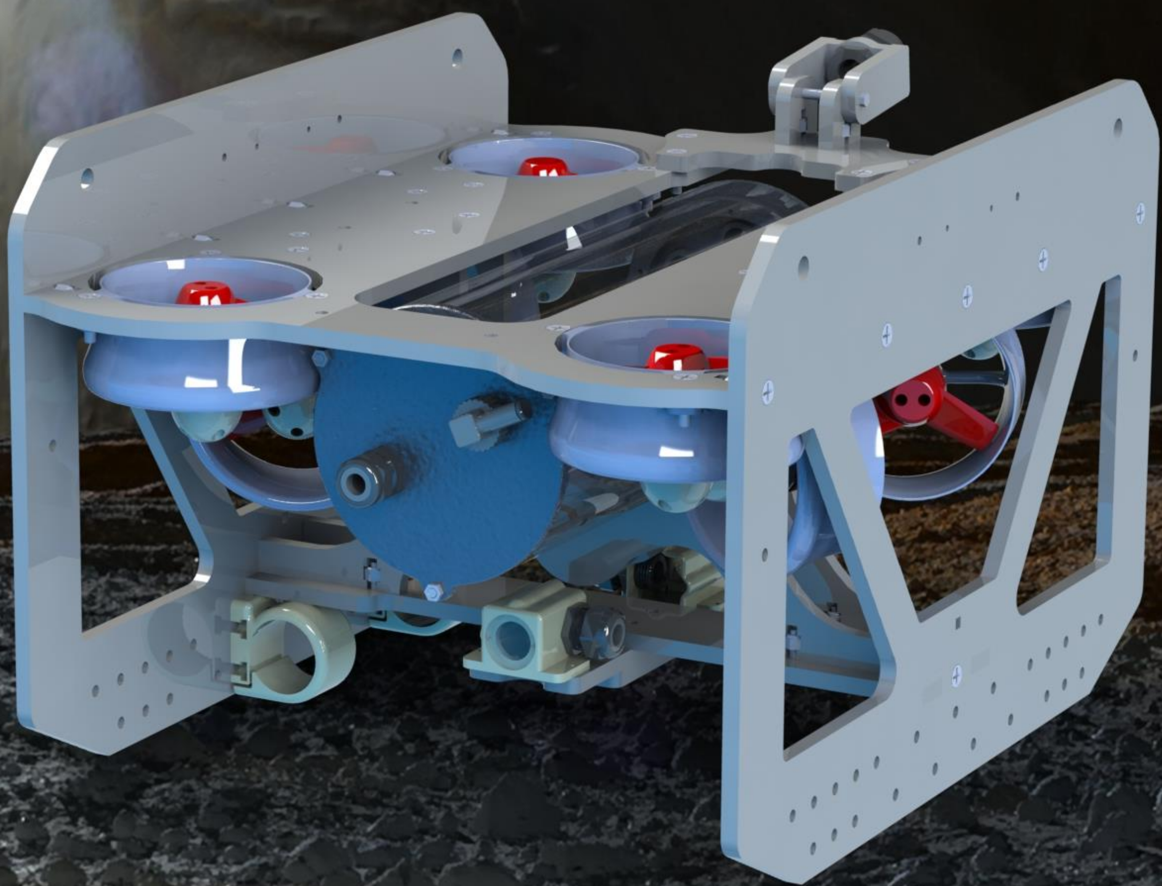
AMNO & CO

SEATTLE, WA

2016 MATE INTERNATIONAL ROV COMPETITION



Nicholas Orndorff (Chief Executive Officer) 11th grade, Ingraham High School*

Clara Orndorff (Chief Product Officer) Freshman, University of Washington*

Alex Miller (Chief Technology Officer) 11th grade, Garfield High School*

Mentors: Mary Chang & Rachel Miller

***AMNO & CO is not affiliated with any school or organization**

(background image: an artist's rendering of Jupiter from Europa's surface, credit NASA/JPL)

ABSTRACT

AMNO & CO brings seven years of experience building Remotely Operated Vehicles (ROVs) to this year's goal of developing versatile and professional technology for exploration of two environmental extremes: underwater in the Gulf of Mexico and outer space on Jupiter's moon Europa.

Special features of this year's ROV include a control system composed of custom printed circuit boards which allow the control system to reach the optimal blend of capability, precision and reliability, a built-in LED simulator that provides a real-time view of the control system and enables testing without being connected to the ROV, a remote programming feature to aid troubleshooting and dual control boxes which facilitate the company's efficient collaborative piloting system.

The controls are connected to the onboard systems through a 55 meter long tether, braided for flexibility. The ROV features full speed control in six axes of motion (three translational and three rotational), provided by efficient and cost-effective encapsulated brushless thrusters.

To accomplish the 2016 MATE competition tasks, the ROV's versatile mission specific tooling includes a robust electromagnet system and a custom-machined aluminum manipulator with interlocking end effectors, both of which are also suitable for tasks in the real world.

TABLE OF CONTENTS

2. COMPANY INFORMATION

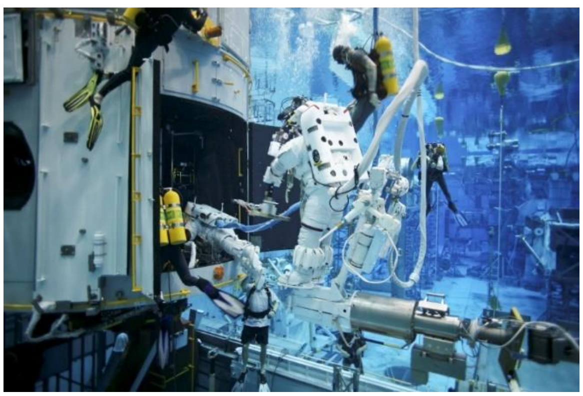
From left, Alex Miller, Nicholas Orndorff and Clara Orndorff

Nicholas Orndorff (Pilot, CEO)
11th grade, Ingraham High School
Career goals: mechanical or electrical engineering

Clara Orndorff (Tether Manager, CPO)
Freshman, University of Washington
Career goals: mechanical engineering

Alex Miller (Pilot, CTO)
11th grade, Garfield High School
Career goals: mechanical or electrical engineering

3. MISSION THEME



Astronauts simulate a spacewalk in NASA's Neutral Buoyancy Lab[1]

A newly re-inhabited oil rig[2]

The environment in outer space is strikingly similar to that of the underwater world. Currently, NASA is planning a mission to Jupiter's moon Europa, which has an ocean that might have the requirements for life. This mission will conduct 45 flybys and is likely to include an ROV designed to operate in the harsh environment of this ocean, as well as a range of sensors including an imaging spectrometer, a magnetometer and a surface dust mass analyzer[3]. ROVs built for the 2016 competition will not only have to perform tasks related to this mission but also to accommodate specific requirements related to size and weight that are relevant to the high cost of shipping equipment to outer space (roughly $22,000 per kg[4]).

Another of the many uses of ROVs is related to the concept of rigs-to-reefs, in which old and unused oil rigs are converted into underwater habitats such as coral reefs. The 2016 MATE competition focuses in particular on the rehabilitation of the Deepwater Horizon platform, which sank in the Gulf of Mexico in 2010.

Soon, ROVs will make a major contribution not only to exploring outer space but also to protecting inner space.

4. SAFETY

Safety features and practices relate not only to protecting personnel (both the company as well as observers) but also to preventing irreparable damage to a sophisticated and expensive vehicle. Therefore, this year's vehicle has all of the MATE Center's required safety features including: caution labels for moving parts, strain relief on the tether as well as all other cables and a 40 amp fuse within 25 cm of the battery on the positive line. The proper value for the fuse was determined by summing the amperages of all systems (measured individually with an ammeter), then confirming the ROV's total amp draw and factoring in the proper overcurrent protection coefficient (see calculations on the Systems Integration Diagram in Appendix 1). In addition to the safety features required for the MATE competition, the company has implemented some of its own, including a main power shutoff switch, surface voltage and amperage meters, a vacuum depressurization system to test for water leakage, 3D-printed shrouds for all thrusters and DC-DC isolated switching power supplies to eliminate voltage surges to sensitive electronic systems.

