# VORTEX
## NTNU

**Trondheim, Norway**

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# Abstract

*Terrapin* is an ROV designed to operate in the Port of Long Beach. The "sometimes confined and often precarious conditions of one of the busiest ports in the world" requires robust solutions, and *Terrapin* is therefore developed and fully equipped to address the specific needs outlined by the port management with both high reliability and swiftness.

*Terrapin*'s main components are an ABS frame attached to a two-part electronics enclosure. The enclosure is made out of an aluminum plate and a transparent acrylic lid, which clamp together for easy access to the internals. It has seven redundant cameras, and three individual robotic tools. Eighth in-house designed thrusters provide vectored thrust in any direction, which aided by a sophisticated motion control system allows for high mobility.

Vortex NTNU, a fifteen-person company, has throughout the development acquired essential organizational and technical skills by delivering a state-of-the-art product. Company members have dedicated over 6000 hours to fully meet the requirements specified in the Port of Long Beach Request of Proposals (RFP). The fair market materials value of *Terrapin* is 7100 USD. This technical document presents the process which resulted in our most advanced vehicle yet.

*Figure 1: Vortex NTNU Team 2017 with Terrapin.*

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# 1 Logistics

## 1.1 Project management

The varied and challenging nature of the tasks posed by a modern port environment mandates close collaboration between multiple engineering disciplines. The multidisciplinary nature of the challenges is reflected in organizational structure of Vortex, which is specifically set up to nurture communication between the technical groups, as well as the marketing and administrative staff. To this end, each member of Vortex is assigned responsibility for a specific task. The rationale for this approach is twofold: First, it ensures that every member of Vortex, senior or junior, can point to a part of the final product that they were responsible for, fostering broad ownership of the product throughout the organization. Secondly, having a single responsible person for each task eases the cooperation between different groups and disciplines.

To exemplify the benefits of our approach, consider our camera system: By giving one of our engineers' responsibility for the camera system the organization ensures that he can actively partake in shaping our product instead of simply following someone else's design. Additionally, by having the person responsible for the camera system, any member who needs to discuss an issue relating to cameras may talk directly to him, allowing communication to flow horizontally in a decentralized fashion. It is important to note that in Vortex, when a member is given responsibility for a task, that member may delegate work to other members. In Vortex, being responsible for a task is not equivalent with having to do it all by yourself.

The decentralized management structure of Vortex necessitates the use of modern collaboration tools. Tasks are assigned and tracked through the online "Kanban" task planner *Trello*, making it easy to track the progress, history and involved staff for any task, as well as managing deadlines. Combining Trello with the shared cloud storage offered by *Google Drive* ensures that it is easy for team members to track dependencies across groups, facilitating lateral communication. For day-to-day communications, Vortex has adopted the team communication platform *Slack* which offers instant messaging and chat rooms, allowing all Vortex communication to happen on a single official platform, rather than leaving each group to their own incompatible platforms. Finally, Vortex employs the version control system *git* to maintain the source-code for the software systems as well as tracking software specific tasks not relevant for the rest of Vortex.

## 1.2 Scheduling

The project schedule was carefully constructed with inputs from the group leaders of electronics, software, mechanical and marketing. We followed the principles behind the work breakdown structure (WBS) when drafting the schedule. At first, we broke down each groups' tasks into four phases; designing, manufacturing, testing and assembling, then we assigned specific tasks to each phase and in the end, we evaluated the possible duration of each task in each phase and made a draft of the schedule. The draft was then sent to each group leader for review and inputs, so they could comment on whether the schedule was realistic and come up with eventual tasks which were left out. After the review, we completed the draft and declared it as the final schedule. From the beginning of this year's project, the board of the company has agreed upon one board meeting a week in order to keep each other updated. Since the publication of the final schedule, we have been following up the schedule weekly. Whenever the deviation from the schedule arose we first tried to identify the causes to avoid being in the same situation again. Then we examined possibilities to catch up with the schedule again. In the end, namely by the deadline for submitting the qualification video, many of us had to work many overnights just to complete the mission. This indicates a potential to improve our project schedule planning and following in the future.

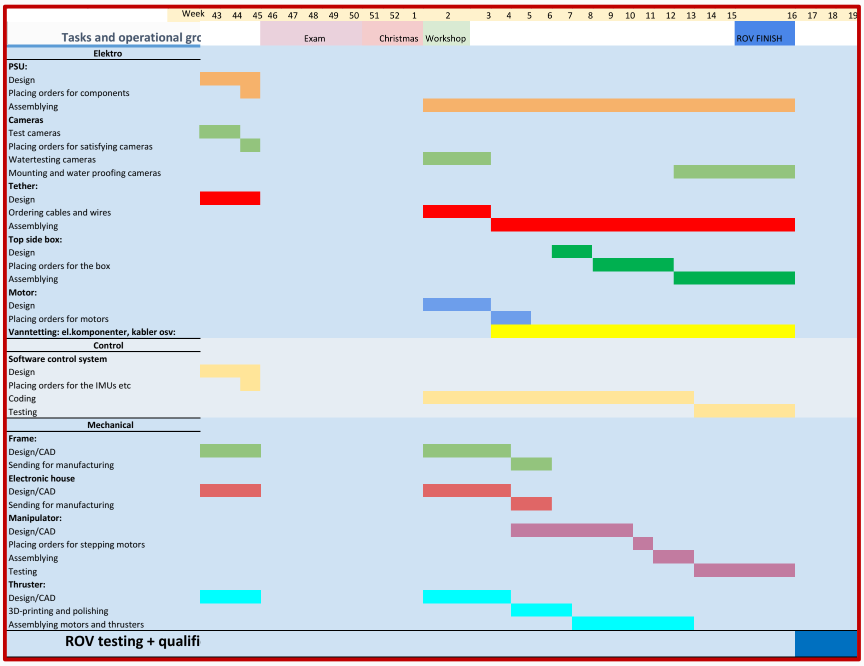


*Figure 2: Project scheduling 2016/2017*

## 1.3 Budget

Our accounting is written in Norwegian kroner (NOK), which we converted to U.S. dollars (USD) using the conversion rate of May 1, 2017. The rate was 1 NOK = 0.1166 USD. The reason we have chosen this currency rate instead of a mean value was that we wanted to present the latest value of our budget and cost; what everything is worth "today".

When we drew up the budget, it was based on our last year's budget (2015/2016) and previous experience from the MATE competition; what needed to be improved and what needed to be maintained. We made two big changes in the 2016/2017s budget:

1. Last year some of the electrical components on our ROV were industrial grade and could go thousands of meters deep in the water. We found out that using those expensive high quality components was not necessary in the MATE competition and

they could be replaced with cheaper ones. Therefore, we reduced the Electronics' budget with 10 %.

2. We also learned that we needed great improvements when it comes to the marketing of our ROV. Both with respect to the MATE competition and back in Trondheim, Norway, to attract skilled students to our organization. We tripled the budget to our marketing group, so we could have roll-ups, posters, banners and stands either when we were to recruit students or unveil our ROV.

We have also increased budgeting for travel expenses which was mainly due to more team members being eager to participate in the competition.

