SURO

Technical Documentation

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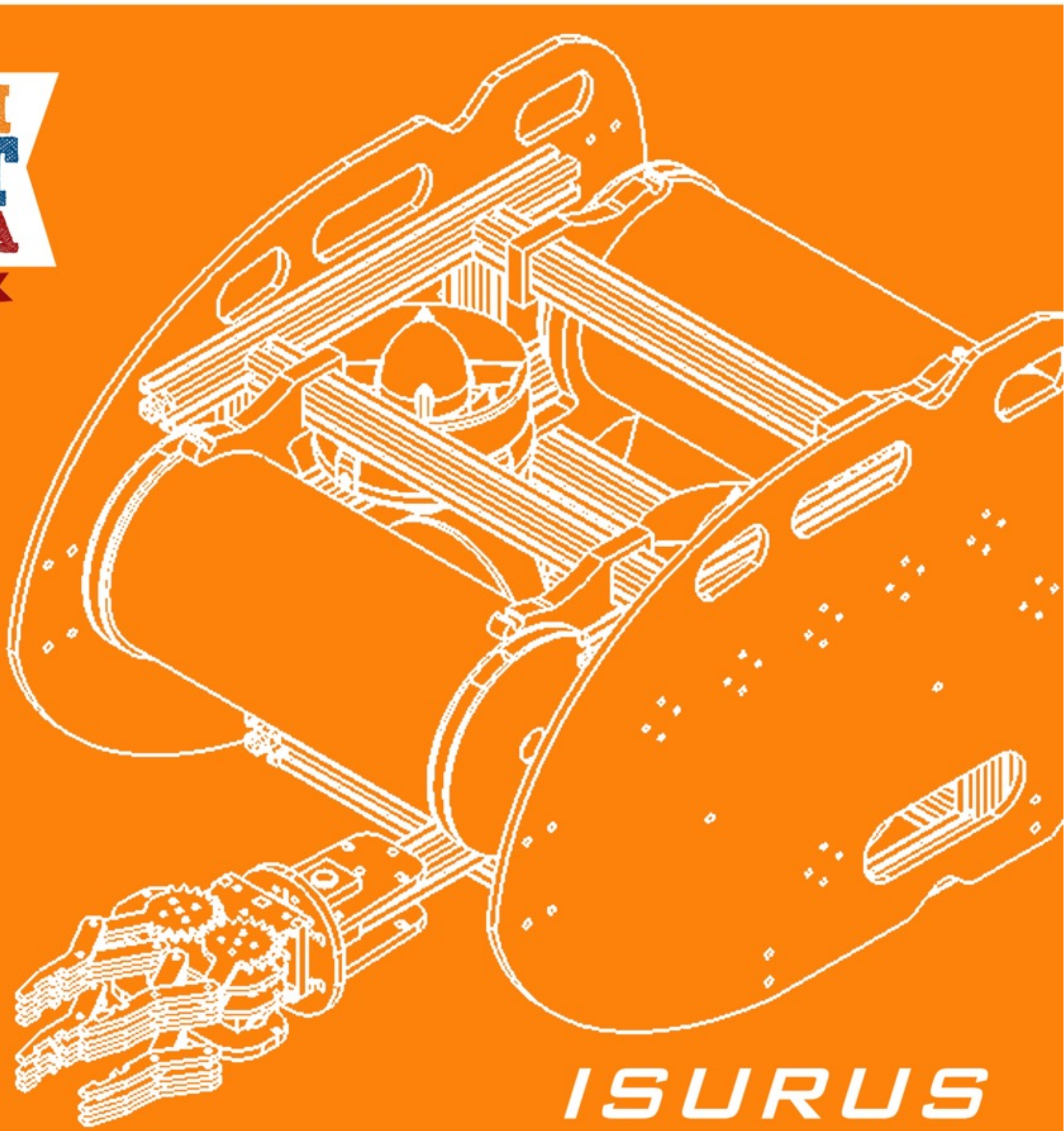
SEKOLAH ROBOT INDONESIA
SERUNYA BELAJAR MEMBUAT ROBOT

2016
MATE
ROV
International
Competition



Surabaya, Indonesia

Abstract

It is the second time for Sekolah Robot Indonesia to compete in MATE International Competition, however all of our members in SURO Robotics company are new to this competition. Nevertheless, our company has done countless research about ROV. The design of our ROV is influenced by the missions and tasks given. We believe that maneuver capability in a small design and stability is the key to success in the missions. We named our ROV Isurus, the genus of a shark that is small and quick, just like our ROV.

ISURUS is able to grab the ESP connector, open the door, connect to power and communications hub, and measure temperature accurately. With depth sensor and camera guidance, ISURUS can measure the thickness and depth of ice crust. Our 3 cameras can capture photos of corals. We design a custom built dual hook for ISURUS to easily take two samples of coral. ISURUS' main gripper is rotatable to 180°. This capability is used for installing bolts. ISURUS is equipped with a nozzle that can manipulate the water flow by 8° for better maneuverability. We use Proportional-Integral-Derivative Control (PID control) algorithm for ISURUS to be able to hold its depth position. We also designed a Graphical User Interface (GUI) to help visualization of Inertial Measurement Unit (IMU) sensor and also displaying other datas from the other sensors.

We are optimistic in the performance of our ROV, since SURO Robotics company is a new but devoted participant in marine exploration.

Figure 1: All team members and mentors with ISURUS
left to right: Dhadhang SBW, Daffa Hanif, David, Edward Pandji, Nicholas Patrick, Samuel Alexander, Ghevaldo Geraldio, Tri Susanto
(Credit: Jallson S.)

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Company Information

Figure 2: Indonesia's very vast water
(Credit: Wikipedia.org)

Organisation in our company is mainly based off the necessary sectors when one is trying to develop ROVs. We are divided into the software, hardware, general sciences and economics division, with intensive cooperation in between each section. The software section manages the programming of the ROVs, and also responsible for configuring the GUI for the control application which is displayed in a computer. The hardware section conducts a lot of research and work in the hardware of the ROV, obviously, and as such, responsible for the circuitry and type of material suitable for the ROV. Both of this are crucial to the ROV, to give it an interior body and an existing "nervous system."

On the other hand, the general sciences department manages the design of the ROV and measures the overall performance of the ROV. The difference between hardware, is that while the hardware pays attention at the circuity and PCB configuration of the ROV, the general sciences pays attention to the performance and exterior design that results from the hardware section's works. As stated before, our focus is manoeuvrability, portability and speed. Therefore, this section is very crucial.

Meanwhile, the economics section is unique. It is involved in not only promoting our company, but also providing general information to the public, especially Indonesian citizens, about ROVs. Indonesia is the base of our company, a maritime nation located in Southeast Asia. Many Indonesian oceans is yet to be explored thoroughly, especially by Indonesian people. We strive to benefit our nation, Indonesia.