During construction of the ROV, the company followed a safety protocol which requires proper lifting techniques and Personal Protective Equipment (PPE). This includes the use of safety glasses, closed-toe shoes, gloves and masks (for potentially hazardous substances). The company complies with all Health, Safety and Environmental (HSE) standards to maintain a safe workspace.

Initial here when completed:	Safety items:
	Are we wearing closed toe shoes and safety glasses?
	Is there a viable fuse in the fuse holder?
	Is there a Ground Fault Circuit Interrupter (GFCI)?
	Has the ROV been airlock tested?
	Is the airlock port closed?
	Is the tether/control case clamped to the table?
	Are all the underwater connectors plugged in?
	Is the airlock system on the ROV? Is the port closed?
	Are the Anderson connectors plugged in properly?
	Are all the switches in the off position? (Main power)?
	Is the tether/control case clamped to the table?

Table 1: The mission station safety checklist

The company also developed a more detailed safety protocol in the form of a comprehensive Job Safety Analysis (JSA).

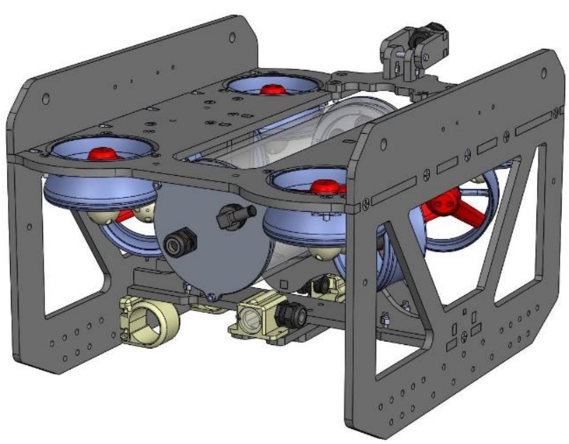
5. DESIGN RATIONALE

There were many special considerations that the company evaluated in order to design an ROV adept in both deep sea and outer space environments. Due to the high cost of interplanetary transportation, size had to be minimized, although the vehicle still had to be large enough to withstand high current conditions of Earth's oceans. The 2016 MATE missions at a 12 m depth in NASA's Neutral Buoyancy Laboratory (NBL) also necessitated high speed and agility, for which the company developed and accomplished its goals of constructing powerful waterproof thrusters and appropriate control software. To further enhance mission performance in these conditions, the company developed an efficient task order to minimize the number of trips to the surface.

Tasks in ideal order	Points
Take Ice Crust Thickness Measurements at Surface	< 10 cm from true depth – 10 pts
Descend and Determine Ocean Depth	< 10 cm from true depth – 10 pts
Measure Venting Fluid Temperature	Inserting temperature sensor in venting fluid – 10 pts Measuring the temperature– up to 20 pts
Connect the ESP to the Power and Communications Hub	Retrieve ESP cable connector from elevator – 5 pts Lay the ESP cable through three waypoints –15 pts total Open the door to the port on the power and communications hub – 10 pts Insert the cable connector into the port on the power and communications hub – 20 pts
Find and Identify the Serial Numbers of Four Mission Critical Cubesats	20 pts total
Recover the Four Cubesats to the Collection Basket	20 pts total
Photograph Two Coral Colonies (Showing 3" Lettering)	10 pts total
Compare and Report Coral Colony Growth to Judges	10 pts total
Collecting and Returning Two Coral Samples to the Surface	10 pts total
Collect One Sample of Two Oil Mats on the Seafloor	10 pts total
Return the Sample to the Surface	10 pts total
Place Flange and Bolts in manipulator(s)	N/A
Analyze the Gas Chromatographs	20 pts total
Install a Flange to the Top of the Wellhead	*10 pts*
Secure the Flange with Two Bolts	*10 pts total*
Install a Wellhead Cap Over the Flange	*10 pts*
Secure the Cap with Four Bolts	*20 pts total*

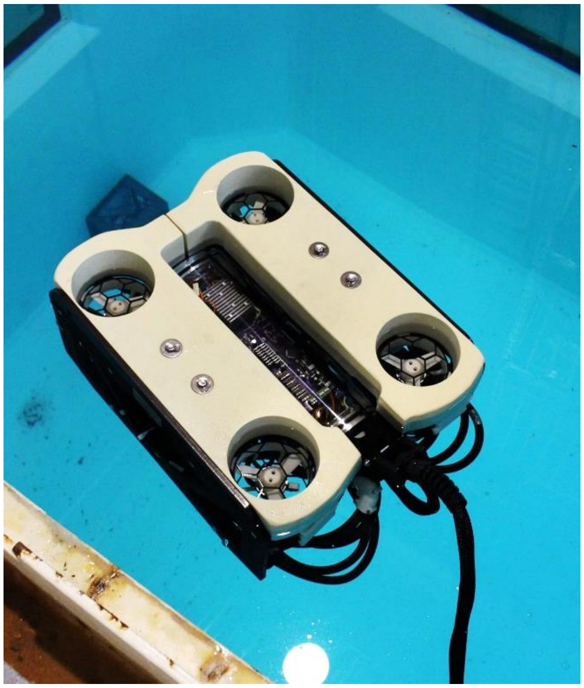
Table 2: The efficient task order (italics indicate tasks that must be done in order)

5.1 Frame and Flotation



A CAD model of the ROV's frame and major components

The frame was constructed from laser-cut Starboard (a marine-grade version of high density polyethylene, or HDPE). Among its beneficial properties, Starboard is durable and dimensionally stable (it retains its physical characteristics in harsh environmental conditions). The frame was designed and modeled using Solidworks CAD, which provided the ability to implement slot and tab construction, integrated hardware and convenient lift points. The structure of the frame was optimized for thrust flow, hydrodynamics, component visibility and cable management. The frame also features a hinged tether connection, which not only provides strain relief but also prevents the tether from negatively affecting the ROV's motion at a depth of 12 m.



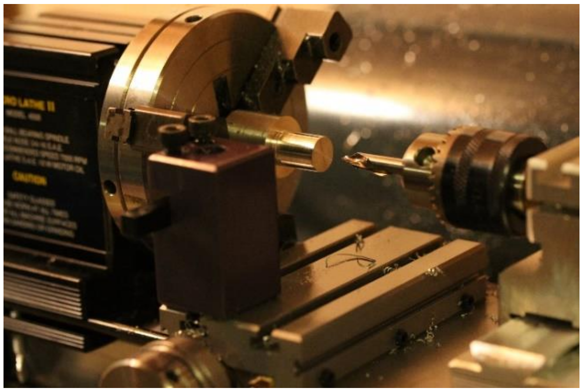
A top view of the frame during a pool test

The ROV is neutrally buoyant. A float was constructed from closed-cell, incompressible polyisocyanurate foam rated to 426 m. The desired amount of flotation was determined through calculations using Archimedes' principle and the estimated mass of the vehicle (20 kg). Using Newton's 2nd Law, $F_{net} = (ma)_{net}$, the ROV was calculated to have a weight force $F_W = 196.2$ N, which (due to the properties of the polyisocyanurate) led to a projected required volume of 0.014 m^3 of foam. Due to the vehicle's geometry, the final float had a volume of 0.015 m^3, and the finished ROV was fine-tuned through empirical testing. The float was mounted on the top of the frame for the desired stability (to maximize the distance between buoyancy and ballast).