**Expenses**

| | | | |
|---|---|---|---|
| **Operational** | Electronics | *Motor* | $900,00 |
| | | *Cameras* | $450,00 |
| | | *Connectors* | $450,00 |
| | | *Penetrators* | $450,00 |
| | | *Tether: cabels, coax* | $600,00 |
| | | *Other: waterproofing, assembly kits, LED, diodes etc.* | $550,00 |
| | | *Circuit boards* | $450,00 |
| | | *Backup buffer* | $500,00 |
| | | *VAT* | $900,00 |
| | | *Total* | $5 250,00 |
| | Control | *IMU* | $100,00 |
| | | *Pi* | $30,00 |
| | | *Single board computers* | $100,00 |
| | | *Sensors* | $50,00 |
| | | *Backup Buffer* | $30,00 |
| | | *VAT* | $50,00 |
| | | *Total* | $360,00 |
| | Mechanical | *Frame* | $600,00 |
| | | *Electronic house* | $600,00 |
| | | *Thrusters* | $300,00 |
| | | *Manipulator* | $700,00 |
| | | *Other: assembly kits, paint,* | $150,00 |
| | | *Back up buffer* | $100,00 |
| | | *VAT* | $500,00 |
| | | *Total* | $2 950,00 |
| | **Total** | | **$8 560,00** |
| **Administrative** | Marketing | *Team jerseys* | $1 000,00 |
| | | *Roll-ups* | $100,00 |
| | | *Banners* | $100,00 |
| | | *Posters* | $100,00 |
| | | *Stands* | $100,00 |
| | | *Backup buffer* | $100,00 |
| | | *VAT* | $400,00 |
| | | *Total* | $1 900,00 |
| | Teambuilding | *Recruitment* | $350,00 |
| | | *Christmas party* | $300,00 |
| | | *Project celebration* | $350,00 |
| | | *Office supplies* | $300,00 |
| | | *Beverages: coffee, tea* | $300,00 |
| | | *General Tools* | $100,00 |
| | | *Backup buffer* | $400,00 |
| | | *VAT* | $500,00 |
| | | *Total* | $2 600,00 |
| | **Total** | | **$4 500,00** |
| **Travel/competition (10 days, 14 people)** | | *MATE registration fee* | $250,00 |
| | | *ROV transportation fee* | $750,00 |
| | | *2 rental vans* | $1 200,00 |
| | | *Airbnb appartment* | $4 700,00 |
| | | *Flight tickets round trip* | $8 000,00 |
| | | *Food* | $4 500,00 |
| | | **Total** | **$19 400,00** |
| **Total Expenses** | | | **$32 460,00** |

**Incomes**

| | |
|---|---|
| *Sponsorship (Norsk Elektro Optikk)* | $17 500,00 |
| *NTNU School funding* | $2 000,00 |
| *Sponsorship (Forening for fjernstryt undervannsteknologi)* | $2 300,00 |
| *Individual payment for the trip (14 people)* | $11 000,00 |
| *Total* | $32 800,00 |
| **Total Income** | **$32 800,00** |
| **Surplus (deficit)** | **$340,00** |

*Figure 3: Project budget 2016/2017*

## 1.4 Budget scheduling and follow-up

In addition to our budget for each department in our, we have also budgeted with respect to time; how much to spend in each month. When we compared the budgeted expense to the actual expense, it gave us some clues about the project's progress and workload; whether things were ordered and manufactured in time and how much more time should be invested in each period. Also, by observing the accumulated budget and accumulated actual expense told us whether we were ahead, behind or on schedule.

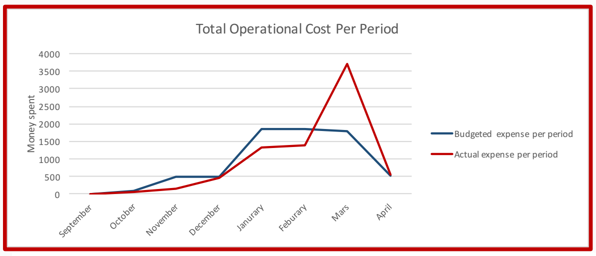


*Figure 5: Project operational cost per period 2016/2017*

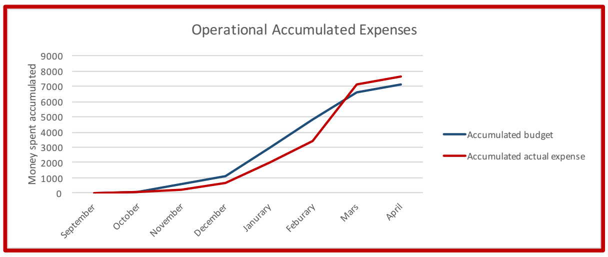


*Figure 4: Project accumulated expenses 2016/2017*

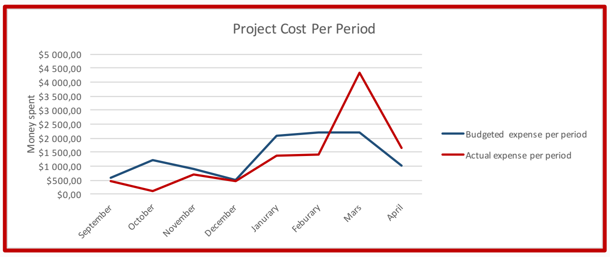


*Figure 7: Project cost per period 2016/2017*

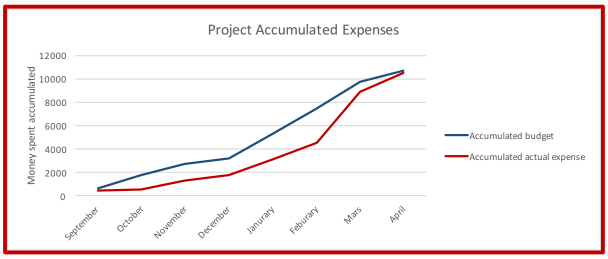


*Figure 6: Project accumulated expenses 2016/2017*

We have excluded value added taxes (VAT) because many VAT-bills arrived and were paid one or two months after we had ordered the components. By including them would give a wrong picture of the project progress when compared to budgeted expense.

December and March are two interesting periods (see figure 4-7):

1. December: due to the exam preparation for the autumn semester and combined with Christmas break, we had very low budget and actual expense in this month and very little progress was made.

2. In March the actual expense exceeded the budgeted expense the most, though we tried to allocate resources as uniformly as possible between January, February and March. We believe the exceedance was a combination of that it took time to design our brand new ROV, *Terrapin*, and the team members realized deadlines were nearing and it was time to ensure progress.

