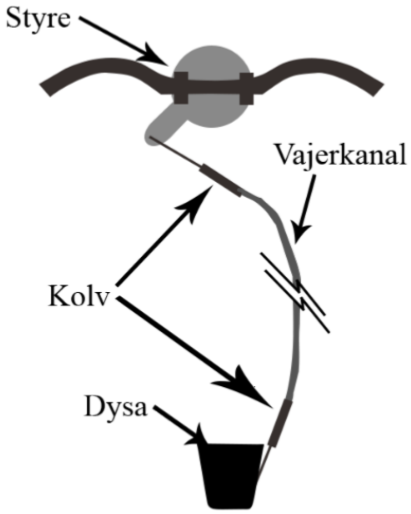


Figure 13: Construction connecting the steering wire with the steering shaft, from [22]

The mechanism that connects the steering shaft and the steering wire can be seen in figure 13. By turning the handlebar the metal arm that sticks out will pull or push on the steering wire. This will the make the nozzle angle itself so that the WR turns in the desired direction.

The original system has a steering angle of 26.4° in both directions on the steering handlebar. Because of the positioning of the steering wire the nozzle can turn 24° in both directions.

5.2 Earlier solutions

Similar projects have been done a few times before and previous years have all used different solutions for steering the WR.

In 2018 a solution where an electric motor together with a gearbox was directly connected to the drive shaft was developed. By turning the axis on the motor the WR would also turn. In combination with the motor a disc brake was mounted between the connection of the motor and the drive shaft. This made it possible to disconnect or connect the motor from the drive shaft by making the brake either clamp together or release [5].

In 2016 a system was implemented where the steering wire was disconnected from the steering shaft. The wire was instead connected to a linear actuator that pulled or pushed it. Since the steering wire and the steering shaft are not connected a rotary position sensor was used to measure the angle of the steering handlebar. Provided that the system was in manual mode, the angle would then be sent electrically to the linear actuator, which would then angle the nozzle to the desired angle [23].

The bachelor group of 2015 developed a solution using a drive belt and a motor to turn the steering shaft. A drive belt and pulleys was used to connect the motor to a metal rod that itself was connected to a metal arm on the steering shaft. This meant that when the motor turned it pushed or pulled the rod which then adjusted the steering shaft and therefore also the craft. A linear motor that pushde on the drive belt was used to switch between manual and automated mode. By tightening the belt the system would enter automated steering and by releasing the belt it would enter manual mode [22].

5.3 Requirements and requests

Since this bachelor's project is in cooperation with the SSRS a number external requirements are present. The SSRS only have two requirements, which are that the WR has to be able to switch between manual mode and automatic mode. It's also very important that the manual steering is not impacted by the NCU. Our contact person to the SSRS, Fredrik Falkman, also wished for a way to change modes on the WR. This is very important because at any time the rescuers may need to take control of the WR in case of emergency. Because lives are at stake the mode change has to work. When the rescuer has control of the WR it is not good if the NCU impacts the steering in any way. Any risk that the steering becomes harder to turn or gets stuck is not allowed.

The group has also internally produced a number of criteria for the steering system. All of the criteria were set through discussions in the group. Afterwards there were also some comparisons to the criteria of previous bachelor projects. The set criteria can be seen in table 11.

Table 11: Requirements and requests on the steering system

Criteria	**Control method**	**Goal value**	**Priority**
Usable steering angle	measurement	>95%	requirement
absolute precision of steering angle	measurement	<5%	requirement
absolute precision of steering angle	measurement	<2%	request
steady state error	measurement	<5%	requirement
steady state error	measurement	<2%	request
turning time over the whole steering angle	measurement	<1 s	requirement
turning time over the whole steering angle	measurement	<0.5 s	request
function that changes between manual and automated steering	assessment		requirement
minimal impact on the manual steering	testing	Yes	requirement
steering of nozzle in the vertical plane	testing	Yes	request
change to manual mode when electrical outage occurs	testing	Yes	requirement
The robustness of the construction	assessment	Yes	request
Easiness to construct	assessment	Yes	request

The usable steering angle of the WR is important for the automated system. It can perform better if it can do steeper turns. But it is also important to take into consideration that it is not necessarily good if the steering reaches all the way to the maximum angles. This is because the motor that rotates the steering shaft may damage the construction if it hits or presses against the end points with either high force or high velocity.

The precision of the steering angle is important for the parallel bachelor group. The performance of the automated steering depends on the precision and performance of the internal systems in the WR. An even higher precision was set as a request.

The steady state error refers to any mechanical or external problems that may cause any backlash in the system. This could affect the systems ability to correct any fault in the steering angle.

A fast turning time is necessary for the reaction time of the WR. The waves and direction of the leader vessel are constantly changing the and WR needs to be able to react and keep up with the changes in its surroundings.

Steering of the nozzle in the vertical plane is not necessary for the WR to work. Later on in the project it was discovered that the nozzle could not be controlled in the vertical plane on the WR. Therefore no solutions for steering it will be developed in this project. If it is possible it would be something that may be interesting for continued development of the WR.

It is very important that the steering system is able to switch to manual mode even if something in the electrical system has gone wrong. By having the WR always go back to manual mode when experiencing problems this can be solved. This means that a rescuer can take over control of the WR and drive it as normal if something has gone wrong with the electrics.

The robustness of the system refers to how it handles the tough conditions that occur when the WR drives. It is unavoidable that water will leak into the boat and the technology needs to be able to withstand it or be protected from it. Fredrik Falkman from SSRS mentioned that IP67 is what SSRS aim to use in their equipment. When a craft as small as a WR drives through waves it will jump around a lot. Therefore all the equipment will need to be able to withstand large and frequent impacts.

The solution that is developed for the steering will not only aim to be robust but also as simple as possible. This is not only to save time in construction, but also to make it easier to repair or service for the SSRS. If the solution is to complex it may be almost impossible for the SSRS to repair it without some sort of understanding of the system. If the system is very simple it will also become easier to repair or disconnect it out in the field with only tools that can be brought on the leader boat.

The above criteria were set early on in the project so that they can act as a guide when developing solutions. They also help to know what performance is required of the system.

5.4 FMEA on the steering system

A FMEA was carried out on the steering system as a whole. The reason for this is so that the different possible failures are taken into account and not forgotten. The FMEA of the steering system can be seen in (see appendix figure 50 - 51). One of the biggest risks with for the system is that the WR makes a sharp turn at a speed that is too high. Worst case is that the passenger is flung off and possibly injured. It should also be noticed that several of the potential failures have a severity of 10, which is the highest rating. Therefore it is important that the failures are not overlooked, even if they have a low probability of happening.

5.5 Solution process

Different solutions for the NCU were produced through brain storming. Using the requirements of the NCU the following solutions were deemed as possible:

1. Stepper motor directly connected the steering shaft
2. **Stepper motor connected to the steering shaft via a driving belt and pulley system**
3. Stepper motor connected to the steering shaft via a driving belt and a pulley system. The stepper motor can be disconnected from the system by a magnetic coupling.
4. Servo motor directly connected to the steering shaft

One of the biggest problems for the NCU is the force that the motor needs to turn the steering shaft with. There is no reliable way to measure the force. In previous projects a dynamometer [22] has been connected to the steering handlebar or the steering wire to measure the force needed to turn the steering shaft. But this only gives the static friction force. One group measured the force while moving the steering handlebar between different angles. To get a correct force the dynamometer needs to move at a constant velocity, which is very hard to do by hand. Therefore this way of measuring was deemed as ineffective and was not used. Instead a test made by Formula student[24] was used as to approximate the needed force. The test measured the force a human needed to turn the steering wheel of a normal car, which reached around 8 Nm. The WR resembles a car in how hard it is to turn and a human can steer the WR without assistance. Therefore this measurement can be used as a guideline for the torque needed. It is worth to note that once the motor is installed it is possible to measure the torque needed. By measuring the current and some other motor parameters it is possible to estimate the exact torque needed[25]. But as a motor is needed for this kind of estimate the results from formula student will be used initially. This can instead be used later on for optimising the system.

Solution two was eventually chosen as the final solution. The biggest advantage of this solution is the flexibility. By using different sized pulleys the exchange between the motor and the steering shaft can be changed. This way any uncertainty in torque needed to turn can be adjusted for.

In addition to the chosen solution there are two things that are needed for the NCU to work: a control unit that can receive and interpret the commands that are sent via CAN, and some sort of angle sensor so that the angle of the steering shaft is known.

5.6 Motor selection

A stepper motor is used in the system mainly because of two reasons. It has a high holding torque meaning that it can easily hold the steering shaft in place when the WR is driving. It also has a high torque at low motor speeds, which is good since the steering shaft is not supposed to turn at any high speeds [26].

The result from Formula student showed that a person needed around 8 Nm to turn a normal car. Since the result from a car are not fully applicable to a jet ski, that has a handle bar, the motor that is used will be over dimensioned. As a safety margin the torque needed was also doubled. This means that the motor will need to have a torque of more than 16 Nm. The motor will also need to fulfil SSRS requirement of being IP67 rated.

At early stages when making the motor selection an IP67 classed motor from JVL was considered. The motor fulfilled all requirement, but it was later decided against as this motor had a very long delivery time and a much higher cost. Instead the motor ACT 34SSM1460EC from Reichelt was chosen[27]. This motor had a lower cost and could be delivered relatively fast. One disadvantage is that this motor is not IP67 rated. Despite it not being IP67 rated the motor was deemed durable enough to be used temporarily. The motor only has a torque of 9 Nm, which means that some sort of exchange is need to reach the required torque. As mentioned earlier a pulley system will be used for this purpose.

5.7 Pulley system

The pulley system is designed to have two pulleys and a belt connecting the two. One of the pulleys are placed on the motor and the other on the end of the drive shaft, which can be seen in figure 14. The belt that connects the two pulley transfers the torque created by the motor to the steering shaft. By using two differently sized pulleys it is also possible to create an exchange between torque and speed from the motor to the steering shaft.

Figure 14: Steering shaft (Note that it is upside down compared to when inside the WR)

5.7.1 Pulleys

For the motor that was presented in the previous section to reach the necessary torque an exchange of 9/5 is needed. This means that the pulley on the steering shaft will be the larger one. As the torque need is only an estimate several pulleys were ordered. This is so that the correct exchange between the motor and the steering shaft could be determined through testing. The pulleys were going to be used as the smaller pulley on the motor. The larger pulley on the steering shaft was instead going to be a fixed size to test different exchanges with the three smaller pulleys. The pulleys that are used have AT5 profile and are 25 mm in width. AT5 is the shape of the teeth on the pulley system and was chosen out of accessibility when buying from Norelem. Initially the large pulley was supposed to have 72 teeth and have a radius of 57,3 mm. The sizes of the smaller pulley can be seen in table 12. The pulleys were chosen so that an exchange that is smaller, equal to and greater than 9/5 could be tested. Because of the limited selection at Norelem and the fact that a pulley can only have a whole number of teeth none of the pulley sizes exactly fit the exchange 9/5. Instead an exchange of 2 was used.

Table 12: Size of three smaller pulleys and the created exchange

Pulley	Number of teeth	Radius	Exchange
1	26	20,7	2,77
2	36	28,6	2
3	42	33,4	1,71

It was later discovered that pulley 1 and 2 may have a big enough exchange if pulley 2 acts as the big pulley. This setup will give an 1,62 exchange, which results in 14,5 Nm of torque on the steering shaft. This setup was also preferred as 42 teeth is the maximum size of AT5 pulley at Norelem. The best alternative seller of pulleys that was found is Aratron, which had an unknown delivery time and price. Therefore an exchange of 1,62 would suffice for an initial test, and if necessary a bigger pulley could be ordered for another test.

5.7.2 Belt

The belt connects the two pulleys and transfers the torque from the motor to the steering shaft. It needs to be stronger than the forces that it transfers or else it will break or be damaged. According to Norelems data sheets on steel cord reinforced polyurethane timing belts with profile AT5 it can withstand 3758 Ncm/cm (torque/width) when the it is rotating with 20 rpm[28]. According to the request set in section 5.3 the belt will not normally rotate faster than 52,7 degrees per second, which equals to 8,8 rpm. The following equation gives the force that the belt is exposed to from the pulleys:

$$F = \frac{T}{r}, \text{ F = force on belt, T = torque, r = radius of the pulley} \tag{1}$$

This means that the greatest force appears at the smaller pulley. Since the motor has a torque of 9 Nm and the pulley a radius of 20,7 mm the resulting force is 434,8 N. As a safety margin the force that belt will need to withstand will be doubled, this means that it needs to resist 869,7 N. The polyurethane belt from Norelem can withstand up to 3758 N at that speed, which is why a 16 mm wide one is used for the system. A belt made from polyurethane and steel cord reinforcements was also chosen because it is very strong and resistant to any chemicals that it may be exposed to inside the WR, for example salt water or oil.

The length of the belt is important as the belt needs to be properly tensioned for the system to work. The following equation gives the length of the belt:

$B_1 = 180 - 120 \cdot \frac{(R_3 - R_1)}{D}$
$B_3 = 180 - 120 \cdot \frac{(R_1 - R_3)}{D}$

B_x = arc sector of pulley with contact to belt, R_x = radius of pulley number x,
D = distance between pulley centres

$$L = \frac{B_1}{360} \cdot R_1 + \frac{B_3}{360} \cdot R_3 + R_3 + 2 \cdot \sqrt{(D - \cos 180 - \frac{B_3}{2} \cdot R_3 + \cos \frac{B_1}{2} \cdot R_1)^2 + (-\sin 180 - \frac{B_3}{2} \cdot R_3 + \sin \frac{B_1}{2} * R_1)^2)}$$

The distance between the pulleys is 105 mm, which means that the length of the belt should be 371,6 mm. As a belt needs to have a whole amount of teeth and is restricted by Norelems selection the selected belt is 375 mm long. This is no problem as the mounting construction that is presented in section 5.12 allows for the motor to move and in that way add tension to the belt.

5.8 Motor driver

A stepper motor differs from regular brushed direct current motors in that they require active commutation in order to move [29]. The selected motor is a bipolar stepper, which means that the stepper has two motor coils with one wire connected to each end, that is, four wires in total. This configuration requires the use of two full H-bridges, a configuration of transistors capable of switching the current in both directions for the coils [29]. However, driving a stepper motor in the optimal way also requires high resolution current measurements, current regulation and high accuracy timing when switching the transistors [29].

With this in mind, the use of an off the shelf motor driver was decided. The motor driver had to be able to supply the motor with 6 A of coil current and also be able to work with the 12-14 V supply in the Waverunner. Additionally, a motor driver with integrated motion planning which would make the implementation easier was desirable. A small module which could easily be integrated in a waterproof enclosure was also one of the requirements. Based on fulfilling these specifications and for providing excellent documentation over both firmware and hardware features, the TMCM-1260 [30] stepper driver from Trinamic was selected.

The TMCM-1260 is configured to drive bipolar stepper motors with up to 6 A using supply voltages from 12 V [30]. It provides a high-level serial interface that can be used for setting motor and motion parameters as well as sending motion commands. In addition to the serial interface it has a lower level interface which controls the motor with a direction signal and a pulsed step signal. The module also has a small footprint which makes it possible to integrate on a circuit board.

5.9 Angle sensor

The angle sensor will feed the motor control unit with the angle of the steering shaft. It will be placed on one side of the pulley that is mounted on the steering shaft. The angle sensor will also need to be IP 67 rated as it will sit in the open without protection from any water inside the WR. It should also not break from any impact that can occur when the WR is driving over waves.

Eventually the sensor Honeywell AIDC RTY090HVEAX from Conrad was chosen. The sensor is a hall-effect sensor that can measures between 0-90 degrees. But as the steering shaft only turns 52,7 degrees this is enough. The sensor is also IP 67 rated and can withstand any impacts or water that it may be exposed to. A hall-effect sensor was chosen because it measures the absolute angle and it remembers its last angle when being turned off and on again. This is very important as the WR will shift between manual and automatic mode relatively often and without warning. If the sensor did not remember the angle the system would need to be calibrated every time it is put in automatic mode.

5.10 Integration of the electrical components

In order to integrate the stepper motor, stepper driver and angle sensor into the planned drive by wire system, several additional electrical components were needed. First and foremost, a STM32F303K8 microcontroller from STM, like in the other nodes, was selected. The microcontroller has a CAN interface to communicate on the bus, a serial interface to communicate with the stepper driver and it also has analogue inputs which are needed to measure the signal from the position sensor.

During the initial testing a circuit consisting of the microcontroller, a can transceiver for the bus and a RS485 transceiver for the stepper driver was assembled using jumper wires on a solderless breadboard. While this method was suitable for inital testing, the circuit would not work well in the rugged environment inside the WR.

Therefore, a printed circuit board (PCB), as can be seen in figure 15 was designed for the NCU. The PCB has input connectors for the data bus on the right side of the PCB for 12 V, 5 V and CAN signals. As the 5V is always on, it is upconverted with two separate DC-DC converters to 12 V to power both the angle sensor and the logic part of the stepper driver. The switched 12 V supply which is only turned on in automatic is used to power the motor driving part of the stepper driver, putting the motor in a freewheeling state when the drive by wire system is in its manual mode.

The PCB also serves as the mounting plate for the stepper driver with 4 M4 holes as can be seen in the top part of the PCB. The PCB is also prepared with a charge pump configured to derive a 24 V line from the 12 V line and two transistors intended to be used for driving up to two of the digital inputs (which are isolated with an opto-isolator) on the stepper driver, for example to use the step and direction interface instead of the internal motion planning of the TMCM.

The full schematic of the PCB is available in the appendix.52 53

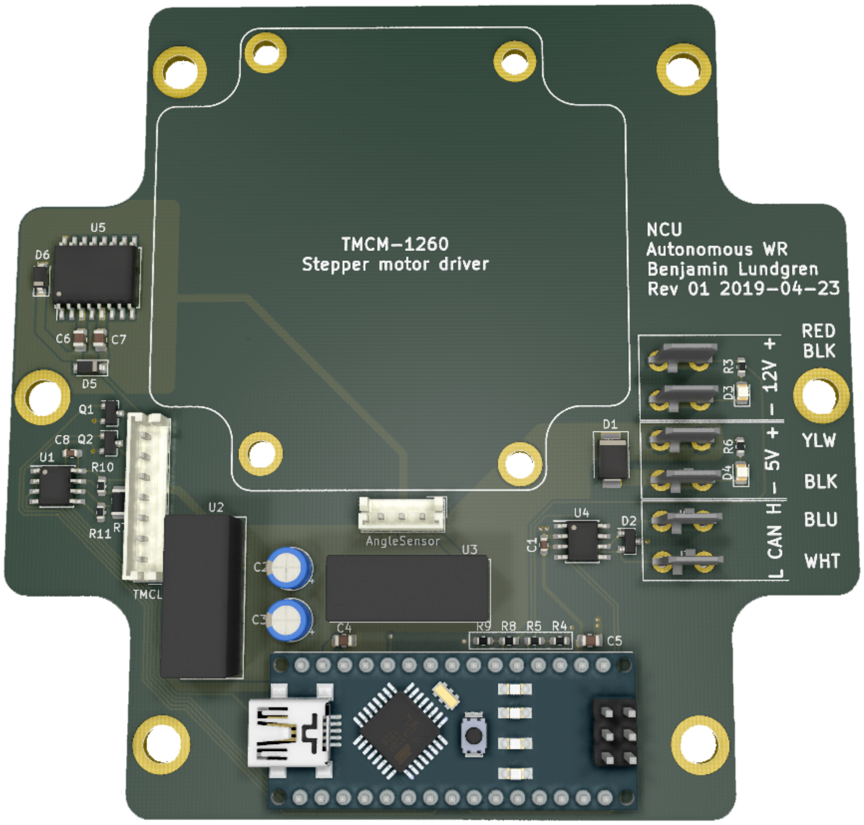


Figure 15: Printed circuit board for the NCU

5.11 Programming of the motor control unit

This section will explain the part of the code that controls the motor. How the CAN bus works can be seen in earlier sections.

The program receives input from two sources, the CAN-bus and the analogue signal from the angle sensor. The CAN-bus gives the program an angle, which is scaled with 100, that the motor should turn to. So if the CAN bus sends the value 2000 the motor should turn to the absolute angle 20 degrees. To do this the program consists of three parts:

- Initialisation
- Calibration
- Main while loop

In the initialisation the program sets all the necessary parameters for the motor. These can be seen in table 13.

Table 13: Parameters set in the initialisation[31]

Parameter	**Description**
Maximum positioning speed	Maximum speed when rotating to a position
Velocity V1	Target velocity of first acceleration phase
Maximum deceleration	Maximum deceleration
Maximum acceleration	Maximum acceleration
Acceleration A1	Acceleration during the first acceleration phase
Microstep resolution	Microstep of the motor
Maximum current	Maximum current used when rotating
Standby current	Maximum current used when holding a position

The calibration synchronises the angel sensor with the program and puts the steering handle in the middle. The angle sensor can measure 0-90 degrees and the steering handle can only turn 52.7 degrees. Because of this the program needs to check in which interval of the angle sensors scope it is. It's not guaranteed that the sensor will go from 0.0-52.7 degrees, it could be 15.3-68.0 degrees. The calibration checks this by turning the motor for 1,5 s with low current in both directions. By doing this the steering handle will reach both its end points, and the low current prevents the motor from destroying anything. The program saves the angles that the angle sensor gives at each end point, which results in the scope that the motor is allowed to turn. The calibration then turns the steering handle to position 0, which means that it faces forward. This process is only necessary to do once every time the WR starts. This is because even when the motor driver is unpowered in manual mode, the power supply to the logic part of the driver is still active. Therefore the board will save the measured endpoints until the drive by wire system is completely turned off.

The main while loop continuously reads from the CAN bus and sends the necessary commands for the motor to turn to where it should be. When the main loop receives an angle it first translates it to the right position, since the motor is controlled via steps. When the position is determined a command is sent that tells the motor to rotate to said position. The main loop also continuously synchronises the current position of the motor with the angle of the angle sensor. Because the movement of the motor is disturbed when setting the position during movement, the loop only synchronises the position when the motor is still or does not move much during a set amount of time. The main loop also keeps track if the calibration and initialisation codes have been run. The calibration is only done once when the WR goes into automatic mode for the first time since being turned on. The initialisation is done every time the WR switches from manual to automatic mode. This is because the motor loses all its parameters when it loses its power supply, and they need to be set for the motor and code to work.

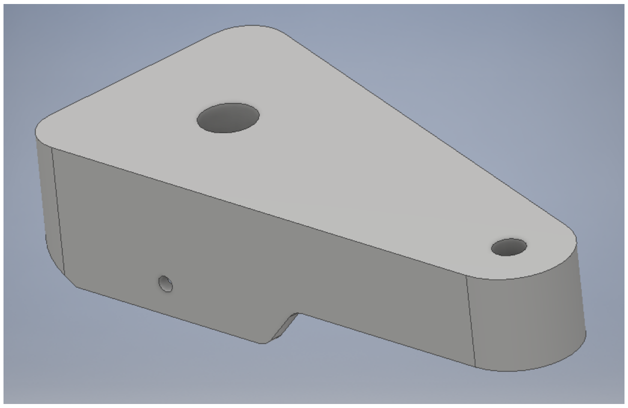


Figure 16: Adapter, side that pulley attaches to

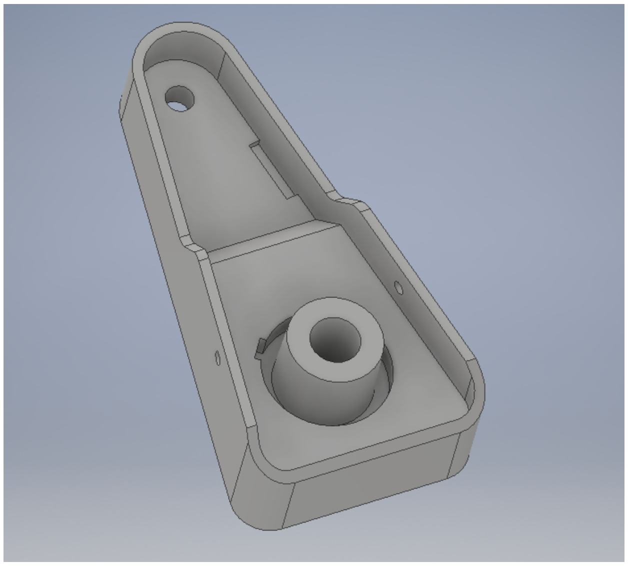


Figure 17: Adapter, side that fits into steering shaft

5.12 Design for mounting motor and pulley system

The motor, pulley system and angle sensor of the NCU will be located at the front of the WR right under the steering handle. There are three main parts for the mounting:

- Construction that attaches the larger pulley to the steering shaft.
- Construction that mounts the motor in ”parallel” with the steering shaft.
- Construction that attaches the angle sensor to the steering shaft.

The large pulley is attached under the arm of the steering shaft, which can be seen in figure 14. As the arm is not completely flat a 3D-printed adapter was designed, see figure 16 and 17. The pulley is attached to the adapter with a M12 screw and nut. As the adapter is forced into place by the motor mount and the belt, it is only attached with two straps.

The motor is mounted in parallel to the steering shaft. This means that the shaft of the motor is in parallel with the steering shaft, as the pulleys have to be lined up for the pulley system to work. The mounting construction that is used for the motor can be seen in figure 18. The strange shade and angle of the construction comes from that the motor and its mount can not be in the way of the steering wire and the arm that pulls/pushes it. The space inside the WR is also very limited because of wires and air intakes that lie in the same area. The mounting attaches to the same screws as the module that holds the steering shaft and handle, see figure 14. The bigger holes in the bottom is where it attaches. The figure also shows the longer holes for attaching the motor. The longer holes makes it possible to slide the motor back and forth, which in turn makes it possible to tense the belt when it is fitted around both pulleys. It is important to note that the steering shaft is not perpendicular to the plane of the screws that holds it in place. Instead it has an angle of 84,2 degrees as can be seen in figure 19. The mounting holds the motor in the same plane/angle as the steering shaft so that the pulleys are aligned, see figure 20. The motor also has two plates that it is fitted with. One of them acts as a spacer since the motor front stick out a bit, and the other holds the nuts that the motor screws into. This makes it much easier to attach the motor to the mount.

The main construction in figure 18 is made from 2 mm thick steel. All the smaller parts are 3D-printed since not as much strength is needed and it is easier and faster to make.