5.2 Waterproof Electronics Canister (WEC)

The rear end cap to the WEC

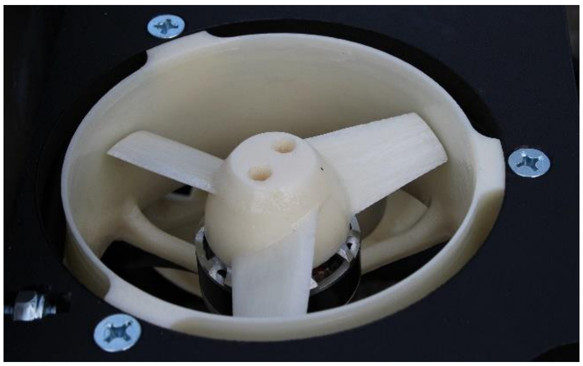
The WEC contains all of the ROV's onboard electronics, which are mounted on a 3-layer acrylic rack designed to hold printed circuit boards (PCBs), power infrastructure and video electronics in a compact and signal-conscious format. The rack assembly is housed inside a 12.7 cm inner diameter acrylic tube with 0.635 cm thick clear walls to assist troubleshooting. Two aluminum end caps, CNC-machined by the company for high accuracy, waterproof the canister via piston-fit O-ring seals. The front end cap holds an AirLock depressurization device used for leak detection. Cables enter and exit the end caps through in-line wet-mate connectors and liquid-tight cord grips. The maximum depth rating of the WEC is 40 m.



AMNO & CO machining a cable penetrator for the WEC

The completed WEC, with the electronics rack

5.3 Propulsion



A vertical thruster, mounted in the frame

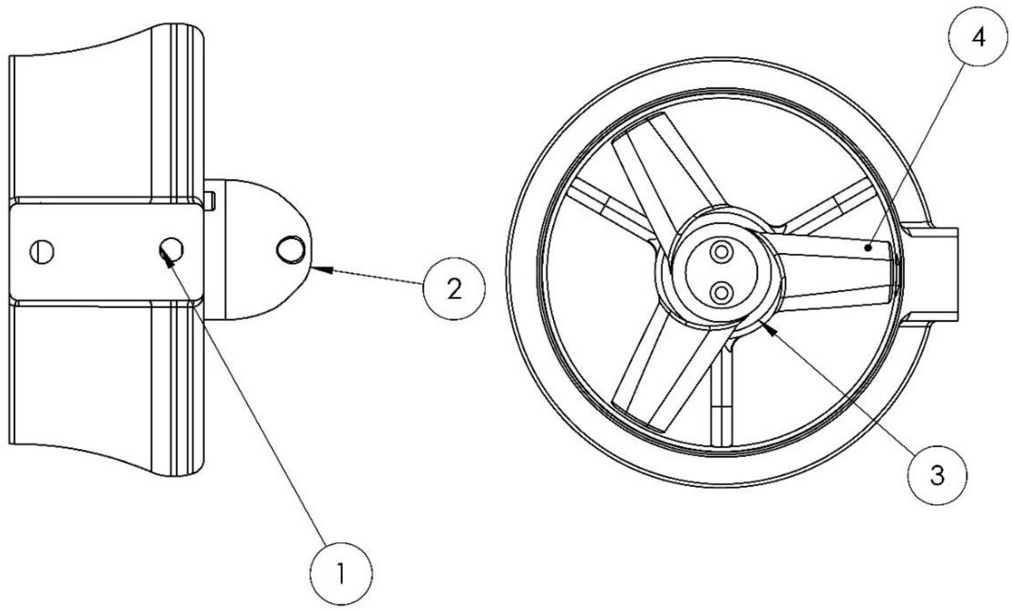
The ROV has eight thrusters (four horizontal and four vertical), which are highly efficient at 10.9 watts/kg (24 watts/lb) of thrust. Each individual thruster, based on an encapsulated brushless motor, provides 2.7 kg (6 lbs) of thrust at 12VDC, powered by isolated 48V to 12V converters with 96% efficiency in conversion. The motors were infused with resin in a vacuum chamber to ensure complete coverage and electrical insulation. Every motor was quality controlled for electrical conductivity to resistances at or greater than 10 MΩ at 500V. In addition, the motors are run at their peak efficiency point of ~70% of their maximum power.

A selection of the propellers that were tested

The 3D-printed nozzles were developed to maximize thrust and efficiency according to the Rice nozzle principles[5], which propose that in addition to the inside, the outside surface also has a substantial positive impact on overall thrust. The nozzles also minimize cavitation from the 3D-printed propellers, which were optimized to produce identical forward and reverse thrust.

The final nozzle design

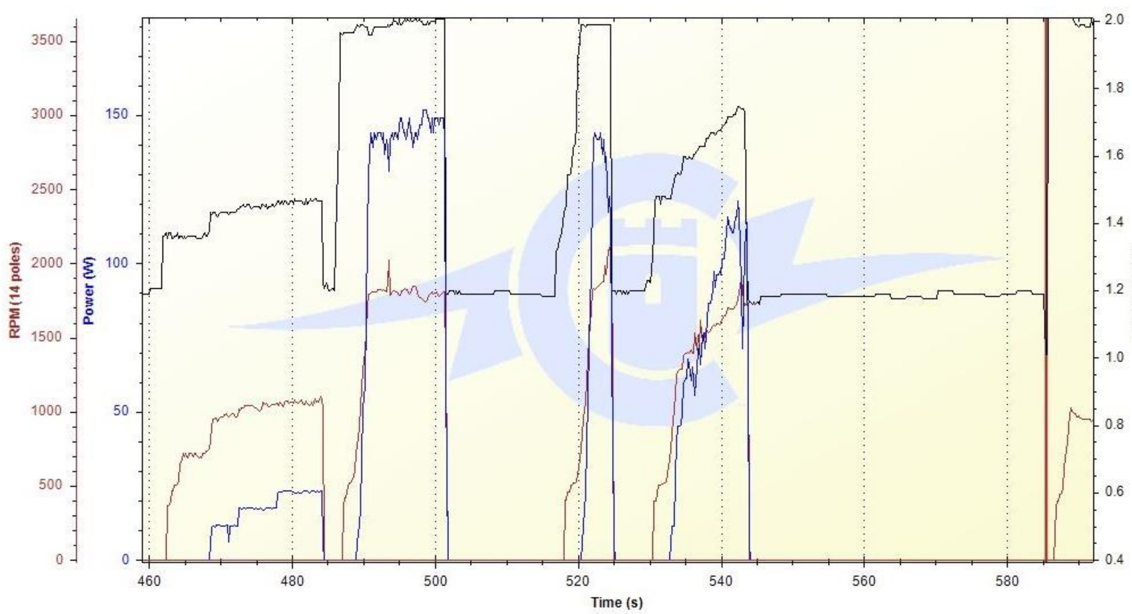
The use of rapid prototyping technology allowed the company to conduct iterative testing on over 30 different combinations of propellers and nozzles before choosing the best combination. Rapid prototyping also facilitated construction of thruster guards to prevent the propellers from causing injuries or becoming tangled in ropes from the mission props, while not detracting from total thrust.



Solidworks drawings of the thruster assembly, side and front views.
1: nozzle; 2: rear thruster cone; 3: motor; 4: propeller.

Each thruster is controlled with a commercial electronic speed controller (ESC) that was reprogrammed with the company's own custom firmware for improved underwater braking and response characteristics.

The thruster firmware was determined by evaluating thruster data logs, which were used to determine the best settings for acceleration, braking and efficiency. The graph shown below compares power, throttle input and revolutions per minute (rpm) for 90 seconds of operation.