## 1.5 Project costing

When evaluating the market value of *Terrapin*, neither VATs nor shipping fees (of different components) are included because they do not represent the real value of the components which *Terrapin* is made of. Figure 8 indicates the fair market value of *Terrapin*, which is estimated to be approximately 7 000 USD and is only based on operational costs.

| Fair market value evaluation of Terrapin based on Operational Expences (VATs, shipping fees and team's travel expenses are not included) | | | | | |
|---|---|---|---|---|---|
| **Operational fields** | **Item** | **Notes** | **Type** | **Quantity** | **Amount spent** |
| | Top electronic house | Machined in China, made of PMMA | Purchased | 1 | $900,00 |
| | Bottom eletronic house | Machined by Kongsberg Gruppen, made of aluminium | Donated | 1 | $510,00 |
| | Frame | Machined in China, made of ABS | Purchased | 1 | $337,00 |
| | Testing material | For drilling into the top elektronic house, made of PMMA | Purchased | 1 | $65,00 |
| Mechanical | Hinges | To connect top electronic house and frame | purchased | 6 | $127,79 |
| | Stepper motor driver | For manipulator | Purchased | 3 | $62,10 |
| | Threaded rod | External linear stepper motor for manipulator | Purchased | 3 | $101,34 |
| | Ball bearings | For manipulator | Purchased | 2 | $11,93 |
| | 3D-computer mouse | For CADing | Purchased | 1 | $120,00 |
| Total Mechanical cost contribution to fair market value | | | | $2 235,16 | |
| | IMU: Orientation sensor | BNO055 Absolute orientation sensor for the control system | Purchased | 1 | $69,92 |
| | General Purpose USB to GPIO+SPI+I2C | For LEDs, switchers and buttons | Purchased | 1 | $14,95 |
| | Servo HAT for Raspberry Pi | Controlling DC servo motors | Purchased | 1 | $17,50 |
| | Standoffs for Pi HATs | Attachments for Servo HAT for Raspberry Pi | Purchased | 2 | $1,50 |
| Control | Sensors | TE connectivity pressure sensors | Purchased | 2 | $38,66 |
| | BeagleBoards | | Purchased | 2 | $97,46 |
| | PCB | Printed circuit board for pressur sensors | Purchased | 2 sets of 3 | $4,00 |
| | Capacitors | | Purchased | 12 | $0,38 |
| | Diodes | For power supply | Purchased | 6 | $1,32 |
| | Regulators | For voltage and power supply | Purchased | 6 | $0,72 |
| Total Control cost contribution to fair market value | | | | $246,41 | |
| | Motors | M100 Brushless motors from BlueRobotocs for thrusters | Purchased | 10 | $665,00 |
| | Electronic speed controller | For motors | Purchased | 9 | $225,00 |
| | Cable penetrators | For cables connected to thrusters and tether | Purchased | 70 | $247,50 |
| | LCD Display for Raspberry PI | For ROV "pelicase" control | Purchased | 4 | $237,24 |
| | Wires | For power supply, 100 ft and hook up wire | Purchased | 4 | $158,93 |
| | Cables and cable sleeve | For tether cables and coaxial cables, and ethernet cable, chassis mount cable and conductor cable | Purchased | 15 | $261,74 |
| | RF Transceiver Module | For arduino | Purchased | 2 | $14,64 |
| | LED lights | For "pelicase" control and both inside and outside ROV | Purchased | 24 | $74,98 |
| | Converters | Including: AC/DC and DC/DC converters and video to TV Converter Switch box for "Pelicase" control | Purchased | 4 | $71,83 |
| | Test camera lenses for ROV | 800TVL and 100TVL HD CMOS Wide angle lens and Focus lens | Purchased | 7 | $59,90 |
| | Camera for ROV | CMOS 16:9 3 MP FPV Camera and Wide angle Lens HD FPV camera NTSC PAL | Purchased | 8 | $192,48 |
| | Coaxial attachments | Connector for Chassis Panel Mount Coaxial Cable | Purchased | 2 | $5,93 |
| | Safety Flip Cover and toggle switch | For "Pelicase" control and ROV | Purchased | 3 | $32,00 |
| | Fusjon PCBs | For ROVs inner electronics. Type 1, 2 and 3 | Purchased | 15 | $318,42 |
| | Dual Synchronous Buck Regulator | Evaluation board: voltage regulator for power supply of ROV | Purchased | 1 | $70,10 |
| | Buck Regulator Step-Down DC-DC Controller | Voltage regulators for ROV | Purchased | 10 | $78,40 |
| | Coaxial connectors, cables and attachments | Including: straight jack and plug, right angle jack, straight bulkhead jack, receptables and all other plu | Purchased | 54 | $125,99 |
| | Electromagnet | For ROV holding components inside | Purchased | 1 | $63,99 |
| | Sonar ranging module | For ROV distance meassurement system | Purchased | 1 | $24,83 |
| Electronics | Polysynthetic Thermal Compound | For connecting CPU and heatsinks | Purchased | 1 | $24,41 |
| | CARTRIDGE FUSE | For Power supply | Purchased | 10 | $16,82 |
| | Plug and socket connector Type 1 and 2 | For power supply | Purchased | 60 | $48,78 |
| | Transceivers | Bus buffers | Purchased | 10 | $3,24 |
| | Temperature sensors | For ROV inside electronic house | Puchased | 6 | $14,25 |
| | Power connectors | For power supply | Purchased | 6 | $84,51 |
| | Fuse holders | For fuses (waterproof) | Purchased | 2 | $54,94 |
| | Mounting clamp sets | For ROV | Purchased | 4 | $28,50 |
| | Capacitors | For ROV PCBs | Purchased | 504 | $121,67 |
| | Inductors | For ROV PCBs | Purchased | 18 | $53,88 |
| | Metal oxides | For ROV protection | Purchased | 111 | $178,52 |
| | Relays | Switches for PCBs | Purchased | 15 | $13,85 |
| | Terminal Blocks | For PCBs | Purchased | 21 | $20,85 |
| | Connectors | For ROV PCBs | Purchased | 354 | $34,39 |
| | Semiconductors | Diodes for PCBs | Purchased | 40 | $16,26 |
| | Back up PSU (Power board) | For ROV back up | Purchased | 1 | $312,48 |
| | Sitches | For PCBs including: multiplexers and analogue switches | Purchased | 75 | $36,81 |
| | Resistors | For PCBs | Purchased | 10 | $5,52 |
| | Power cords | For power supply | Purchased | 2 | $10,66 |
| | AMP connectors | For cables and wires | Purchased | 55 | $27,71 |
| | Waterproofing equipements | Scotchcast and epoxys | Purchased | 7 pck | $219,18 |
| Total Electronics cost contribution to fair market value | | | | $4 256,13 | |
| Tools and assembly kits | Including: Screws, nuts, discs, sprays, 3D-printer palstics, potting kit, gel, tape, penetrator wrentch, thimble for tether etc. | | Purchased | | $402,50 |
| Fair Market Value of the ROV: Terrapin (no VATs and shipping fees) | | | | $7 140,20 | |

*Figure 8: Fair market value evaluation of Terrapin.*

# 2 Design rationale

## 2.1 Design philosophy

In the fall, after the last year competition, the team sat down to brainstorm areas for improvement, and our goals for the new ROV. The team came up with multiple enhancements. Some examples are better accessibility and visibility of the internal electronics, eight thrusters for six degrees of freedom (6 DOF) control, low weight and small size relative to the competition requirement, and to make the ROV neutrally buoyant without needing buoyancy elements. To preserve last year's ROV, most of the electronics and mechanical parts is entirely new, and none of them originate from a previous ROV.

With these design improvements in mind, the mechanical team prototyped numerous designs, incorporating the improvements in various ways. When the designs were sketched up, the entire team reviewed the designs together, and the mechanical team explained the benefits of each design.

During the reviews, it was made clear that the team should take into consideration multiple aspects when taking a decision. One of them was size and weight. To obtain the maximum score at the competition, the team had to follow the restriction on size and weight. On a limited budget, it was also important to keep the cost in mind. Even though the competition tasks were still not released at that point, it was crucial to think about what payloads could be needed and how the team would make available space for them.