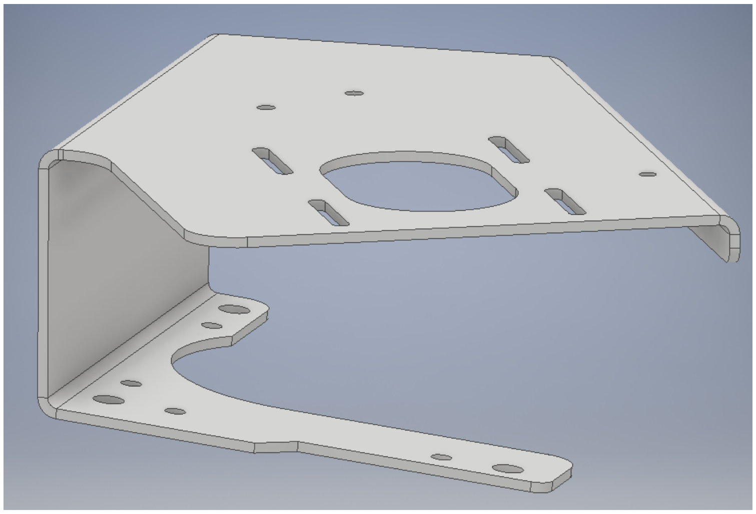


Figure 18: Construction for mounting the motor

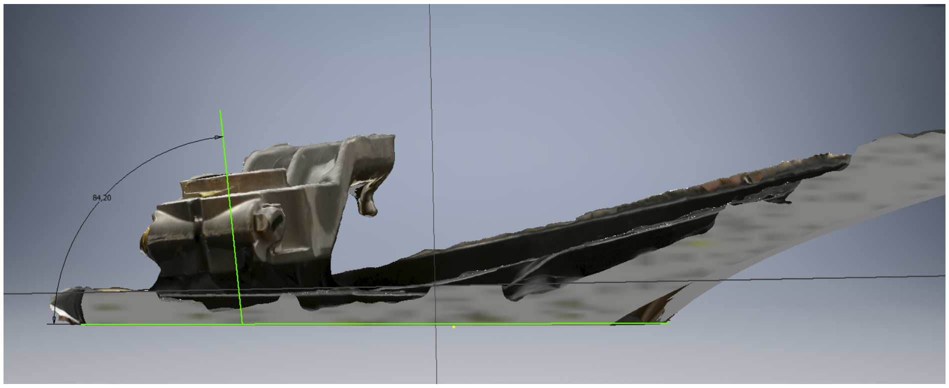


Figure 19: Angle of steering shaft

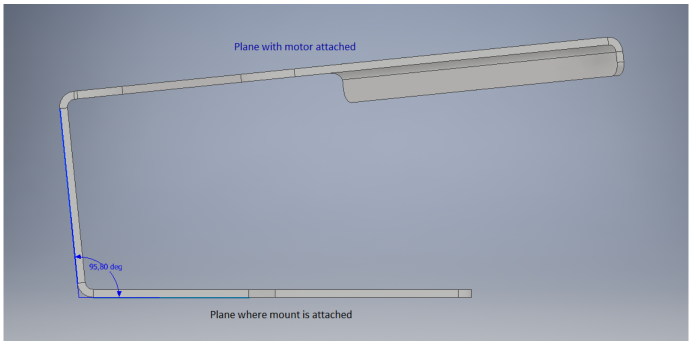


Figure 20: Angle of the mount

The angle sensor is attached to the same construction as the motor as it is supposed to connect to the steering shaft. It is screwed into a small spacer that is then screwed into the two smaller holes in the back of figure 18. A hole is also drilled for the shaft of the sensor. The sensor is connected to the hat of the M12 screw that attaches the larger pulley via a 3D-printed adapter. The shaft of the sensor goes into the adapter which then fits into the hat of the M12 screw.

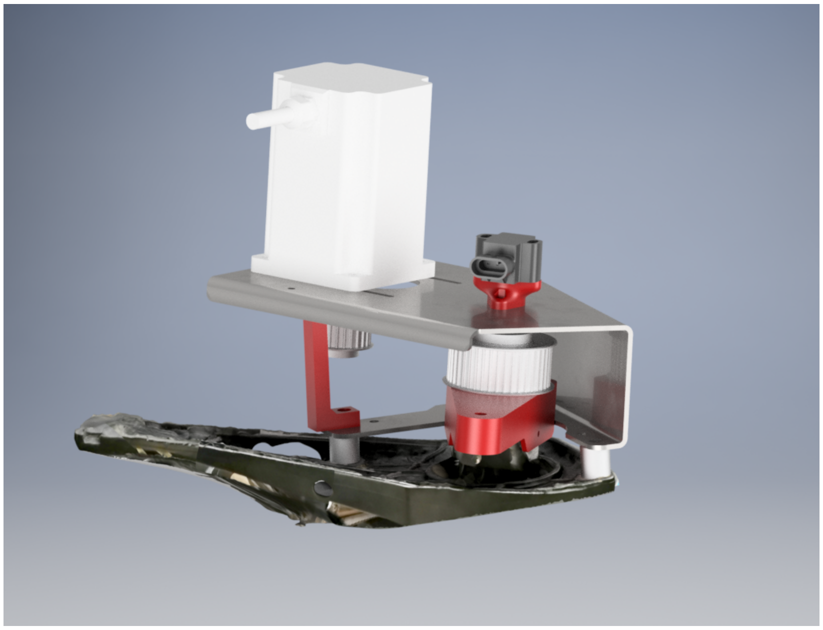


Figure 21: The complete construction for mounting the motor, pulleys and angle sensor

5.13 Testing

The NCU was initially tested on land as the steering handle does not need water to work. Much of the code was debugged by testing the system while the WR was still in the lab. By uploading code to the motor control unit and sending CAN-messages to it the system could be tested. One test was also carried out in the water. The test was carried out by letting a person drive the WR some distance away in the water, as to not risk any damage to others if the system did not work. The driver then switched from manual mode to automatic mode and let go of the steering handle. The NCU was then tested by sending CAN-messages to it to make the steering handle turn. This was also tested when the WR was driving at different speeds. One problem arose with the system when the WR had a high rpm on its motor. When the WR works hard, much more water is pressured out through the water jet and a lot of force is put on the nozzle. This meant that the NCU was not strong enough to turn or hold its angle when the WR accelerated a lot. Even when the micro stepping and speed of the stepper motor was set to a minimum it was not strong enough. But this is to be expected as the test was done with an exchange between the motor and the steering shaft of 1,62 instead of 2. The NCU was almost strong enough during this test as it could turn during speeds of up to around 30 km/h, which is around the speed that it is supposed to drive when in automatic mode.

5.14 Evaluation of results

The tests that were done on the NCU showed that it preformed pretty good. The WR turned to the requested angle by sending an angle via the CAN-bus to the NCU. Almost all of the requirements and request that were presented in table 5.3 are fulfilled. All of the steering angle is use able. The precision of the NCU reaches the request as the motor has a step of 1,8 degrees, and it can become even more precise if needed. Steady state error has not been a problem, and because the motor synchronises with the angle sensor all the time it will not lose any precision. The motor can easily turn the steering wheel at 1 rpm, which more than fulfils the request of 52,7 degrees in 0,5 seconds. The NCU never had a problem with switching from automatic to manual mode. That is because the motor is not powered at all when the WR in manual mode, which means that it is not possible for the NCU to do anything to the rest of the system. This also means that the requirement that the NCU stops interfering during a power outage works, since it is the same as switching to manual mode. The performance in manual mode received little to no impact from the NCU. Even if the motor is always connected to the steering handle it has so low resistance that it is barely noticeable. The request to control the nozzle in the vertical plane was not fulfilled as it became clear later on that it is not possible. The robustness of the construction lasted through the first test in water without anything breaking. Unfortunately only one test can not prove if the construction is robust enough to last a long time. The NCU is relatively easy to construct, provided that the necessary tool are available. The steel mounting for the motor for example was made by bending into its shape and water jetting out the necessary holes. The motor mount is also very hard to install into the WR. There are a lot of wire in the way and the place where it is attached is not easily reachable. Some parts of the design is also in the way of screwing the mount into place. Therefore the NCU has not fulfilled the request of being easy to construct.

Even if the NCU performed very well in the tests, there are some things that can be improved. The gear ratio from the motor to the steering shaft can be increased so that the motor is strong enough to turn at high engine speed. Even if the current exchange barely is enough to turn sufficiently high speeds, some margin is good to have. It is also very hard to tension the belt in the pulley system as the motor is hard to reach. Some sort of mechanisms for tensioning the belt would be advantageous as the performance and precision of the system increases. One idea is to put a screw that pushes on the motor so that the belt is tensioned. The design of the motor mount can also be modified so that the screws that attaches it to the WR are more easily reachable. Over all the NCU preformed very well and with just some minor modifications it will fulfil all requirements that have been set.

6 Throttle control unit

To control the speed of the watercraft through the water the throttle control unit (TCU) is developed. The speed control aims both the forward and reverse movement. The unit is attached to the databus 2 (DB2) and the speed will be controlled in accordance to data given at this bus. The TCU will be added on to the existing electric system in the WR to fulfil this task and a fundamental knowledge to the original system is therefore essential.

6.1 Original system

The engine control is mainly performed by the Engine Control Module (ECM). The ECM uses various sensors, i.e camshaft position sensor and throttle position sensor to control the ignition timing and fuel injection. The users control input to the ECM is realised through the Acceleration Position Sensor (APS) and the RiDE Position Sensor (RPS). The APS is connected on the right hand lever of the steer handle and the RPS is connected to the left hand lever [7]. Variation of the throttle increase is not only affected by the APS but also the RPS and the existing speed of the vessel. The intention is a smoother driver experience [32].

The RPS controls the the lowering of the shield behind the nozzle. The lowering of the shield is referred to as the shift. The shift will control the vessel from forward speed to a lower speed and after time to reverse movement. The shift sequence is controlled by the ECM with input from the user and with respect to current speed, given be the speed sensor. The controlled reverse sequence is performed by the Yamaha RiDE system (Reverse with Intuitive Deceleration Electronics) [7]

Table 14: original APS&RPS wiring

Signal	Cable1 colour	Cable2 colour
APS1	Orange/Red	Black/Red
APS2	Orange/White	Black/White
APS FC	Orange/Green	Black/Green

The APS uses three signal cables, APS1, APS2 and APS full closed switch(APS FC), se table above. The cables can be measured from the pins on cable connectors reached from the front compartment of the vessel [7]. With no power on, measuring between a pair of pins on the APS connector right after the handle results in no change in resistance when adjusting the lever. Because of this the sensor can not be a potentiometer. After disassembly of the handle the sensors in the levers seems to be non mechanic. This is because there are no moving parts except the lever fastener with a spring. Also the sensor can be removed by itself and separated from the lever fastener. Because of this the sensor is likely to be a hall effect sensor which will be the assumption in the following design.

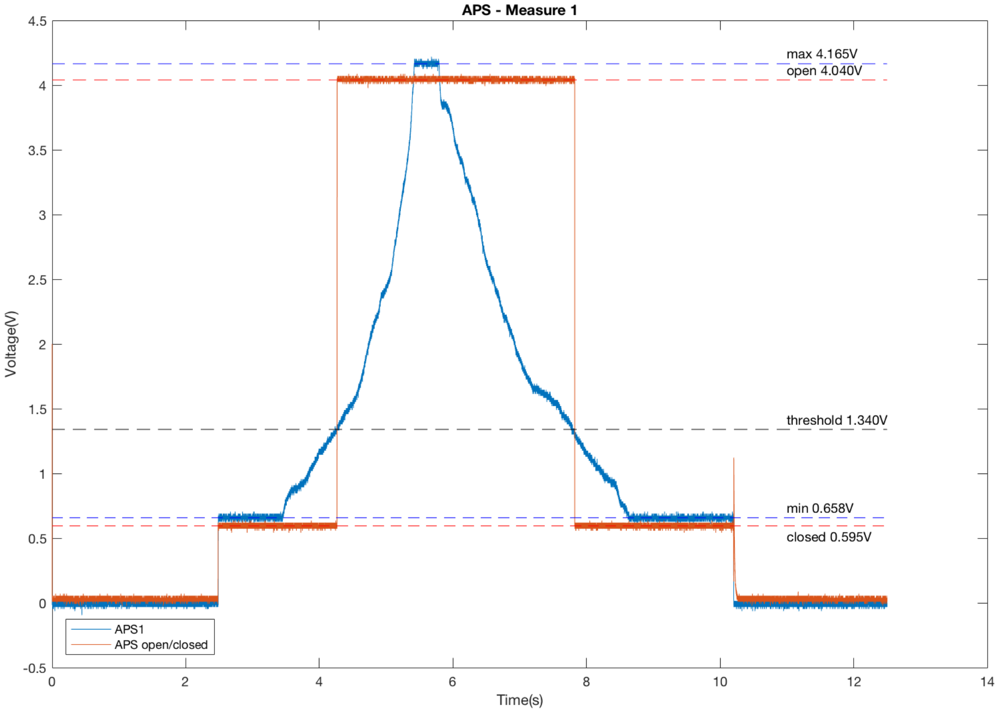


Figure 22: APS signal characteristics

Further tests are performed with an oscilloscope. The APS1 and APS2 have the same behaviour when varying the lever. The APS FC is high if an threshold value is reached in the APS. In other words, the lever has to be depressed a certain length to get signal high (open). Otherwise the signal is low (closed). The min value is the voltage of the signal when the ignition is on but no levers are pressed down. The Max value is reached when the lever is pressed all the way down.

According to the service manual the min and max value must be in the span of 0.68-0.74 V to 3.95-4.15 V [7]. In the measurements with the oscilloscope some variations to this values were found. Several measurements where performed and after visual readout only small deviation between the measurements on each test were found, in general no greater than 0.05 V. A graph of the APS and the APS FC can be found in figure 22. In this figure values can also be found.

6.2 Earlier solution

Earlier projects have been working with a craft that have analogue potentiometers to tell the lever position. One solution have used digital potentiometers, controlled with a microcontroller to mimic the APS signal. [5]

6.3 Requirements and requests

As the general system requirements indicated the control interval for the throttle and the shift must be the same in automatic steering as in the manual mode. The general system requirements also specify that the TCU must not affect the original system.

Table 15: TCU requirements

Object	**Criteria**	**Control method**	**Goal Value**	**Priority**
APS	Speed min to max value	Throttle angle measurement	50 ms	Requirement
APS&RPS	Resolution	Voltage measurement	100 steps	Requirement
APS&RPS	Span of current system	Voltage measurement	0-100%	Requirement
APS&RPS	Impact to Yamaha System	Stress test	Not visible	Requirement
RPS	Speed min to max angle	Shield angle measurement	Yamaha System	Requirement
RPS	Span of current system	Shield movement test	0-100%	Requirement

Since the goal is to reach the same throttle and reverse response in manual mode as in automatic steering mode an effective control method will thereby be able to control the WR in both manual and automatic steering mode and let the on board driver/passenger explain their experience.

6.4 Final solution

The results from testing the original system suggests that an added system, can be added between the handle and the ECM. This system should be able to emulate the signals from the handlebar lever. Earlier solutions also show that such a solution have the possibility to meet the problem definition. This added system will be called the Throttle Control Unit (TCU).

6.4.1 Concept

The goal is to generate a signal with the same behaviour as the measured in the original system. The initial theory is that the min and max value must be the same as the value measured in the original system in order not to trigger any error codes from the ECM. The approach will also be to emulate the behaviour of the APS signal.

Another feature that can be included in the TCU is the ability to read the signals from the handle while in both manual and automatic mode. This should not be hard to implement and it can prove useful for several reasons. The first one is that it allows the system to monitor the signal and check if it matches the expected output. Another reason is that it makes it possible to implement the capability to manually override the system if the driver pushes the handlebar lever during the automatic mode. In case of an override the TCU would then have to shut down the rest of the system so that is switches to the manual mode. It is yet to be discussed if this feature is to be implemented and how it should work but it should be possible if one of the other controller units is able to switch between modes. Both the possibility to read and write signals should be included in the TCU.

If the TCU module should be able to both read and write signals from and to the original system, it presents us with a challenge. To read a signal it is possible to just make a three way splice, with other words a ”T” connection, thus tapping on and listening on what is happening. The hard part comes when it should also be able to write. This can not be done without breaking the original connection between the handle and the

ECM. If the handle is always connected, even during automatic mode it can create unexpected behaviour because the driver can press the lever at the same time as the TCU. This results in a collision between the two signal levels which could cause problems when controlling the ECM. This can cause TCU to lose its control over the WR when it should have it fully. There is also a chance that the hall effect sensor can be damaged if the TCU outputs a higher or lower voltage level than the lever. Although this is not likely but it can not be precluded since the kind of sensor is not completely known. To solve this problem the method described in 6.4.5 is used. Where the original wire harness is cut in half, each half connects to the TCU in the middle where the logic happens.

6.4.2 Hardware - Overview

Several components are needed to be able to construct the TCU. The first component is the PCB, where all the components are mounted. The goal is to have a prototype PCB where there are no loose cables or components, that is robust enough to be used during real testing conditions. The TCU is also enclosed like the rest of the system in an enclosure with a rating of at least IP67. It is also fitted with Lumberg signal connectors and a Bulgin USB connectors that meets the required IP67 rating. These are needed to be able to communicate both with the original and drive by wire system.

6.4.3 Hardware - Components

A motivation for the larger components, the microcontroller, enclosure and connectors can be found below. The microcontroller development board used for the PCB is the STM Nucleo-F303K8 [12]. The enclosure used is a Hammond 1554P2GY. This box i made out of Polycarbonate with an IP68 rating, the outer measurements are 119x119x89mm. It was chosen partly because there are a lot of connectors going in and out of the box which requires significant space. There are only connectors going out on two sides of the box since it is harder to place and mount it the more sides that is occupied by connectors. The TCU should not require any extensive cooling and a plastic enclosure can thereby be used in favour to a metal one. The plastic enclosure weights less and holes are easier to drill and its therefor advantageous [33].

The same data and power connectors as for the rest of the system was used when constructing the TCU. These are circular Lumberg connectors from the 02X0 and 02X1 series [34], [35]. Although is should be noted that the same kind of connector is used both for IN and OUT of the TCU. This means that the user should take care when connecting them and reading the labels on the connectors to see where they should be connected. The IN connector comes from the ECM and the OUT connector should go to the function which should be controlled. For a more in-depth draft of the connectors used for connecting the TCU to the original system, see section 6.4.5. The CAN Interface PCB used in the rest of the project is also mounted on the PCB. The power distribution to the TCU is 5 V and if attended to be used in automatic mode, a 12 V voltage is applied. Both sources are connected to the the CAN interface and then distributed further to the TCU PCB.

6.4.4 Hardware - Design of the PCB

The PCB outline is taken from the Hammond Enclosure with an offset of 4 mm from the inner wall which could be seen as the yellow line in figure 23. It has also been cut of on one side to allow easier removal of the PCB when all the connectors are mounted to the enclosure.

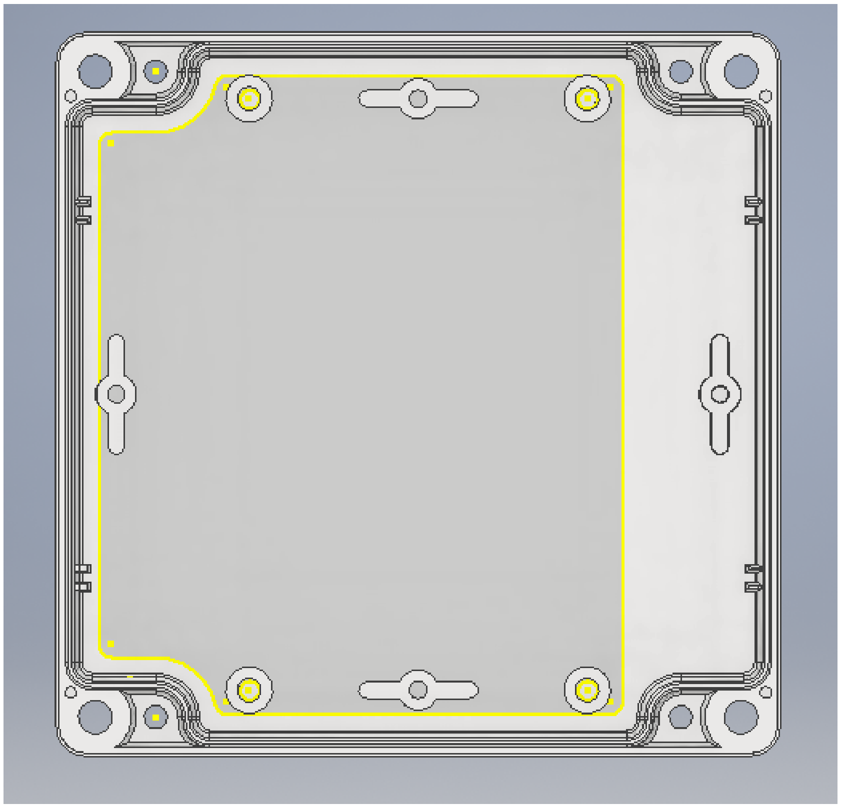


Figure 23: The outline of the TCU PCB in yellow, an offset of 4 mm from the enclosure.

The ECAD software used for designing the TCU PCB is Autodesk Eagle. The top side of the PCB can be seen in figure 24

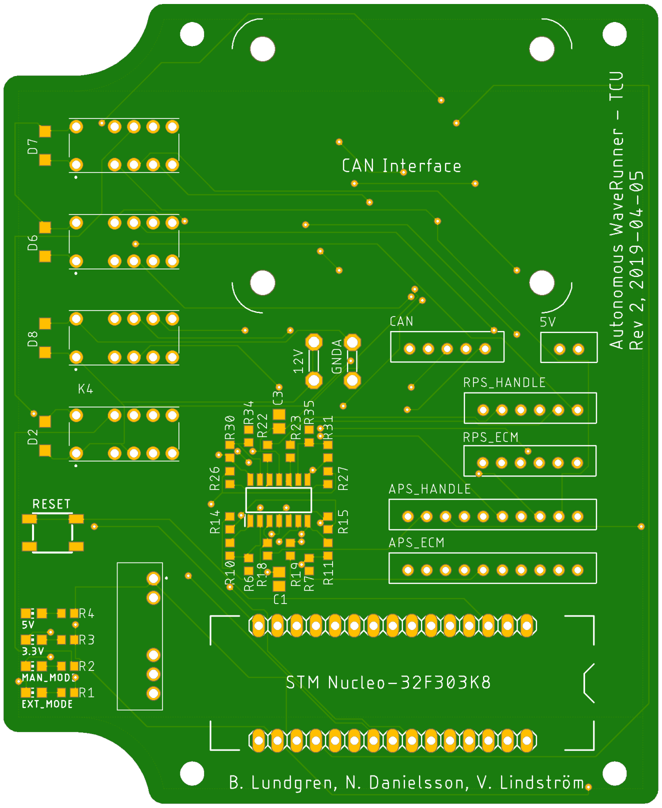


Figure 24: Top side of the TCU-Rev2 PCB from Autodesk Eagle.

The schematic consists of three pages which could be found in the appendix figure 65. Below is an explanation of the most important parts of the circuit.

The first page on the STM32F303K8 microcontroller development board is connected to the CAN connector which connects the PCB to the CAN Interface board. The development board also uses several IO ports, a full definition and functions could be found in the appendix figure 62. The TL074ID, a quad op amplifier, is used as a buffer for the digital to analogue converter (DAC) controlling the APS, APSFC and RPS signals. These are then connected to the difference amplifier circuit on the second page. The status LEDs shows if the system has 3.3 V, 5 V and if it is in manual or automatic mode. A signal relay is used for switching between the manual and automatic mode. The relays switch if the 12 V is applied and a set of LEDs is then lit up. The 12 V from the CAN interface board is supplied to the PCB through FastCon connectors. The DC-DC converter gives power to the operational amplifiers.

The second page contains two quad op amplifiers. The op amplifier are used for the difference amplifier circuit which consists of a total of eight in and out signal conversions. The circuit shifts the logic level from 3.3 V to 5 V and the other way around depending on if the system should output or read signals. This is needed since the original system uses 5 V logic and the microcontroller in the TCU uses 3.3 V. This conversion factor can be calculated by taking the higher resistor value divided by the lower, for example, an output circuit from the STM has resistors with a value of 6.8K and 4.7K which gives us a conversion level of $\frac{6.8}{4.7} \approx 1.44$ [36]. This means that a 3.3 V signal will gets 1.44 times higher when converting to 5 V logic, resulting in a maximum signal level of 4.77V. This leaves a small safety margin so that the original system should not be damaged if the output signal raises over the normal threshold. The same goes for the input circuits to the STM but in this case other resistor values are used resulting in a conversion of $\frac{6.8}{3.9} \approx 1.74$

which is a slightly higher conversion level than for the output circuit resulting in the highest possible input signal of 2.87V, this time to avoid damaging the system if there is a small voltage spike.

The other reason for using the difference op amplifier circuit is that it prevents any current going from the separate ground paths of the original and TCU system. This is the reason why the circuit also has two grounds, for example the the APS1, GND and the normal GND of the TCU [36].

The third page consists of the connectors for the APS and RPS which can be seen in table 16.

Table 16: The pin numbering for APS and RPS.

Function	Pin
APS1	1-3
APS2	4-6
APSFC	7-9
RPS1	1-3
RPS2	4-6

The signal relays are again used for switching connection between the internal or automatic system depending on if the system is in manual or automatic mode. The reason for using signal relays is that they prevent two modes form being active at a time. They also provide a mechanical safety, when the power supply is cut to the TCU the system will always return to the manual mode. This is why the original system is connected to the normally closed (NC) pins of the signal relays. Flyback diodes have been used to suppress voltage spikes which can damage the relay when the power is cut, i.e. switching between modes [37]. The lowpass filters are used to make the output signal more stable when changing modes. It prevents the signal from falling to fast which would otherwise create a spike that could in the worst case induce an error code.

It should be noted that the PCB uses two different GND nets for the 5 V and the 12 V, this applies to all the pages above. This is because if one of the power lines fail it can otherwise cause the current to pass through the other, overloading it and causing it to also fail. Thus these are isolated in the TCU end.

6.4.5 Hardware - Cable interface and wire labelling

There are a lot of connectors going in and out of the enclosure. The reason behind the connectors going in and out, or through the enclosure is that it is easier if the logic is done on the PCB instead. If the signal is only being read, it is possible to only read the signal level. This can be done with only one wire or connector. If the signal should also be written to, it is necessary to disconnect the original system, so the drive by wire system is the only one giving a signal. This is done in a safe way by the 12 V relays on the PCB. The logic behind this switching happens on the PCB which is why it is easier to just cut the original wires in half and let them go through the enclosure. For the TCU this method gives the possibility to both write to the ECM and read the input from the handle at the same time if needed.

The cutting of the wire harnesses for both the TCU and UCU are done in a specific way which can be seen in figure 25. The original system's wires both have a male and a female connector, giving the possibility to disconnect the drive by wire system and only use the original system.

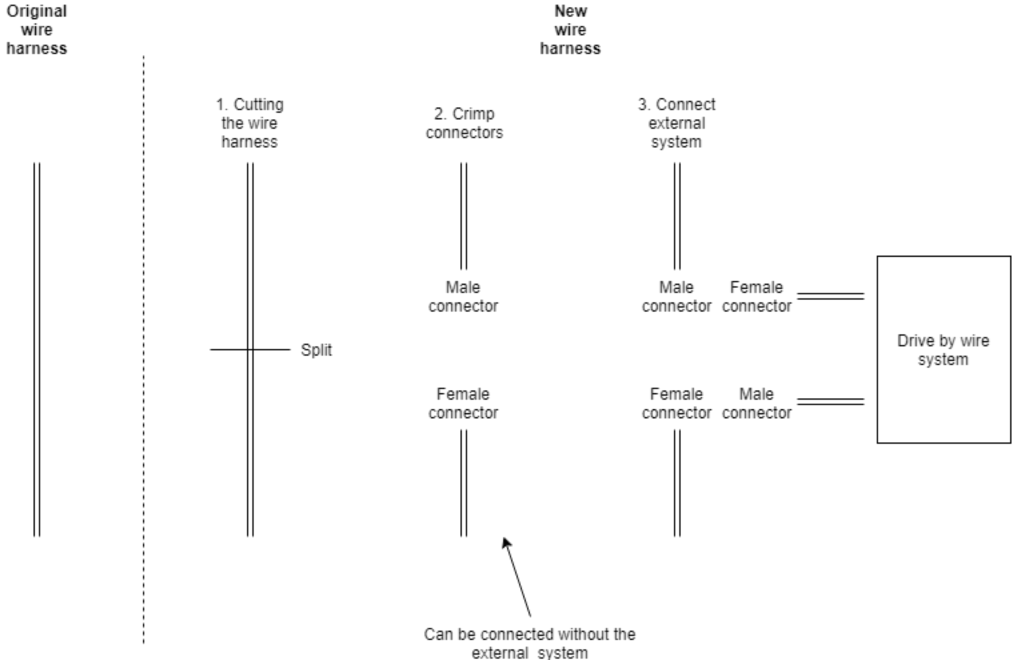


Figure 25: Cutting the wire harness for the TCU and UCU.