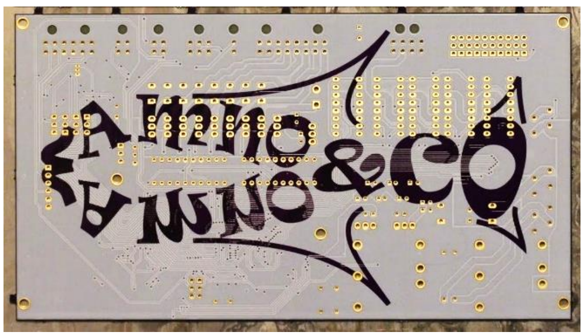


The data log for the ESCs used to control the thrusters (data was collected by AMNO & CO with the Castle Creations Link software)

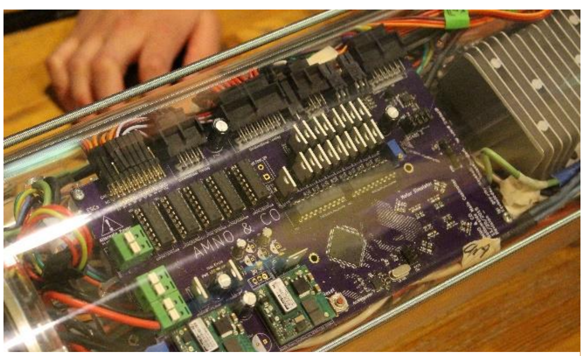
5.4 Control System and Tether

5.4.1 Hardware

The custom PCB for topside communications



The custom PCB, unpopulated, for onboard control



A top view of the electronics rack

The control system was designed as a solution to integrate advanced user features and to allow for non-invasive prototyping via rapid implementation of new systems.

Previous ROVs built by the company utilized distributed control systems based on numerous custom printed circuit boards (PCBs); while this did allow for rapid diagnostics, it was extremely time consuming to implement and introduced latency. Many of the PCBs were also unnecessarily powerful for their tasks. On this year's ROV, the entire function of a distributed control system has been condensed into a single main controller board.

At the surface, the control interface is designed to provide an intuitive and collaborative piloting system using two ergonomically designed user control boxes, each of which connects to the main control case. The first box, for piloting, features a three-axis joystick for horizontal motion, a two-axis joystick for vertical and rolling motion and a potentiometer for pitch control. The second box features SPST and DPDT switches for the ROV's manipulators, electromagnets, and other auxiliary tooling functions. Other functions such as lights, backwards mode and precision mode are controlled by switches in the main control case.

In the main control case, the topside communications PCB processes signals from the two external boxes, then transmits the data through the tether via a full-duplex RS485 communications protocol, created with a MAX488 transceiver. The RS485 network uses differential balanced lines that can maintain robust connection over long distances or near sources of interference as well as simultaneously send and receive. Sensor readings from the vehicle are relayed through the topside communications PCB to a custom liquid crystal display controller PCB, which displays the readings to the pilots.

The bottomside controller PCB uses the ATMEGA 2560 processor to control every system on the ROV. With its integrated power conversion infrastructure, the board can receive any power input from 9v to 75v while isolating 3.3v and 5v signals from higher power electronics. The controller can control up to 10 brushless motors. An LED-based thruster simulator allows for rapid debugging and standalone software testing. There are also 10 channels of unidirectional tooling

The main topside control case at a pool test

control, 4 channels of bidirectional tooling control, as well as various sensor inputs. For future expandability, due to the processing power required to implement active data stream refinement, such as an unscented Kalman filter necessary for full stability control, the integrated bottomside controller board includes high-speed communications capacity for the addition of a separate sensor processor. The wire to board connections are made reliable through locking board mount connectors as well as vibration-proof spring terminals for power.

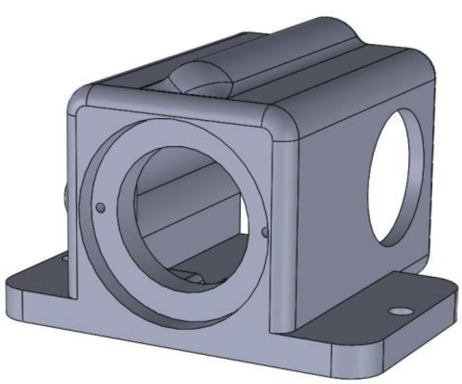
5.4.2 Software

The electronic hardware supports a software system that facilitates complete speed control over the six axes of ROV motion (three translational and three rotational) through a signum-aware component vector addition algorithm. The vehicle also has precision mode, backwards mode (which reverses the forward/backward orientation of the user controls) and an adaptable depth hold function based on a proportional integral algorithm to assist with fine maneuvering. A remote programming feature allows the main bottomside controller PCB to be programmed even with the WEC closed, allowing for ROV diagnostics and active testing.

5.4.3 Tether

Due to the inherent challenges presented by the depth of NASA's NBL, the tether was designed for optimum power transmission over its length. The individual cables, originally 60 m, were hand braided for minimum size and maximum flexibility, leading to a final tether length of 55 m. It contains two silicone wires (8 gauge, 1600 strand) for power, five wires (18-gauge, 32 strand) for signal and two miniature coaxial cables for video.

5.5 Cameras



The enclosure for the forwards and backwards facing cameras

The ROV has three high definition (700TVL), wide angle (90º), wide aperture, low light cameras. These cameras face forwards (for main piloting), backwards (to allow for additional tooling to be mounted on the back of the ROV) and downwards (to provide the pilots with multiple perspectives as well as to help with general location and positioning). The forward and backward cameras are both encapsulated with epoxy in 3D-printed enclosures while the downwards camera is mounted on the inside of the clear WEC.

5.6 Mission Specific Tooling

The machined manipulator sealing system

The complete manipulator housing

To accomplish the diverse range of mission tasks, the ROV primarily relies on a versatile manipulator system. This manipulator is centered on an electric geared motor, secured in a lathed aluminum housing and waterproofed with a low-friction, particulate-tolerant ceramic-graphite pump shaft seal. The motor drives a lead screw, which links mechanically to a set of interlocking end effectors built specifically to transport the temperature sensor, return the coral samples and install the flange on the wellhead. The ROV also has an auxiliary manipulator, based on the same design principles, allowing the vehicle to grasp multiple objects at once and reduce the number of trips to the surface. Apart from these general tools, the ROV has specialized tools that include a dual-electromagnet wand (to stably transport and insert the ESP connector into the tight fitting port) and a solenoid-driven tool for inserting horizontally and vertically oriented pairs of bolts into a flange.

The ROV also features an array of onboard sensors for scientific measurements; these include a temperature sensor to measure the thermal potential of venting fluid and a pressure-based depth sensor to measure both the thickness of the surface ice and the depth of the ocean. Other sensors contribute to the functionality of the ROV, such as a leak detector for safety and protection of the electronics. Also onboard the ROV are an accelerometer and a gyroscope, which allow for an inertial measurement system and improve the ROV's control and maneuverability.

6. TROUBLESHOOTING

In the systems integration phase, troubleshooting the control software required a unique process, due to the need to bridge the gap between mathematical control theory and real world implementation. After multiple years of using simpler matrices for vehicle control in 2 axes, this year's vehicle relies on a streamlined component-vector-based algorithm providing full speed control on all 6 axes. At first this algorithm was developed on paper, and tested in a case-tracking spreadsheet. When implementing these new control ideologies, however, conceptual errors soon materialized in how the algorithm needed to interact with the actual physical and electrical components (the communications network, ESCs and joysticks). Troubleshooting this system required a whole team effort, as each of us caught and corrected bugs that the others overlooked.

In terms of the entire ROV, we have found that building and practicing with the mission props is one of the best ways to determine if aspects of the ROV require adjustment – for example, because water affects the way light travels, we have needed to adjust mission tooling placement so that it could be viewed by the cameras.