After debating and discussing, there was one design that all agreed upon to be the most suitable, which is shown in figure (see figure 9). This design enables us to mount a wide variety of tools underneath the ROV and has incorporated the improvements above.

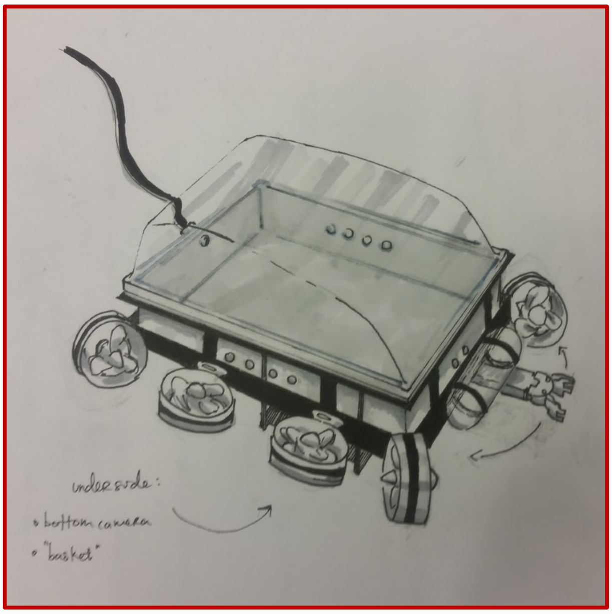

*Figure 9: The concept design that the team ended up with.*

After the design was finished, the mechanical team started to design *Terrapin* on the computer using Autodesk Inventor. During the design and CAD phase, it was clear that the team needed two different production methods. One was CNC milling and the other was 3D-printing. To make it less costly, the team decided to use 3D-printing whenever it was possible. On the main parts of *Terrapin,* that was not an option and therefore it was decided to use CNC milling on those. During the CAD phase, small changes were made to facilitate for the production method that was chosen for each component of the ROV. The plexiglas lid and the frame of the ROV were made by 3A Prototype located in China, while the bottom part (which along with the plexiglas lid comprises the electrical housing) was made by one of our sponsors, Kongsberg Gruppen. Everything else was made in-house at our university, Norwegian University of Science and Technology (NTNU).

## 2.2 Frame and electronics housing

The electronics housing is split into two parts: An aluminium bottom plate onto which the electronics are attached, and a transparent lid made of acrylic, or polymethyl methacrylate (PMMA).

6082-T6 aluminum was chosen as the material for the bottom part due to its high strength relative to mass, corrosion resistance and high thermal conductivity. This year, the team wanted to make their own PSU instead of purchasing it. This would require more cooling than something that was store bought. Aluminium was found to be the best option, taking cost, weight, and thermal conductance into consideration. The size of the bottom plate is 350x250x25 mm. 350x250 mm would give enough space for all of the electronics to be mounted, and it would be able to fit inside the size requirement, once the thrusters were mounted. 25 mm height was a constraint of the aluminium milling facility. Due to this constraint, we designed the bottom plate with slanted walls, to accommodate the size of the cable penetrators. This also made it easier to route the cables.

The lid of the electronics enclosure is made of PMMA. This is a material that gives both tensile and flexural strength, and transparency. The transparency makes it easy to detect leaks early, and it allows us to see status lights on various electronic devices inside. The height of the lid was determined by the displacement volume needed to give *Terrapin* a small but positive buoyancy. Slight positive buoyancy was chosen to make sure that the ROV rises to the surface in case of malfunction or loss of power. Autodesk Inventor helped us calculate the volume and weight of the ROV, and the team would compute the weight of all electronics and parts within the housing. Knowing these parameters, the team could then calculate the needed volume inside the enclosure and adjust the height accordingly, with the help of Archimedes' principle. A small amount of trimming weight was added afterwards, for fine adjustments.

The frame for the electronics housing is made of ABS plastic, which has a low density of 1.060 g/cm$^3$, and is strong enough to attach tools, thrusters and hinges to it. The frame itself is a key component for waterproofing *Terrapin*. Adjustable hinges are mounted on all four sides, to hold the upper, middle, and lower parts of the frame together. When closing the hinges, all three parts are squeezed together. A groove is milled into the perimeter of the aluminium sheet, which is fitted with a properly sized O-ring to create a waterproof seal between the top and bottom parts of the electronics housing. The composition of this can be seen in figure 10.

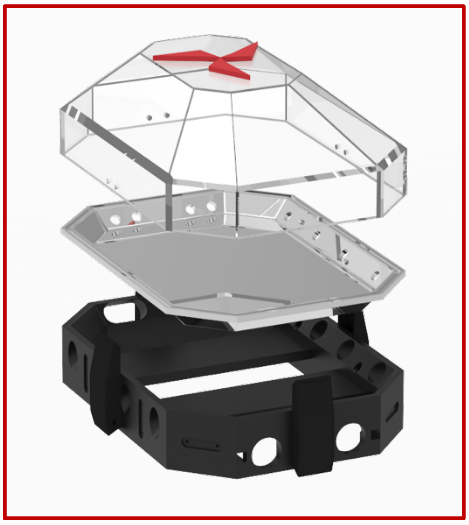

*Figure 10: The composition of frame, top, and bottom part of the electronics housing.*

Two crossbeams have been added to the inside of the frame to make room for all the tools and cameras. The front cameras and the front lights have been recessed into the frame itself.

## 2.3 Thrusters

Being the first year that Vortex makes their own thrusters, the team had limited experience in their design. The BlueRobotics T100 thrusters used for the previous year's ROV were used as a reference in design and making of CAD files, but everything was designed from the ground up. The team ended up using BlueRobotics M100 brushless motors, as they were already waterproof and give sufficient thrust. One feature of our new thrusters is that they are symmetric, meaning that they give the same amount of thrust forward and backward unlike the T100 which has a higher forward thrust. All of the components on the thrusters were 3D-printed with a Ultimaker 2+ using PLA material. PLA is easily printable, and can be surface treated afterwards. We sanded all components and spray painted them, to give them a smoother surface. Thruster guards were also 3D printed to assure safe operation of the ROV.

During the the design and production phase, over ten different propeller designs were 3D printed and tested in water to obtain the best propeller with max force. In our self-built test rig, the best propeller had a maximum thrust of 16 Newton, equally balanced in both directions.

The eight thrusters of *Terrapin* are arranged along its perimeter as shown in figure 11. The number and locations of the thrusters have been optimized for fast and accurate maneuvering in 6 DOF, within the constraint of a 58 cm vehicle diameter. 6 DOF motion is also possible with fewer thrusters (minimum six), but using eight gives redundancy — which overall increases power efficiency, and more remarkably allows the ROV to move with full freedom of motion even if one of the thrusters fails. By mounting all thrusters in a plane at roughly the same height as the vehicle's center of mass (COM), we avoid unwanted rotations when moving in straight lines. This is an improvement upon last year's ROV, *Maelstrom*, which had its thrusters above the COM. Driving *Maelstrom* forward would create a pitching moment, which required compensation by the vertical thrusters, wasting energy and reducing its maximal velocity.