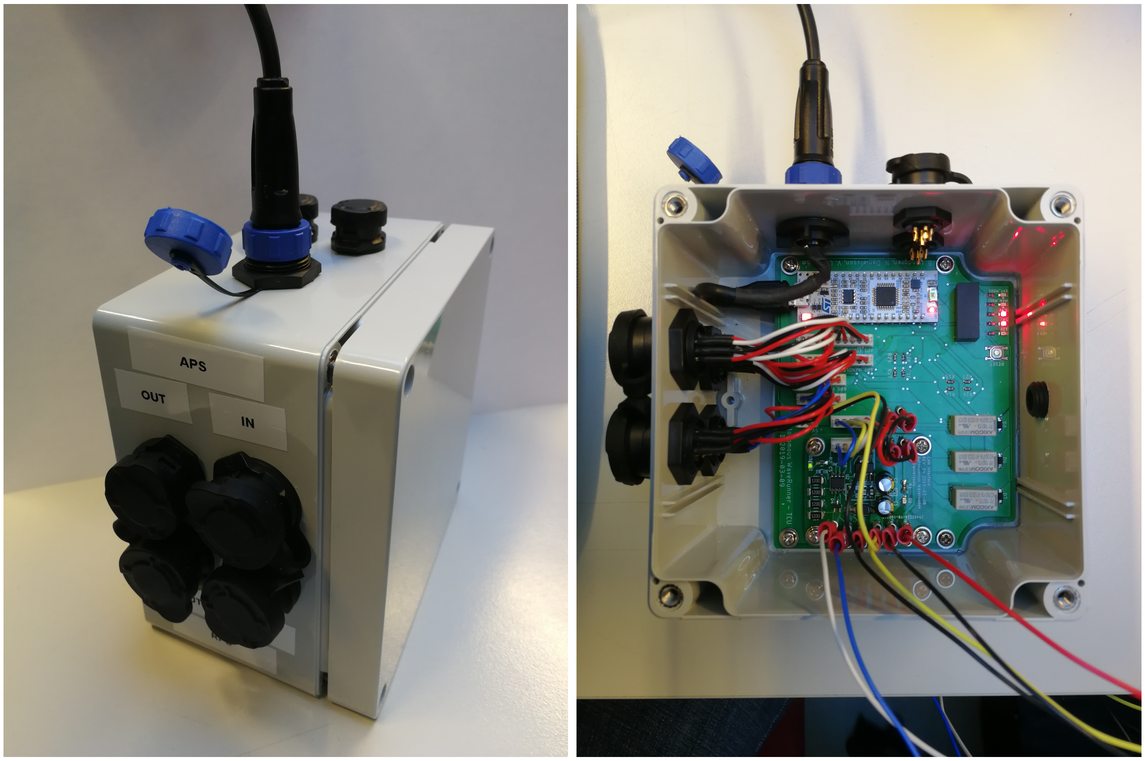
The following connectors seen in table 17 are needed for the TCU module. The full wire labelling and colour coding can be found in appendix figure 64. The connectors used for the signals can be found in appendix figure 63.

Table 17: TCU connectors

Connector	**From/To**	**Enclosure label**	**PCB label**
APS in	ECM	APS IN	APS_ECM
APS out	Handle	APS OUT	APS_HANDLE
RPS in	ECM	RPS IN	RPS_ECM
RPS out	Handle	RPS OUT	RPS_HANDLE
CAN and Power	DB2	CAN	”CAN interface board”
CAN and Power	DB2	CAN	”CAN interface board”
USB	Programming, i.e. to computer	none	”To STM32 USB port”

6.4.6 Hardware - Final enclosure

The final TCU enclosure can be seen in figure 26. The PCB is mounted to the enclosure with M3 screws. The CAN interface board can be seen on top of the PCB. All of the connectors are going in and out of the enclosure, connected to either FastCon connectors for the DB2 and with JST EH connectors for the rest, except for the USB cable.



(a) TCU enclosure, closed.

(b) TCU enclosure, open.

Figure 26: The final TCU enclosure.

6.4.7 Software

The TCU software is flashed to the STM mounted on the TCU board. The software will according to input control the APS and the RPS with appropriate signal characteristics. The input is given by the CAN bus which is read with an interrupt, for further explanation see 2.3.2. The input will here be abstracted to two variables, inputRPS and inputAPS. Both of them defined by the databus 2 (DB2) architecture to hold values 0-10 000 (0x2710).

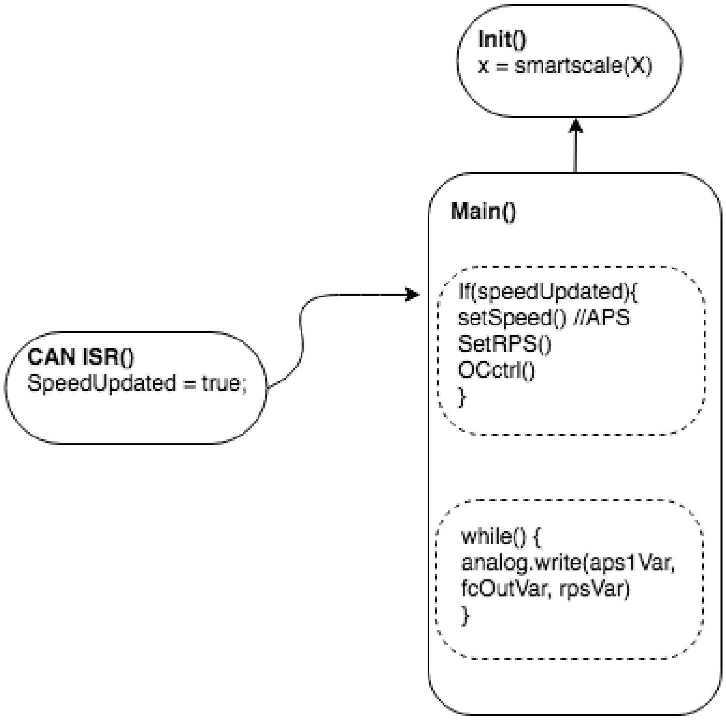


Figure 27: TCU flow

Each signal defined from measuring the original system is equally scaled in the software to be on the same voltage level. If the scaling of the defined signal X is assigned to the float variable x, then:

$$x = REFSKALE \cdot ANALOGREF \cdot X$$

The hardware pins for analogue write and read is defined in accordance to appendix figure 62.

Table 18: Some of the constants defined in RCU software

Defined Variable	**Value**
Measured values	mV
APSCLOSED	595
APSOPEN	4040
APSTHRESHOLD	1340
APSMIN	658
APSMAX	4165
RPSMIN	689
RPSMAX	4173
Scale factors	
REFSCALE	$\frac{1}{3300}$
ANALOGREF	$\frac{4700}{6800}$
ANALOGREADREF	$\frac{3800}{6800}$

The ANALOGREF and the ANALOGREADREF are derived in TCU hardware design. The constants are used to scale the signal to levels desired by the TCU electronics. The analog read and write function handles a value from 0-1 corresponding to a voltage 0-3.3 V. The defined signals are therefor scaled by REFSCALE to enter a value in the interval 0-1. Software to read the APS and RPS is not implemented yet. The ANALOGREADREF is therefor not used in the current revision of the program.

An update of the output signals; APS, APSFC and RPS is performed when the global variable speedUpdated is set true. This variable is set when a new CAN message with the correct CAN id is received. The output signal is then adjusted between its min and max value in accordance with the input signal. For the APS the output signal, aps1Var, is calculated as follows,

$$playground = apsMax - apsMin$$

$$aps1Var = apsMin + inputSpeed \cdot playground$$

Where the inputSpeed takes values from 0-1 derived from the inputAPS. If the APS is set to higher values than the apsMax the software will correct it to apsMax. If the APS is set to lower value than apsMin the software will correct it to apsMin. The same logic is used for the RPS. The software then compares the output of the APS with the threshold to set the open/closed variable (fcOutVar) to apsOpen or apsClosed. Open is set if the APS has a value greater than the threshold and closed is set if the APS value is lower than the threshold. This is done by the OCctrl function and the goal is to achieve a behaviour similar to the original Yamaha system. The OCctrl uses hysteresis control to avoid flickering around the threshold. Such flickering may make the throttle close and open in a way that may stress the engine or the engine control in an unpredictable way. It may also affect the possibilities to control the engine. The OCctrl function and its hysteresis control uses the states open (O) and closed (C) according the the last updated APS value. If in state C the threshold variable is set to threshold + hysteresis. If in state O, the threshold is set to threshold - hysteresis [38]. Figure 28 illustrates the hysteresis control. The hysteresis variable is set to 0.01, which is around 3.6% of the scaled APSTHRESHOLD. The hysteresis variable may need calibration at the time the engine is tested with the DBW system.

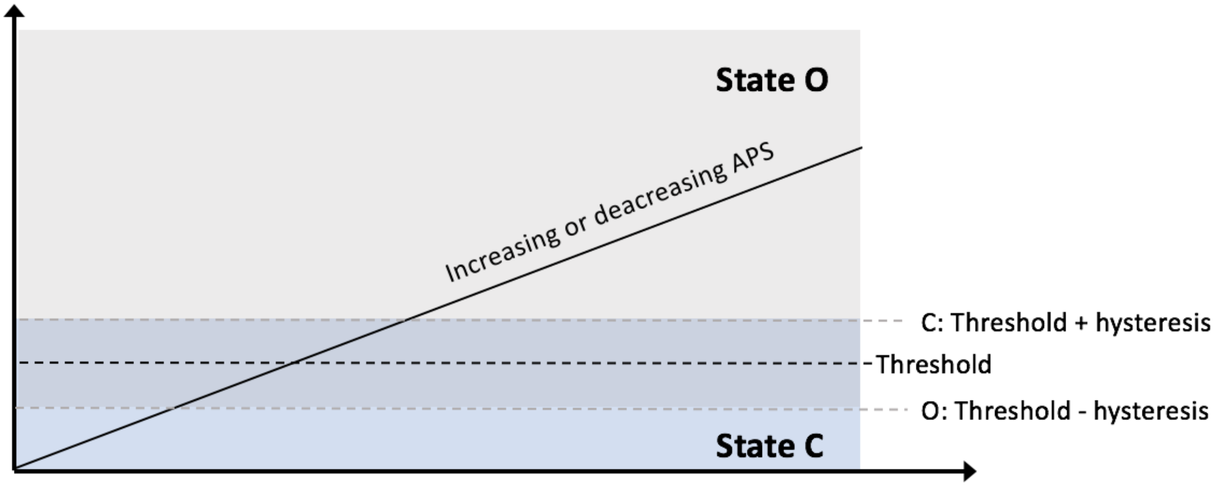


Figure 28: Hysteresis control

6.5 Testing

The unit was attach to a 12 V power supply and the signal switching functioned as intended.

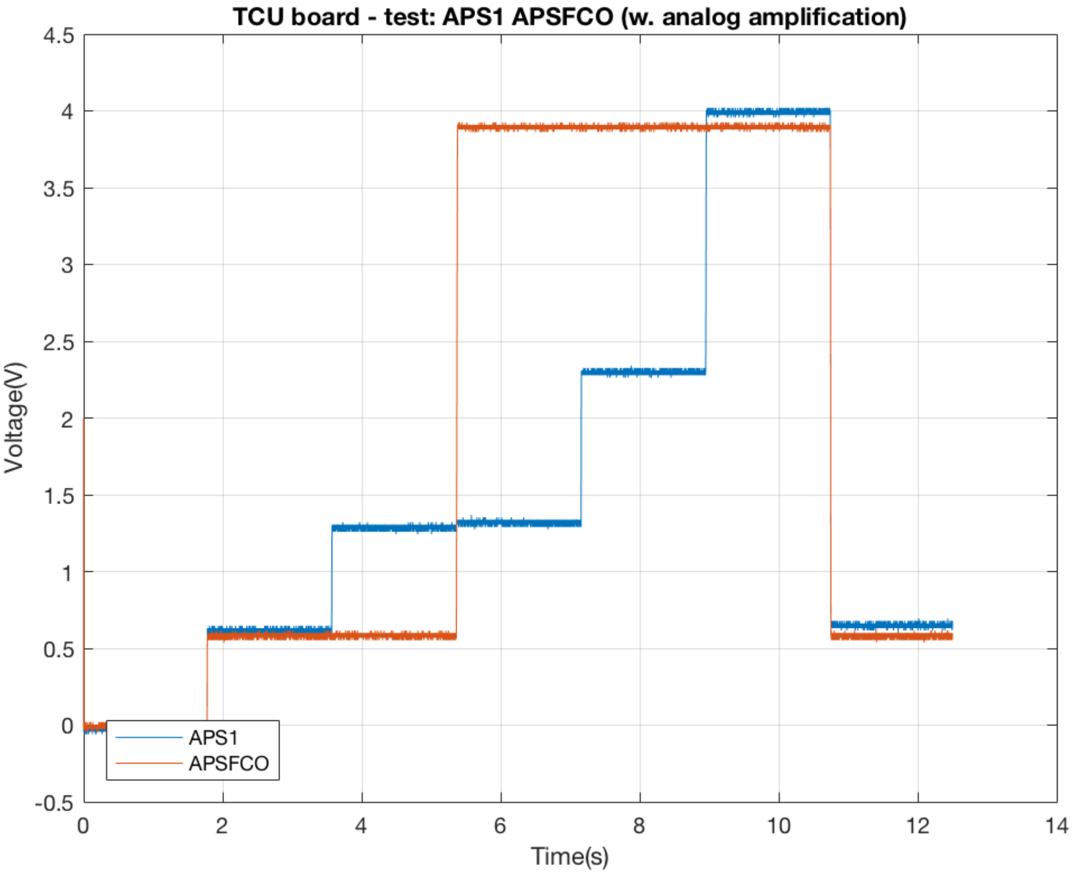


Figure 29: APS and threshold test of the APSFC

A function to read values from the serial port was implemented in the software to test the TCU. The function reads a value from 0-100 to accordingly set an APS value. The APS and APSFC singal wires to the ECM was then measured by an oscilloscope. The data is represented in figure 29. The RPS was tested in a similar way. In this test it was found that the signal values was lower than expected. The analogue scale factor in the software had to be adjusted to correctly match the analogue hardware on the PCB.

The TCU was then tested with the engine started. In some initial tests error codes were given from the WR and it did not start. Incorrect installation of the TCU in the WR was the reason behind the failure. It was corrected with good results.

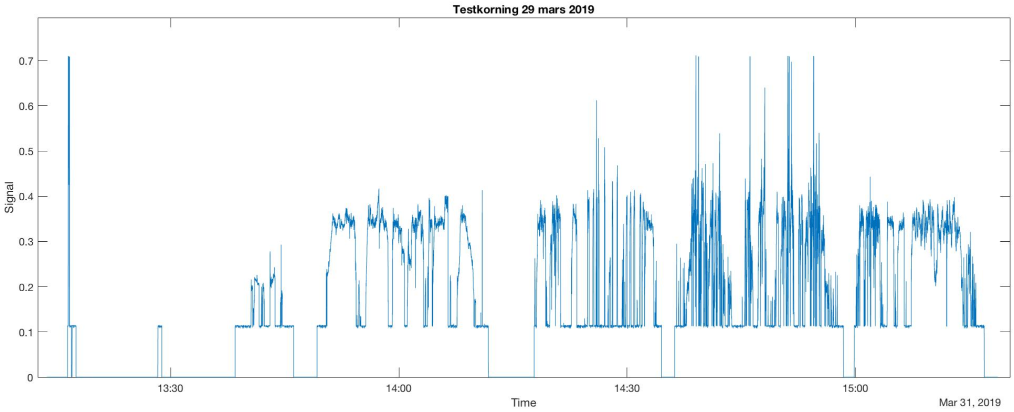


Figure 30: APS log from WR testdrive

The system was then adjusted to only read values and print them on the serial port. This to log values from APS, APSFC and RPS when a first test drive on the sea was performed, see figure 30. The signal did not only reveal the different driving behaviour of the group members, it also showed that the TCU system could be installed at the APS and RPS signal wires without errors from the ECM.

The TCU was also tested in the general DBW system tests, both on land and on water.

6.6 Evaluation

To evaluate the criterion regarding speed reasoning indicate that both the digital and analogue electronics could be the bottle neck. Since no measurement of the control latency were performed the speed could not be correctly evaluated. General engine test did however indicate the the speed is lower than 50ms.

When a zero input is given on the APS and the RPS the engine behaves as in the original system, the throttle is not increased. For the highest values, early oscilloscope measurements announce that the signal output from the TCU is 0.2 voltage to low. This means that ≈ 95 % of the max values at that point are reached. The max values after the correction is not measured.

In the general DBW system tests the passenger did notice speeds up to at least 75km/h when the DBW system was operating. If compared with speed reached in manual mode, $\approx 85\%$ was reached. However at this test the top speed was not in focus. Factors related to the environment or other parts of the system may also affect the top speed. In summary at least $\approx 95\%$ of the original system output was reached. Further voltage measurements are suggested to be done.

In test drives on water the operator did not notice any lack off controllability of the reverse and the WR generated no error code on the display. The shield movement is therefor approved to be function as in the original system.

7 External steering and the remote control unit

To control the WR an external system will be used. The external system can either be the Autonomous Control Unit (ACU) or the Remote Control Unit (RCU). Since the purpose of the DBW project is to remote control the WR, the RCU will be in focus. The goal is to use the same interface for the RCU and the ACU, together referred as automatic steering.

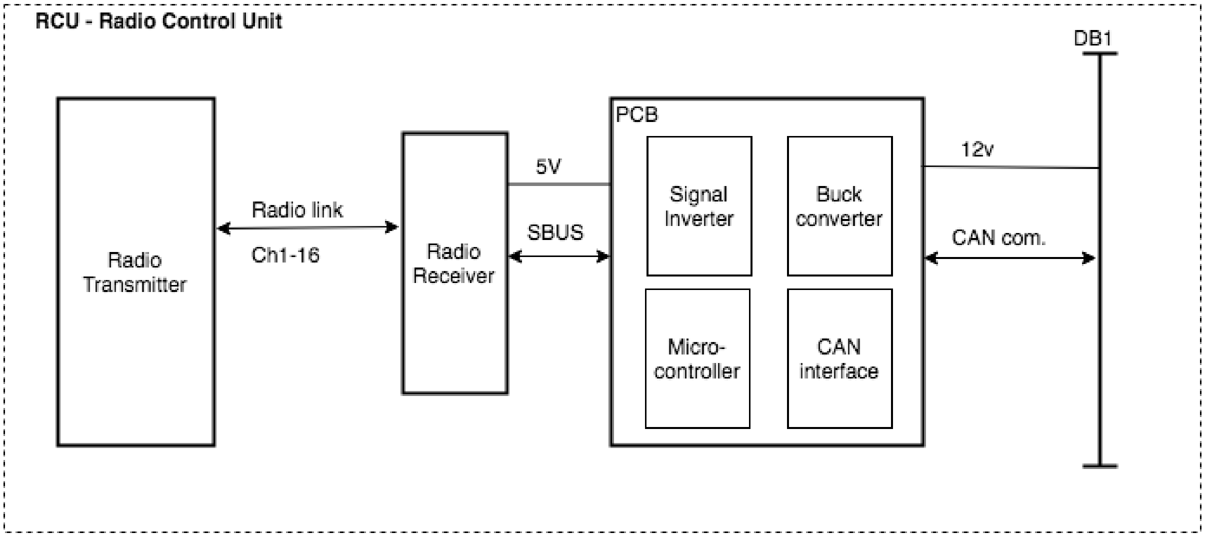


Figure 31: RCU Overview

The RCU uses a radio link connected between the user operated transmitter placed on land and the receiver in the WR. The receiver and its associated system in the WR will handle signals from the radio system and convert them accordance with the CAN protocol. As figure 3 indicates the RCU will be attached to DB1. See figure 31 for an overview over the RCU. Observe that DB1 also provides 12 V power.

Earlier projects that have worked with the WR at Chalmers did research to compare bluetooth, wifi and other radio frequencies as alternatives to remotely control the RR. In the bachelor thesis 2018 a 2,4GHz module was chosen to be used. In general it has a longer range than both Wifi and Bluetooth and fewer protocol indicates a faster communication [5]. This project will use a 2.4GHz radio remote control to control the RR.

A reliable product with range capabilities over 250 m is requested for this project. A user friendly interface and programmable settings are desirable. The message length desired is relatively short and have not been reviewed as a challenge.

The user interface of the transmitter is also essential since the RCU should reflect the user behaviour as if the driver is sitting on the WR. This to be able to test the drive by wire system without disturbance from other software. RC products used in hobby applications as for example rc planes meet those criteria well.

The usability is determined booth of the hardware and the software. The software is realised by the firmware of the transmitter. A product from FrSky is intended to be used [39] in the RCU. Products from FrSky uses the open source firmware called OpenTX [40]. The firmware was considered to be easy used with many possibilities.

The number of channels should also be considered when buying an RC system. A channel is a set of data that is mixed from the transmitter. Each stick on the transmitter is often associated with one channel, other inputs can also be allocated with a channel. Since the group will remote control throttle and steering at least 2 channels are needed. 4 or more channels are commonly used. The RiDE system on the WR is also in interest to remote and the autonomous system indicate that more parameters than this could be in interest to steer, 6 channels or more are therefore preferred.

The receiver output protocol also needs to be considered. It affects the complexity and the transfer speed of the communication with the connected system. It also affects the amount of wiring in the RCU. To achieve a fast and robust communication, RCU SBUS is chosen as a receiver output protocol and the receiver therefor needs this feature [41]. Premade Mbed library for SBUS decoding also indicated that this bus protocol could be used without to complex coding. However this library was later found to be pursued by errors.

Figure 32: The FrSky Taranis Q X7

Figure 33: The Frsky Rx8r

The Taranis QX7 from FrSky will be the transmitter implemented to the RCU, see figure 32. It is capable to use 16 channels programmable from the OpenTX firmware. The transmitter operates at 2.4 GHz[42]. The receiver that will be used is the FrSky RX8R, see figure 33. The system is capable to send telemetry data from the receiver to the transmitter [43].

7.1 Decoding SBUS

To use relevant data from the SBUS protocol the data needs to be separated and arranged in an more way that is more usable in the RCU software. There seems to be no official documentation for the SBUS protocol but other sources have been used in combination with a oscilloscope to decode the SBUS protocol.

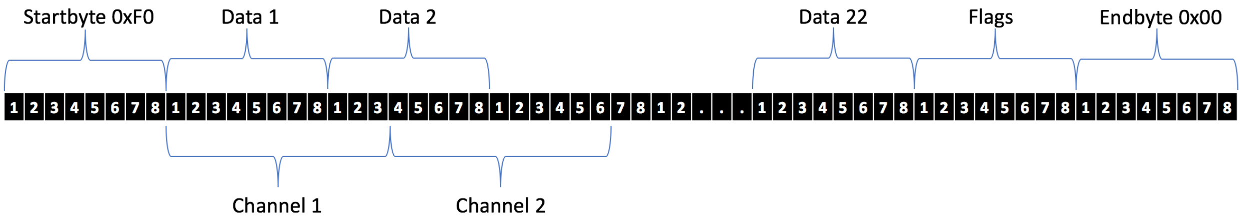


Figure 34: An SBUS frame

The frame of the SBUS protocol is 25 byte. It starts with a startbyte followed by databytes, a byte with flags, and ended by the endbyte. The 16 channels, where the relevant data from the rc transmitter is located, covers 11 bits starting from the first databyte, se figure 34. A frame is sent every 7ms and the baudrate is 100'000 bit/s. The logic level is inverted from the commonly used serial communication. Therefor the signal must be inverted when read on a microcontroller [44].

The speed of the protocol is used to distinguish a frame from the protocol. The start- and endbyte is then used to verify the validity of a frame. The bytes of data is shifted, arranged and added in a way so that a separate channel can be easily accessed. A channel can then be stored in a integer of width 16. At this point, one must observe that the protocol is sent as presented in figure 34, but the highest bit in every byte is sent first. So when read, the bit numbering in every byte must be inverted.

7.2 System implementation

The parameters to control is determined of the end nodes of the databus 2, the TCU and the NCU. It's interface is defined by the system architecture and more specific described by CAN architecture. In accordance with the TCU, an external steering system needs to control the speed forward and the reverse/breake. In the TCU chapter described as APS and RPS respectively. The NCU needs the angle of the nozzle as data input. Those parameters and its allocated channel is overviewed in table 19.

Table 19: RCU control paramaters

Paramter	**Interface**	**Channel**
APS	0-10 000	1
RPS	0-10 000	2
Nozzle	(-2500) - 2500	3

The part placed on land is locked in by the choice of the transmitter. Here the Taranis QX7 is chosen. The parts placed on the WR needs a process of design and development. However, one part of the ones placed on the WR is selected in association with the transmitter, that is the receiver. With this part as constraint the process can continue. The RCU abbreviation may from here on be used to only describe the parts of the system placed on the WR.

The general system requirements, described in section 2.1 indicate that the RCU must be able to handle vibrations, shock, dust and temporary immersion. The last criterion is specified to the standard rating IP67. To achieve those criterion, the RCU will be placed in a plastic enclosure. A pcb will be designed and connectors for the pcb and the enclosure will be picked with respect to the requirements.

The enclosure to the RCU is in the 1554F series from Hammond manufacturing, specially picked with a transparent cover to be able to see leds on the receiver. The outer dimension is 120x90x60.5 (mm) and the manufacturer part. nr is 1554F2GYCL [45]. Decoding of the SBUS indicate that the signal must be inverted, this is decided to be done by hardware. The single inverter gate from Texas Instrument with serial number SN74LVC1G04DBVT is a IC that is found to be suitable [46]. The Inverted SBUS signal is processed and decoded by an STM NUCLEO-F303K8 (STM), the same microcontroller that is also used in earlier units in the DBW project. The debugging is further explain in section 7.1. To remain the modularity that in some areas is used in the DBW project, the CAN interface is realised by the CAN interface pcb. This modularity make it possible to reuse knowledge and to use premade and thus existing hardware instead of developing it again. The CAN interface PCB documentation announce that the CAN interface pcb need the signals labeled D and R to transmit respectively receive CAN data. The CAN interface pcb and the RC receiver needs 5V as power distribution. The signal handling and processing of the signals is made by the program in the STM, see section 7.2.1. The 5V distribution is performed with a DC/DC buck converter. This converts the 12V power distributed by the DB1. A through hole DC/DC converter with part number R-78E5.0-0.5 from RECOM is chosen. It has the feature to be compatible with the "78 series" of regulators which ease the pcb design[47]. The result of this study is described by the initial figure 31 in this section and realised by manufacturing, testing and evaluation of the RCU. The electric schematic of the RCU PCB can be found in appendix 56. A render of the PCB with some components mounted is illustrated in figure 35.

