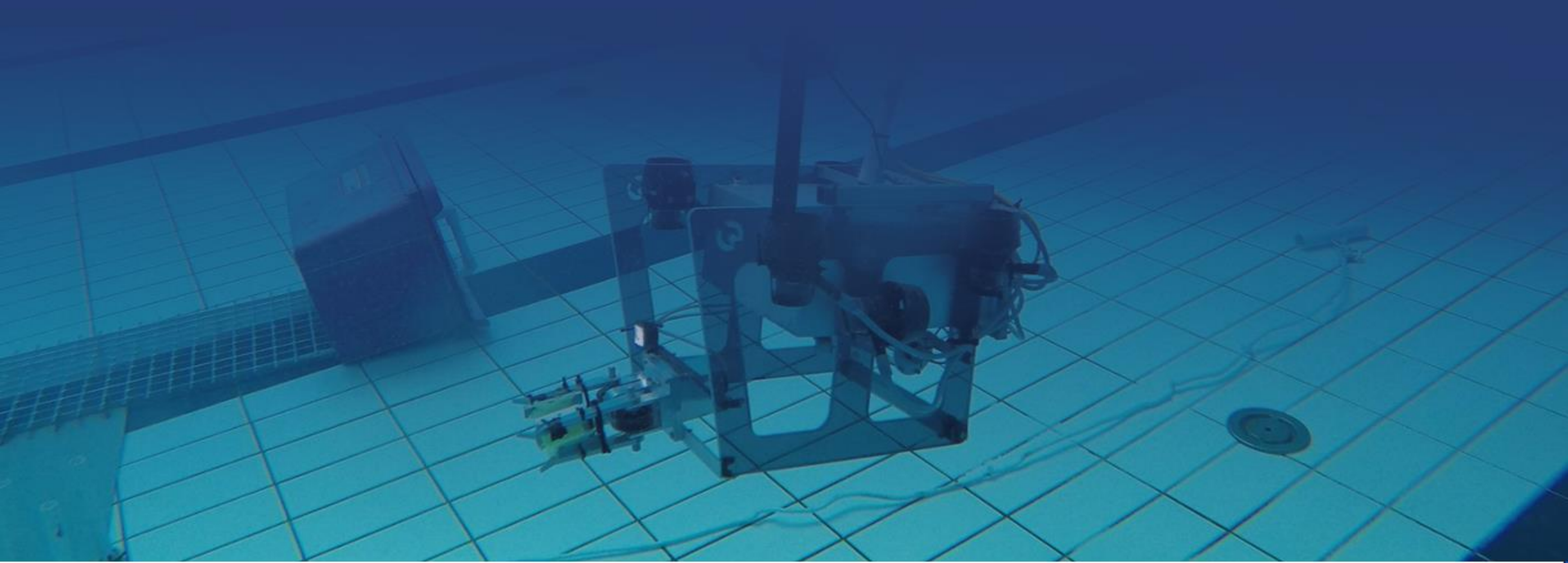
SURA

Students Underwater Robotics Association

Team for MATE 2016 Competition



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ABSTRACT

AHTI is the first Polish Remotely Operated Underwater Vehicle taking part in the MATE competition. Designed from scratch, without previous experience in underwater robotics by the new, established in December 2015, Students Underwater Robotics Association is a perfect example of passion and commitment of young people from the Warsaw University of Technology. With an essential help from our mentor, Paweł Malczyk, Assistant Professor at the Faculty of Power and Aeronautical Engineering we have created an underwater robot able to work in the harshest environments with the potential to be used by the oil and gas or to explore the rich bottom of the Baltic See. This is accomplished thanks to the ROV's great maneuverability, "mechanical hand" (gripper), and on-board cameras supported by strong LED lighting. Its features gave us the opportunity to present the vehicle on the XXIII International Fair Petrol Station 2016 Expo in Warsaw, where it has drawn a great attention from the various Polish and foreign investors.

Figure 1 Students Underwater Robotics Association presents AHTI on the students' constructions exhibition

The team consisting of three mechanical engineers, one electrical engineer, two software engineers, and the person responsible for finance and marketing has been, working on the design and development of the vehicle ince December 2015. We were able to cope with all the tasks proposed by the most recognizable underwater robotics competition – Marine Advanced Technology Education.

The entire technical documentation does touch upon the point of project design, organization and logistics, construction and the assembly of the ROV. Finally, it concludes and evaluates all the obstacles that we encountered and our reflections on the adventures that AHTI brought us.