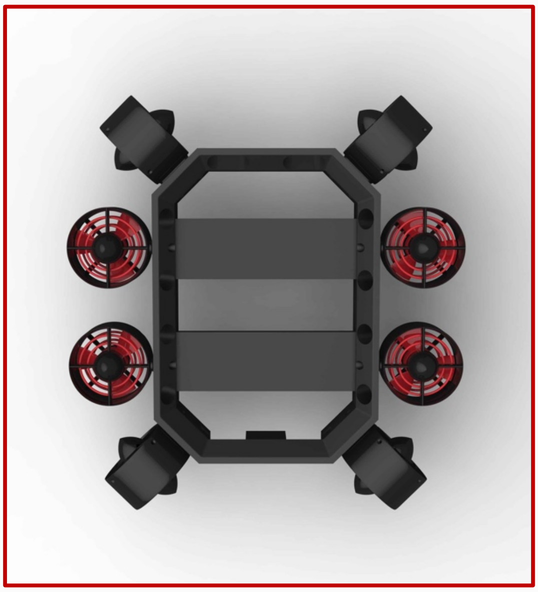

*Figure 11: The thruster configuration of Terrapin.*

There are four vertical and four horizontal thrusters. The vertical thrusters give exceptional speed when diving and surfacing — a slow direction of travel for most ROVs — and robust control of the roll and pitch angles. Horizontal corner thrusters allow motion forwards/backwards/sideways, and change of heading angle. Their configuration mirrors that of the horizontal thrusters on *Maelstrom*, with each thruster at a 45 degree angle from the centerline. We considered other mounting angles of the corner thrusters, such as 30 degrees off the centerline. That would have given greater forward speed at the expense of sideways speed, but we decided against based on that nimble movement in all directions is more important than a very fast forward speed.

## 2.4 Payload

*Terrapin* is equipped with a variety of different payloads. Common for all of them is that they are 3D-printed, due to the low cost and the ability to make complex structures rapidly.

In the front, we have a manipulator arm that is controlled by a servo with a single DOF (see blue object in figure 12). Since the manipulator arm only has one DOF, the grippers have been designed to pick up objects both horizontally and vertically. This allows the team to pick up all the props that is required during the competition. Each part is also easy to swap out, in case something breaks or improvements need to be made.

Located underneath one of the thrusters in the front is a stepper motor which is mounted and attached to a tool designed to mesh with the valve head (see green object in figure 12). The tool fits around the head, and a stepper motor can easily turn the valve. It has been designed such that the pilot can easily see how many rounds the valve has been turned. In order to pick up agar samples, two stepper motors are used (see white object in figure 12). One for lowering the tube and the other for rotating that tube. The inside of the tube is shaped like an ice drill to make it easier to collect the agar into the tube. Once the tube has rotated enough and is full of agar, the other stepper raises the tube into a horizontal position, so that no agar can fall out during transport.

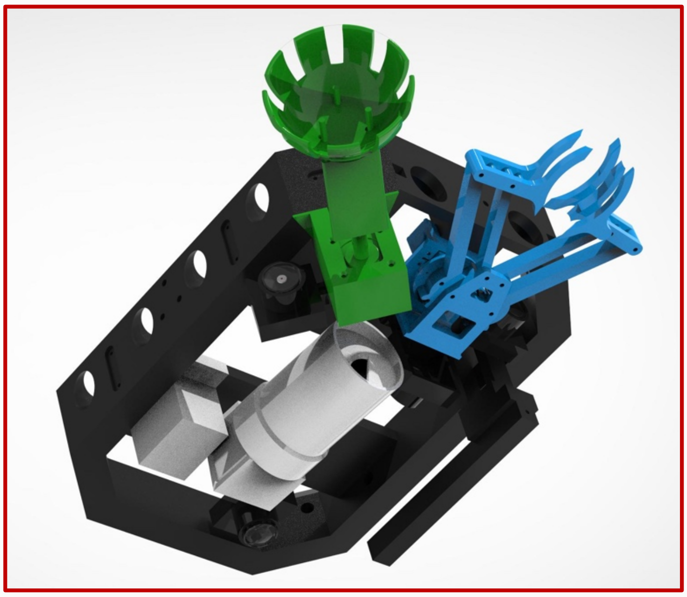

*Figure 12: Tools underneath Terrapin, highlighted with different colors.*

The Bluetooth tool is combined into two parts (see black object under the manipulator in figure 12). One for the LED-light that is activating the Bluetooth module inside the tube, and another part for receiving data from the module. The long part of the Bluetooth tool fits inside the diameter of the tube and activates the light sensor. When it is far enough in, the Bluetooth receiver, which is located above the long part, is close enough to the transmitter to receive data. Both the LED-light and Bluetooth module have been embedded into the 3D printed part and sealed with epoxy for waterproofing.

All of the stepper motors have been filled with epoxy and tested based on this guide.[1] The servo has been filled with canola oil and sealed with epoxy.

Multiple items shall be retrieved from the bottom of the pool and therefore a basket has been made to transport all the items. Since the basket can be lowered and raised by the operator, a rope will be attached to the handle. The pilot of *Terrapin* will therefore only need to place each object into the basket and don't need to worry about the transportation to and from the poolside.

On the side of the basket, a buoy will be place with magnets. The buoy will have a rope attached to it with a hook at the end. *Terrapin* can then grab the buoy from the basket, place

[1] MATE TECHNICAL BULLETIN. "Sealing Brushless Motors - MTB-001".

the hook onto the container and release. The rope is tied in such a way that it will uncoil itself when the buoy is released and will get to the surface.

## 2.5 Software

All control software on *Terrapin* is written in-house in C++ and Python using the Robot Operating System (ROS) framework[2]. ROS was chosen as it provides an extremely flexible platform for development of real-time software, making it effortless to add and remove features, and easy to debug. Our software is divided into a number of modules, or *nodes*, each with a specific responsibility. The nodes are not tied to a specific computer, such as a topside or a onboard, rather they can be run on whichever computer is preferred. (The exception being nodes that interface hardware, such as thrusters and sensors onboard the ROV, and the pilot's joystick.) The nodes that make up *Terrapin*'s control system, and their interconnections, are shown in figure 13. The 'Control system' nodes are set to run onboard the ROV, to reduce network traffic and latency, and to make the ROV as self-contained as possible. Another effect of the modular, networked structure is that any communication between nodes is openly readable by any other node on the network. This eases all program communication, including debugging and the display of information at the graphical user interface.

We have put extensive effort into the safety and reliability of the software this year. Each node automatically checks all incoming communication, and discards any invalid data so that it does not propagate further in the system and cause harm. All nodes are designed to shut down gracefully in case of fatal errors, without affecting the other parts of the system. We have also written software tests for the nodes, which automatically run on a Travis CI server, to aid in detection and removal of software bugs during development.