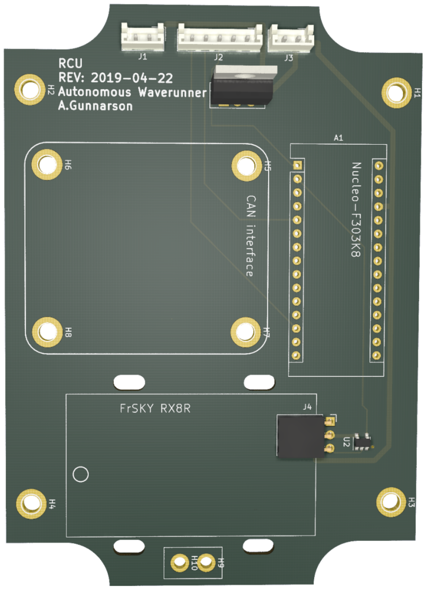


Figure 35: Render of the RCU PCB

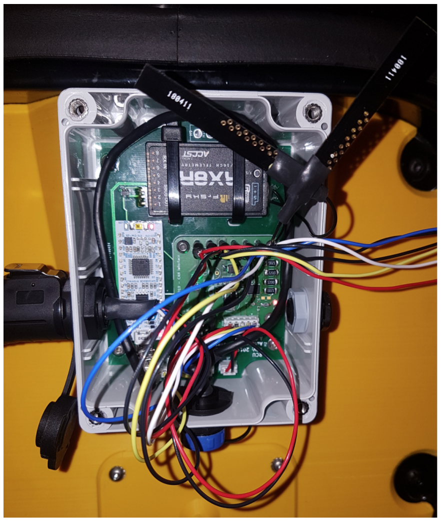
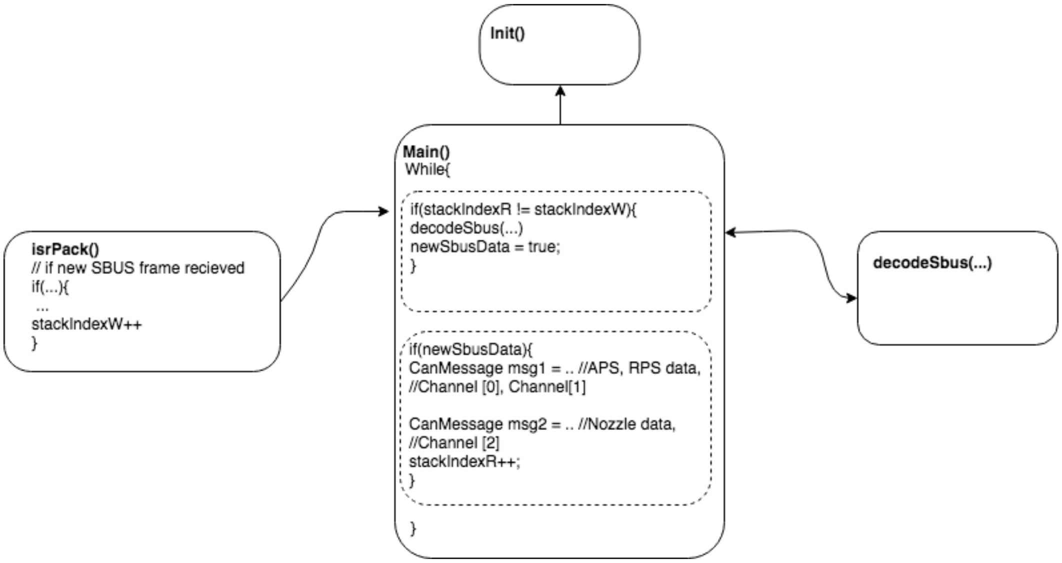


Figure 36: The RCU unit assembled and installed

The RCU is placed in the front compartment of the WR. The assembled and installed unit is pictured in figure 36. To decrease the risk of shielding from metal parts and electronics in the other units the receiver was screwed to the back of the front hatch on the WR. Testing of the shielding from the front hatch is described in section 7.4.

7.2.1 Software



```
Init()
```

```
isrPack()
// if new SBUS frame recieved
if(...){
 ...
stackIndexW++
}
```

```
Main()
While{
if(stackIndexR != stackIndexW){
decodeSbus(...)
newSbusData = true;
}

if(newSbusData){
CanMessage msg1 = .. //APS, RPS data,
//Channel [0], Channel[1]

CanMessage msg2 = .. //Nozzle data,
//Channel [2]
stackIndexR++;
}

}
```

```
decodeSbus(...)
```

Figure 37: RCU software flowchart

The main goal of the RCU firmware is to get SBUS data, decode it and then communicate on the CAN bus. The SBUS data is stored in a global stack array. If a whole SBUS frame is received a write index is increased and the frame is decoded. If the write index differentiate from the read index the data is prepared for the CAN communication and then sent in two CAN messages, one for the APS and the RPS data and one for the Nozzle data.

The stack array is defined as, char stack[stackSize][frameSize];

Where the stackSize is defined as 3 and the frameSize aims the SBUS frame which has the size of 25. The SBUS frame is sometimes referred to in the code as a package.

7.3 Transmitter setup

The transmitter is setup with with the model called "waverunn". Here the initial setup page is used to setup the receiver. The input page is used to setup input from to sources and the mixing page is used to mix the output from the throttle gimbal. This is to be able to use the throttle for both the APS and the RPS according to to switch positions.

Figure 38: The transmitter with labeled gimbals and switches

The result is a illustrated in fiqure 38. The throttle gimbal controls the APS if both of the Forward/Reverse selector is pointing forward. If the Forward/Reverse selector is pointing against the radio operator the throttle gimbal controls RPS. Observe that both of the Forward/Reverse selector has to be set equally and if they are in their middle position no output from the left input is given. The operator should also be observant on that if the throttle is increased when switching the Forward/Reverse selectors, the same input will still be given, but in the opposite direction. Which may result an a uncomfortable ride for the person sitting on the WR. It is thereby recommended to always lower the throttle stick before switching the Forward/Reverse selectors. The steering gimbal controls the nozzle in a similar way the steering handle on the WR moves. The Throttle kill switch will always cut the input from the throttle and can be used on both the APS and RPS control. The Throttle kill switch is setup as a safety feature and the radio operator should be well familiar with it's position.

7.4 Evaluation and testing

Tests of the RCU were done ongoing during the development of the software. Early revisions prints value between 0-1000 for channel 1-3 when connected to the STM serial port. The lower end positions of every stick on the transmitter sends 0 and the greatest stick movement sends 1000. All values from 0-1000 could be reached, the resolution was experienced as sufficiently high compared to the general DBW system.

A test were performed to test the signal shielding of the front hatch off the WR. The front hatch were unscrewed from the WR and the receiver was placed in its plastic enclosure screwed to the back of the front hatch. Visual assumptions indicate that the front hatch is made out of plastic and fibreglass. Tests were performed in ranges up to 150 m and no sign of interference or lost of signal were found to be due to shielding from the front hatch. The test fulfilled it's purpose and the result gave answer to questions regarding the shielding of the front hatch.

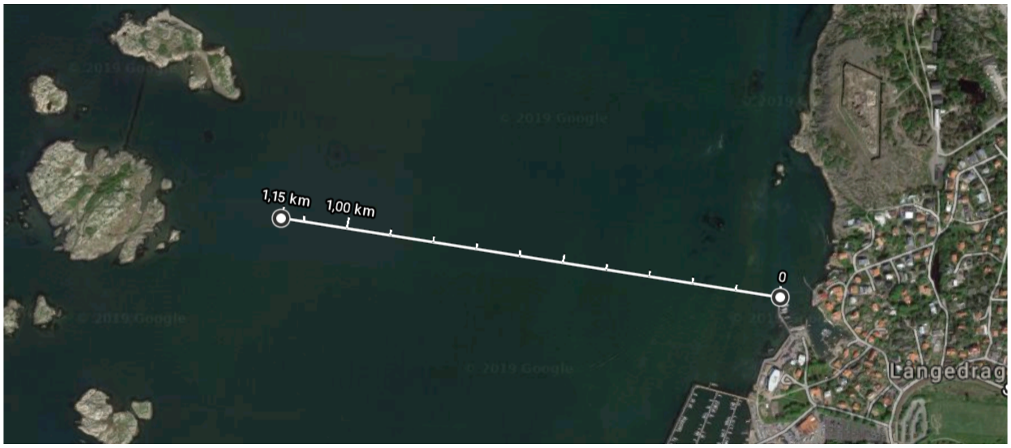


Figure 39: Satellite image from Google Maps showing the achieved range of the radio remote controller[48].

The range of the RCU was then tested. The receiver was placed in its final position, at the inside of the hatch screwed to the WR. The WR was placed in the environment it was attended to be used in. See figure 39. Output from Channel 1-3 was continuously varied and no interference was noticed. Thus the system requirement regarding regarding a range above 250 was fulfilled. In this test some shielding were found if the WR was directed from the transmitter. A different antenna placement is proposed as a solution to this issue. The RCU was then used for 2 hours as the external steering. The distances were generally shorter than 1km but the driving directions and behaviour varied. From this part of the test the radio link from the transmitter was experienced as reliable, with no loss of connection. However more test has to be carried out to further evaluate the reliability of the radio link in other environments and perhaps in other weather conditions.

8 Utility control unit

The Utility Control Unit (UCU) is a control unit with several functions that does not fit anywhere else. This unit is more of an experiment for what is needed in the future and it implements functions that are outside the scope of this project. The UCU is therefore not in the main focus and it is unfortunately not yet completed.

The planned features for the UCU are:

- The ability to read the speed sensor
- The ability to control the buzzer
- The ability to start and stop the engine
- The ability to switch between modes (not in this version)
- The ability to unlock the vessel (not in this version)

8.1 Original system

In the original system it looks like the following for the first three functions,

The ability to read the speed sensor: The speed sensor has three wires, 12 V (Red/Yellow), GND (Black/Yellow) and signal (Yellow). After measurements between the GND and signal wires it is clear that the signal switches between less than 400 mV and more than 11.6 V four times for each turn of the wheel.[49]

The ability to control the buzzer: The buzzer has a fixed tone. It is powered by two wires, 12 V (Red), GND (Black).[50]

The ability to start and stop the engine: The start and stop function works simply by short circuiting any of the cable pares, this was tested by simply putting a wire between them. These wires goes straight from the buttons on the handle to the ECM. The start function's wires is red and brown while the stop function's wires are white and black.[51] The safety harness simply disables the stop function when it is used, if removed the system instantly gets a stop signal.

8.2 Earlier solutions

There are no earlier solutions for the UCU which is why there is an interest in trying out the functions it provides.

8.3 Requirements and requests

For the complete autonomous WR system the whole idea is that the system should be fully automatic. This means that the implemented system should be able to fully control the vessel. In order for this to become reality there are several functions outside the scope of this project that needs to be implemented. The idea is that the WR should be able to boot its own system, unlock the vessel, switch mode to automatic, start the engine and join up with the leader boat. A presentation and the reason behind these features that are needed in order for this to work, will be presented below,

The ability to read the speed sensor: This feature can not only provide the system with an indication of how the vessel's speed responses to different manoeuvres, it can also act as an extra layer of safety. The drive by wire system consists of several different modules communicating with each other. This requires a lot of hardware and software that should be able to work together. The complexity can lead to system faults by bugs in the software or hardware failures. If each module that physically controls the vessel (TCU and NCU for now) have the ability to decide themselves if a manoeuvre is safe to execute, then they can prevent faults from arising, despite receiving faulty commands. This can be implemented by giving the modules the ability to read the speed, placing the safety as close as possible to the module itself. For example, the NCU's steering range can be divided into several intervals depending on the speed. This can prevent the autonomous system to steer so much that the person on board can not hold on, or prevent manoeuvres that is not possible to do in a certain speed.

The idea of placing an extra safety layer as close to the module as possible came from Anders Grauers at the Department of Electrical Engineering at Chalmers. Grauers explained that this is often done in the automotive industry where much more complex systems than the drive by wire system should be able to cooperate safely.

Implementing the ability to limit the range to intervals depending on the speed can of course create bugs on its own. It can cause the system to behave in a way that is not easy to predict. But if this feature is implemented correctly in the drive by wire system it could certainly provide that extra layer of safety.

The ability to control the buzzer: This feature can provide an extra way of interacting with the system. It gives the system the ability to alert the user of what is happening and if any action is being needed. This can for example be faults arising, switching between modes or just indicating that everything works as it should.

The ability to start and stop the engine: This feature can allow the system to control the on and off functions of the motor. It is needed for the final version of the autonomous WR where it should be able to start by its own and join up with the leader boat. Of course, implementing this feature gives the system more control which has two sides. It is needed in some way as mentioned above but if the system does not work as it is supposed to but can instead be a safety issue. The WR can be stopped by a bugging system which goes against several of the hazards in the TCU FMEA analysis. This is why it important to implement it in a safe way.

The ability to switch between modes: This feature is can allow the system to control in which mode it is in by software. This is also needed to be able to start the WR remotely so it can join up with the leader boat. Although this feature is highly experimental and can cause real consequences if the system if bugging. It is currently not planned for the UCU. It is better if this it implemented in the Operator Control Unit (OCU) which is already handling which mode the system is in. Is it to be implemented it is absolutely necessary to that this is done in a safe way. Often hardware limitations is safer than software. This is why this feature needs to have a hardware restriction preventing it from working when it should not. One thought of how this could work is that it can be limited to only work for a few seconds after the vessel is unlocked, then it is blocked by for example a circuit that is charged by a capacitor.

The ability unlock the vessel: This feature can allow the system to unlock the vessel from locked mode. Normally this is done by using the key by hand. It is also needed in order for the WR to become fully autonomous, filling the last piece of the puzzle that are needed. One idea of how this should be implemented is to make a circuit that just uses the original key. It should be possible to just control the button of the unlock key with a signal relay. At the same time the key can be powered by the system, replacing the built in button cell battery, allowing the system to work reliably.

8.4 Final solution

The UCU is very much like the TCU. They are using the same enclosure, PCB outline, microcontroller, CAN interface board and series of connectors from Lumberg. The only differences are which connectors that are used in the series and of course the circuit on the PCB. Therefore the parts that are the same will not be explained for the UCU.

8.4.1 Hardware - Overview

The current version of the UCU implements the functions mentioned in the system description, reading the speed sensor, controlling the buzzer, starting and stopping the engine.

8.4.2 Hardware - Design of the PCB

The UCU's PCB is also designed in the ECAD software Autodesk Eagle. The top side of the PCB from Eagle can be seen in figure 40.

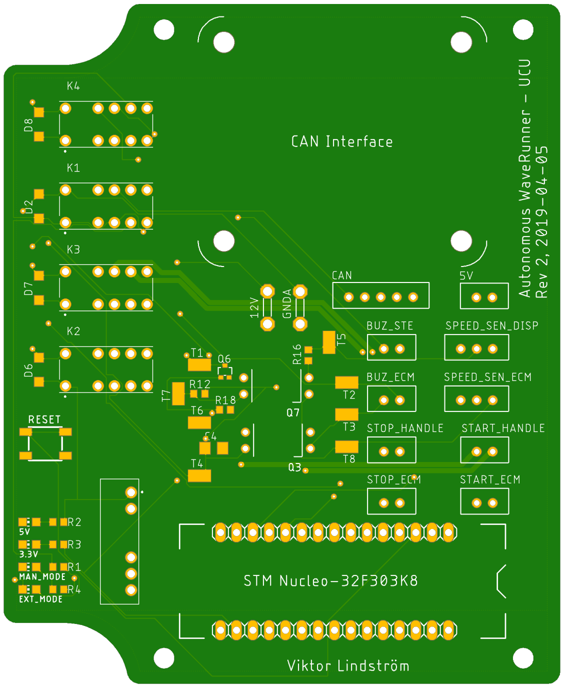


Figure 40: Top side of the UCU-Rev2 PCB from Autodesk Eagle.

The schematic consists of three pages which could be found in the appendix figure 68. Below is an explanation of the most important parts of the circuit.

The first page contains the MCU, power input, a DC-DC converter for giving power to the buzzer, a relay for switching the status LEDs depending on the mode, the CAN connector and the footprint for the CAN interface board.

The second page contains the circuit for the start and stop function. This works by just sending a signal from the MCU to control an N-MOSFET, which then switches the relay for the start or stop function.

The third page contains the buzzer and speed sensor circuit with several testing points which can be hooked up to an oscilloscope if necessary. The buzzer itself is driven by switching an n-channel mosfet on and off. This is enabled by switching the relay. The original and drive by wire system is isolated from each other which prevents any damage to the original system. The optocoupler is used to override the drive by wire system. If the original system wants to use the buzzer the drive by wire system will be blocked. There is also a lowpass-filter to prevent the drive by wire system to use the signal to early after the original system have been using it. This is to prevent any confusion from where the signal is coming from.

The speed sensor circuit is also isolated between the systems. This is simply done by an optocoupler. The last circuit on this page is the 12 V indicator. This is just a simple voltage divider which gives the MCU the capability of sensing when 12 V is enabled, i.e. in automatic mode.

8.4.3 Hardware - Cable interface and wire labelling

In order to connect the UCU to the original system the same procedure for cutting the wires as for the TCU was taken, which can be found in 6.4.5.

The module is fitted with the following connectors seen in table 20. The full wire labelling and colour coding can be found in appendix figure 64. The connectors used for the signals can be found in appendix figure 63.

Table 20: UCU connectors

Connector	From/To	Enclosure label	PCB label
Speed Sensor in	Sensor	SP IN	SPEED_SEN_ECM
Speed Sensor out	Display	SP OUT	SPEED_SEN_DISP
Buzzer in	ECM	BUZ IN	BUZ_ECM
Buzzer out	Steering mechanism	BUZ OUT	BUZ_STE
Start and Stop in	ECM	STA/STP IN	START_ECM/STOP_ECM
Start and Stop out	Handle	STA/STP OUT	START_HANDLE/STOP_HANDLE
CAN and Power	DB2	CAN	”CAN interface board”
CAN and Power	DB2	CAN	”CAN interface board”
USB	Programming, i.e. to computer	none	none

8.4.4 Hardware - Final enclosure

The final CAD model of the UCU enclosure can be seen in figure 41. It looks very much the same as the TCU except the number of connectors on the front.

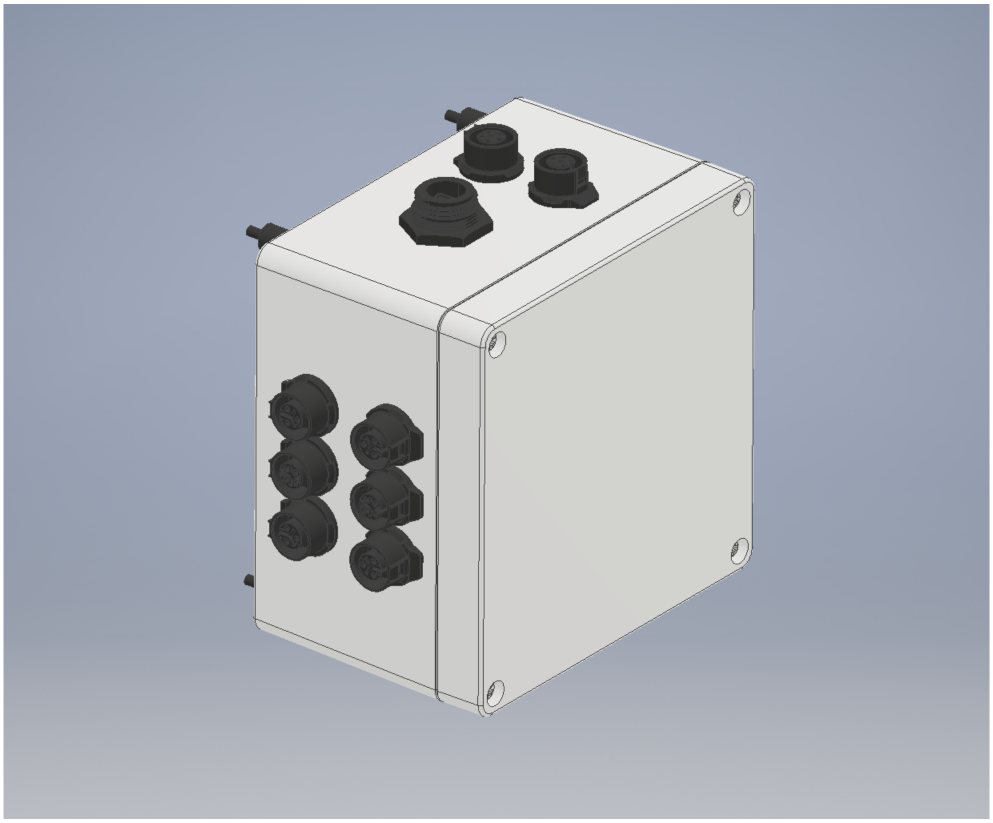


Figure 41: The final CAD mpdel of the UCU enclosure.

8.4.5 Software

The software for the UCU is yet to be completed. At the moment there is a simple program which uses the 12 V indicator to make a sound with the buzzer each time the mode is switched. This sound is two tones one after the other for switching to automatic mode, one tone for switching to manual mode. These tones are a bit different than the original sound. This is accomplished but using a PWM signal, although this buzzer has a fixed tone it is still possible to change it a bit. This is important so that the user does not confuse the drive by wire system with the original system.

To implement the rest of the features some additional CAN software is needed so the UCU can communicate with the rest of the modules over DB2. The program needed to execute commands can be an easy one that just responds to command by sending data back in case of the speed sensor or by giving a signal out for the start, stop and buzzer.

The IO pins that can be used when programming the UCU can be found in appendix figure 62.

8.5 Evaluation

It is uncertain if the UCU works as it should, only the buzzer have been tested and it works. The rest of the features needs to be tested but it is quite simple circuits and therefore they should be able to work. In the worst case a new revision of the PCB needs to be done. In the future of the autonomous WR project the rest of the functions should also be implemented. This version of the UCU is as mentioned above, just an experiment and some research on what is needed to be done in order to build a complete autonomous system.

9 Front mounting system

9.1 System description

The Front Mounting System (FMS) is the attachment for the ACU, NCU, UCU, TCU and Inertial Navigation System (INS) in the front of the WR, under the hatch. It consists of four brackets that are glued to the hull, a 2020 aluminium extrusion system and aluminium fixtures with vibration dampeners that holds the modules. It is supposed to be a modular system for attaching different modules depending on what the user want to install. The complete drawings and parts list can be found in appendix figure 57 to 61.

9.2 Earlier solutions

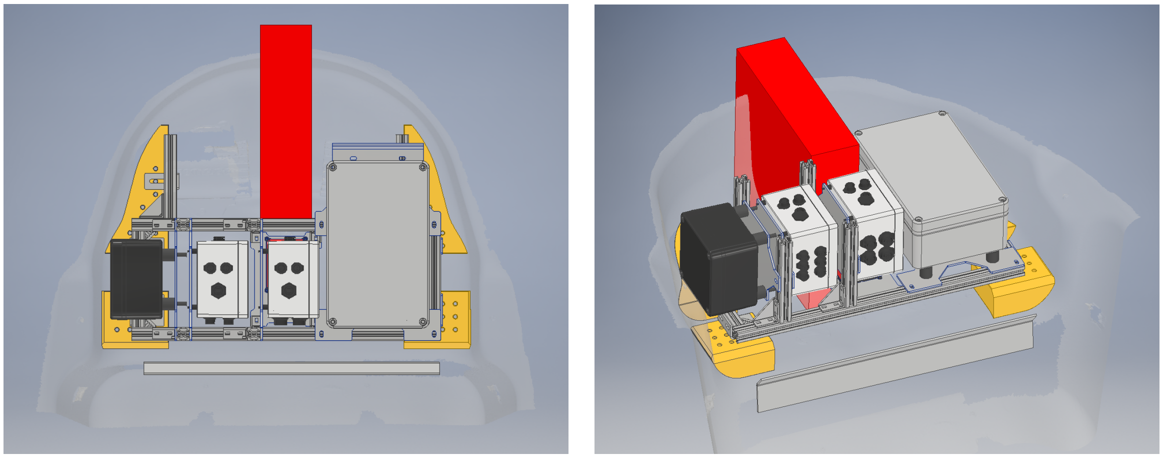
There are no earlier solutions for the FMS. In the original Yamaha VX Cruiser this space is used for personal storage. The front compartment is separated from the engine compartment with a wall and there is a place for a fire extinguisher that can be strapped down.

9.3 Requirements and requests

There is a need to attach all of the the modules of the added system in an easily accessible way. From the beginning the thought was that they were supposed to be placed in different places inside the engine and front compartment, depending on purpose of the module. This would have minimised the length of the cables needed to connect the modules but at the same time making it harder to reach some of them. Because of this as many modules as possible have been gathered in the front compartment which easily accessible by the front hatch. This compartment also protects the modules from water since it has a seal. However the seal is not completely watertight but it does not matter since all the modules are supposed to be watertight

9.4 Final solution

The FMS is designed in many steps to assure a modular system that will last, without the need to change the foundation. The idea is that the specially formed brackets are permanently attached to the hull of the front compartment, while the rest of the FMS is replaceable. The brackets provides a way to attach the 2020 aluminium extrusion system with accessories, or any other construction that can be needed in the future. The CAD model for the final solution can be seen together with a translucent 3D scan of the hull in figure 42a and 42b. The red box is the blocked zone from the hatch's arm, nothing can be placed there. The brackets can be seen in yellow. From left to right are the NCU, TCU, UCU and ACU modules. The INS unit is located underneath the UCU and can not be seen in these figures.

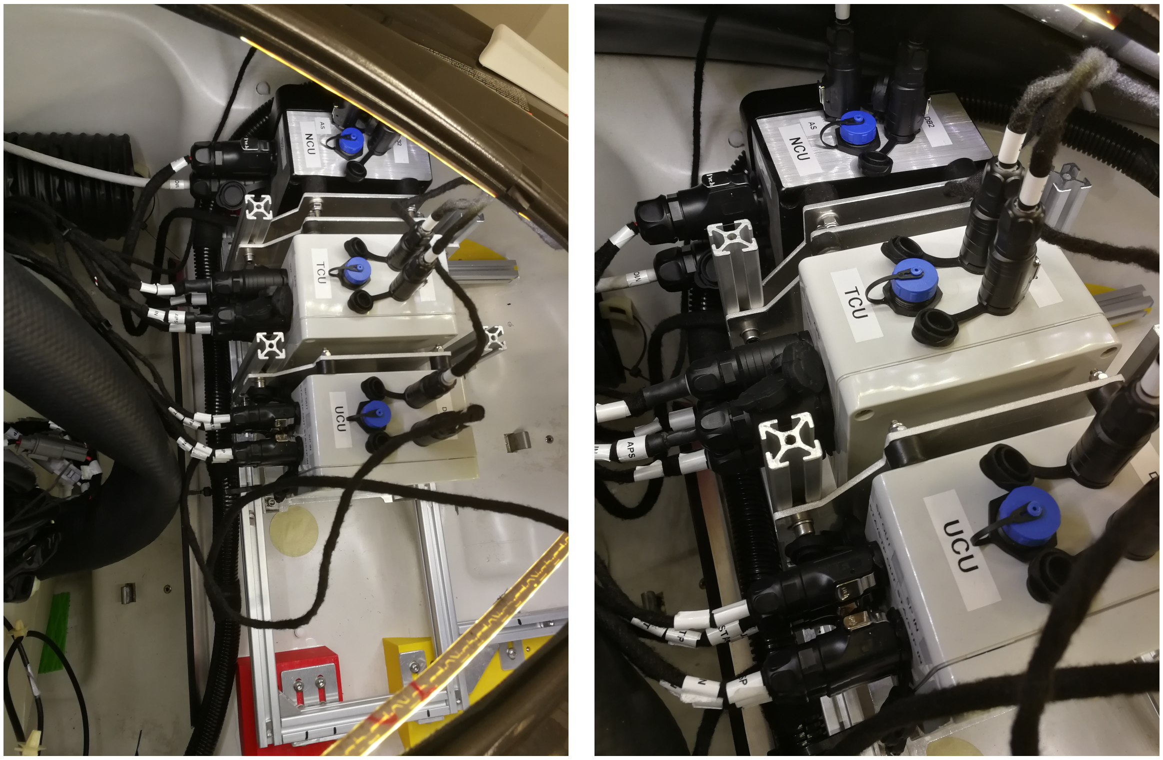


(a) FMS top view.