Indonesia's waters covers more than 75% of Indonesia. ROVs would be very useful to more easily observe wildlife, including some dangerous ones such as poisonous stingrays and sharks. Moreover, ROVs assist in deeper dives to plant corals, which are currently dying in Indonesia. Not only that, ROVs help archaeologists to explore sunken ships. Currently, they would dive directly to retrieve sunken treasures. Besides all these uniqueness of the economic section, they would of course manage basic economic mechanism of the company such as budget, sponsoring, etc.

Finally, our purpose of this young company is to pioneer a new age of scientific researches in the maritime nation of Indonesia, from Indonesian water to Indonesian citizens, improve knowledge so that we can understand and respect nature more than before. Through cooperation, we will achieve this.

Mission Theme

As we all know, ROV are usually deployed for missions to places that are beyond human reach, too dangerous, or even to an unexplored territory. This time the mission will be held in outer space, which is in Europa; one of Jupiter's moons. NASA predicted that bellow Europa's ice crust there is almost twice as much water as on Earth. If the prediction is proven to be true, the ROV must collect data from its ocean. The ROV must be able to measure temperature, measure thickness of ice crust, and connect ESP to power and communications hub. Our ROV must have high maneuver capability, precision movements, and strong holding grip. The small size and lightweight body is the key factor to economically transport the ROV to Europa.

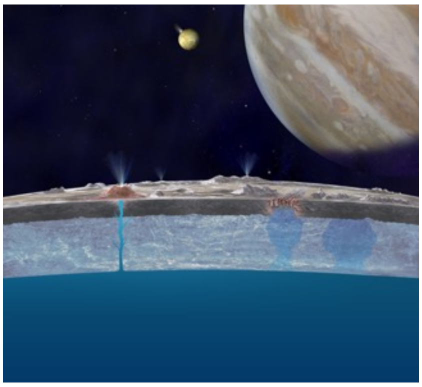


Figure 3: Europa's ocean
(Credit: nasa.gov)

Besides outer space missions, the other missions are located inner space in The Gulf of Mexico. ROV is used to retrieve and identify sunken CubeSats; a miniaturized satellites that were put into orbit. After the 2010 oil spill tragedy, the ROV must collect data of oil samples, so researchers can analyse and fingerprint the oil samples. The ROV also must be able to capture images of corals to study and compare its condition from the previous year. The last mission is to install a flange on top of a wellhead to convert decommissioned offshore oil and gas platforms into artificial reefs to conserve underwater life. So the specific tooling such as the double hook, 2 Degree of Freedom (DOF) gripper and hi-res cameras hold and important role for the missions.

Figure 4: Macondo corals in the Gulf of Mexico
(Credit: livescience.com)

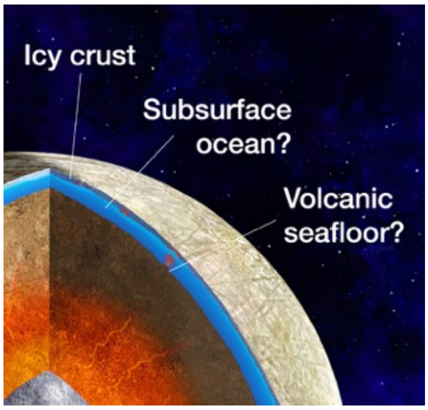


Figure 5: Europa cutaway
(Credit: solarsystem.nasa.gov)

Safety

Philosophy

Safety is our company's highest priority. All of our members build the ROV in our workshop which is fully equipped with safety equipments and provides a safe environment for working. Our company also provide an ROV with complete safety features to prevent users from unwanted accidents. Our training, safety procedures, and Personal Protective Equipment (PPE) allow us to prevent unwanted accidents.

Required Personal Protective Equipment (PPE)

- Safety glasses, masks, an hearing protection when using power tools
- Masks when soldering PCB parts and other electronic components
- Working gloves when doing mechanical work
- Silicone gloves and masks when applying Epoxy glue

Working Environment Safety

- Solder fume extractor when soldering cables and electronic components
- Open space/outdoor when applying and drying epoxy glue or casting resin

ROV Mechanical

- No sharp edges
- Strain relief for tether
- Double O-ring for waterproof electronics tube lid (tested in 20 meters depth)
- Implement danger labels for moving parts