7. TEAMWORK AND ORGANIZATION

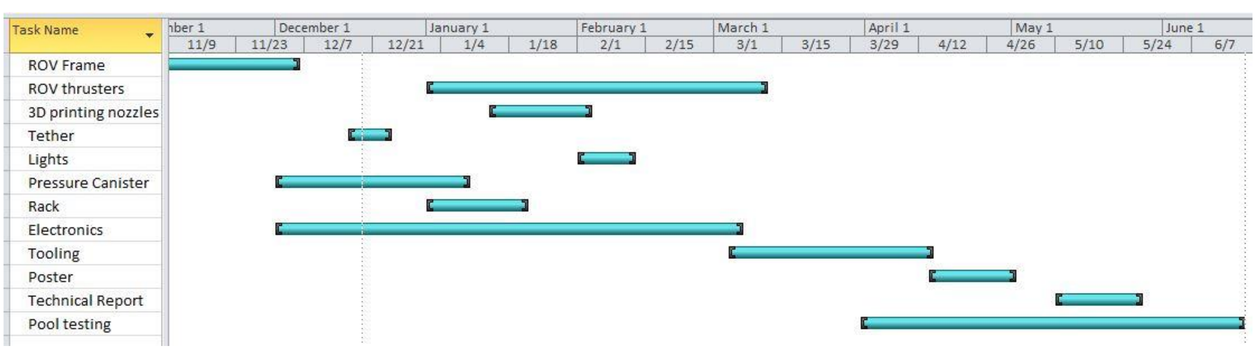
AMNO & CO working together to waterproof their motors

Through our past experiences, it is clear that systems integration and troubleshooting are challenging at both technical and interpersonal levels. Our strategy is for our whole company to participate together in every aspect of the design and build process. Knowing that our entire company has the same knowledge base allows us to implement and integrate risky and innovative ideas with more confidence and sophistication in a more supportive environment. In addition, practices such as peer programming significantly reduce errors and time spent troubleshooting.

8. PROJECT MANAGEMENT

This year's design process began in June of 2015 – as with every other year, we met soon after the international competition to discuss the many ways in which our previous systems could be improved. Although we've been competing together as AMNO & CO for seven years, this is our first year at the Explorer class, and while in past years we have strategically reused certain parts (usually the expensive or hard-to-obtain components), several factors prevented us from doing so again this year. First, our previous vehicle is highly specialized and still functional (we used it for other events), and second, the Explorer class has different power requirements (48 volts versus the 12 volts allowed in the Ranger class), which necessitated completely new and different power and electronics systems. We also wanted to take this year as an opportunity to combine all the skills that we've learned over the last seven years in a completely new ROV.

In order to achieve our goals, we made firm deadlines. When we wanted to engage in a new development process, we allocated limited timeframes in order to conserve time, effort and money.



A Gantt chart to assist with project management by providing a schedule, with deadlines for different components

9. CHALLENGES

9.1 Technical Challenge

Due to this being our first year in the Explorer class, we were faced with the new challenge of powering our ROV off of a 48VDC power supply. Many of our systems required power conversions; for example, our thrusters and cameras run on 12V and many of our control system electronics run on 5V. We had to take special precautions in order to make sure that all of our systems were protected, as anything over the designated input voltages of our electronics posed a serious risk of damaging our control system. As a precaution, we protected our more sensitive PCBs and cameras with isolated switching power supplies that prevent back over voltage. In addition, many of the power converters had an automatic latching shutoff feature to protect electronics from back electromotive force (EMF), but they detected the back EMF produced by our motors. To allow the motors to run properly, we added fast acting Schottky diodes to protect these power converters from the back EMF. Including a power conversion infrastructure also meant that more electronics had to fit in our WEC, which necessitated careful planning to ensure a proper fit.

9.2 Non-technical Challenge

AMNO & CO preparing their 2015 ROV in Washington, DC

This year, we also had the pleasure of dealing with an unexpected huge surprise: attending the White House Science Fair! We had just over two weeks to get everything ready at a time when we were already working hard to prepare for the MATE competition. We didn't want to risk shipping this year's ROV, so we refurbished our 2015 vehicle in time for it to be shipped (just one of many logistical difficulties that led up to an incredibly wonderful experience). We were challenged to be more flexible, and to get work done on short notice in order to meet various deadlines, but it was the experience of a lifetime (besides President Obama, we met influential members of the White House staff, astronauts, NASA engineers, media and many other people we never would have dreamed of meeting). We were excited to be able to do live demos of our ROV – it really added interest to our presentation, and we were thrilled to tell everyone about the amazing opportunity that is the MATE competition. We learned a lot from talking with other students, all of whom had fascinating projects, and we're incredibly grateful to the MATE Center for this opportunity.

AMNO & CO preparing a 350 gallon tank to demo the ROV in at the White House Science Fair

AMNO & CO presenting about the MATE Center and demonstrating the ROV

10. LESSONS LEARNED

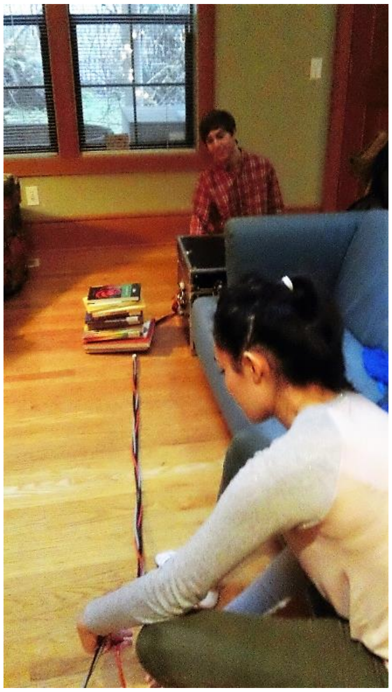
10.1 Technical Lesson

This year, one of our goals was to make an ROV that contained all of its systems within its frame, lending to a compact, space-efficient design. To begin with, the entire ROV and the majority of its components were modeled in Solidworks CAD with carefully measured tolerances. Next, we learned and used a variety of advanced manufacturing techniques (including CNC machining and 3D printing) to achieve fully inboard thrusters without thrust impediments, inboard wire routing and an elegant float, all of which we felt were necessary for a professional ROV. Throughout the troubleshooting process, however, we had an increasing need to access inboard components for testing – we learned that while a perfect component fit is desired on a finished project, it can often impede development. For example, unplugging our underwater connectors takes a considerable amount of work and time, and although all the components do fit neatly, this was a useful lesson in maintainable design.

10.2 Interpersonal Lesson

We’ve often had a hard time settling on a single ideal solution to a given problem, especially under pressure. This year, before making our qualification video, we were trying to rapidly construct a tooling solution capable of picking up the ESP connector from the elevator. The quickest and simplest way would have been to use a static hook, but the idea we wanted to implement eventually involved using two electromagnets for stability. After much discussion we decided it would be best to make the electromagnet tool, and we learned that the small amount of extra time this took was worth the long term benefit of not having to remake this tool.

11. FUTURE IMPROVEMENTS



Alex and Clara braiding the tether

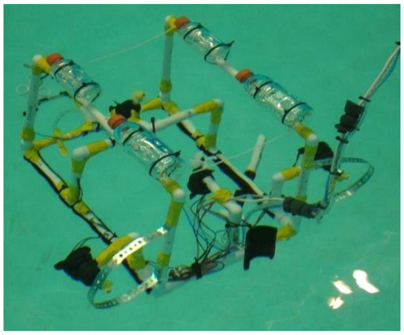
One of the aspects of the ROV that could be improved is the size and weight of the tether. We decided that a length of 55 m would allow flexibility for good maneuverability at the bottom of NASA's Neutral Buoyancy Lab and for the ROV to be useful in real world exploration. However, the weight of our cables became significant and we needed to build an ROV that was large enough to manage this amount of tether. Ultimately, this precluded our ability to rise to the challenge of building a smaller vehicle. In order to successfully work towards a smaller size in the future, we would like to experiment with different ways of transmitting camera signals that would eliminate the need for coaxial cables in our tether. The Arduino-based custom PCBs that we use do not have the processing power required to transmit video signal, but we'd like to look into other processing platforms that do in order to reduce the size of both our tether and our vehicle.