(b) FMS back view.

Figure 42: FMS CAD assembly.

The assembled version of the FMS can be seen in figure 43a and 43b. In this version the only thing that is different is that the brackets on the back of the mount are printed in red ABS plastic, while the ones in the front are yellow. Other than that and the blocked zone which could only be seen in the CAD model, everything is the same.



(a) The final Front Mounting System.

(b) The final mounting of the NCU, TCU and UCU.

Figure 43: FMS final assembly.

9.5 Design process

The design process for the FMS is taken in several steps. The most complicated parts are the brackets because they are formed by the hull. The process for the brackets can be seen in figure 44. A more in depth explanation how the whole mounting system is designed can be found in the steps below.

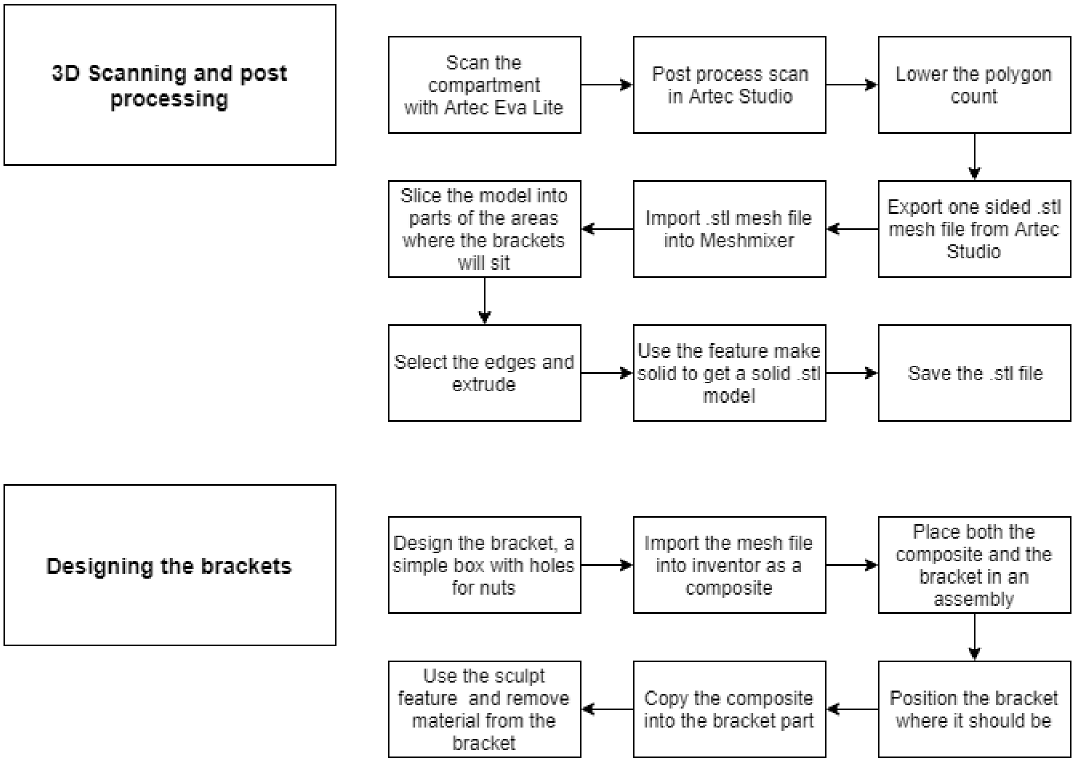


Figure 44: The design process for the FMS brackets

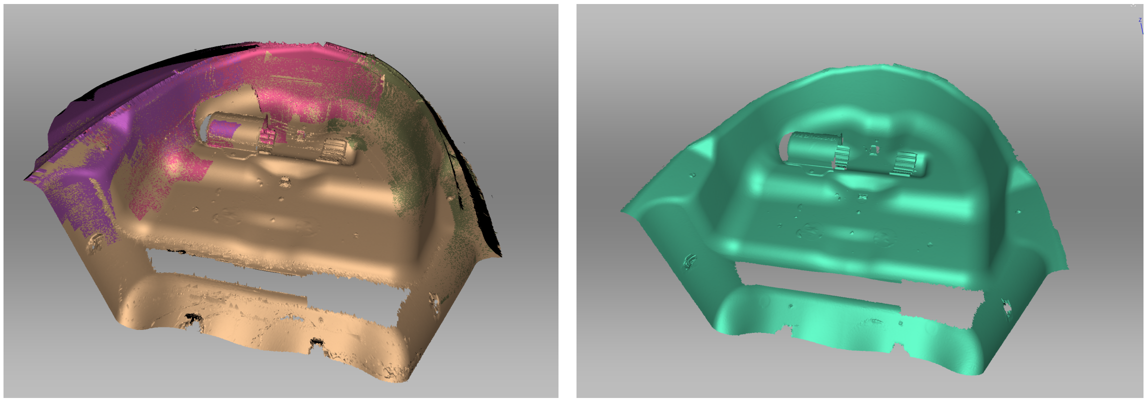
9.5.1 3D scanning and post processing

The first step is to make an accurate 3D scan of the front compartment. This makes it possible to design the extrusion system without the need to measure the compartment manually. The front compartment is by no means a simple geometric shape, this is why manual measurements could result in an inferior final solution.

There are several methods of 3D scanning. One of them is photogrammetry, which has become easily accessible because it can be done with a normal camera. This is a method where a lot of overlapping photos are taken making it possible to make a 3D model of the photographed object [52]. However this method was tried and did not work for this case. The software gave several different objects instead of only giving one complete model. The problem can be the fact that the compartment is quite small, making it hard to take photographs that overlap in the right way. Another problem is that the inside of the compartment is homogeneous. Despite using electrical tape to form a grid, it was hard for the software to distinguish between the photographs, they look almost the same.

Another method of 3D scanning is with a hand held 3D Scanner. The Artec Eva Lite [53] is a scanner which uses structured light technology. It projects a pattern of light onto the object while measuring the distortion thus making it possible to recreate the object in 3D [54].

By scanning the front compartment with this scanner it is possible to make an accurate model with a 3D point accuracy of 0.2 mm according to the scanner software Artec Studio, which can be seen in figure 45.



(a) Before processing of the scan. Frames taken by the 3D scanner, different colours represent different scans.

(b) After processing of the scan. The frames have now built up a mesh of polygons.

Figure 45: Before and after processing of the 3D scan of the front compartment.

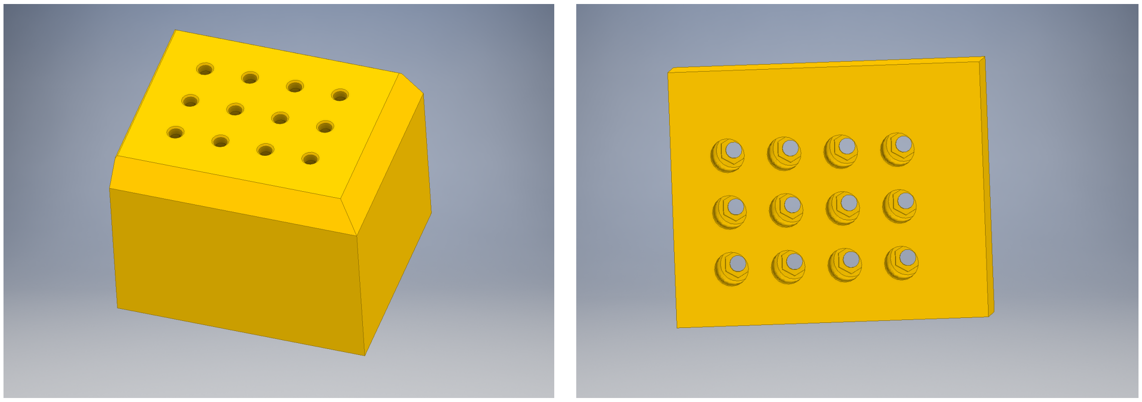
The scanner itself is able to produce a 3D point accuracy of up to 0.1 mm[55], but this could not be achieved when scanning the front compartment. It can be due to the fact that it was hard to scan the front compartment without loosing tracking. The result of this is that the model of the compartment consists of several scans which are combined. This causes the software to estimate the accuracy to 0.2 mm, although this is more than enough.

When the scanning is done is should be post processed and the polygon count lowered to simplify the model, reducing the final file size. Then converted to a .stl mesh file and exported form Artec Studio. The problem with with the scanning of the front compartment is that this mesh file only has one side, since it only covers the inside. A one sided mesh file can not be used as a mould for making the brackets. The advantage of making a mould for the brackets is that they fit perfectly, instead of trying to manually come up with a shape that can be mounted.

The one sided mesh file should therefore be imported into Meshmixer, a program for editing mesh files [56]. Since the mesh file for the front compartment is still a quite large and complex object it is sliced into the parts required for making the moulds for the brackets. This should be done since the CAD program used, Autodesk Inventor can not handle such a large mesh. The separate parts of the 3D scan can be made into solid mesh files by selecting and extruding the edges and using the feature ”make solid”. The solid mesh files should then be saved and imported into the CAD program Inventor.

9.5.2 Designing the brackets

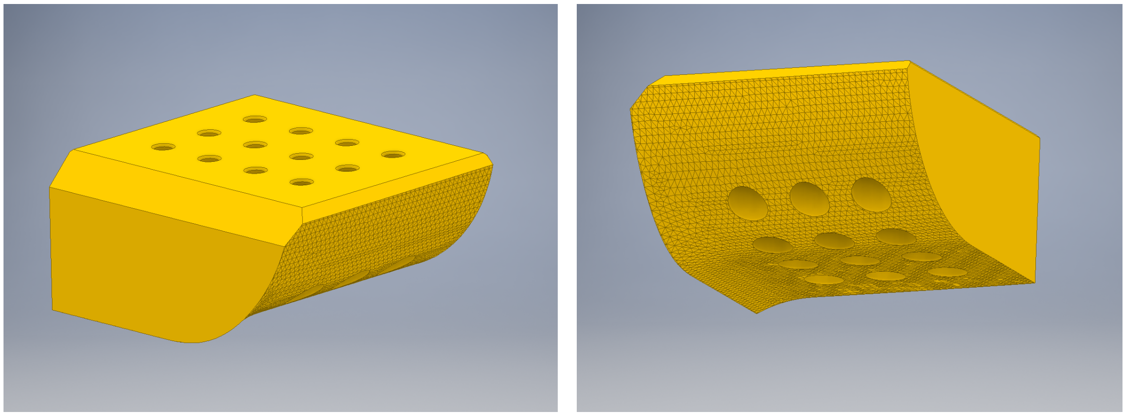
To make the brackets the first step it to come up with a simple design that can easily be manufactured while at the same time begin modular and durable. The chosen manufacturing method is to use a standard standard FDM 3D printer, mostly because it is one of the easier ways while it also provides the freedom of form that is required to make these parts. The chosen design is to make simple blocks with screw holes. In these holes a nut is placed locked in a hexagonal pattern. The nut is then locked by a plastic insert from underneath. The right back bracket can be seen in figure 46.


(a) Isometric top view.

(b) Bottom view.

Figure 46: Right back mount before moulding.

The solid mesh files are used to mold these simple blocks after the hull. This is done by importing the mesh file into Autodesk Inventor as a composite, placing both the bracket and the composite in the same assembly, positioning the bracket where it should be, copying the composite into the bracket part and then using sculpt to remove material from the bracket [57]. Sculpting these brackets takes approximately 15 minutes each time a change is made to the design which is also why the polygon count had to be lowered in the previous step. The final result can be seen in figure 47 where the right back bracket is shown. The drawings and parts list can be found in appendix figure 57.


(a) Isometric top view.

(b) Isometric bottom view.

Figure 47: Right back mount after moulding.

9.5.3 Designing the aluminium extrusion system

For the aluminium extrusion system, 2020 profiles are chosen. With only 20x20 mm in size, they are easy to work with while at the same time robust enough for this case. They are assembled by using standard stainless T-nuts and 2020 angle irons. The aluminium extrusion system can be seen in figure 48. The drawings and parts list can be found in appendix figure 58.

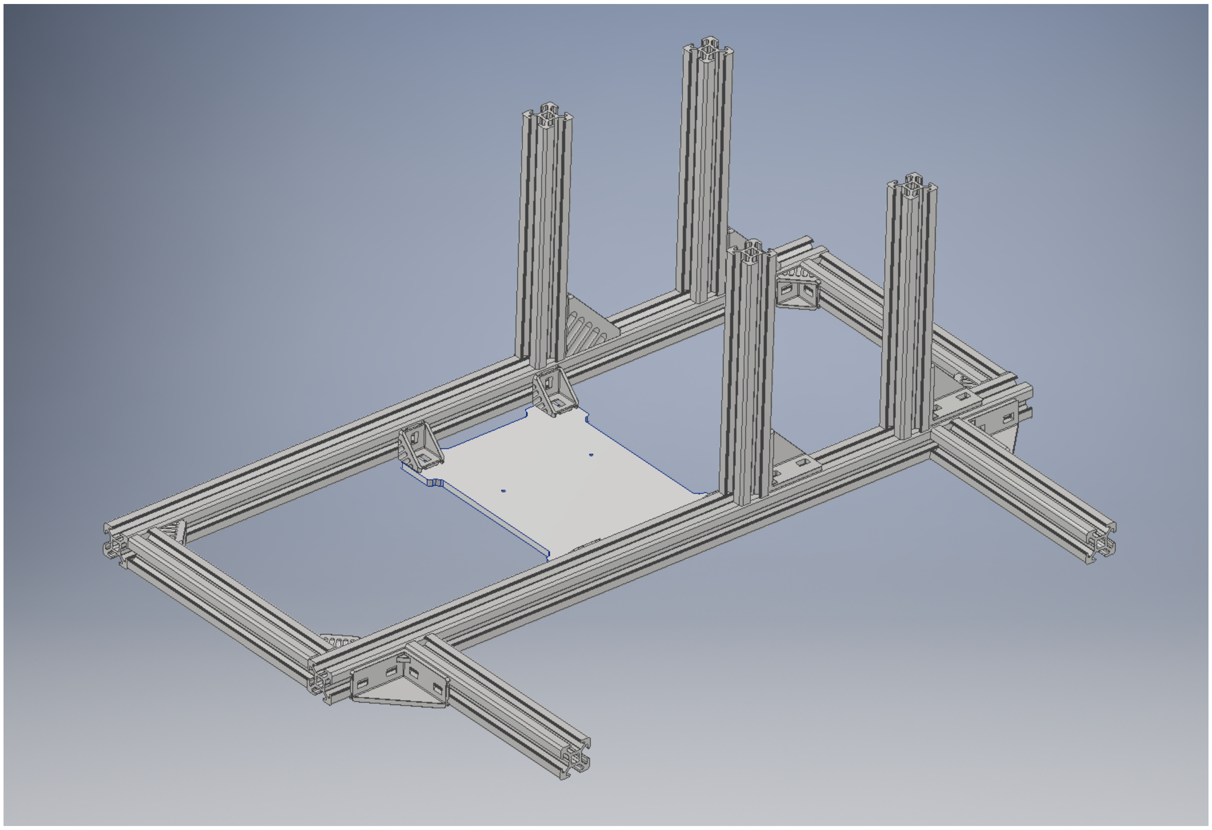


Figure 48: The 2020 aluminium extrusion system with a fixture for the INS in the middle.

9.5.4 Designing the module fixtures

Sine the modules can not be mounted directly onto the aluminium extrusion system some fixtures between them are needed. These are simply cut out of 3 mm thick aluminium with a water jet cutter. The fixture for the ACU is also bent in the corner to increase stability. The drawings and parts list for the fixtures can be found in the appendix figure 58.

To reduce the vibrations being transferred to the modules from the WR standard diabolic vibration dampeners are added between the modules and the fixtures. Unfortunately vibrations is not the only problem. The shocks that the modules are exposed to could also potentially damage the electronics inside. However this seems to be harder to solve, the dampening needs to calculated for each module and there are still not guaranties. therefore this problem is ignored, because of the lack of time.

9.5.5 Assembling the FMS

To assemble the FMS the brackets first needs to be mounted onto the hull. There are of course several ways to do this but strong double adhesive tape did not work. This is due to the complex form of the brackets, which will not give enough surface contact if placed only a bit incorrectly. Instead a strong structural adhesive is used. To mount the aluminium profile system onto the brackets there is a need for several angle irons. These can be cut out with a water jet cutter and bent to the exact form needed. The drawings and parts list for these can be found in the appendix figure 60. The aluminium extrusion system can be seen in figure 49.

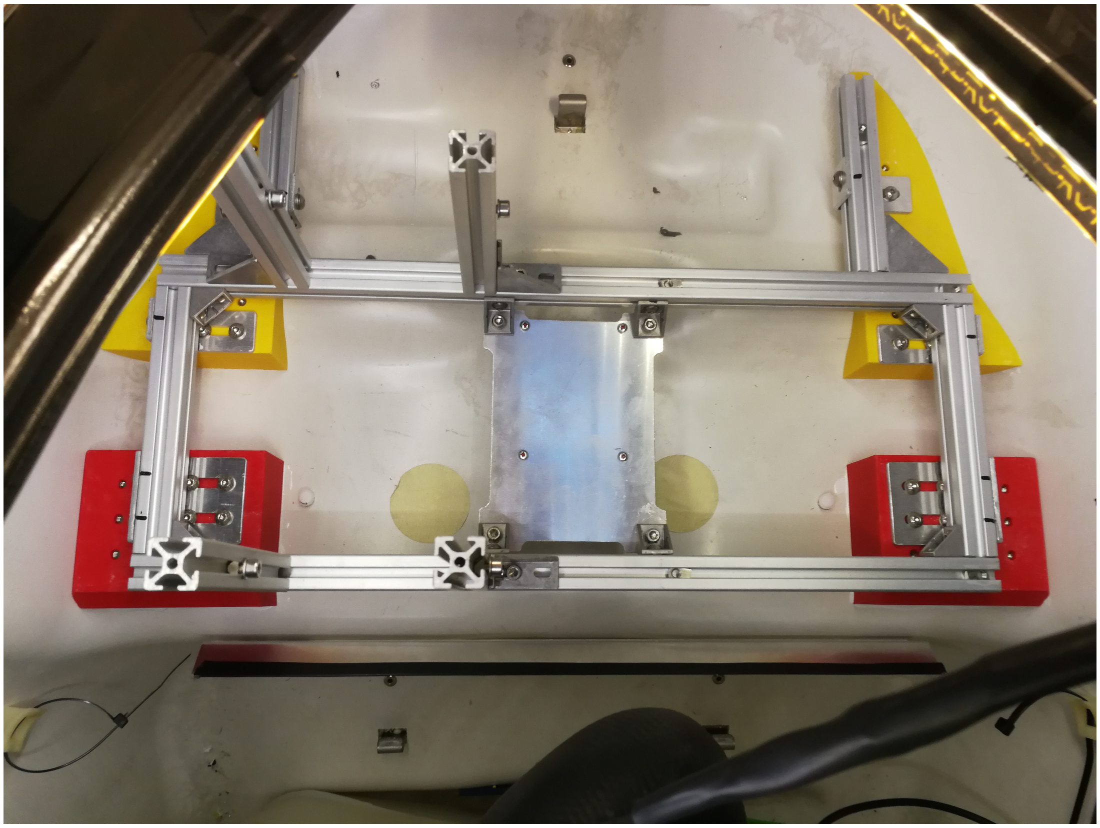


Figure 49: The aluminium extrusion system mounted to the hull.

The modules with fixtures can then be mounted onto the whole assembly and the final result is the same as shown in figure 42. Every screw used in the FMS should coated with threadlocker to prevent them from coming loose during use. The final drawing and parts list needed for assembly of the FMS can be found in appendix 61.

9.6 Evaluation

The FMS has since installation worked as it is supposed to. It have been used in one test drive which lasted for several hours. After inspection, all the modules are still sitting as they should and all the screws are still tightened which is a good result. During the test drive the hatch were opened several times to remove and to put back the modules, unplug and re plug cables, this also worked as it was supposed to, fast and easy. The only thing that is a bit hard is to refit the modules on to the aluminium extrusions. The T-nuts often comes lose when trying to screw the modules back on and falls down, although they could easily be picked up and put back but this is something that could be improved in the future.

10 Evaluation and recommendations for further work

The main purpose of the project was to implement a technical solution that enables the WR to be remote controlled. This has been mostly successful and testing has verified that the different subsystems can work together to allow for remote control. The system also managed to reliably switch between manual and automatic mode. When in manual mode the additional resistance from the automatic steering did not adversely affect the handling of the WR. There are still improvements that remain to be explored and further test are needed to thoroughly verify that the system fulfils the set requirements.

Some of the general system requirements have been completely verified like radio range, full actuator control, emergency stop functionality and mode switching. Other criteria like usability in coastal environments have been verified using design review, but will likely require further real life testing before any any eventual problems occur.

Much of the evaluation of the current systems has been based on user feedback from real testing. Any data logging done during the project has been implemented on a case by case basis. Therefore a good recommendation for further work on the system would be to add a centralised logging system that is able to provide more data to increase the confidence of the measured system performance. Taking this a step further would be to create a telemetry system that allows for live monitoring of system parameters during testing.

Improvements can also be made to the current system to more reliably handle fault conditions. The current system implements no such checks and the safe operation of the system is the responsibility of the operator. Adding basic checks to make sure that all nodes are present and ready to receive data before switching over to the automatic mode would be a relatively simple but significant improvement.

Another area of future improvements concerns the gear ratio and tuning of the motor and motions parameters of the NCU. When a large thrust is directed through nozzle, the current solution stalls and reverts the nozzle to its middle position. Increasing the gear ratio and tuning the speed and acceleration of the stepper motor are the first recommended actions to alleviate the problem. A further step of inquiry would be to measure the torque exerted on the steering axis when full thrust is applied while the steering angle is fixed in one end of its travel.

Some current components of the system were chosen for their availability rather than having fulfilled all relevant qualifications. The most notable example of this is the motor for the NCU that does not have any liquid ingress protection and needs to be replaced with a more suitable variant for long term usage. The current motor mounting bracket is also not manufactured from stainless steel and also needs to be replaced or painted to protect it from corrosion.

The system should hopefully be a useful and flexible platform for implementing a completely autonomous solution in the future.

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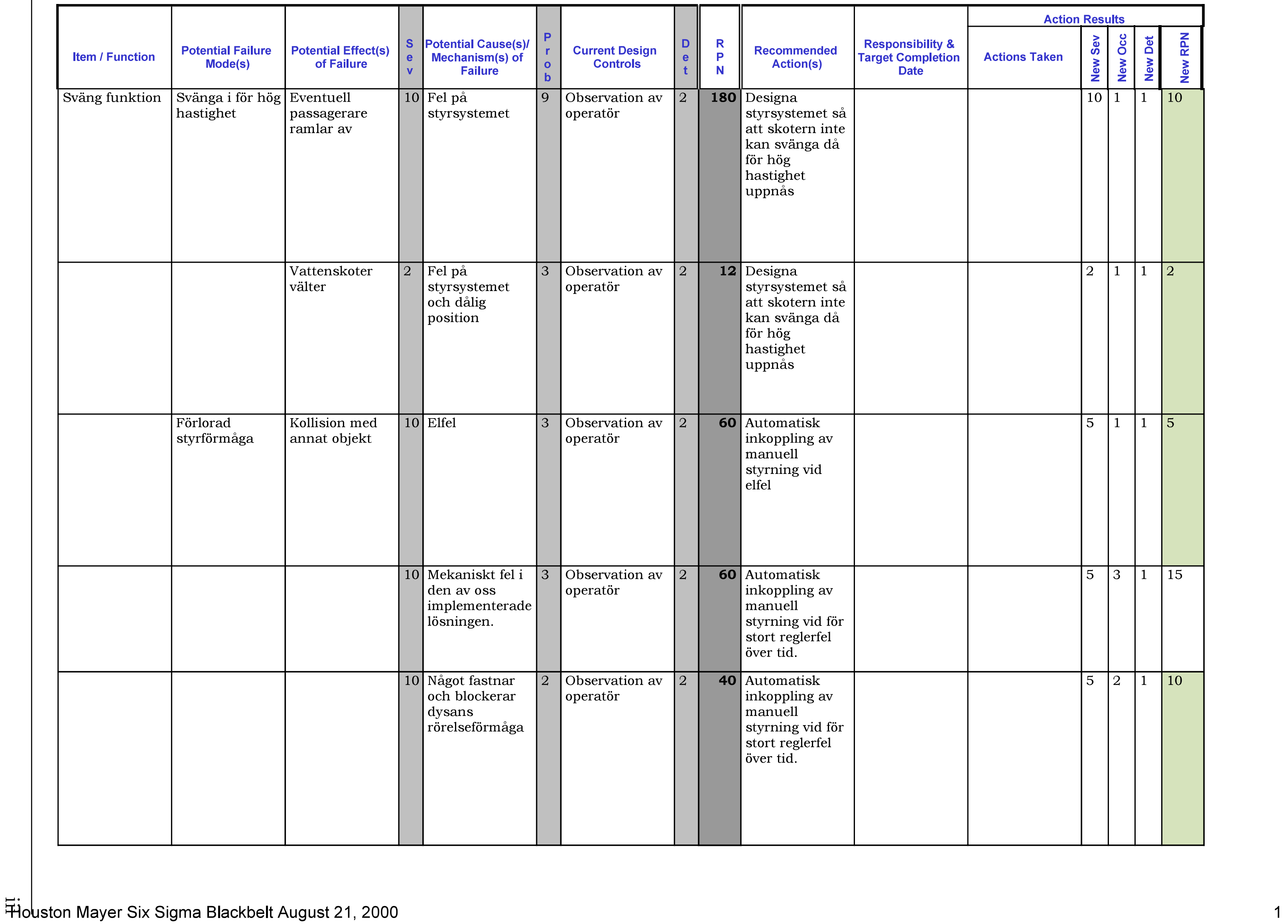
11 Appendix



Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results				
											Actions Taken	New Sev	New Occ	New Det	New RPN
Sväng funktion	Svänga i för hög hastighet	Eventuell passagerare ramlar av	10	Fel på styrsystemet	9	Observation av operatör	2	**180**	Designa styrsystemet så att skotern inte kan svänga då för hög hastighet uppnås			10	1	1	10
		Vattenskoter välter	2	Fel på styrsystemet och dålig position	3	Observation av operatör	2	**12**	Designa styrsystemet så att skotern inte kan svänga då för hög hastighet uppnås			2	1	1	2
	Förlorad styrförmåga	Kollision med annat objekt	10	Elfel	3	Observation av operatör	2	**60**	Automatisk inkoppling av manuell styrning vid elfel			5	1	1	5
			10	Mekaniskt fel i den av oss implementerade lösningen.	3	Observation av operatör	2	**60**	Automatisk inkoppling av manuell styrning vid för stort reglerfel över tid.			5	3	1	15
			10	Något fastnar och blockerar dysans rörelseförmåga	2	Observation av operatör	2	**40**	Automatisk inkoppling av manuell styrning vid för stort reglerfel över tid.			5	2	1	10

Houston Mayer Six Sigma Blackbelt August 21, 2000

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Figure 50: FMEA of NCU, part 1

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results				
											Actions Taken	New Sev	New Occ	New Det	New RPN
			10	Styrvarjer går av eller fästen på dysa/styre lossnar	2	Observation av operatör	2	**40**				10	2	2	40
			10	Fel styrvinkel visas	3	Observation av operatör	2	**60**	Kontroll av styrvinkel mot skoterns egna styrvinkelgivare			5	3	1	15