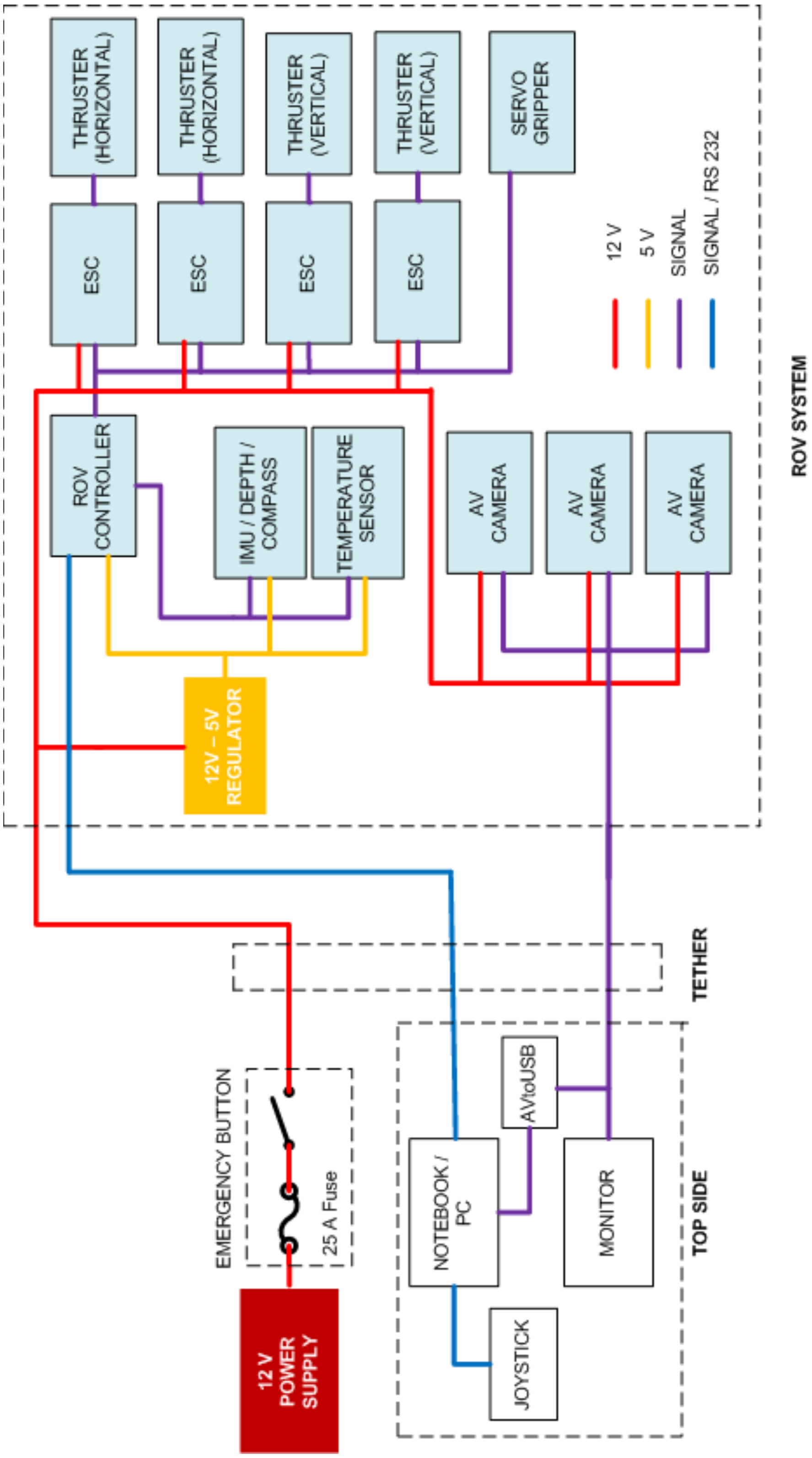
ROV Electronics

- 25 Amp fuse on the positive side of the main power source
- All electronics parts are placed inside the electronics tube
- All wiring and electrical parts are properly waterproofed
- Emergency Cut Off Switch (panic button)
- Ampere and volt meter display

Safety Checklist

Pre-mission Safety Checklist	
	All items attached to ROV are secure
	All cables are securely fastened
	Single inline 25 Amp fuse is in place
	Sharp edges have been smoothed
	No exposed propellers
	Tether is not tangled and fully secured
	All wiring and components for ground control is properly connected
	All ground control elements are secured inside an enclosure
	Check electrical power connections
	Make sure waterproof electronics tubes (WET) are tightly sealed
	Dry test to check manipulators, thrusters, cameras, and sensors are functioning properly
	On-deck team is wearing safety glasses and closed toed shoes

System Integration Diagram (SID)



Design Rationale

Frame and Structure

ISURUS' frame is mainly built using aluminium extrusion 20x20 for the purpose of compact design, lightweight, and high durability. The use of aluminium extrusion also enables us to easily attach, detach, and adjust the position of manipulators, cameras, thrusters, and lights.

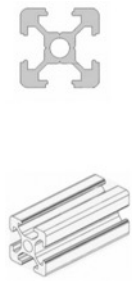


Figure 6: 2020 aluminium extrusion
(Credit: Daffa H.)

We do notice that unlike HDPE, aluminium sinks in the water, but with the placement of two acrylic tubes as bouyancy (also use for the waterproof electronics container) it increases ISURUS' stability.

In designing ISURUS we also use SolidWorks, so that we can configure the Center Of Gravity (COG), Center Of Balance (COB), and hydrodynamics using software simulations. For the left and right sides of ISURUS we use 5mm thick acrylic sheet that functions to protect the weak spots of ISURUS. The acrylic sheets also effectively works as fins to increase ISURUS' stability and also makes ISURUS looks aesthetically pleasing.

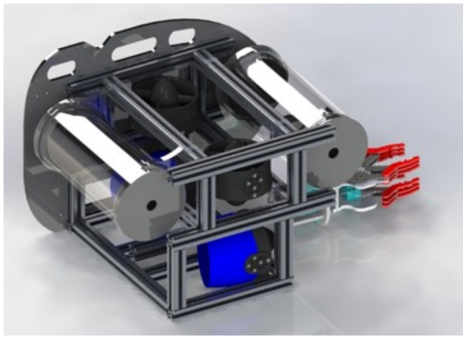


Figure 7: Isometric view of frame, WET, and thrusters configuration
(Credit: Daffa H.)

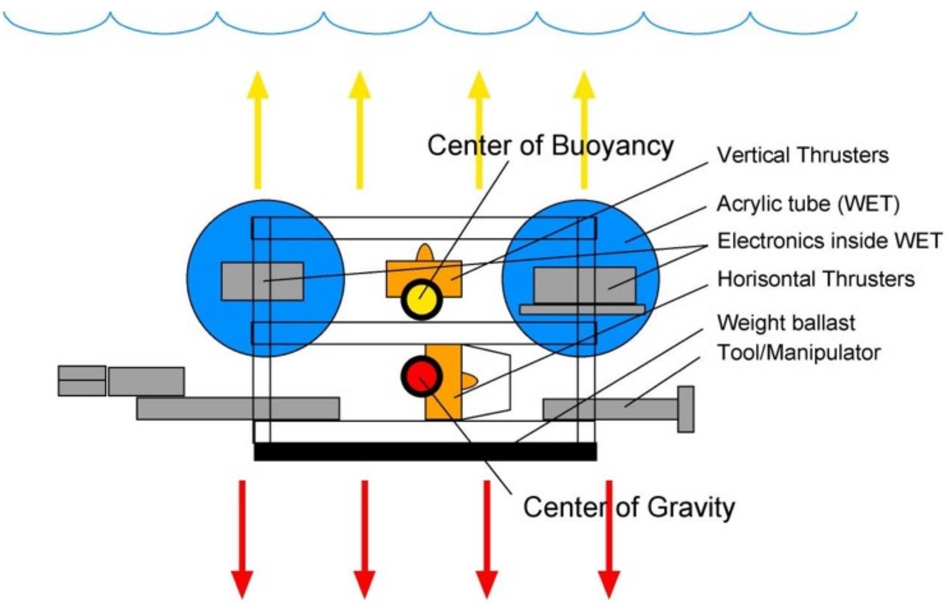


Figure 8: ISURUS' COG and COB
(Credit: Samuel A.)

Floatation

Figure 9: Acrylic tube
(Credit: Edward P.)

In order to conquer all the missions, ISURUS' needs extreme precision and stability. High precision and stability can be achieved by having a good floatation, this is why we really pay attention to ISURUS' floatation. Configuring the COG and also COB is our first step of designing ISURUS. The use of two waterproof acrylics tube are also for buoyancy, which we put on top of the ROV as the floatation element. While for the manipulators, frame, and thrusters are located below to provide the best buoyancy and gravity distribution. The position of manipulators, thrusters, waterproof electronics tube, and frame design follows the COG and COB principle, any objects with the tendency to float should be put on the upper-side while objects that have the tendency to sink should be located on the bottom side. We also put buoyancy foams on top of ISURUS to provide small trims and stability.

Waterproof Electronics Tube (WET)

Figure 10: WET water-tight lid
(Credit: David)

All the electronic components of ISURUS is located inside our custom built Waterproof Electronics Tube (WET) to prevent it from water and also protection against impact. The other main function ISURUS' 2 WETs has been explained previously which is as the floatation (because of air spaces inside it). Acrylic tube of 10cm ø with 5mm thickness because it is resistant to high water pressure. We placed our custom built acrylic lids on both side of the acrylic tube. On each lid we use double O-rings so that water is less likely to enter the WET even in higher pressure. (We have tested it in 20 meters water depth). We learn this waterproofing technique from OpenROV and also from other MATE ROV contestants from the previous years. During our mission testing and practice there has never been water leakage and this technique has been proven to work effectively and is reliable for the missions to be faced by ISURUS. For the cable penetrators we insert our cables to a 3cm long 1/2 inch PVC pipe that is attached on the lid, then we use 5 minutes epoxy glue to secure the cables and seal it to the lid preventing water leak.