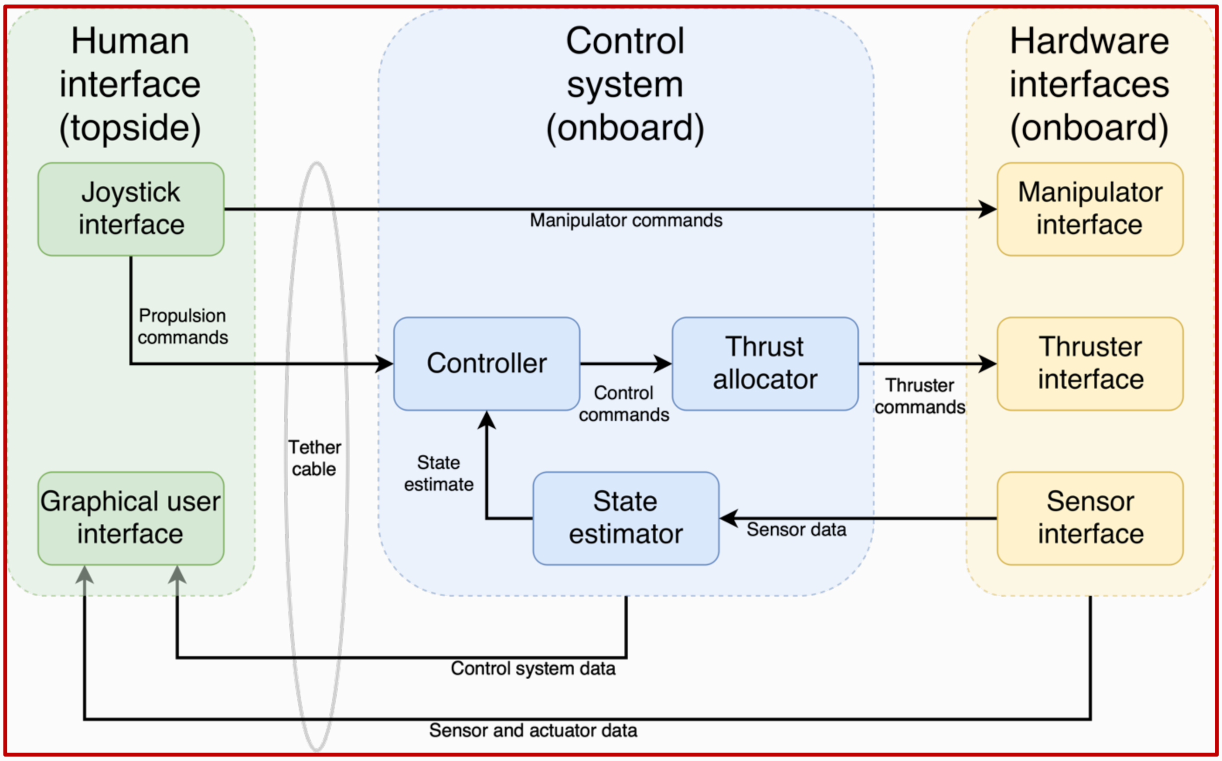


*Figure 13: An overview of software modules and their communication.*

[2] The Open Source Robotics Foundation. "About ROS".

The control system provides five control modes, which help the pilot to control the ROV more easily. The control modes are:

- Open loop, which has no automatic control.
- Depth hold, where the ROV will maintain a specific depth.
- Heading hold, where the ROV will maintain a specific heading.
- Attitude hold, where the ROV will maintain a specific orientation (heading, roll, and pitch).
- Depth and heading hold, where the ROV will maintain both depth and heading.

The control modes can easily be switched between at any time via buttons on the joystick, so that the pilot can quickly drive to an area of interest in open loop mode, and then switch to one of the automatic control modes for easier precision operation.

In last year's competition, information from the software system was displayed in a command-line interface. This was unintuitive and hard to read, which is why we have focused on creating a custom graphical user interface (GUI) this year. The GUI is written in ROS's framework for GUI development, *rqt*, which is based on the well-known Qt framework.[3] Our GUI is shown in figure 14.

The components of the GUI are implemented as rqt plugins. These have the advantage of being easy to edit and manage, depending on the specific case of use. Some plugins are available as part of ROS, while we have created others in-house. The in-house components are:

- A thruster enable/disable button, which allows immediate shutdown of the thrusters, for added safety and convenience.
- Light controls, which toggles the RAMAN and Bluetooth lights, and dims the headlights.
- Bluetooth output, which displays the data received by the Bluetooth receiver.
- Camera selection, which allows selection of which three of the seven camera feeds to display.
- Current depth, which displays the depth visually.
- Sensor calibration, which tells us the calibration status of the IMU.
- Control mode, which displays the current control mode.
- Heading, which displays the current heading angle.

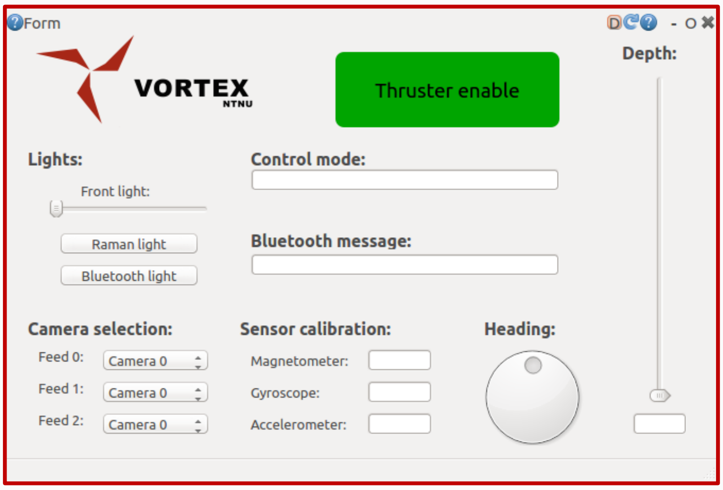


*Figure 14: The GUI for Terrapin.*

[3] The Open Source Robotics Foundation. "RQT Package Summary".

## 2.6 Topside

The topside control box is designed to be a compact, sturdy system that is easy to transport and quick to set up. It includes four screens to simultaneously show three of the seven interchangeable feeds as well as the Graphic User Interface. The system is mounted in a modified Peli case for protection, and is transported as a briefcase. The control box contains a AC-DC voltage converter, an ethernet switch, four 10.1” LCD screens, a Raspberry Pi and a killswitch for the power to the ROV.

The setup of the control box only requires plugging in two power cables and tether, and flipping the power switch — *Terrapin* can be deployed and operational in the water within minutes of the arrival on site.

### Tether

This year’s tether is custom made to fit the needs of *Terrapin* — it is light, flexible and durable. The tether is composed of two 8 AWG DC power transmission lines, three Coaxial cables carrying analogue video feeds, and an ethernet cat5e cable for communications. The thick 8 AWG cables were specifically chosen for their stranded core, making them very flexible while still maintaining a high transfer efficiency. The three coaxial cables ensure fast and stable transfer of the video feeds through the tether. The sleeve sheathing the cables also provides ample opportunity for variable tuning of the buoyancy.

## 2.7 Subsea Electrical System

Last year we entered the competition without a designated connection hub. This led to a variety of cable management related issues including reduced reliability and harder debugging. Already before entering the water two of our three cameras had malfunctioned, and during the first competition run the last one experienced transient failure as well. Lastly, our system revolved around a very bulky DC-DC Converter that occupied most of the space in our interior. With these experiences in mind we this year set out to radically improve on these solutions.

### Power Supply Units

This year, the electronics team has put great effort into designing our own custom Power supply unit using a MAX17559ACJ+ chip from MAXIM Integrated and designing the surrounding circuitry. Sadly, they were not able to produce a steady enough output from their own design, and so there remains some work on tuning the values of the analogue circuitry. The electronics team have documented this effort very well, so it will be easy for following teams to pick up where they left off, and continue the development without having to start from square one.