Figure 2 SURA Team with the mentor

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INTRODUCTION

We, as a humanity have been constantly struggling with the mysteries of the world, trying to tame the surrounding environment. Invention of the wheel, industrial revolution that led to the development of e.g. steam engines, and the creation of the first steamboat, landing on the moon in July 1969. Finally, receiving more than a half thousand photos from Sojourner Rover exploring the Red Planet – these events seemed to prove the unlimited possibilities of a human brain and indicated that nothing could stop us from going even further. However, there are some places that are much closer to us than Mars, Moon or even our own stratosphere (from where Felix Baumgartner performed his famous jump) about which we still do know virtually nothing about.

Here comes the underwater world. The world that is the more inhospitable the deeper the places that are to be explored. Because of the high pressures acting on the bodies immersed in the water, remotely operated vehicles require the usage of the latest technologies, materials, sealing and combining the parts of the robot together. Building a ROV therefore connects both theoretical abilities such as: planning, designing, computing (MBS, FEM, and CFD) and practical skills such as: setup and assembly.

We, as the members of Students Underwater Robotics Association wanted to pick up the gloves and use our engineering skills to create our own vehicle able to perform various specific and manipulation tasks proposed by MATE 2015 Competition and compete against the best universities in EXPLORER class.

ORGANISATION AND LOGISTICS

I. PURPOSE AND TECHNICAL REQUIREMENTS

The ultimate aim of our team was to design, manufacture and assembly the remotely operated vehicle able to perform specific tasks such as: maneuvering in the water smoothly, being capable to avoid potentially hazardous region, determining the thickness of the ice crust using pressure measurements, measuring the temperature of the venting fluid or recording underwater wildlife. Hence, it was necessary to create relatively light and streamlined vehicle equipped with:

- Proper propulsion system allowing for undisturbed motion in three directions
- Manipulator and gripper allowing for an interaction with environment (grasping various elements, turning the valve etc.)
- Wide-angle cameras allowing for capturing the image
- Inertial measurement unit giving fundamental information about ROV’s velocity, acceleration and three-dimensional orientation
- Adequate sensors

All of this was accomplished by step-by-step, professional engineering approach involving proper organization of time and allocation resources (human, material and financial), and simultaneously by putting particular emphasis on safety procedures and OSH.

II. SCHEDULE AND PLANNING

In order to maximize the efficiency of the allocation of time and resources, one has to undertake means to manage the work of the whole crew. In SURA, all actions were being discussed during weekly meetings, after which all resolutions concerning the duties and plans were posted on Trello (project management application) and on the team’s Gantt’s diagram. To ensure everybody would be present during the meeting have we used

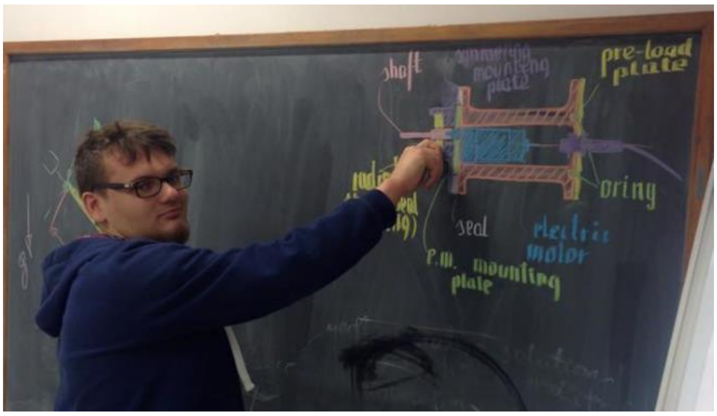


Figure 3 Paweł showing his idea of the gripper during our weekly meetings

Doodle scheduling tool to find the most convenient date for the meeting. During each meeting, each person was supposed to prepare very short presentation showing their accomplishments, plans and needs. The presentation was then followed by a brainstorming phase, during which everybody was free to share their opinion. One person, different each time, was supposed to note everything they have heard during the brainstorm and sum it up briefly at the end of the meeting. This work regime turned up to be very effective: it required a great engagement from everybody and it made people be up-to-date with what their team-mates were dealing with (mechanical engineers were aware of the problems of programmers and vice-versa). Individual presentations gave us chance to show off and let others see our achievements constituting a great incentive for further work.