Houston Mayer Six Sigma Blackbelt August 21, 2000

2

Figure 51: FMEA of NCU, part 2

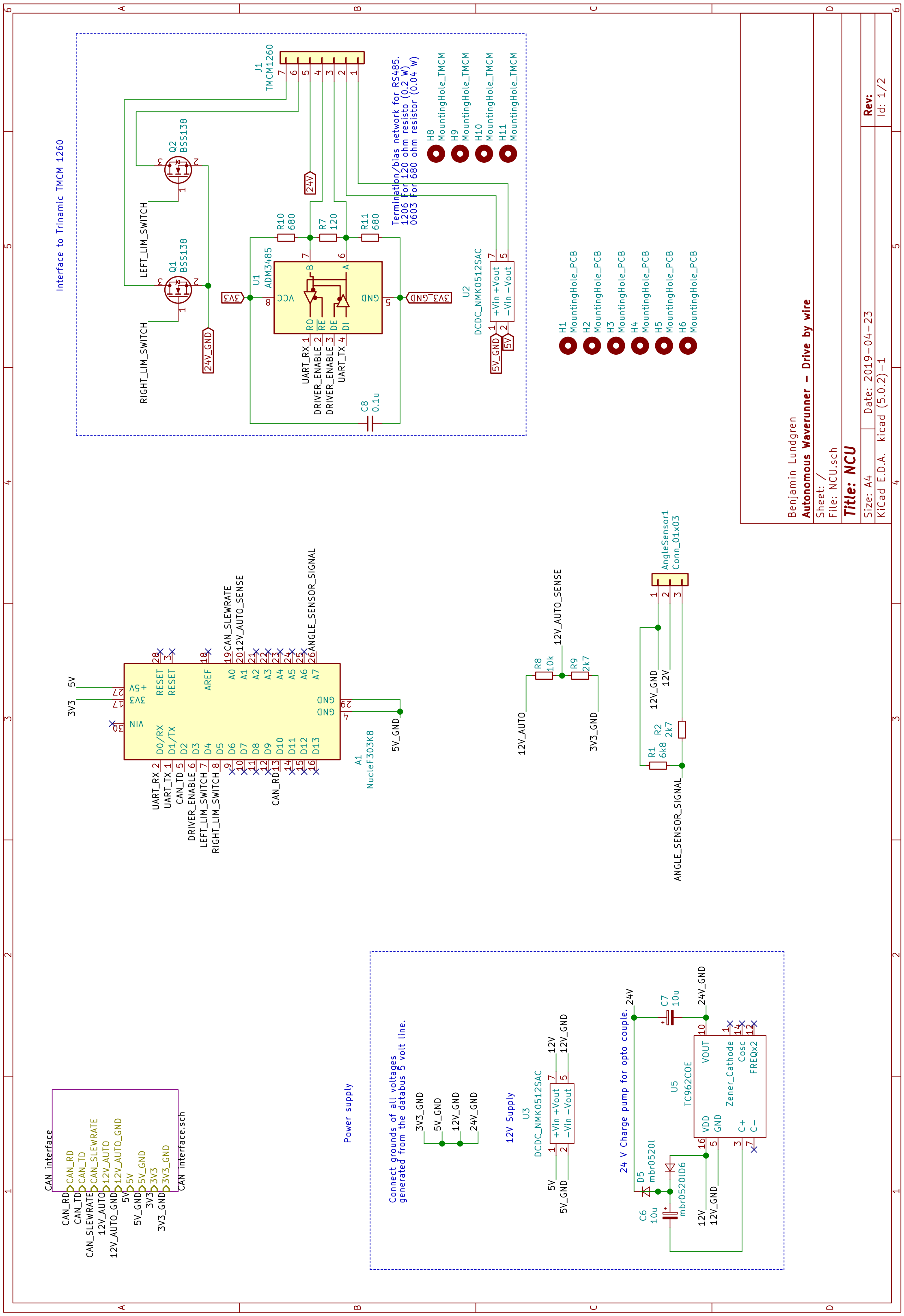


Figure 52: Schematic of NCU PCB page 1/2

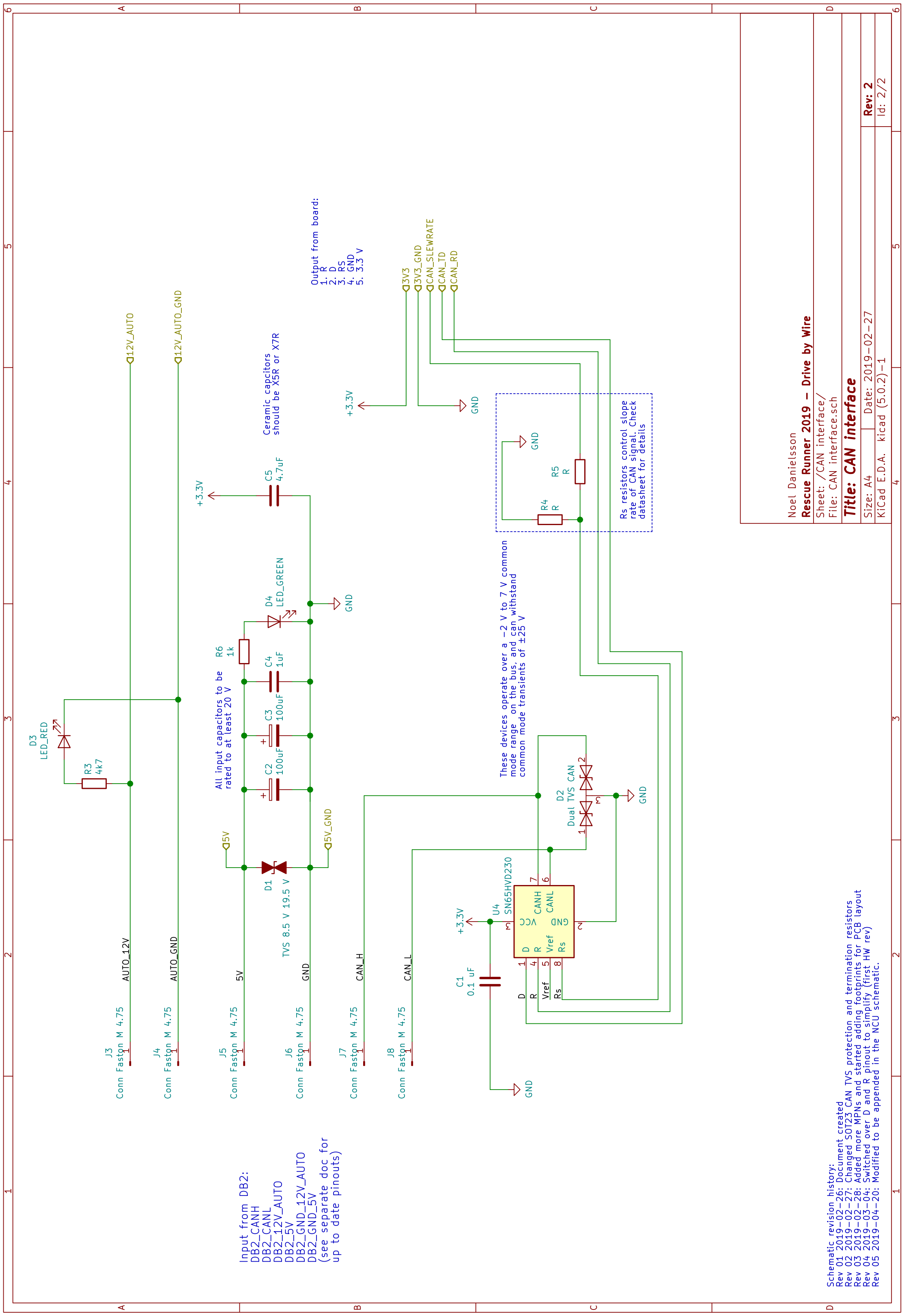


Figure 53: Schematic of NCU PCB page 2/2

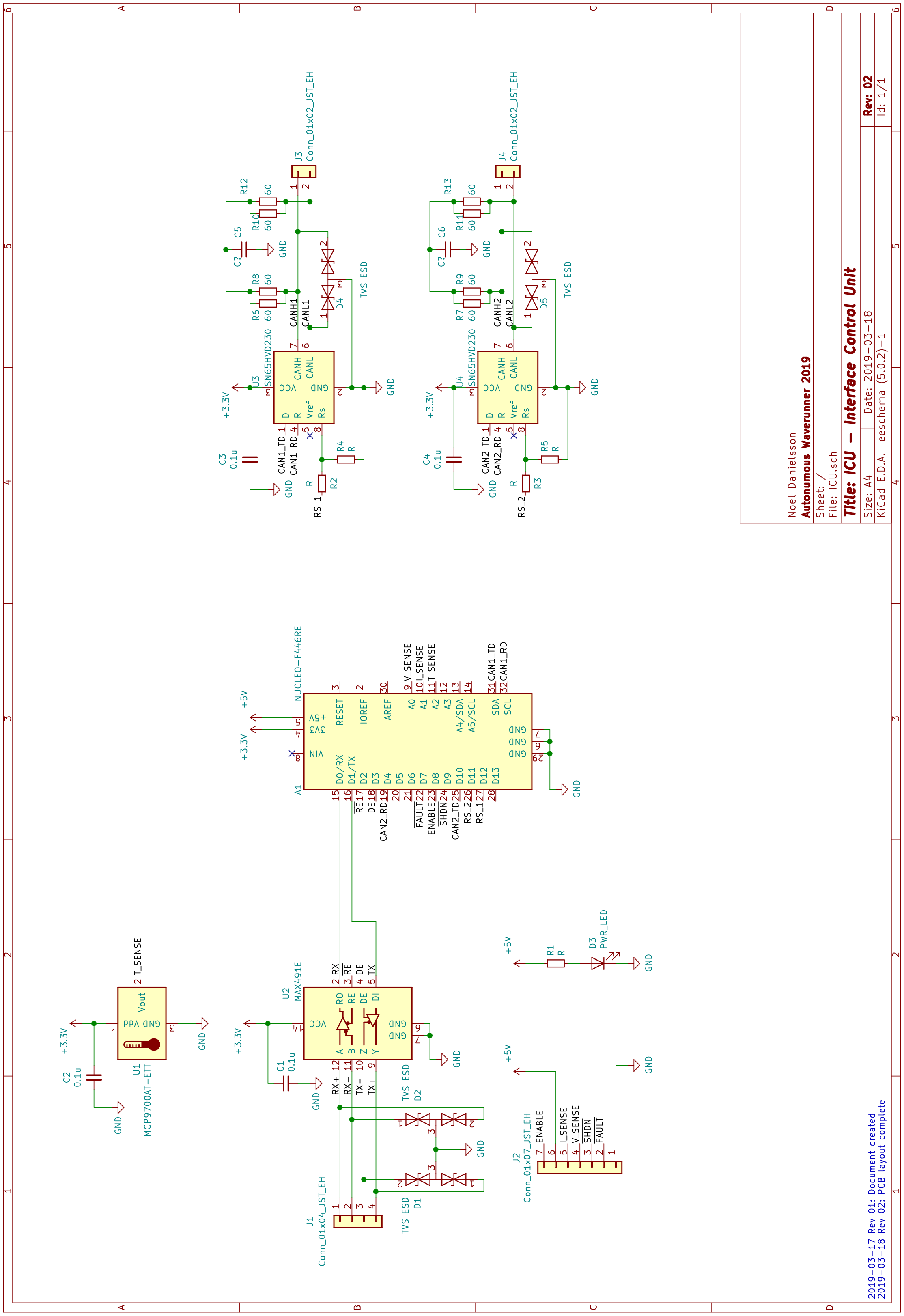


Figure 54: Schematic of ICU

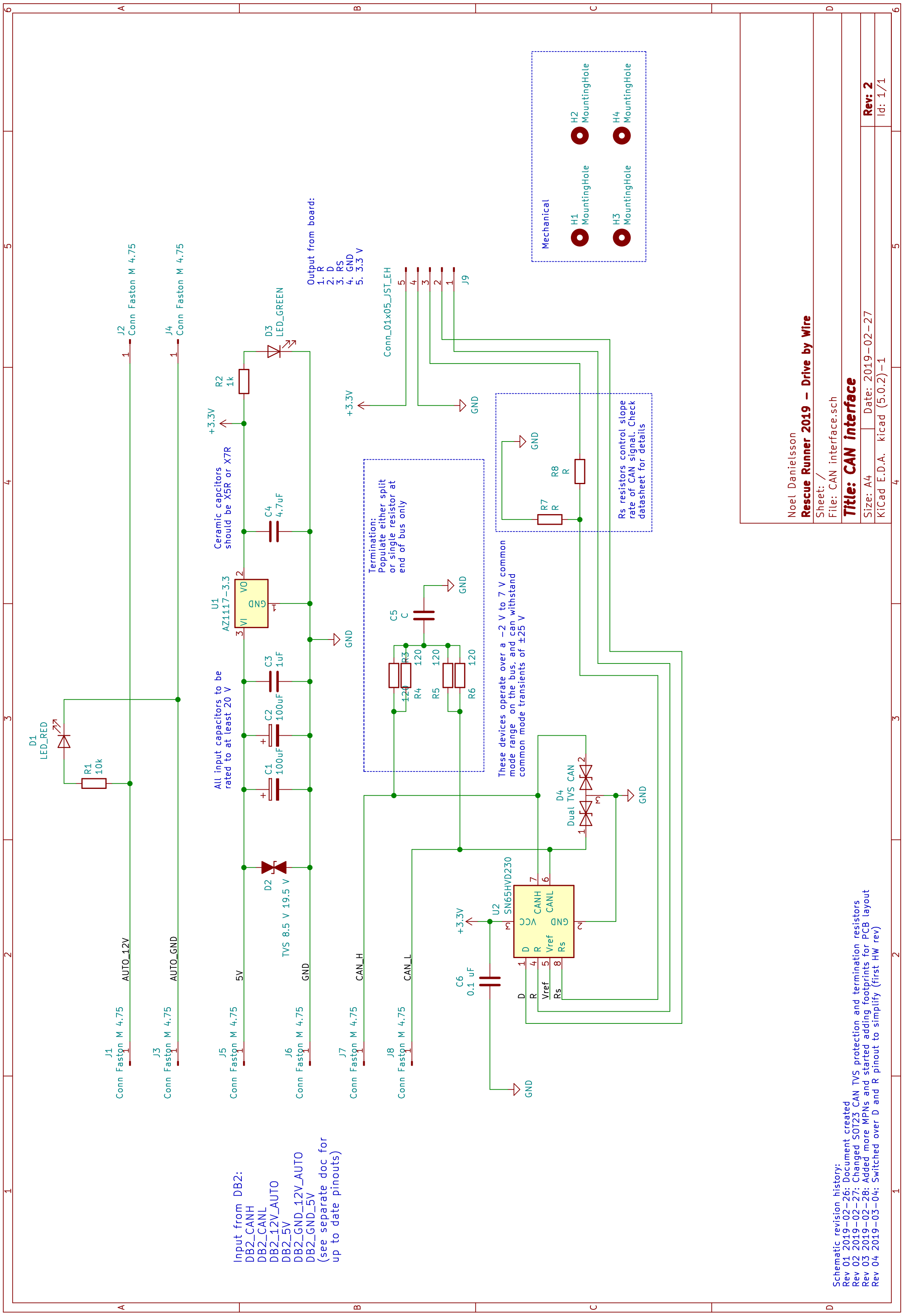


Figure 55: Schematic of CAN interface board

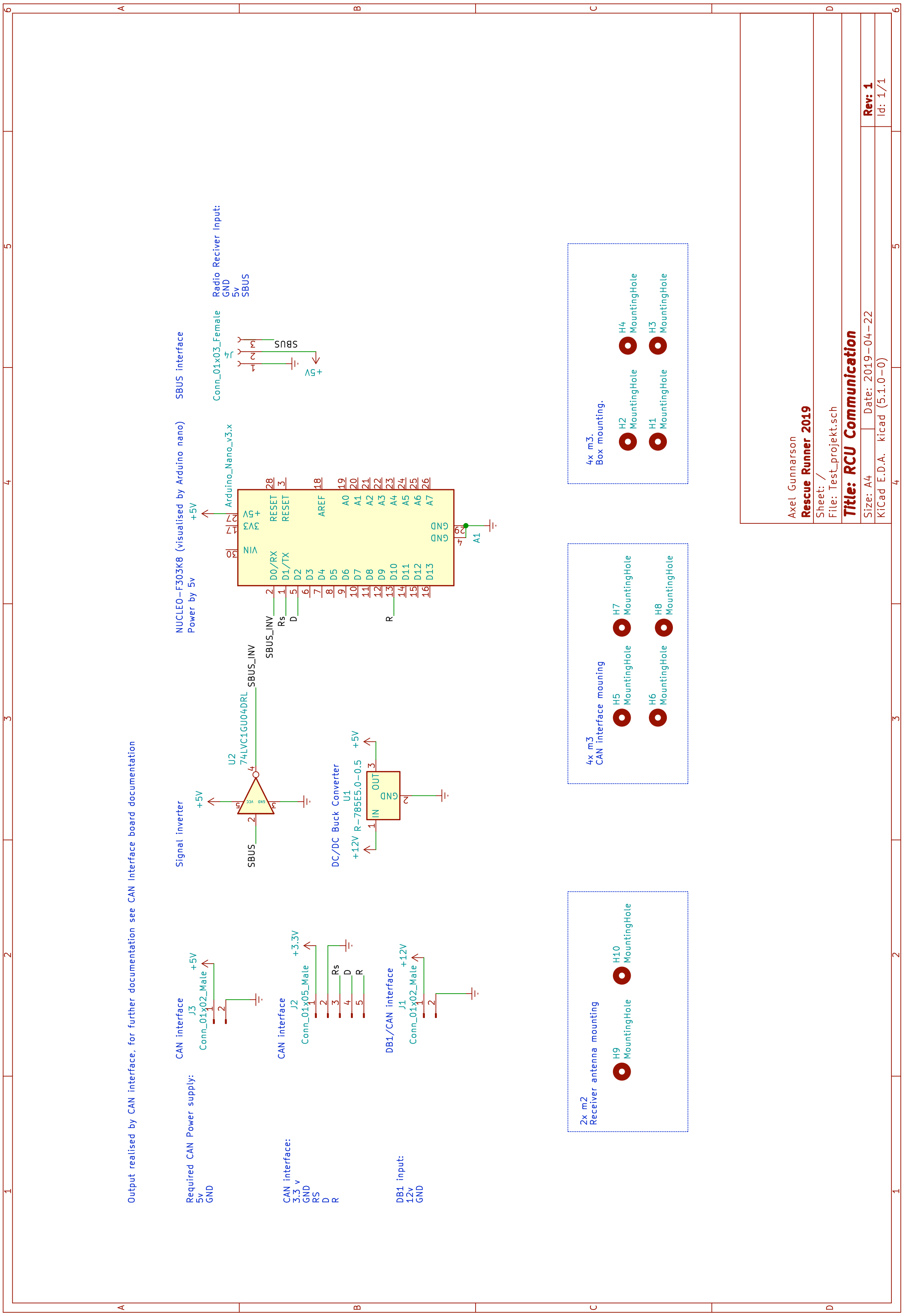
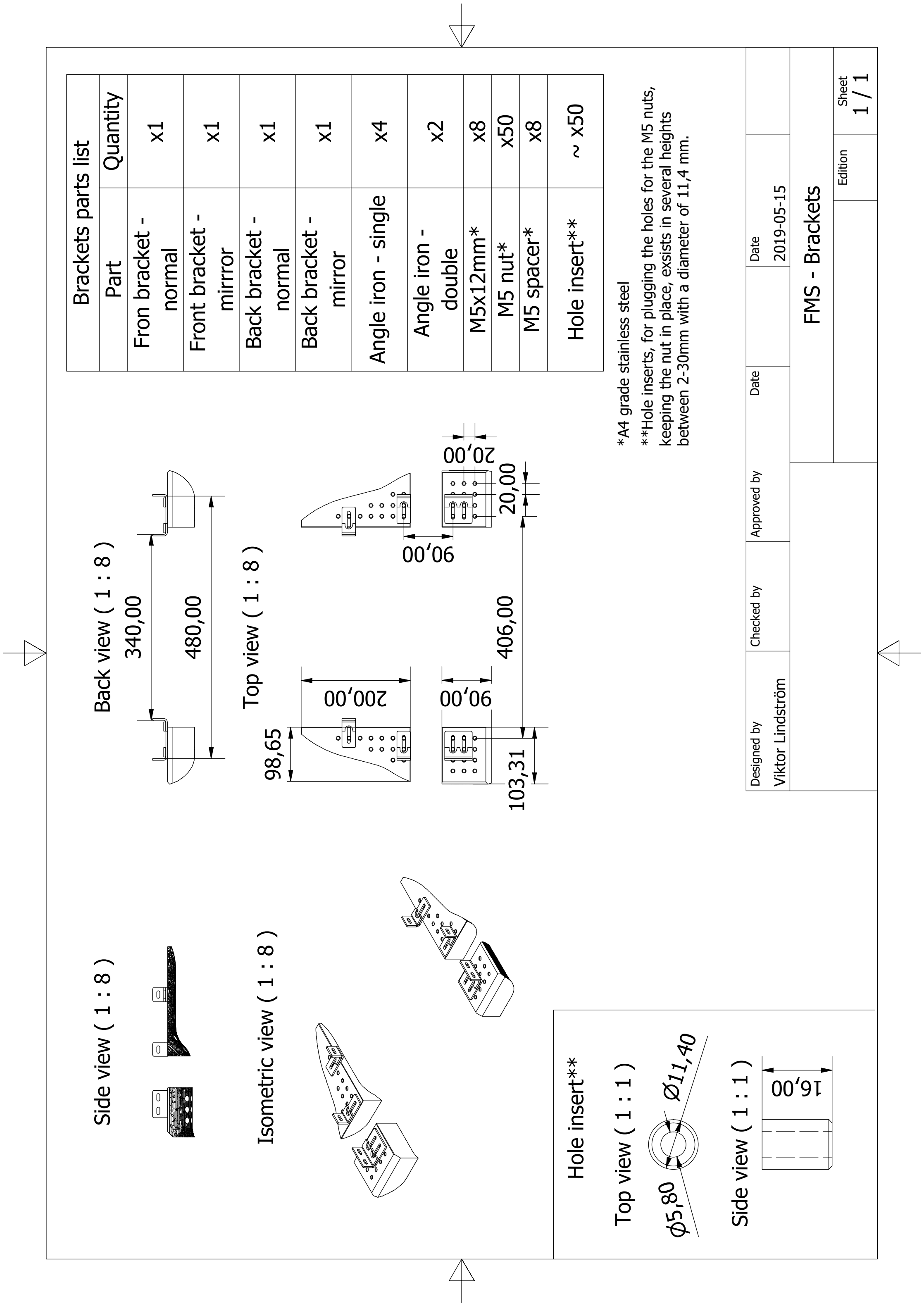


Figure 56: RCU PCB schematic



Brackets parts list

Part	Quantity
Fron bracket - normal	x1
Front bracket - mirrror	x1
Back bracket - normal	x1
Back bracket - mirror	x1
Angle iron - single	x4
Angle iron - double	x2
M5x12mm*	x8
M5 nut*	x50
M5 spacer*	x8
Hole insert**	~ x50

*A4 grade stainless steel

**Hole inserts, for plugging the holes for the M5 nuts, keeping the nut in place, exsists in several heights between 2-30mm with a diameter of 11,4 mm.

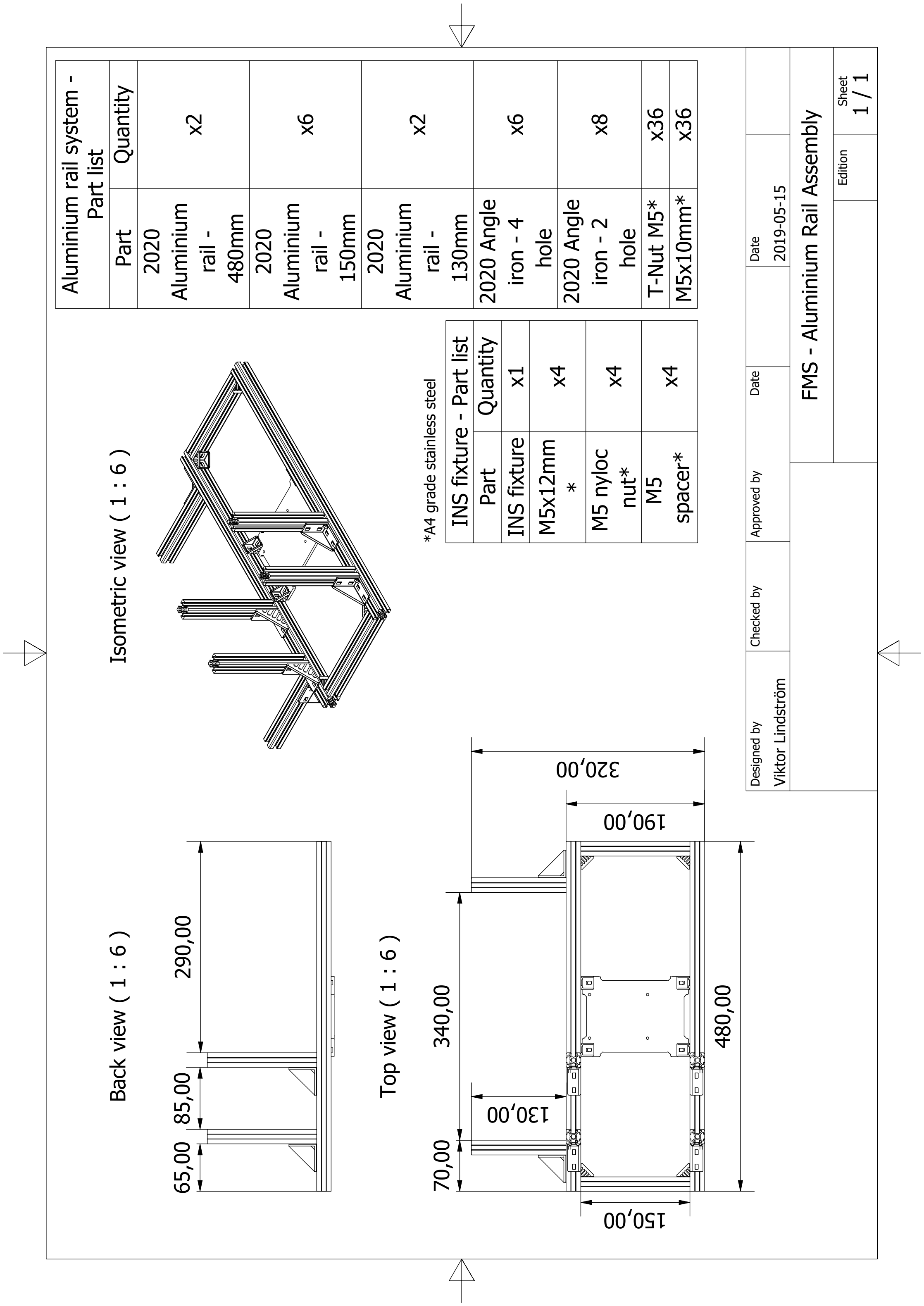
Designed by	Checked by	Approved by	Date	Date
Viktor Lindström				2019-05-15

FMS - Brackets

Edition

Sheet
1 / 1

Figure 57: FMS - Brackets



Aluminium rail system - Part list

Part	Quantity
2020 Aluminium rail - 480mm	x2
2020 Aluminium rail - 150mm	x6
2020 Aluminium rail - 130mm	x2
2020 Angle iron - 4 hole	x6
2020 Angle iron - 2 hole	x8
T-Nut M5*	x36
M5x10mm*	x36