Figure 11: Electronics inside WET
(Credit: Samuel A.)

Propulsion and Custom Nozzle Design

For ISURUS' propulsion system we utilize 4 underwater brushless thrusters, consists of 2 units for vertical movements and 2 other units for horizontal movements. We put the 2 vertical thrusters between the two Waterproof Electronics Tube (WET) for stability when going up and down.

Figure 12: T100 thruster with Jet-drive nozzle
(Credit: Samuel A.)

We chose T100 thrusters from BlueRobotics after we have evaluated for the best power efficiency, torque, thrusting force, and of course at an affordable price. Before we use BlueRobotics T100 thrusters, we used Johnson Bilge Pump cartridges but we feel that this motor is still under powered. We found that T100 thrusters can perform with maximum forward thrust of 2.36 kgf and maximum reverse thrust of 1.85 kgf. After some trials we feel satisfied with the power characteristic for ISURUS. This T100 thruster comes with built in propeller, so we put clockwise (CW) and counter-clockwise (CCW) propeller in pairs to counter torque and stabilize ISURUS' movements. With only 4 thrusters, we need put it in the most optimum position to maximize the function. The other consideration is efficiency of electric energy and of course cost efficient.

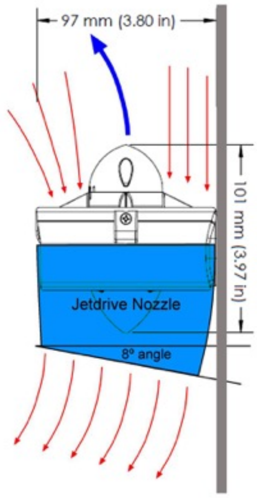


Figure 13: Jet-drive nozzle effect on right horizontal thruster
(Credit: Samuel A.)

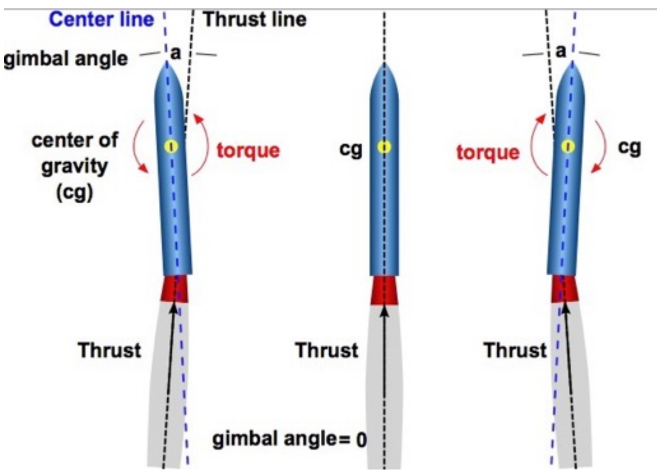


Figure 14: Thrust vectoring nozzle
(Credit: Wikipedia.org)

After a couple of tests in the pool, we found that maneuverability of ISURUS is limited, because the distance between the horizontal thrusters are to tight. This problem leads to our idea of designing a nozzle that can manipulate the water flow from the propeller by 8°. The diameter at the end of the nozzle is also made smaller to increase the thrust energy from the water flow, we call this jet-drive nozzle. Our 3D printed nozzle performed effectively as we expected. The idea of using a nozzle that can manipulate the direction of thrust is inspired from a fighter jet-plane nozzle that can adjust the direction of thrust to help take off in a short runway and also help for maneuver.

Tether

In the world of ROV, the role of tether is essential. The tether is what connects power, data signals, and video signals from the ground control to the ROV and vice versa. The length of our tether is 20 meters and consists of 3 main cables. We use multi-conductor AWM 2464 with with 9 conductors 24 AWG to send video signals and serial data communications. For the main power of ISURUS we use $4mm^2$ (11 AWG) red and black stranded cables with PVC coating. For the power cables we need to do a couple of research for choosing the suitable cable thickness. When the cable is too thick, it will be heavy and stiff, on the other hand if the cable is too thin there will be a drop in voltage because the current reaches 22 Amperes and the resistance is too high because we use 20 meters cable length. According to the maximum standard of 25 Amps we use $4mm^2$ and after we tested there is no drop voltage problem and the cable is also not too stiff, so we decided to use this cable.

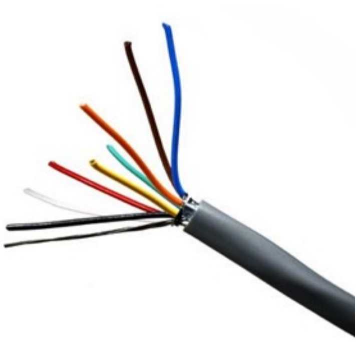


Figure 15: Video and data signal cable
(Credit: Showmecables.com)

To merge all these 3 cables we use braided sleeving net because it is flexible and very light. Also we add some buoyancy foam in every meter of our tether for buoyancy. This tether is almost neutral in buoyancy (sinks a little bit) so this does not interfere with ISURUS' movements. At the end of the tether we use S-video 9 pin port to easily attach and detach to ground control.

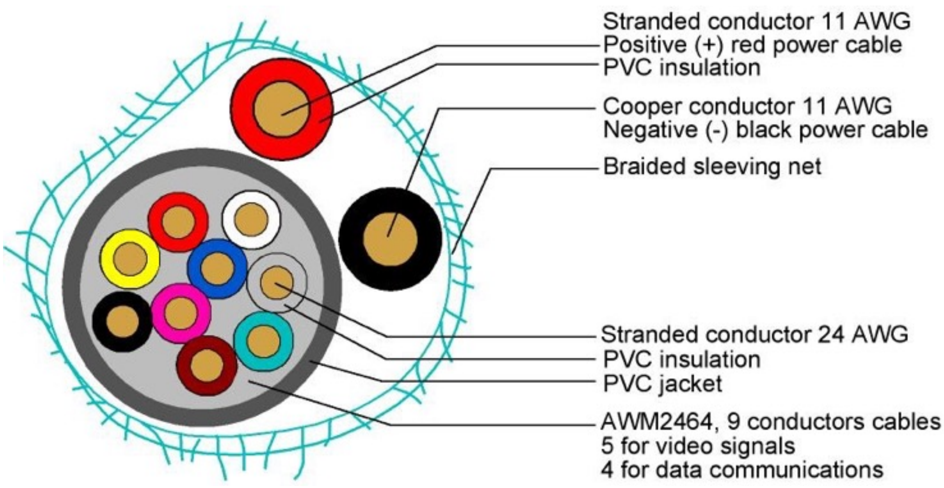


Figure 16: Tether cross section diagram
(Credit: Samuel A.)