*Terrapin* contains in total three different power supply units, please see the attached Subsea SID in the appendices for a complete overview of the interconnections. The main PSU is a VICOR DC-DC Converter that converts from 48V to 12V with a 97.4 % conversion efficiency. The VICOR directly powers *Terrapin*’s thrusters, stepper motors, headlights, cameras, raman laser, and the PSU converting from 12V to 6V that supplies the claw-manipulator servo. The last PSU is a CUI DC-DC converter that converts from 48V to 5V with 78 % efficiency (totaling less than 10W throughput), and supplies 5V to the stepper-driver logic and a BeagleBone — which in turn powers the pressure sensor and IMU.

The VICOR and motor controllers are mounted directly on or thermally connected to the aluminium frame, effectively serving as water-cooling. Because of the very high efficiency of the VICOR there is not much heat generated within the ROV, and the heat that is generated is easily dissipated.

### Motherboard

After having learned from last year's competition, we decided to design a custom motherboard for the new ROV, to serve as a connection hub between all parts of the system. The motherboard connects all components, preventing wiring chaos and saving space by aligning inputs and outputs in an efficient manner. The motherboard consists of two custom designed PCBs stacked on top of each other, connected by eight pins in each corner.

The motherboard, which can be seen in figure 15, features a switching circuit for analog composite video, with up to eight inputs, and three outputs. This enables us to easily choose which of the seven camera feeds that we would like to send to the surface, and quickly switch between them. The switching circuit also gives us a lot of redundancy, which is helpful in case of camera or cable failure.

The eight electric speed controllers (ESCs) for the thrusters are also mounted on the bottom of the motherboard, each with their own slot and easy connection to the PWM signal board for control, and the 12 V bus for power. The motherboard also has support for dimmable headlights, raman laser and bluetooth activation light toggle.

All of the peripherals in the water is connected through one of the three A fuses on the motherboard, as can be seen in the Subsea SID, in case one of our waterproofing at any time should fail. The peripherals are spread out on different fuses (for example, all the cameras do not share a fuse), as to avoid going blind should one of the fuses blow.

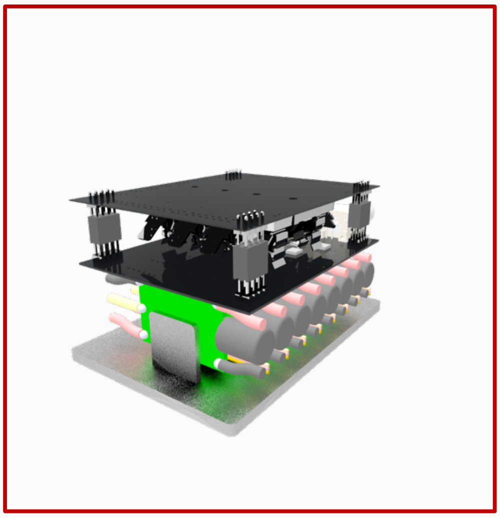

*Figure 15: The motherboard of Terrapin.*

The custom *Terrapin* control systems runs on a BeagleBone Black, a credit-card sized computer similar to the Raspberry Pi, which is mounted on the side of the motherboard. All sensor data from the IMU and the pressure sensor is fed to the BeagleBone, along with the control signals from topside.

### Cameras

*Terrapin* features a new and improved camera system. Last year we had several failures in our camera system, and year we wanted a more robust and reliable solution. We have more than doubled the number of cameras—this year there is a total of seven analog cameras. Analog cameras have superior latency, and require no onboard processing. This allows for a more compact electronics enclosure. The camera feeds are transmitted through three coaxial cables, giving the operator three different live feeds at any time, while also providing redundancy in case of a failure. We have placed cameras at strategic positions under the electronics enclosure, giving a good view of our tools and manipulator. To get the optimal field of view we tested four different lenses before settling on a 150° wide angle lens. It was also important to design the camera modules so they could be easily swapped out if anyone should fail during testing. The camera casings are 3D printed, and waterproofed with marine epoxy. The 3D printed casings allow for effective production and prototyping.

## 2.8 Sensors

Normally, an ROV pilot has to control several things at once: Propulsion requires control of depth, position in the *x*-y-plane, heading, and sometimes roll and pitch, depending on the ROV design. Manipulation tasks require the additional control of one or more robotic arms. We aim to reduce the workload on the pilot(s) as much as possible through automatic feedback control. Automatic control is only possible with appropriate sensors, and we have opted for sensors that allow measurements of depth, heading, roll, and pitch. Other sensors exist, for instance doppler velocity logs (DVLs) for velocity measurements as well as camera-based methods for positioning. However, DVLs are both expensive and physically large, and camera-based positioning is an extremely complex task. For a human-operated low-cost ROV, the drawbacks of these systems outweigh the benefits of the data they provide.

A simple pressure sensor based on the MS5837 unit is chosen for its small size, low cost, and high accuracy. It is small enough to fit inside a standard 10 mm penetrator, and it has a resolution of 2 mm, which is very reasonable for a shallow-water ROV. This will allow us to estimate the ROV's depth, and enable an automatic depth hold mode. Its price is 21 USD for the component alone, and 68 USD for the sensor built into a penetrator bolt.

For measurements of heading, roll, and pitch angles, we use a BNO055-based unit. The BNO055 is a 9-axis inertial measurement unit (IMU); combining an accelerometer, a gyroscope, and a magnetometer on a single chip. Its onboard sensor-fusion algorithms make it easy to use, as both heading, roll, and pitch are output directly, without necessitating further signal processing. The BNO055 is also inexpensive, at roughly 12 USD for the component alone, and 35 USD for a convenient breakout board.

Together, the IMU and pressure sensor provide measurements that allow us to automate control of depth, heading, and tilt. This will assure a swifter, easier, and more successful completion of the competition tasks.

# 3 Safety

## 3.1 Safety philosophy

Safety in all our work and actions is a primary focus for Vortex. We believe that all accidents can be prevented, and we therefore strive to offer a safe work environment for all our employees. A comprehensive safety policy through procedures, protocols and thorough training facilitates avoidance of accidents preemptively.

## 3.2 Lab protocols and training

The lab facilities our company employees utilize are regulated by the Laboratory and Workshop Handbook elaborated by the HSE division of NTNU.[4] Other work areas dedicated to performing risky operations have lab protocols elaborated and supervised by the company's respective technical lead.

All our employees must at all times be aware of the guidelines associated with the facilities. Our seniors review and ensure that new members are given rigorous training instructions on safety practices such as electrical safety, tool safety, workshop tidiness, and handling of hazardous materials. New employees are only allowed to work independently after being able to demonstrate proper and safe operation practices.

## 3.3 Operational safety practices

The operational Job Safety Analysis (JSA) is developed by a group composed of new as well as senior employees from different technical backgrounds. The content of the JSA is based on a toolbox talk. This discussion lays the foundation for a broad understanding of potential hazards as well as encouraging our employees to work more effectively and safely. The procedures are continuously updated when concerns about harmful situations arises. The operational JSA is used to ensure safe deployment, handling and recovery of *Terrapin*.

## 3.4 Vehicle safety features

*Terrapin* is designed with regards to keeping the crew, ROV, and work environment safe during operation. The electronics is waterproofed through diverse methods to protect the components from water exposure. In case of water leakage, *Terrapin* contains various safety features such as fuses on all peripherals. Other safety measures include buses on all high voltage lines to prevent accidental short circuit, a kill switch implemented in the GUI and also physically on the control box, shrouded thrusters with a thruster guard, restricted bend radius and strain relief on tether and peli case. Adequate warning labels are included on power connections and rotating parts.