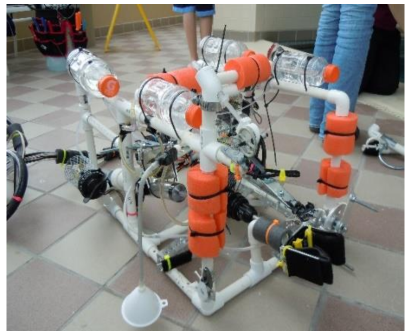
12. COMPANY REFLECTIONS

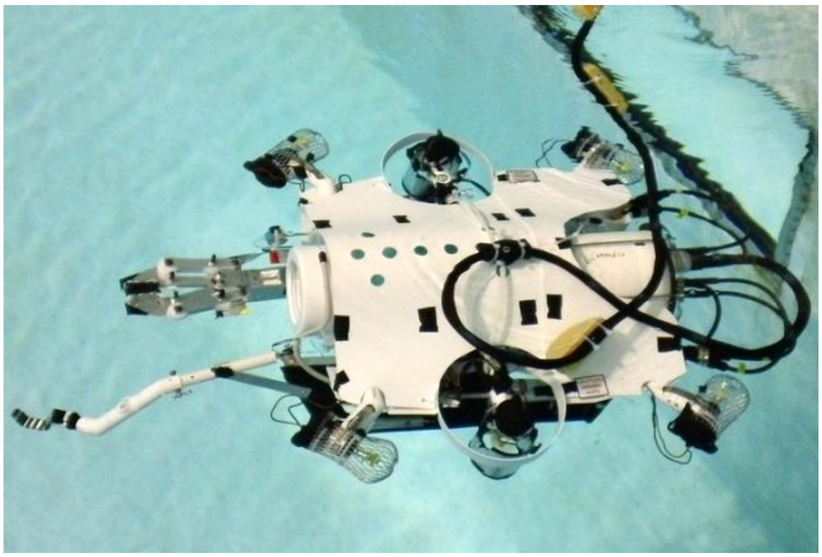
Nicholas machining an end cap for the WEC

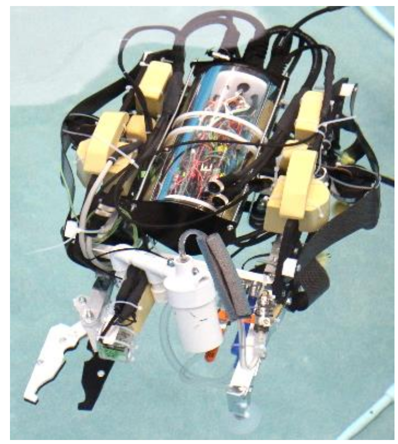
After building this year's ROV, we feel incredibly fortunate that we had the opportunity to participate in the Explorer class, which has been our goal ever since we began at the Scout class. Without the MATE Center, we might never have found an outlet for all the ideas we had and projects we wanted to build. We also started participating together as a way to stay in touch after going to different schools. We've really enjoyed learning new things every year, both from other teams and judges as well as from our own trial and error.

This year we were able to develop skills that dramatically improved our technical capabilities. With the generous help of a local company who taught and trusted us to how to program and operate their 3-axis Haas CNC machines, we were able to manufacture our end caps ourselves. We also took full advantage of the utility of 3D printing for rapid prototyping to create our thruster assemblies. In addition, as a direct outcome of our experience with the MATE Center competition, we have begun planning for an ROV-related startup company through which we hope to create and distribute control PCB kits for the hobby ROV market.









Pictures showing our progression.
Top row, from left, the 2010, 2011 and 2012 ROVs
Middle row, from left, the 2013 and 2014 ROVs
Left, the 2015 ROV

Having had the same team members since we began has also been beneficial. We have been fortunate enough to be able to learn together, thus ensuring that we are all at the same skill level and that we all understand each other. This is a major part of what has allowed us to move from the PVC pipe, bilge pumps and pool noodle flotation that we used in 2010 to the CAD-modeled frame, custom designed thrusters and PCBs that we designed and built from scratch this year. Along the way, some of the major skills we've gained include the ability to do our own machining: we have learned how to use CNC machines, laser cutters, 3D printers and a variety of other tools in order to make everything on this ROV ourselves rather than outsourcing to commercial companies.

13. BUDGET

AMNO & CO is not associated with any school or organization so does not have institutional support in the form of funds, equipment, or materials. Therefore, we must be thoughtful and careful in order to control how much money we spend. To do this, we used an updated approach that has worked for us in the past.

First, we considered the amount we spent on the vehicle we built for the 2015 MATE competition. Second, we estimated that in order to build a more sophisticated vehicle at a higher level of competition we would need to spend more money, largely for prototyping more designs and for using higher quality parts. Third, we dedicated the amount of prize money/income we received from last year's achievements to cover some of these extra costs. Therefore, our final spending budget of $4,550 allows for more sophistication by combining last year’s costs ($3,000), prize money/income ($550) and extra for sophisticated parts ($1,000). In order to stick to this budget, we made conscientious design and purchasing decisions. While we might have liked to use professional, high-precision parts for everything, the costs were prohibitive. In those cases of impractical expense we used a successful letter-writing campaign requesting discounts or donations of products.

This year’s out-of-pocket expenses were $4,924.63, which is fairly close to our projected spending budget. We attribute the small discrepancy to unanticipated costs, such as the high price of power converters required for Explorer class. The value of donated parts and services was $4,086.19, for a total ROV value of $9,560.82.

14. PROJECT COSTING

Category	Amount Spent (USD)	Donated/Discounted	Fair Market Value
Frame/Flotation	**179.06**		**309.63**
Starboard plastic	116.59	Discounted	137.16
Laser cutting	0.00	Donated	60.00
Polyisocyanurate foam	0.00	Donated	50.00
Misc.	62.47	N/A	62.47
WEC	**222.10**		**2,269.87**
Tube	149.76	N/A	149.76
Acrylic rack	72.34	Discounted	85.11
Aluminum, machining	0.00	Donated	500.00
In-line connectors	0.00	Donated	1,500.00
Cable glands	0.00	Donated	35.00
Thrusters	**727.75**		**727.75**
Motors and ESCs	395.88	N/A	395.88
Spare motors/ESCs	224.32	N/A	224.32
Misc.	107.55	N/A	107.55
Electronics	**2,168.69**		**3,644.02**
Printed Circuit Boards	429.00	N/A	429.00
Electronic components	1,200.00	N/A	1,200.00
Topside control boxes	0.00	Donated	241.16

Front panels	0.00	Donated	100.00
Joysticks	46.50	Discounted, donated	504.71
Cable	232.77	N/A	232.77
Power converters	0.00	Donated	530.00
Depth sensor	0.00	Donated	100.00
Misc.	260.42	Some discounted	306.38
Cameras	**171.47**		**171.47**
Cameras and cables	156.37	N/A	156.37
Mini coaxial cable	84.63	N/A	84.63
Tether	**794.05**		**1,076.58**
Cables and sheathing	320.58	N/A	320.58
Silicone wire	473.47	Discounted	756.00
Tooling	**105.00**		**105.00**
Manipulator	85.00	N/A	85.00
Electromagnet tool	20.00	N/A	20.00
Miscellaneous	**1,106.51**		**1,256.50**
Cart	71.97	N/A	71.97
Fasteners, hardware	341.96	N/A	341.96
Power supply	300.00	Discounted	449.99
Registration fee	250.00	N/A	250.00
3D-printing materials	62.97	N/A	62.97
Misc.	79.61	N/A	79.61
Income	**-550.00**		**-550.00**
2015 Awards	-550.00	N/A	-550.00

Amount Spent - Income (USD)	**4,924.63**
Fair Market Value of Donated Parts (USD)	**4,086.19**
Total Value (USD)	**9,560.82**

Other costs include travel and ROV transportation to Houston, which currently have not been finalized. However, AMNO & CO estimates $4,000 will cover transportation for the team, shipping costs for the ROV, and hotel rooms for the duration of the competition.