Figure 17: S-video 9 pin port
(Credit: David)

Control System

ISURUS is controlled from the ground control using a joystick game controller. This remote control communicates via USB to laptop/PC in the ground control box as input variables in our Graphical User Interface (GUI) using Visual Basic software then relays the controller information through RS232 serial communication to our Arduino Nano micro-controller on ISURUS. The micro-controller is programmed using C++ language with various Arduino libraries. The on board Arduino Nano then uses 4 Electronic Speed Controllers (ESC), which drives our 4 brushless motor thrusters. Other input and output on board are 2 servo motors for gripper, 3 cameras, Inertial Measurement Unit (IMU) sensor, temperature sensor, and depth sensor. For the IMU and depth sensor we utilize I2C communication, and for the temperature sensor we use Analog-to-Digital Converter (ADC). All these inputs and outputs are mounted to our custom made Printed Circuit Board (PCB) to connect it to our micro-controller.

Figure 18: Ground control station
(Credit: Samuel A.)

On deck ground control includes Ammeter and Volt meter to easily check power load and voltage input that is supplied to ISURUS. GUI will display the datas from the sensors on ISURUS and help the pilot to control ISURUS' movements and its manipulators. By pressing triangle button on the joystick, the PID control algorithm will be execute so ISURUS can hold its depth position based on the data reading from the depth sensor. This holding position control helps pilot to tackle the missions that require precision movements.

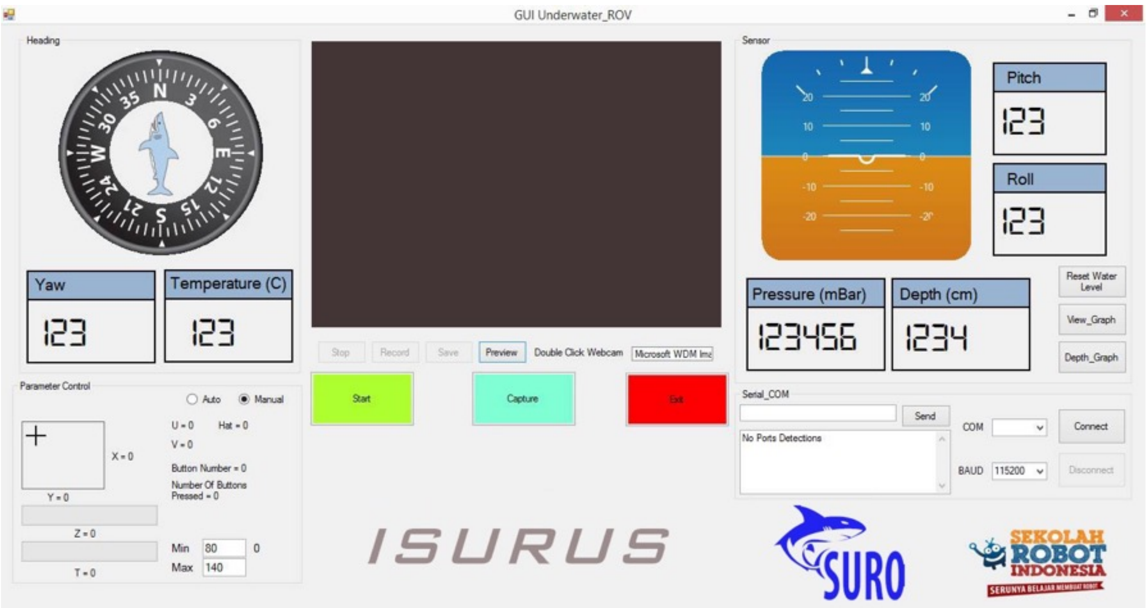
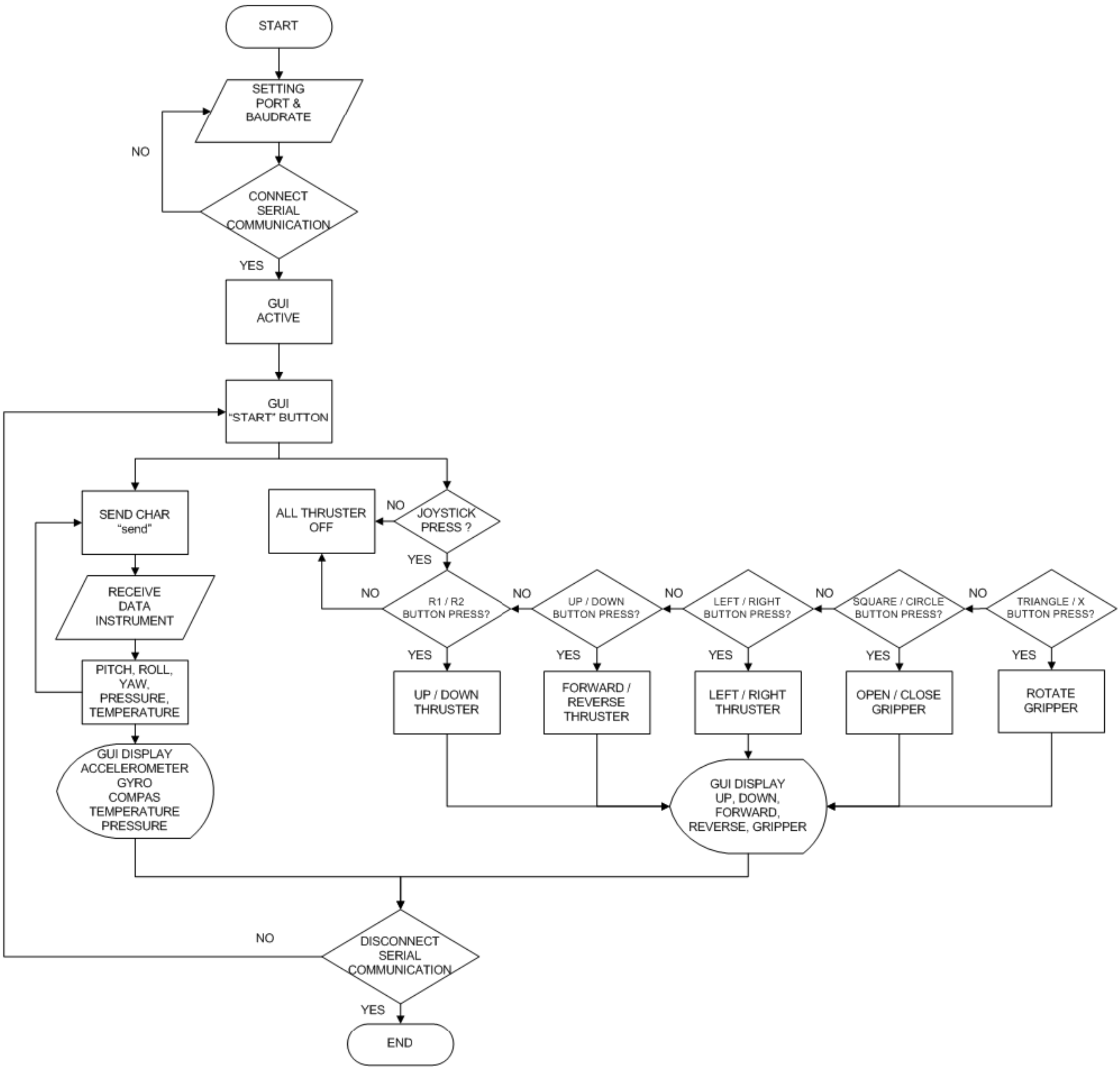
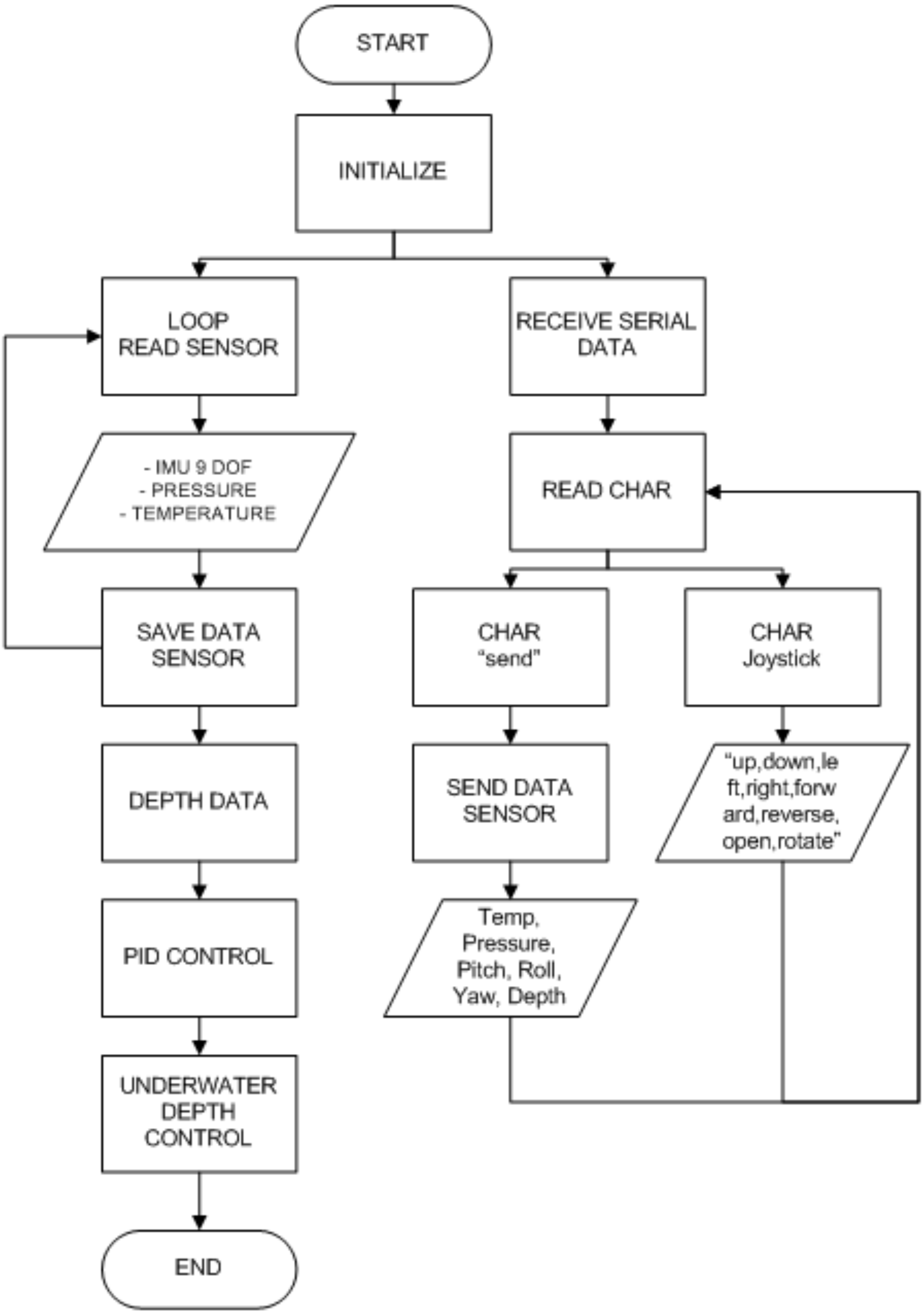