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[4] NTNU, HSE Department. *Laboratory and Workshop Handbook.* Trondheim: Fagtrykk Trondheim AS, 2016.

# 4 Conclusion

## 4.1 Technical challenges

Vortex has a strong commitment to pushing boundaries and challenge ourselves. As a volunteer-based organization we are mostly free to pursue designs that would never be justifiable in a commercial venture. As a result, the most challenging aspect of this year's effort has been managing the growing pains stemming from threading so much new ground. The design and integration of multiple novel systems has proved challenging, and we have designed to accommodate for this uncertainty.

## 4.2 Lessons learned and skills gained

One very clear lesson for this year's team is the importance of protocols and specifications. Much time has been wasted during integration tests where a recurring theme has been components that would not have passed isolated testing causing the entire test to fail. By specifying a testing protocol with a dependency graph between different components ensuring that integration-tests does not happen before individual components have passed testing much time and frustration could have been avoided.

As for skills gained this year's team has faced many challenges beyond the scope of their degrees. The mechanical engineering group has designed and built thrusters with 3D printing. They have learned the basics of CFD software which will be used for next year's product, and they have experienced the process of ordering prototyping machining from China. The electrical engineers of Vortex have designed their own PCB circuits, both for the power supply and for the camera system, and had them printed in China. Another important lesson learned from the PCB designs is the importance of having a plan B, which ended up coming in handy when the custom power supply units did not achieve a stable enough result for use in the competition, making it necessary to switch them out for an off-the-shelf solution.

Just as important as exploring uncharted territory, many of the most important lessons from this year are the ones shared throughout the organization, teaching software engineers what CADing is like, and mechanical engineers learning about PCB design and manufacturing.

## 4.3 Future improvements

There are numerous improvements that can be done to *Terrapin*, such as reducing the size of the enclosure and optimizing the electrical designs. However, these issues are to be expected in a prototype which is why our focus on future improvement is more directed towards Vortex as an organization. The lack of a proper project planning and management tool has been an Achilles' heel for this year's effort, which along with the decentralized organizational structure of Vortex made it difficult to track different tasks and coordinating efforts. By tracking metrics such as track completion, and having clearly defined goals and specifications the organization will be to both get a better overview over the project, as well as gaining vital information for improving and evaluating our next project.

# 5 Acknowledgments

Vortex NTNU would like to thank the following contributors for their endless support and guidance in the development and production of *Terrapin*, and making our journey to the 2017 MATE international ROV competition possible:

- **Norsk Elektro Optikk:** Our main sponsor. Funding most of our components, and cooperation in building test platforms for new optical laser technology.
- **NTNU:** Providing offices, lab and workshop areas. Funding of travel cost, components and pool facilities.
- **Kongsberg Gruppen:** Machining the aluminum bottom plate for the electronics enclosure.
- **Siemens:** Software licence for the CFD analysis program, Star-CCM+.
- **FFU:** Financial support and the opportunity to write for Norway's largest news magazine for subsea technology and underwater robotics, DYP.
- **Kjeldsberg:** Providing good-tasting and invaluable coffee throughout the project development.

Last but not least, the company extends our sincere gratitude to our mentors Peter Aaser, Ingrid Fjordheim Onstein and Vegard Kamsvåg for their administrative support and first-rate insight in technological matters, and their encouragement in our project.

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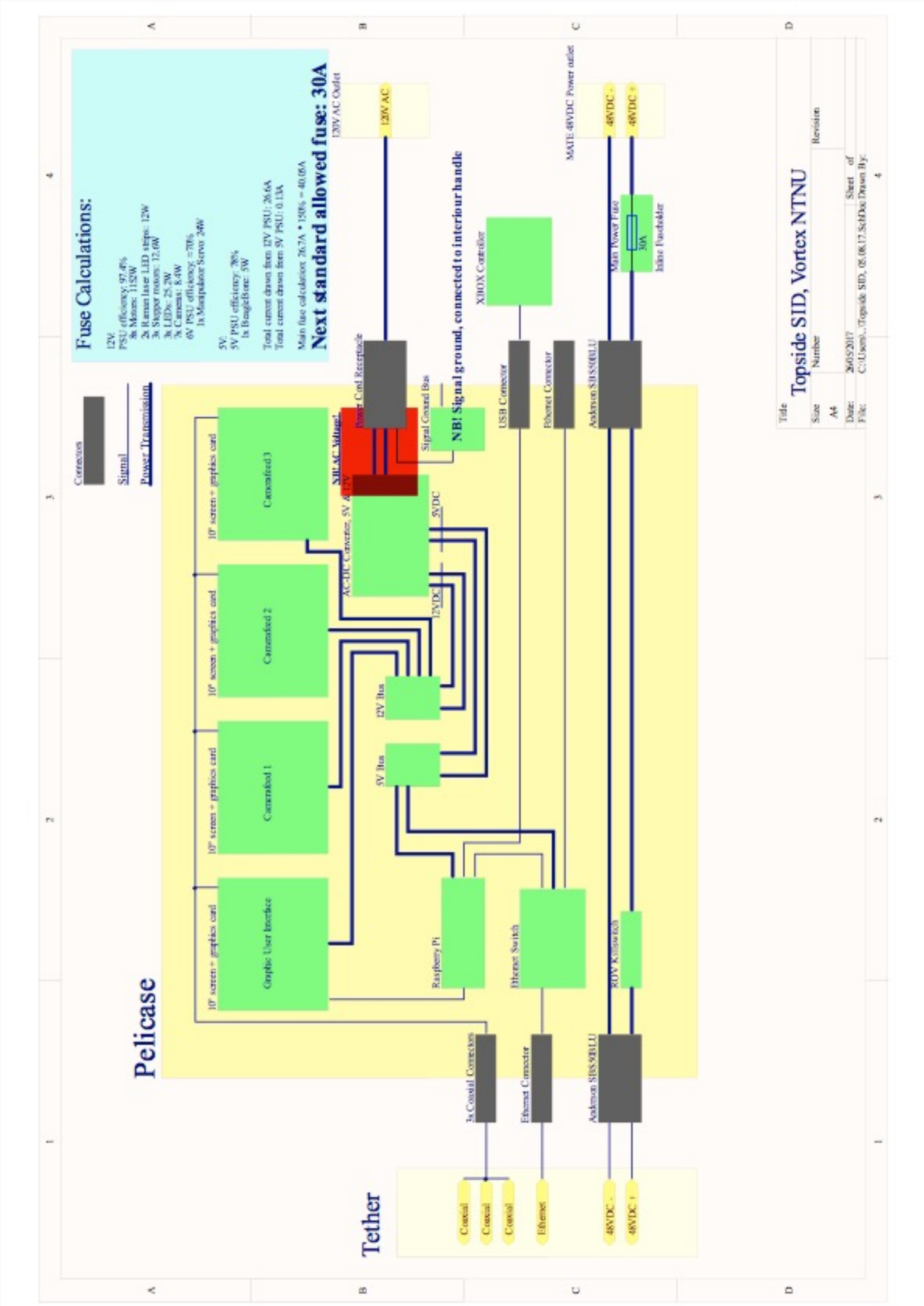
# 7 Appendix A – Topside SID



# 8 Appendix B – Subsea SID