INS fixture - Part list

Part	Quantity
INS fixture	x1
M5x12mm *	x4
M5 nyloc nut*	x4
M5 spacer*	x4

*A4 grade stainless steel

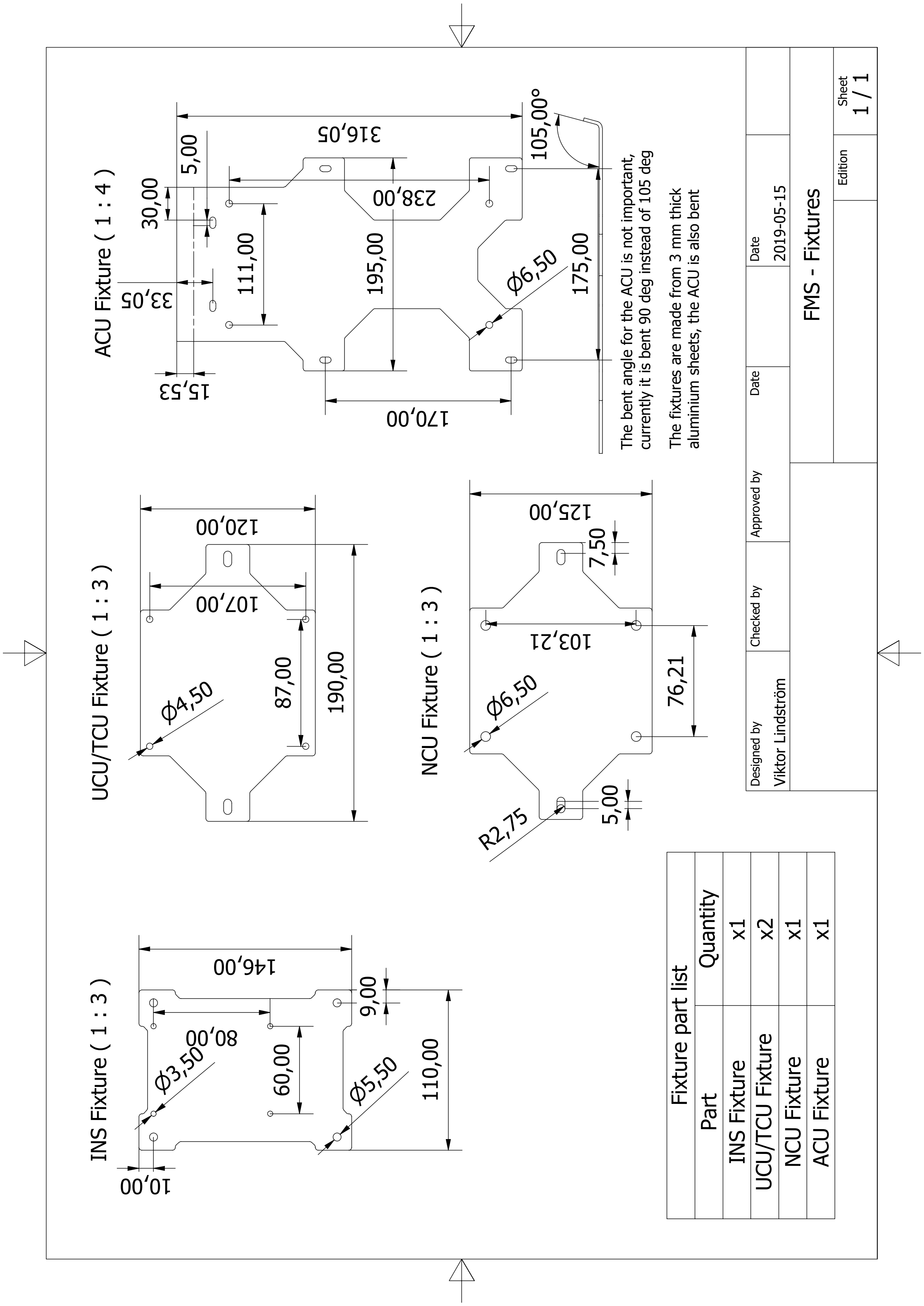
Designed by	Checked by	Approved by	Date	Date
Viktor Lindström				2019-05-15

FMS - Aluminium Rail Assembly

Edition

Sheet
1 / 1

Figure 58: FMS - Aluminium Rail System



The bent angle for the ACU is not important, currently it is bent 90 deg instead of 105 deg

The fixtures are made from 3 mm thick aluminium sheets, the ACU is also bent

Designed by: Viktor Lindström

Checked by:

Approved by:

Date:

Date: 2019-05-15

FMS - Fixtures

Edition:

Sheet: 1 / 1

Fixture part list

Part	Quantity
INS Fixture	x1
UCU/TCU Fixture	x2
NCU Fixture	x1
ACU Fixture	x1

Figure 59: FMS - Fixtures

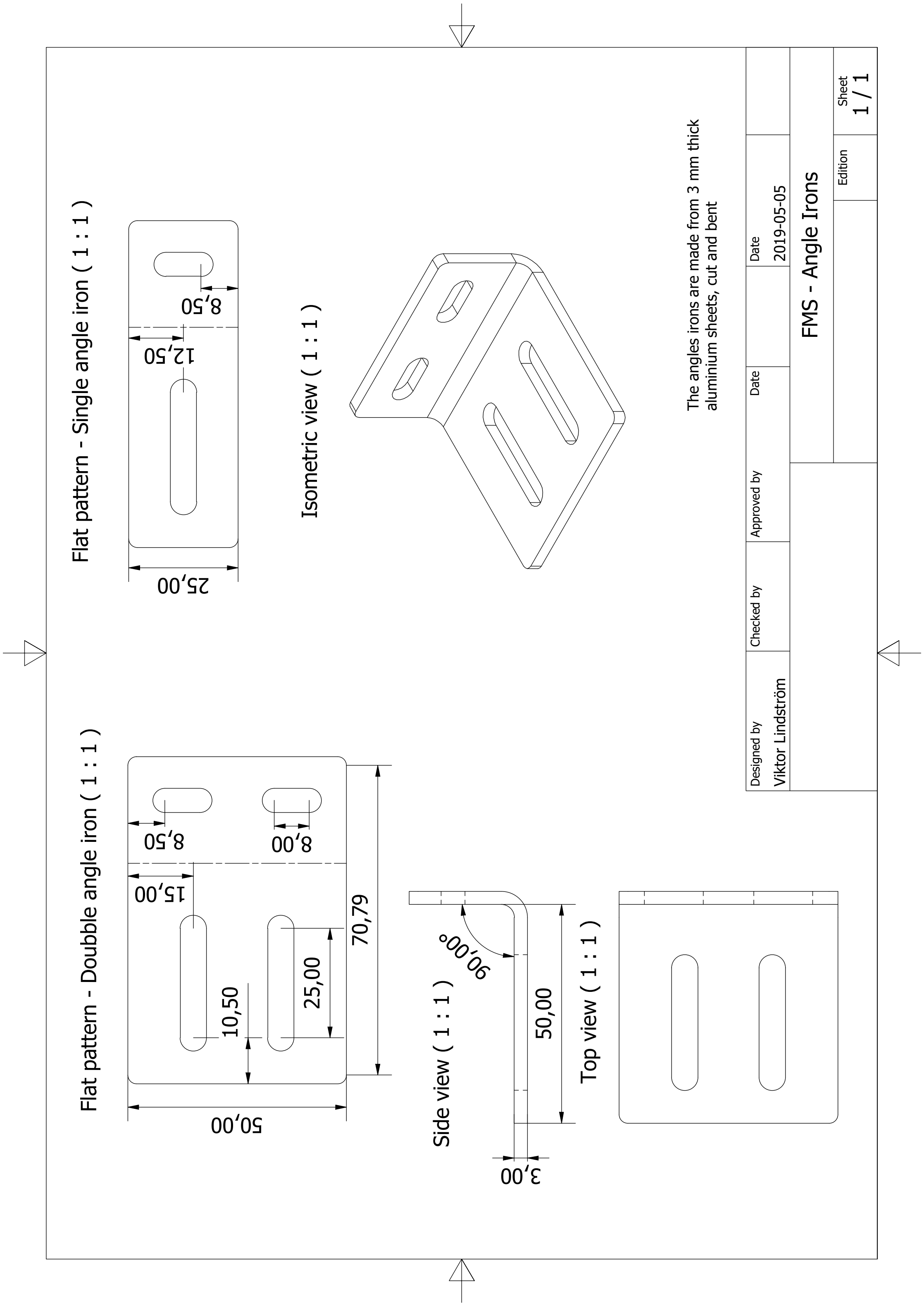
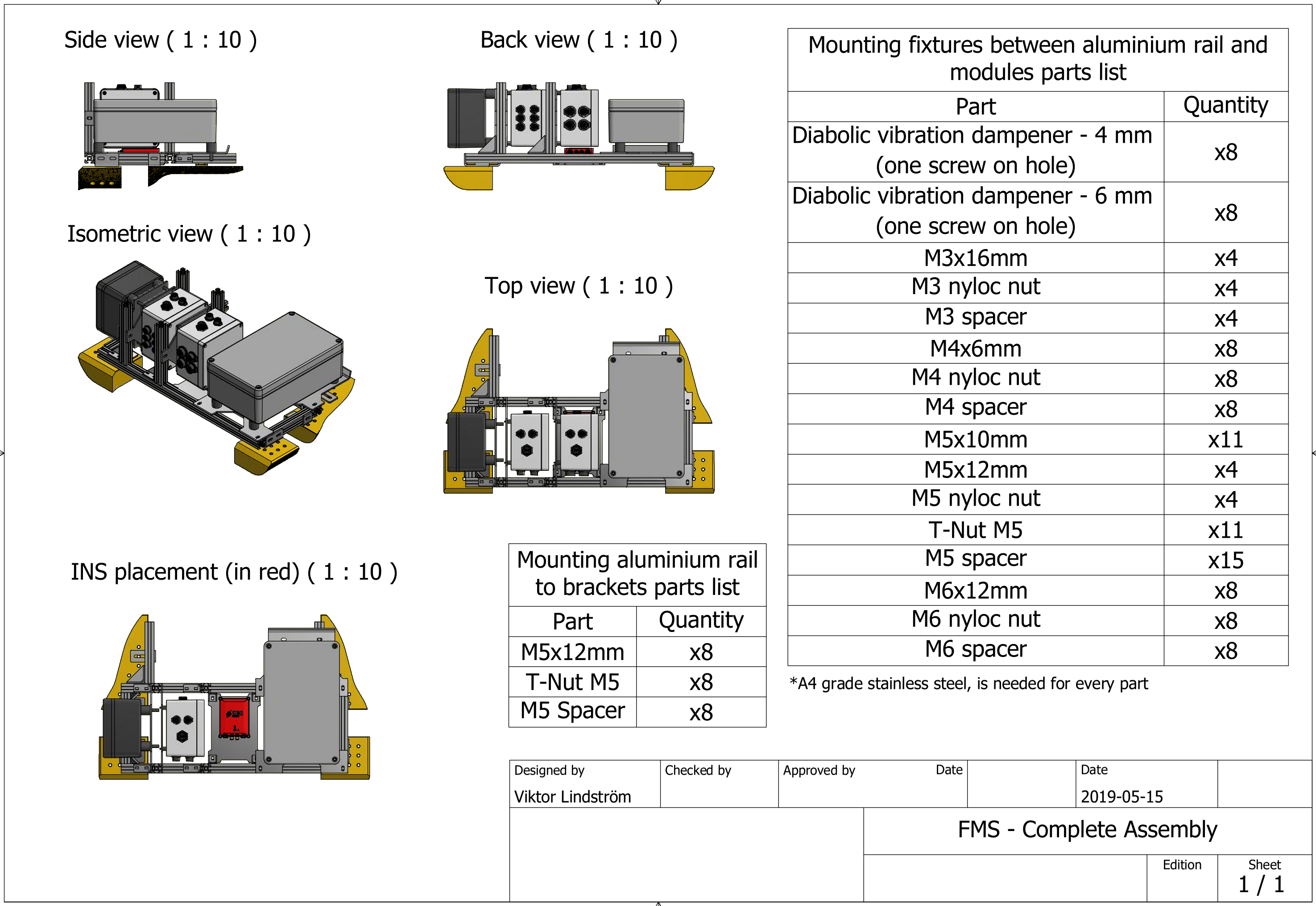


Figure 60: FMS - Angle Irons



Mounting fixtures between aluminium rail and modules parts list	
Part	Quantity
Diabolic vibration dampener - 4 mm (one screw on hole)	x8
Diabolic vibration dampener - 6 mm (one screw on hole)	x8
M3x16mm	x4
M3 nyloc nut	x4
M3 spacer	x4
M4x6mm	x8
M4 nyloc nut	x8
M4 spacer	x8
M5x10mm	x11
M5x12mm	x4
M5 nyloc nut	x4
T-Nut M5	x11
M5 spacer	x15
M6x12mm	x8
M6 nyloc nut	x8
M6 spacer	x8

*A4 grade stainless steel, is needed for every part

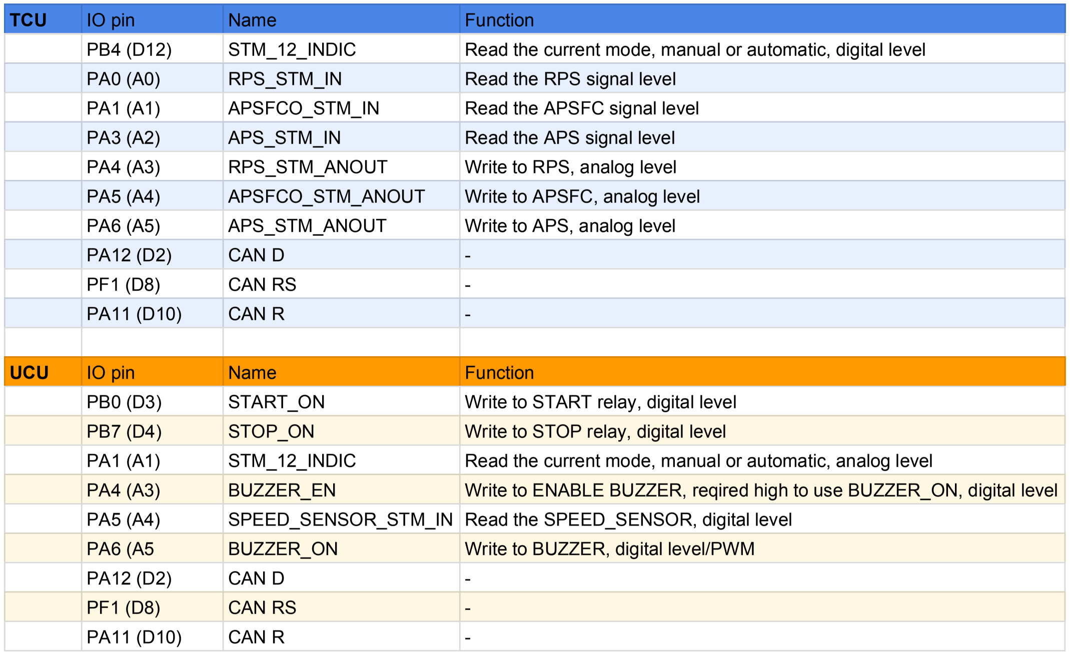
Mounting aluminium rail to brackets parts list	
Part	Quantity
M5x12mm	x8
T-Nut M5	x8
M5 Spacer	x8

Designed by	Checked by	Approved by	Date	Date
Viktor Lindström				2019-05-15

FMS - Complete Assembly

Edition	Sheet
	1 / 1

Figure 61: FMS - Complete Assembly



TCU	IO pin	Name	Function
	PB4 (D12)	STM_12_INDIC	Read the current mode, manual or automatic, digital level
	PA0 (A0)	RPS_STM_IN	Read the RPS signal level
	PA1 (A1)	APSFCO_STM_IN	Read the APSFC signal level
	PA3 (A2)	APS_STM_IN	Read the APS signal level
	PA4 (A3)	RPS_STM_ANOUT	Write to RPS, analog level
	PA5 (A4)	APSFCO_STM_ANOUT	Write to APSFC, analog level
	PA6 (A5)	APS_STM_ANOUT	Write to APS, analog level
	PA12 (D2)	CAN D	-
	PF1 (D8)	CAN RS	-
	PA11 (D10)	CAN R	-

UCU	IO pin	Name	Function
	PB0 (D3)	START_ON	Write to START relay, digital level
	PB7 (D4)	STOP_ON	Write to STOP relay, digital level
	PA1 (A1)	STM_12_INDIC	Read the current mode, manual or automatic, analog level
	PA4 (A3)	BUZZER_EN	Write to ENABLE BUZZER, reqired high to use BUZZER_ON, digital level
	PA5 (A4)	SPEED_SENSOR_STM_IN	Read the SPEED_SENSOR, digital level
	PA6 (A5	BUZZER_ON	Write to BUZZER, digital level/PWM
	PA12 (D2)	CAN D	-
	PF1 (D8)	CAN RS	-
	PA11 (D10)	CAN R	-

Figure 62: TCU/UCU - IO pin definition

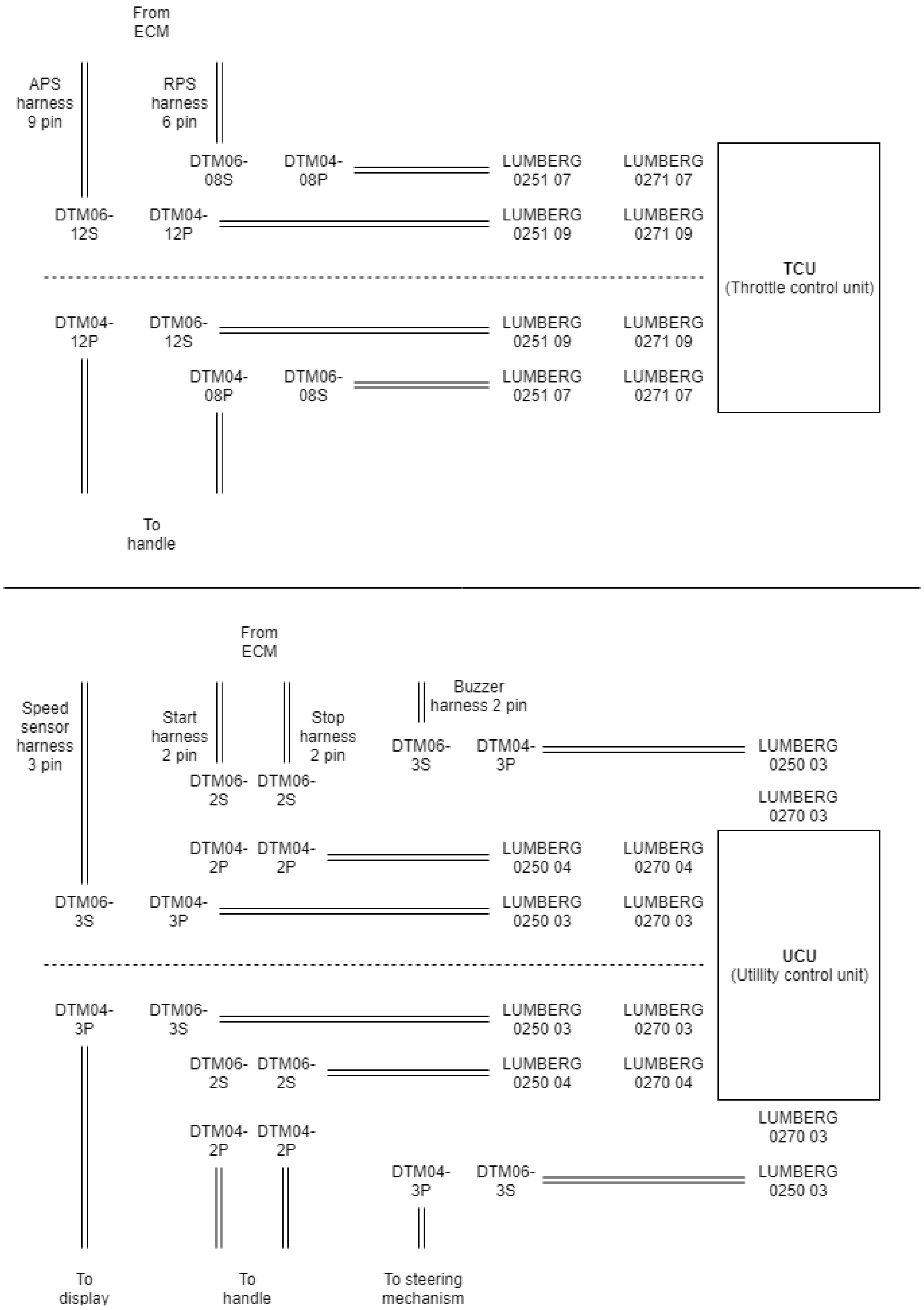
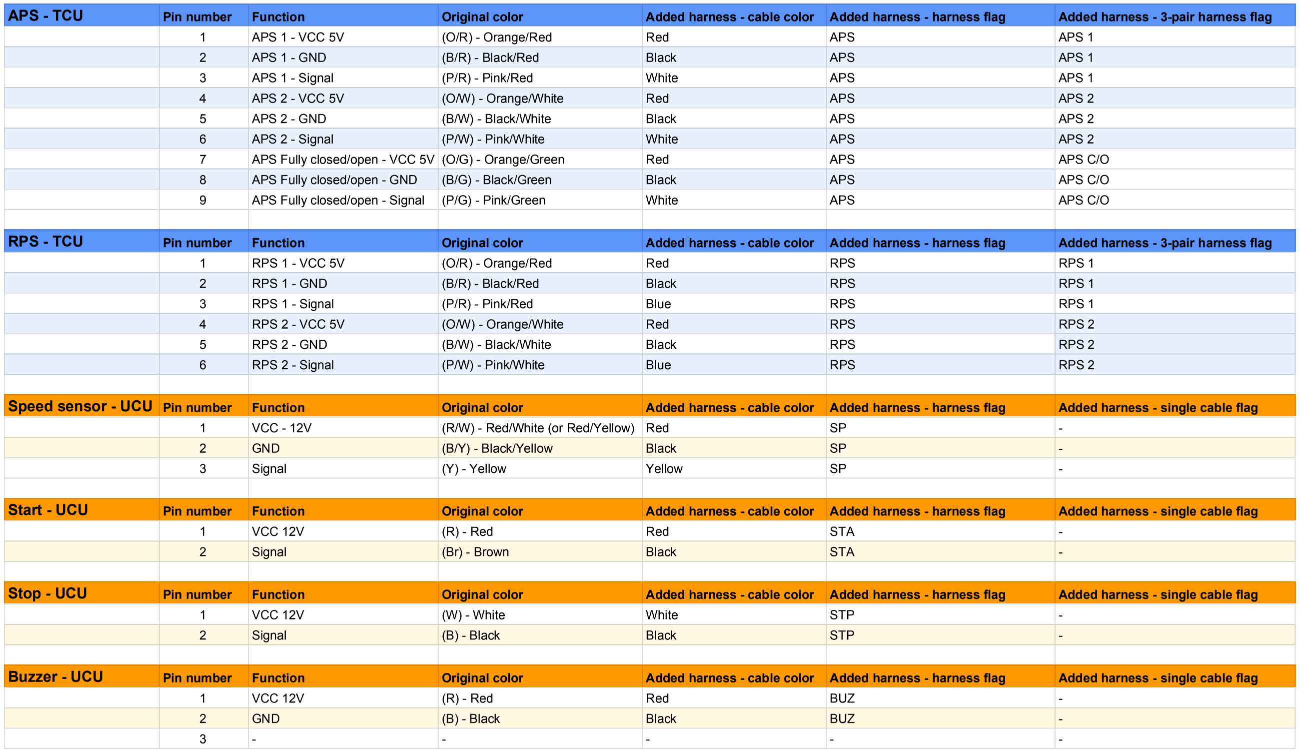


Figure 63: TCU/UCU - Signal connectors



APS - TCU	Pin number	Function	Original color	Added harness - cable color	Added harness - harness flag	Added harness - 3-pair harness flag
	1	APS 1 - VCC 5V	(O/R) - Orange/Red	Red	APS	APS 1
	2	APS 1 - GND	(B/R) - Black/Red	Black	APS	APS 1
	3	APS 1 - Signal	(P/R) - Pink/Red	White	APS	APS 1
	4	APS 2 - VCC 5V	(O/W) - Orange/White	Red	APS	APS 2
	5	APS 2 - GND	(B/W) - Black/White	Black	APS	APS 2
	6	APS 2 - Signal	(P/W) - Pink/White	White	APS	APS 2
	7	APS Fully closed/open - VCC 5V	(O/G) - Orange/Green	Red	APS	APS C/O
	8	APS Fully closed/open - GND	(B/G) - Black/Green	Black	APS	APS C/O
	9	APS Fully closed/open - Signal	(P/G) - Pink/Green	White	APS	APS C/O

RPS - TCU	Pin number	Function	Original color	Added harness - cable color	Added harness - harness flag	Added harness - 3-pair harness flag
	1	RPS 1 - VCC 5V	(O/R) - Orange/Red	Red	RPS	RPS 1
	2	RPS 1 - GND	(B/R) - Black/Red	Black	RPS	RPS 1
	3	RPS 1 - Signal	(P/R) - Pink/Red	Blue	RPS	RPS 1
	4	RPS 2 - VCC 5V	(O/W) - Orange/White	Red	RPS	RPS 2
	5	RPS 2 - GND	(B/W) - Black/White	Black	RPS	RPS 2
	6	RPS 2 - Signal	(P/W) - Pink/White	Blue	RPS	RPS 2

Speed sensor - UCU	Pin number	Function	Original color	Added harness - cable color	Added harness - harness flag	Added harness - single cable flag
	1	VCC - 12V	(R/W) - Red/White (or Red/Yellow)	Red	SP	-
	2	GND	(B/Y) - Black/Yellow	Black	SP	-
	3	Signal	(Y) - Yellow	Yellow	SP	-

Start - UCU	Pin number	Function	Original color	Added harness - cable color	Added harness - harness flag	Added harness - single cable flag
	1	VCC 12V	(R) - Red	Red	STA	-
	2	Signal	(Br) - Brown	Black	STA	-

Stop - UCU	Pin number	Function	Original color	Added harness - cable color	Added harness - harness flag	Added harness - single cable flag
	1	VCC 12V	(W) - White	White	STP	-
	2	Signal	(B) - Black	Black	STP	-

Buzzer - UCU	Pin number	Function	Original color	Added harness - cable color	Added harness - harness flag	Added harness - single cable flag
	1	VCC 12V	(R) - Red	Red	BUZ	-
	2	GND	(B) - Black	Black	BUZ	-
	3	-	-	-	-	-