Figure 19: GUI made using Visual Basic
(Credit: N. Patrick)

Graphical User Interface (GUI) Flowchart



Arduino Microcontroller Flowchart



Mission Specific Tooling

Main Gripper

Our company decided to design and make a gripper with 2 Degrees of Freedom (DOF) with 2 high voltage and high torque analog waterproof servos that can rotate up to 180º. Using collinear gripper grabbing objects with various sizes are much easier especially in mission #1 for grabbing ESP and connecting it to the hub, mission #3 for grabbing forensic fingerprinting oil samples, while the rotating capability is for mission #5 to grab the bolt and secure the flange. The gripper is made using laser cut 3mm and 5mm acrylic sheets for precision.

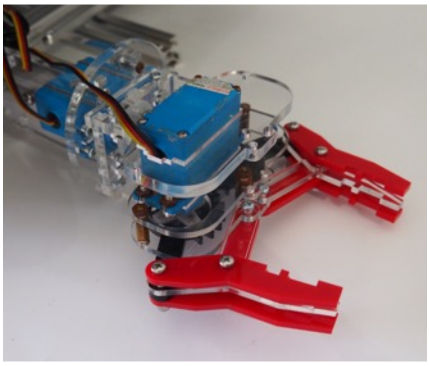


Figure 20: 2 DOF main gripper
(Credit: Ghevaldo G.)

Inertial Measurement Unit (IMU) Sensor

To help visualization of position and direction of ISURUS we added GY85 IMU sensor. Gyro, acceleration, and compass data is translated into our GUI software in the laptop display. This helps pilot to control ISURUS precisely and feel confident to tackle all of the missions.

Depth Sensor

To measure the thickness and depth of ice crust in mission #1, a MS5803 14BA pressure sensor is used. The thickness of ice crust can be measured by measuring the depth difference between the top of the ice and the bottom of the ice. To maintain depth stability automatically, we also use the data from the depth sensor and apply it to our depth holding algorithm.

Dual hook

Our company made this simple non-electronic manipulator to tackle many tasks in the missions. This aluminium clothes hanger hook is capable to open the door in mission #1, flip over CubeSats in mission #2, and also taking coral samples in mission #4.

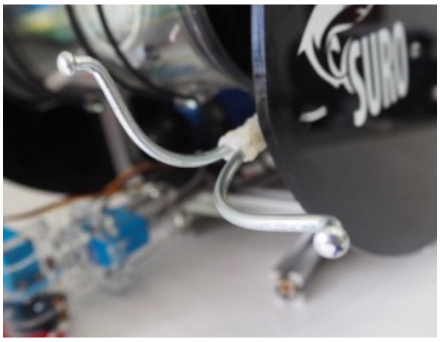


Figure 21: Dual hook
(Credit: Ghevaldo G.)