15. REFERENCES

[1] *Astronauts Simulate a Spacewalk in NASA's NBL*. N.d. *NASA - Neutral Buoyancy Laboratory*. Web. 18 May 2016. <http://dx12.jsc.nasa.gov/site/index.shtml>.

[2] *A Newly Reinhabited Oil Rig*. N.d. *Rigs-to-Reefs*. Web. 18 May 2016. <http://www.rig2reefexploration.org/>.

[3] Jet Propulsion Laboratory. "Europa Mission." Web. 25 May 2016. <http://www.jpl.nasa.gov/missions/europa-mission/>.

[4] "NASA - Advanced Space Transportation Program Fact Sheet." NASA, 2004. Web. 25 May 2016. <http://www.nasa.gov/centers/marshall/news/background/facts/astp.html_prt.htm>.

[5] Rice, Jose Luis. Method of Making a Marine Speed Nozzle. Rice, Jose Luis, assignee. Patent US5799394 A. 5 Feb. 1996. Print.

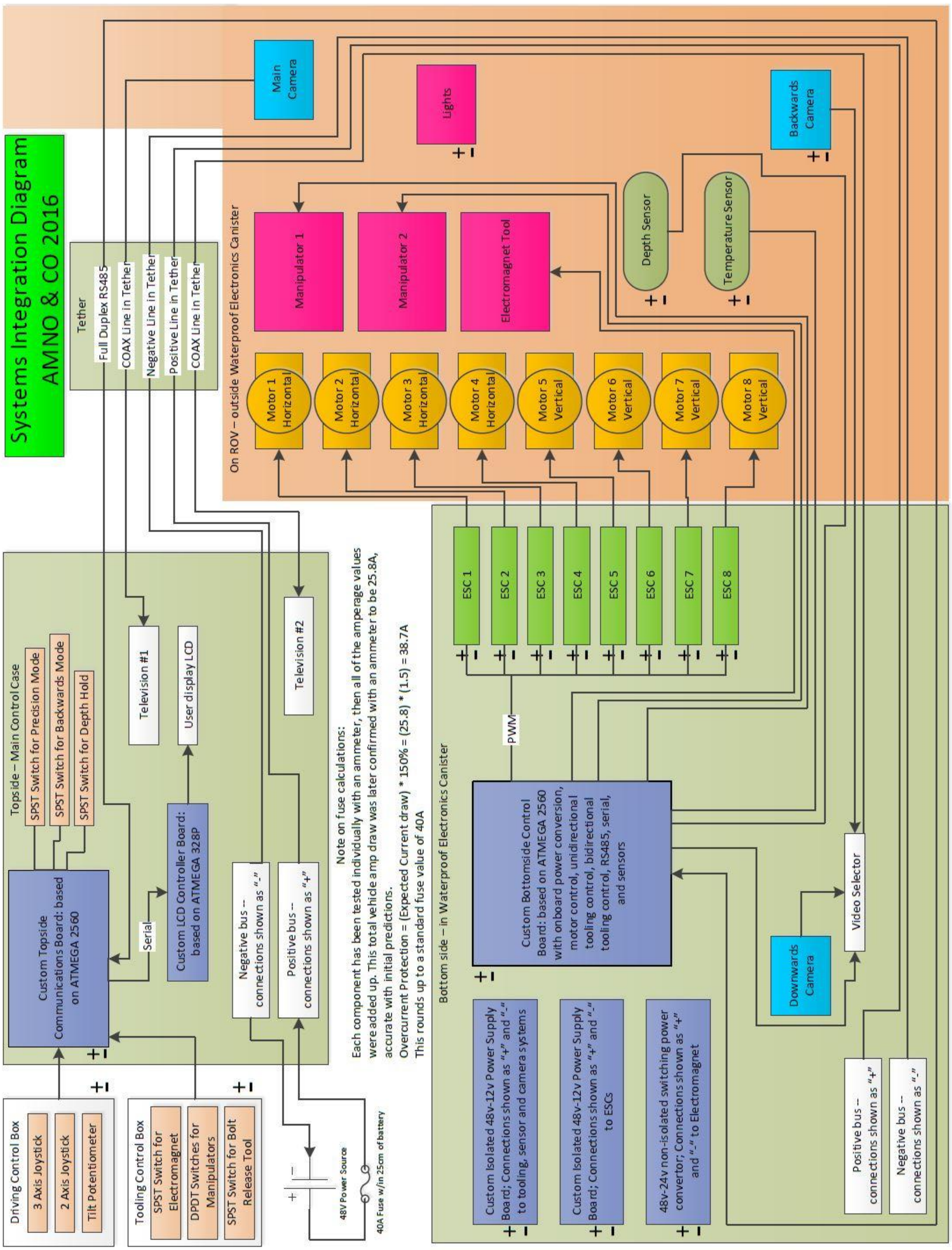
All other photographs and diagrams used in this document belong to AMNO & CO, and were taken by AMNO & CO or their families.

16. ACKNOWLEDGEMENTS

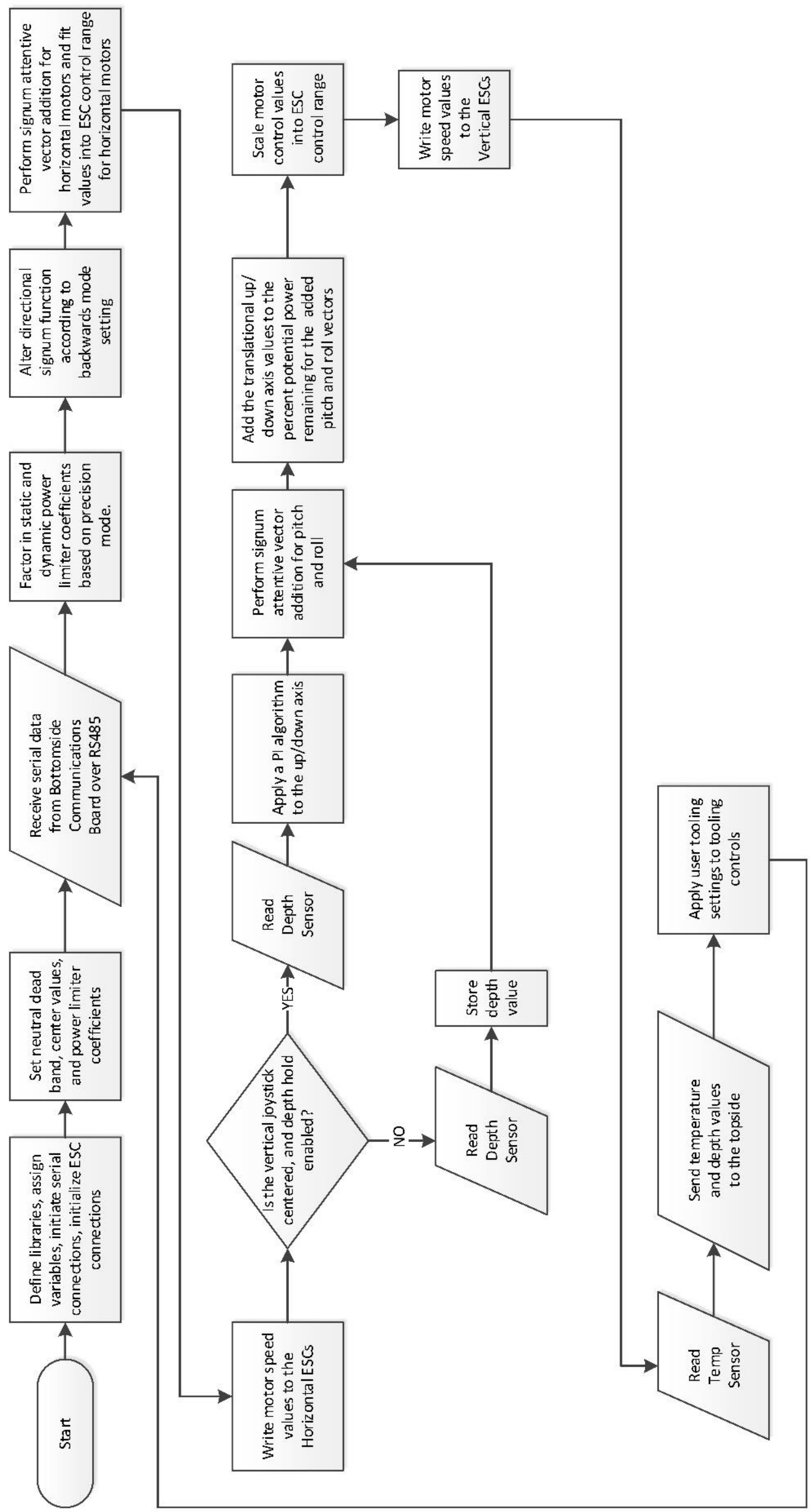
We would like to thank the following individuals and organizations for their support:

- Mary Chang, Robert Orndorff, Rachel and Steve Miller
- Rick Rupan, Fritz Stahr and Wes Thompson
- Martin Klein, Jill Zande, Timmie Sinclair, Ed Ronco, Brett Himeda, Ben McGeever, David Gray, Nick Gammon, Tully Gehan and Maximum Rosencrantz
- All the MATE Competition officials and volunteers

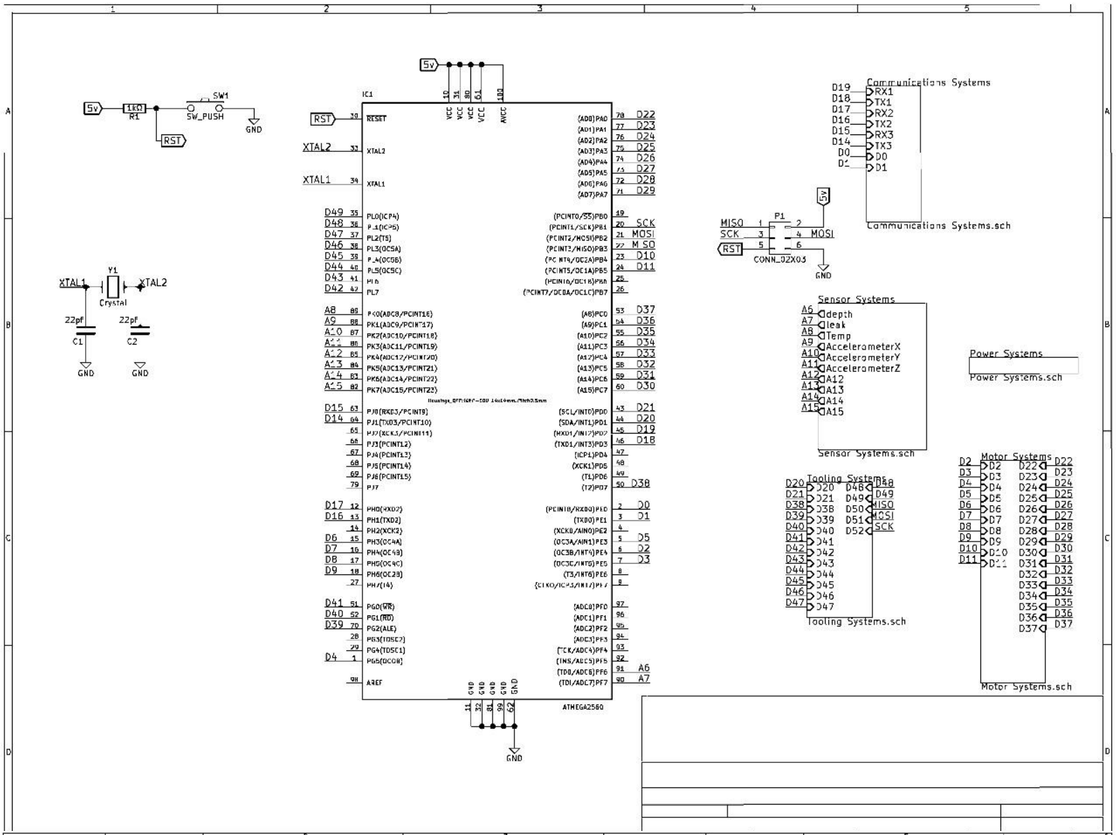
APPENDIX 1: SYSTEMS INTEGRATION DIAGRAM (SID)

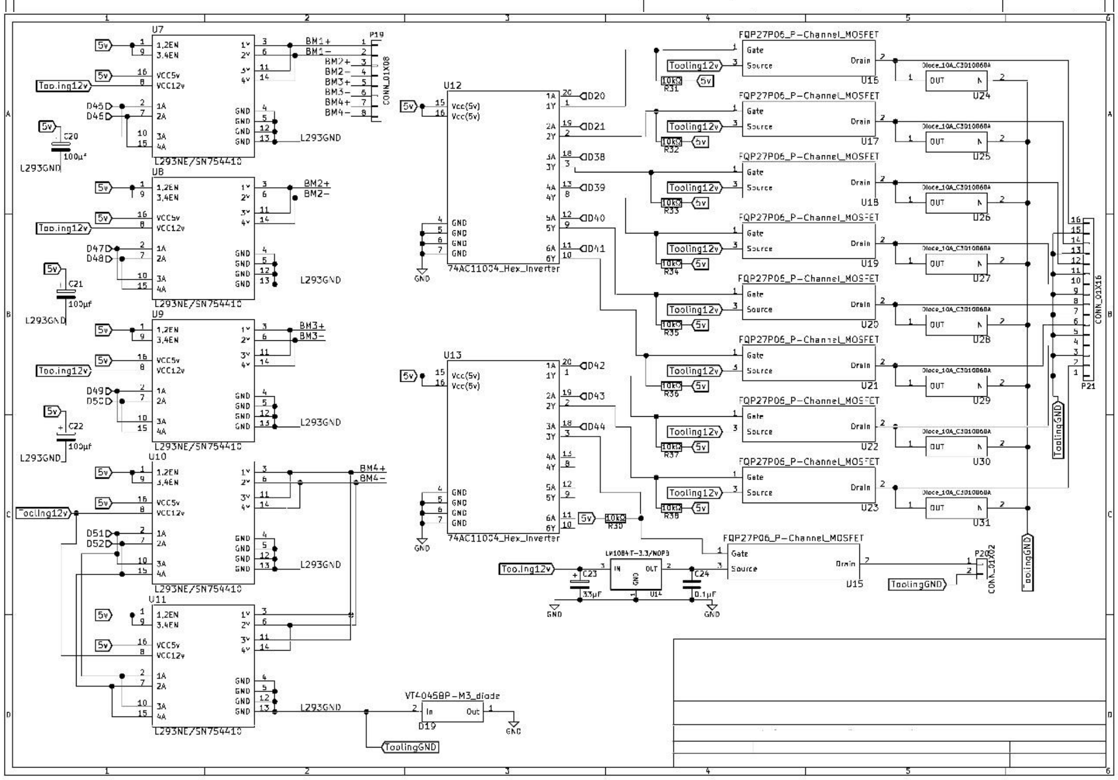


APPENDIX 2: SAMPLE SOFTWARE FLOWCHART, MAIN BOTTOMSIDE CONTROL BOARD



APPENDIX 3: SAMPLE ELECTRICAL SCHEMATIC, MAIN BOTTOMSIDE CONTROL BOARD





These schematics compries two of the six sheets in the main bottomside control board hierarchical schematic structure