Figure 64: TCU/UCU - Wire labelling

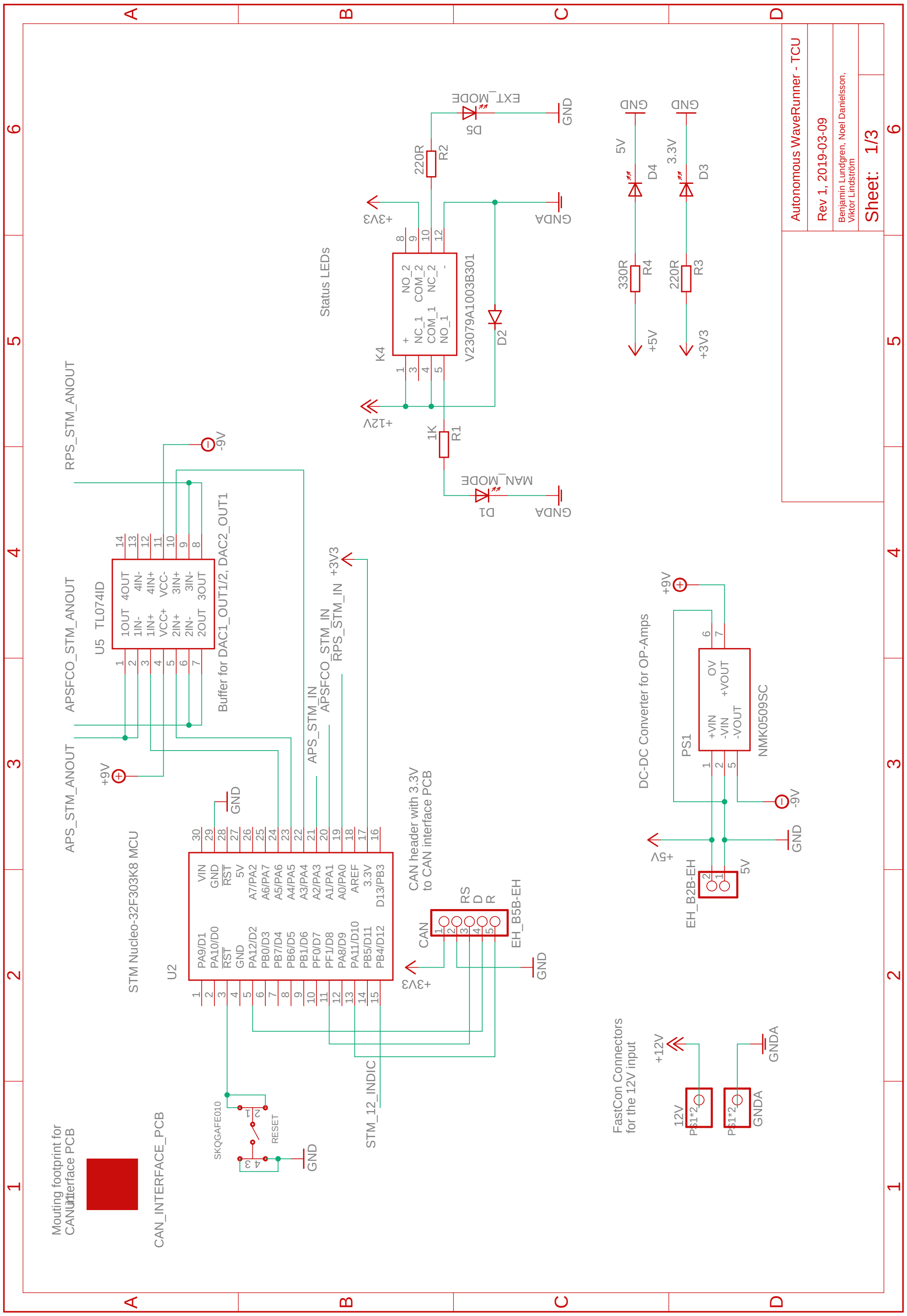


Figure 65: Schematic of TCU PCB, page 1/3

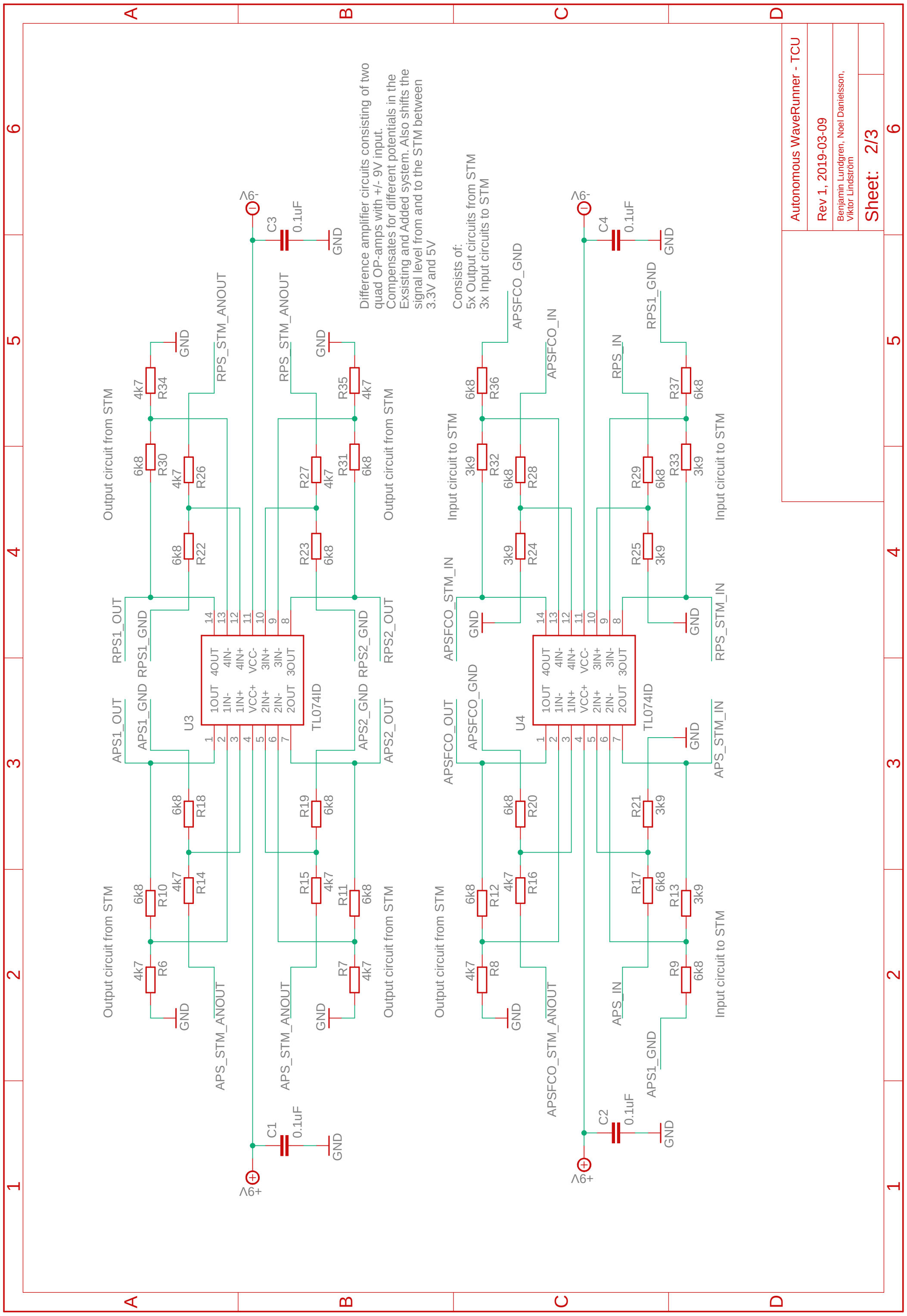


Figure 66: Schematic of TCU PCB, page 2/3

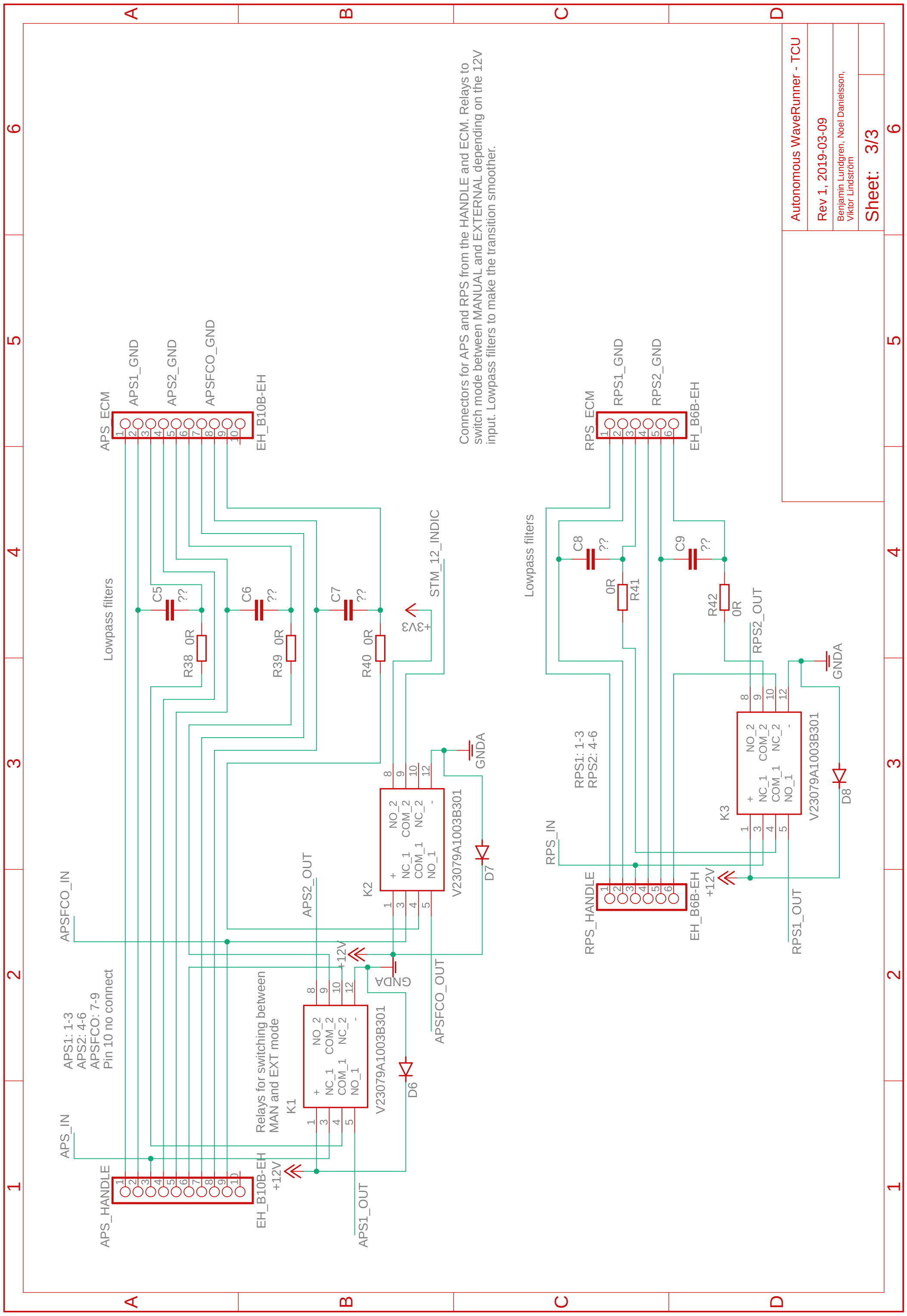


Figure 67: Schematic of TCU PCB, page 3/3

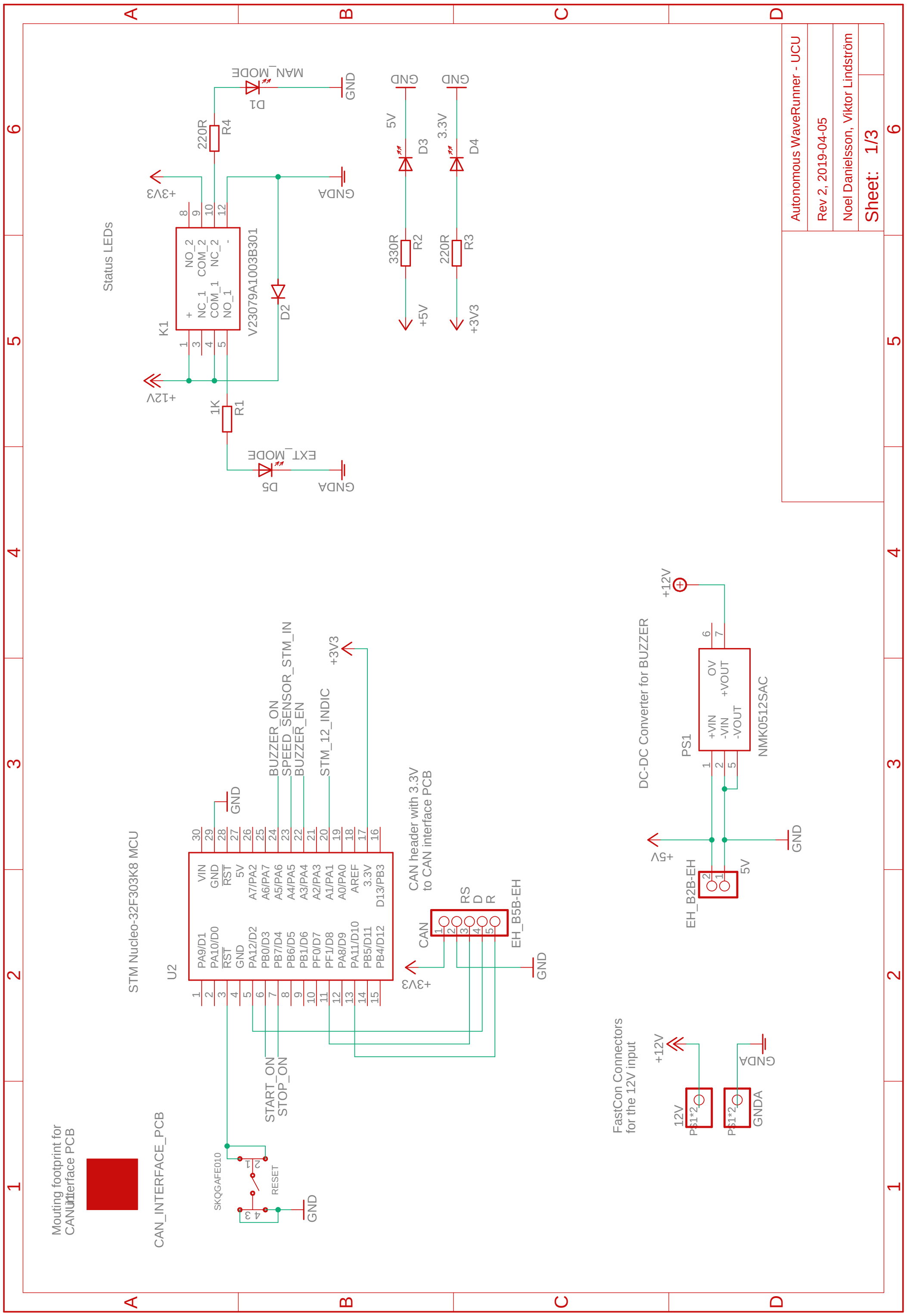


Figure 68: Schematic of UCU PCB, page 1/3

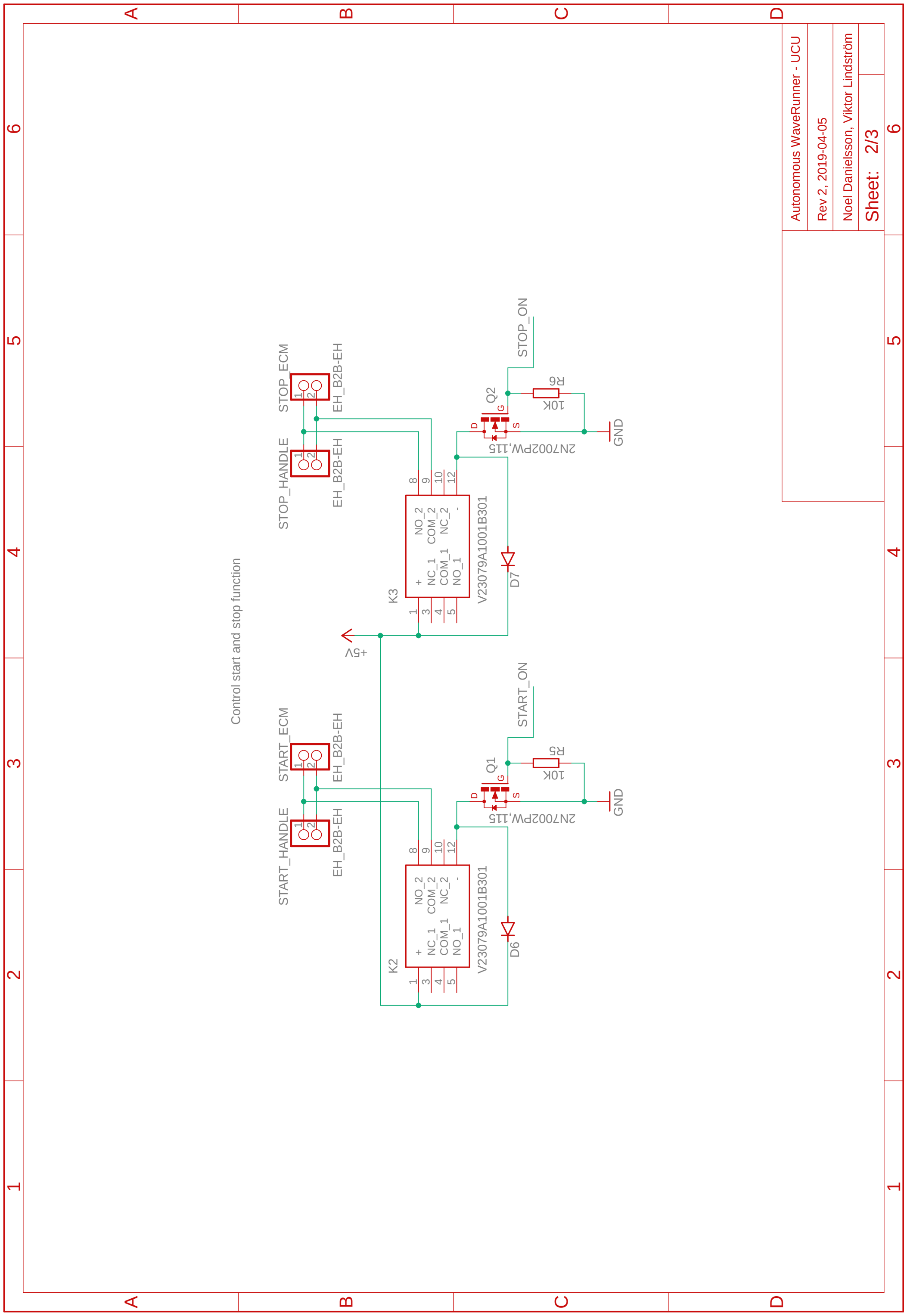


Figure 69: Schematic of UCU PCB, page 2/3

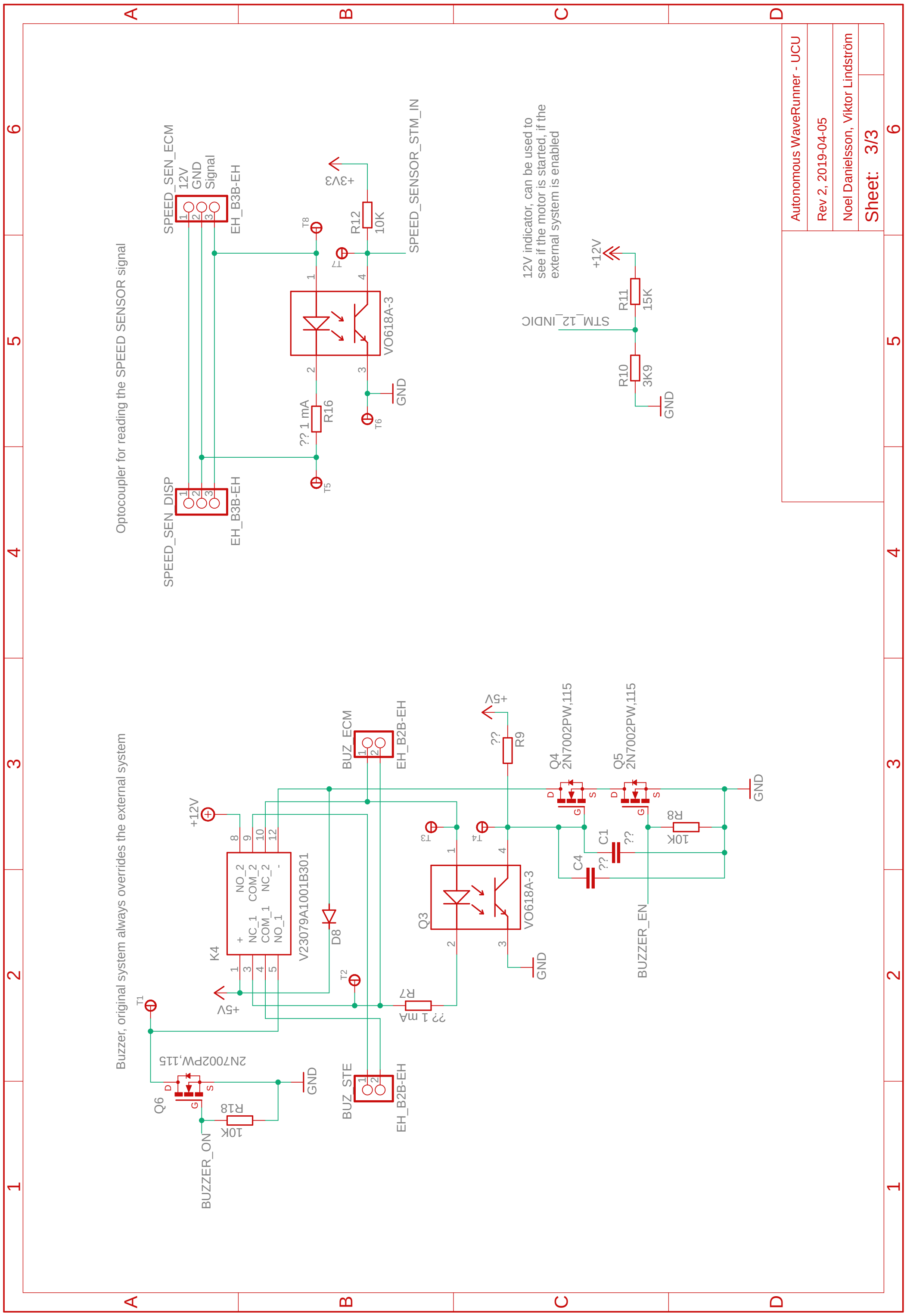
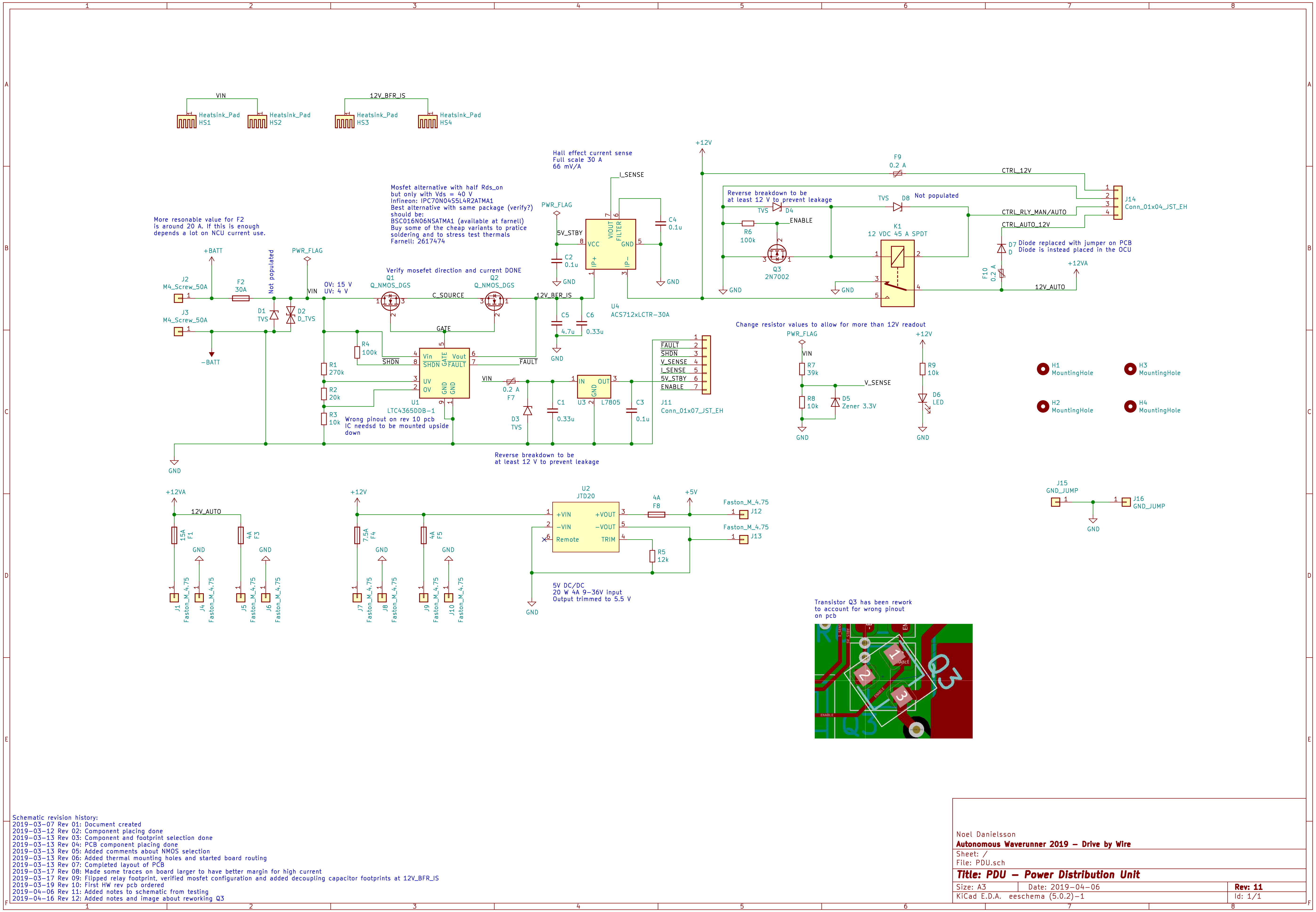


Figure 70: Schematic of UCU PCB, page 3/3


Hall effect current sense
Full scale 30 A
66 mV/A

Mosfet alternative with half Rds_on
but only with Vds = 40 V
Infineon: IPC70N04S5L4R2ATMA1
Best alternative with same package (verify?)
should be:
BSC016N06NSATMA1 (available at farnell)
Buy some of the cheap variants to pratice
soldering and to stress test thermals
Farnell: 2617474

More resonable value for F2
is around 20 A. If this is enough
depends a lot on NCU current use.

Verify mosefet direction and current DONE

Wrong pinout on rev 10 pcb
IC needsd to be mounted upside
down

Reverse breakdown to be
at least 12 V to prevent leakage

Reverse breakdown to be
at least 12 V to prevent leakage

Not populated

Diode replaced with jumper on PCB
Diode is instead placed in the OCU

Change resistor values to allow for more than 12V readout

5V DC/DC
20 W 4A 9-36V input
Output trimmed to 5.5 V

Transistor Q3 has been rework
to account for wrong pinout
on pcb

Schematic revision history:
2019-03-07 Rev 01: Document created
2019-03-12 Rev 02: Component placing done
2019-03-13 Rev 03: Component and footprint selection done
2019-03-13 Rev 04: PCB component placing done
2019-03-13 Rev 05: Added comments about NMOS selection
2019-03-13 Rev 06: Added thermal mounting holes and started board routing
2019-03-13 Rev 07: Completed layout of PCB
2019-03-17 Rev 08: Made some traces on board larger to have better margin for high current
2019-03-17 Rev 09: Flipped relay footprint, verified mosfet configuration and added decoupling capacitor footprints at 12V_BFR_IS
2019-03-19 Rev 10: First HW rev pcb ordered
2019-04-06 Rev 11: Added notes to schematic from testing
2019-04-16 Rev 12: Added notes and image about reworking Q3

Noel Danielsson
Autonomous Waverunner 2019 – Drive by Wire
Sheet: /
File: PDU.sch
Title: PDU – Power Distribution Unit
Size: A3
Date: 2019-04-06
Rev: 11
KiCad E.D.A. eeschema (5.0.2)-1
Id: 1/1

Figure 71: Complete schematic for PDU