Temperature Sensor with Rubber Guide

In order to measure temperature accurately in mission #1 we need to add rubber guide on ISURUS to help measure temperature at the right position and maintaining the position. The temperature sensor we made is using two LM35 temperature sensor that we insert in a 3cm length ø6mm aluminium tube. The use of two sensors is to prevent failure of temperature reading, just like what we experienced during our regional competition

Figure 22: Temperature sensor with rubber guide
(Credit: Samuel A.)

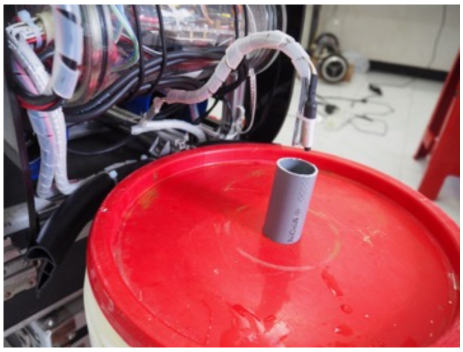


Figure 23: Size measuring using props
(Credit: Samuel A.)

Troubleshooting

When ISURUS failed to work properly, we need to identify and analyze the problem causing the failure and also how to isolate it to solve the problem. We initially dry test our ROV, if there is no problem we move to the bathtub and if everything works fine then we test it in a pool for real test. During this procedure we have tested using 1 Waterproof Electronics Tube (WET) and there is stability issues, so we made another design using 2 WETs. Another troubleshoot that we face is because the use of 2.5 mm^2 (14 AWG) for powerline causes voltage drop and unable to turn on our ESCs. We tried cutting the wire to reduce cable resistance, it works. So we changed our thin cable into a thicker 4 mm^2 (11 AWG) and the voltage drop problem is no longer an issue. Those are some examples of specific problems that we can troubleshoot. All of our members are required to get involved when troubleshooting, so that every member have the troubleshooting experience.

Challenges

Technical Challenge

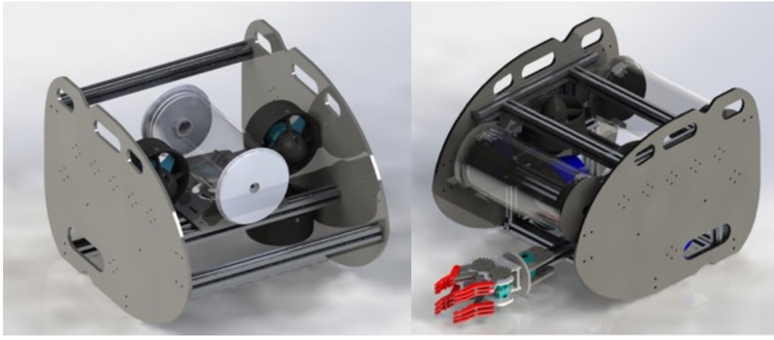


Figure 24: Previous design with 1 WET (left) and current design with 2 WETs
(Credit: Daffa H.)

One challenge we faced was configuring the position of thrusters and Waterproof Electronics Tubes (WET). Before we use ISURUS' current design, we have done a couple of trials and errors. Before we use 2 WETs, we only use 1 WET for our ROV design, but this design is very unstable and it even flips upside down when we use our thrusters at full speed. After doing some research and calculations, we know where to position our thrusters, WETs, additional weight, and buoyancy to achieve the best fit COG and COB. After using our new design, ISURUS never flip over again and it became so stable even at maximum thrust.

Non-technical Challenge

Occasionally, some of our team members cannot attend our team meeting to work on our ROV due to school work, school activities, exams, or other events. However, this problem can be solved with a solid team. Every time there is a team member that is absent, the other team members must be able to communicate and explain about what the other members were doing during the team meeting. All team members also need to make sure that the team member that was absent fully understand and is not left behind. Communications and team discussions are also sometimes done virtually with conference calls so it can be done anywhere and anytime.

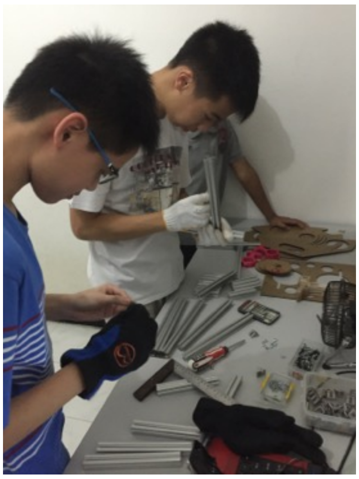


Figure 25: Assembling ISURUS' aluminium frame
(Credit: Ghevaldo G.)

Lesson Learned

Technical

We learn how to apply basic science principles that we have learn at school into real world problems. We learn how the Center of Balance (COB) and Center of Gravity (COG) really affect the ROV precision and stability. We learn how to configure the right position of thrusters, weight, and buoyancy for optimum performance. Our company also learn about waterproofing techniques such as using waterproof electronics tube (WET), casting resin, and also applying epoxy glue.

Interpersonal

Our team members come from different disciplines and backgrounds. Some members are really good in Mathematics, some are good in Chemistry, some are also good in electrical and computer science. This forces us to exchange thoughts and and learn from one another. To ensure we have a solid team, all members must be able to communicate and make contribution based on what they are good at. By having good bonding and collaborations we learn how to work as a company.

Future Improvements

We feel that our 3 cameras still cannot provide sufficient viewing angle for pilot when operating our ROV. With the help of rotating cameras and First Person View (FPV) headset there will be wider range of viewing angle. This technology provides telepresence so that the pilot can really understand the environment situation of the ROV. In the future we would also like to use rotatable thrusters, so that the thrusters can function for movements vertical and horizontal movements. Rotatable thrusters can also be configured to provide maximum maneuver capability.

Figure 26: FPV headset
(Credit: modellhobby.de)

Reflections

SURO Robotics has learned more than merely building the ideal ROV. We learned to work together as a team. Communication, understanding, and commitment are the core values of our teamwork. We have to remind ourselves that we have one common goal, to built the efficient ROV.

Challenges we faced, have motivated us to find the most creative solution to successfully complete the mission of the ROV. Finding creative solutions to enhance our ROV is our approach in designing. Custom designing a nozzle that can manipulate the water flow from the propeller is one of them. Countless trials and error have made us relentless and determined to give our ultimate efforts in reaching our goal.

Figure 27: Regional competition safety check
(Credit: Nicholas P.)

At the end of the day, our experience in designing and building the ROV went beyond what we expected. Life lessons we have learned in the process of building our ROV, turned out to be most valuable to us.

Budget

All members of SURO Robotics company are students of a robotics club named Sekolah Robot Indonesia. All of our members come from different schools, so we cannot raise fund from our school. Therefore, we need to be careful and thoughtful in controlling our budget for making ISURUS. Our strategy is to set a maximum reasonable budget which is USD 2,000. Once we know there is a promo ticket for airfare we directly book, because the flight from Surabaya, Indonesia to Houston is costs around USD 1,600 — 4,000. The airfare ticket is our biggest expense. We managed to set our expenses to approximately USD 19,000 and sponsorship funding for USD 8,800. The rest of the expenses is covered by SURO Robotics members and Sekolah Robot Indonesia.

Project Costing

ISURUS ELECTRICAL AND MECHANICAL EXPENSES	TYPE	QTY	UNIT COST	TOTAL
Brushless Motor Thruster T100 w/ shipping & tax	purchased	6	$165	$990
Basic ESC for brushless motor w/ shipping & tax	purchased	6	$35	$210
Cable penetrator bolt	purchased	6	$5.4	$32.4
Arduino Nano	purchased	2	$15	$30
Aluminium extrusion 2020	purchased	1	$50	$50
Angle bracket die cast	purchased	50	$1	$50
T-nut	purchased	100	$0.5	$50
acrylic tube ø10 3mtrs	purchased	1	$100	$100
acrylic sheet 3mm A3 clear and red	purchased	2	$15	$30
acrylic sheet 5mm A2 black	purchased	1	$50	$50
acrylic sheet 5mm 60x90cm ex Poster frame - clear	donated	2	$30	$60
acrylic laser cutting for WET tube and lid	purchased	1	$11	$11
acrylic laser cutting for gripper and holder	purchased	1	$22	$22
acrylic laser cutting for side body	purchased	1	$8	$8
3D printing for Custom design nozzle	purchased	2	$10	$20
Pool noodle PE Foam	purchased	1	$5	$5
Waterproof Servo	purchased	2	$55	$110
Camera (from camera surveillance)	donated	4	$25	$100
cable 11AWG/4mm black/red for power line 30mtr	donated	2	$10	$20
cable AWM2464 24AWG 9 conductors for tether 30mtr	purchased	1	$50	$50
7inch monitor	re-used	2	$50	$100
Depth sensor	purchased	1	$55	$55
IMU sensor	purchased	1	$20	$20
Temp sensor component	purchased	2	$5	$10
Case for Ground control	re-used	1	$20	$20
Joystick	re-used	2	$32	$64
Amp and Volt meter	purchased	2	$22	$44
Rubber protective line	purchased	1	$4	$4
Switch, Circuit breaker, button, cable ties, etc	purchased	1	$30	$30
Poster print, cutting sticker	purchased	1	$12	$12
TOTAL INVESTED (PURCHASED+RE-USED+DONATED)			$913	$2,357
TOTAL ROV PURCHASED				$1,993

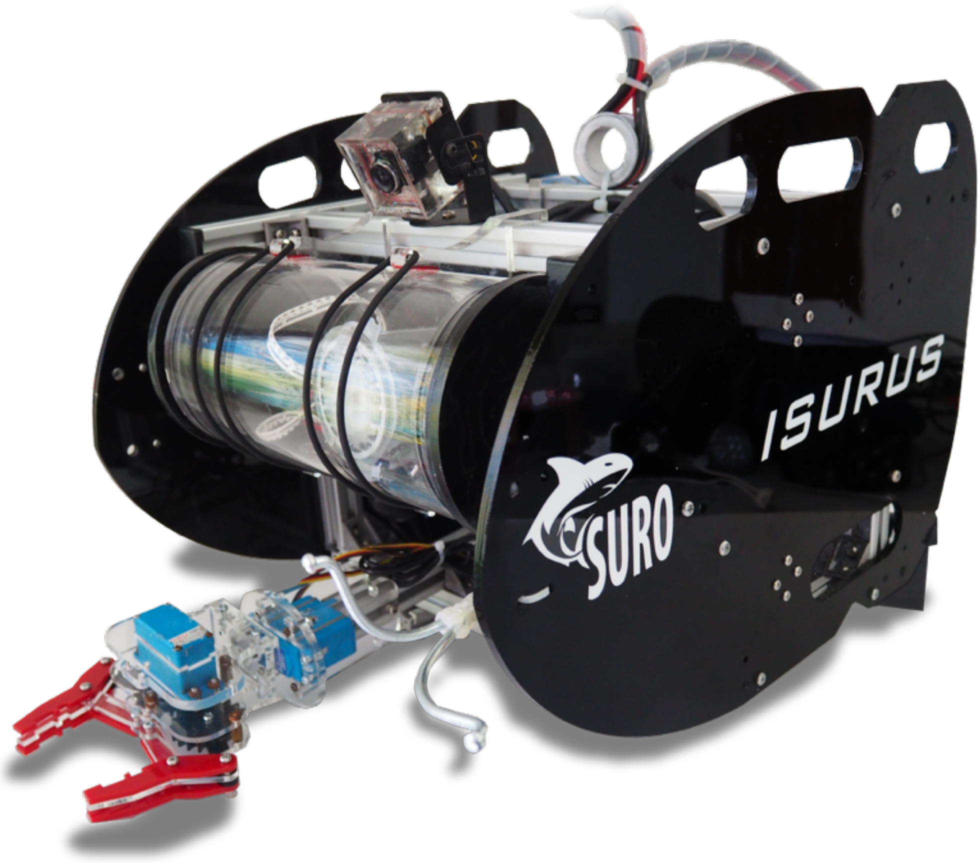
TRAVEL / ACCOMMODATION PURCHASED		QTY	UNIT COST	TOTAL
Air Fare Surabaya - Houston - Surabaya by Cathay	purchased	9	$1,750	$15,750
Accommodation / Hotel for 6 days @Best Western	purchased	3	$480	$1,440
TOTAL TRAVEL PURCHASED				$17,190

INCOME / MONEY IN	QTY		
SURO members	6	$2,000	$12,000
Sekolah Robot Indonesia	1	$650	$650
Kibar	1	$2,200	$2,200
Wismilak	1	$4,400	$4,400
Focus Electric	1	$2,200	$2,200
TOTAL INCOME			$21,450

BALANCE	Total INCOME	TOTAL PURCHASED	BALANCE
Total Income - Total Purchased	$21,450	$19,183	$2,267

ESTIMATED TRAVEL EXPENSES	QTY	UNIT COST	TOTAL
Transportation estimation (taxi, bus, etc) f/ 6 days	9	$50	$450
Meals estimation f/ 6 days	9	$200	$1,800
ESTIMATES FUTURE EXPENSES			$2,250

Summary Sheet



Dimensions: 53 cm x 30 cm x 29 cm

Dry Weight: 6.8 kg

Approximate Total Cost: $2357

References

1. "Underwater Robotics for High School Students". Easter Edge Robotics, December 2010
2. "To Europa! Mission to Jupiter's Moon Gains Support in Congress", Nola Taylor Redd, space.com, November 5, 2014
3. "Thrust vectoring". Wikipedia, April 13, 2016, https://en.wikipedia.org/wiki/Thrust_vectoring

Acknowledgements

We would like to thank the following individuals and organizations for their support:
- Dhadhang SBW, Tri Susanto, Jallson Suryo as mentor/instructor
- Ali, Sobrun, Mamat, and Erik for their technical expertise and supporting communities
- Team personnel's parents to support
- All the MATE Competition officials and volunteers