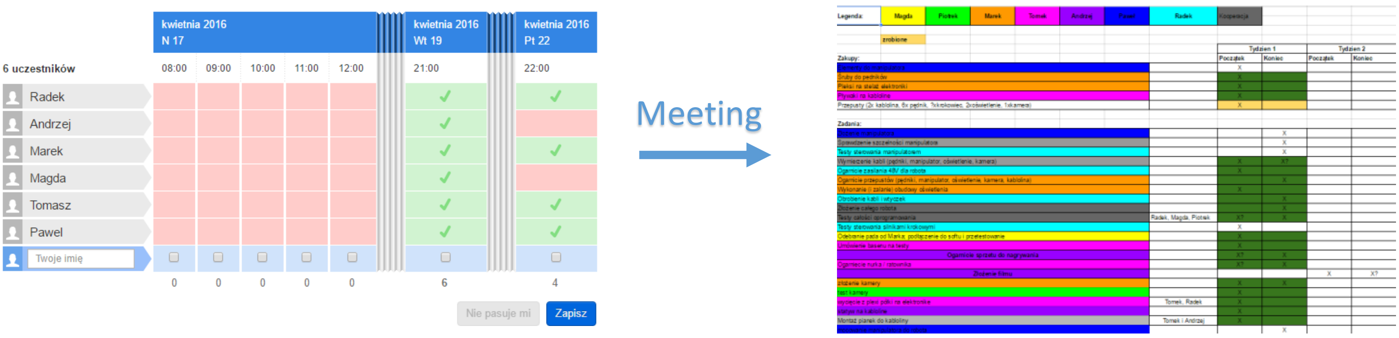


Figure 4 Organization chart

III. TEAM STRUCTURE

The team consists of seven people: three mechanical engineers, two software engineers, one electrical engineer and the person responsible for the public relations and the budget (CFO). The mechanical engineers constituted the core of the team specifying all the mechanical and design requirements, stress calculations, flow/heat simulations. The issues that were later on discussed by the whole team. Electrical engineer was a linkage between the mechanics and the programmers. Work division allowed us to optimize our time efficiency – there was very often a case where, during the, for example, mechanical team meeting, no programmer was actually necessary. Either assembly, leakage testing or estimating the center of gravity of the ROV – the results were all noted and then presented on the weekly whole team's meeting.

IV. BUDGET

In the early phase of our project, the budget was prepared to assess the potential cost of the ROV and then strictly respected during the project development. The SURA's first income was the Alma Mater Donation followed by a successful fundraising – TechOcean, which supported our project by 8,000 PLN and BASS Polska, which donated the Company's first tools. The figures below show the budget in a greater detail.

PROJECT COSTING					
Type	**Discipline**	**Item**	**Description/notes**	**Amount (PLN)**	**Amunt ($)**
ROV expenses					
Purchased	Electrical	Arduino Pro Mini	328 - 5V/16MHz	85,80	21,71
Purchased	Electrical	Cables	2 core – 30.5m, 3 core, 4 core, per M	459,99	116,41
Purchased	Electrical	Computer	processor Exynos5422 + micro SD HC 32GB	551,79	139,65
Purchased	Electrical	Crimp contact		57,00	14,43
Purchased	Electrical	Crimp housing		48,40	12,25
Purchased	Electrical	DC/DC converter	12V, 20A	1338,84	338,84
Purchased	Electrical	DC/DC converter	12V, 6A	117,18	29,66
Purchased	Electrical	Electronics		367,45	92,99
Purchased	Electrical	Header connector	THT 2.54MM, 3 way	58,20	14,73
Purchased	Electrical	Headers	side entry, 2 way	15,60	3,95
Purchased	Electrical	Microsoft LifeCam	HD-3000 (black)	190,00	48,09
Purchased	Electrical	Pressure sensor	10 bar, axial barbless	69,29	17,54
Purchased	Electrical	Raspberry pi		189,00	47,83
Purchased	Electrical	Resistors		13,81	3,50
Purchased	Electrical	Rotation regulator	PULSO DLB 40A	1080,00	273,33
Purchased	Electrical	Temperature sensor		12,90	3,26
Purchased	Electrical	Terminal block		67,05	16,97
Purchased	Electrical	THT Header	2.54mm, 1 row, 4 way	21,40	5,42
Purchased	Electrical	Xbox pads		244,00	61,75
Purchased	General	Brick & heat plate	DC DC, 5V, 10A	112,71	28,52
Purchased	General	Elements for qualification task		121,12	30,65
Purchased	General	Foam noodle		19,98	5,06
Purchased	General	Leaflets		103,80	26,27
Purchased	Manufacturing	Angle iron		178,42	45,15
Purchased	Manufacturing	Box for electronics		761,25	192,66
Purchased	Manufacturing	Box welding		150,00	37,96
Purchased	Manufacturing	Polycarbonate frame		147,00	37,20
Purchased	Mechanical	Bolts		142,16	35,98
Purchased	Mechanical	Brushless engine	FOXY C2213/22 980 kv	630,00	159,44
Purchased	Mechanical	Manipulator casing		799,50	202,34
Purchased	Mechanical	Manipulator dampers		1826,55	462,27
Purchased	Mechanical	Manipulator shaft		678,96	171,83
Purchased	Mechanical	Naves		65,01	16,45
Purchased	Mechanical	O-rings		159,28	40,31
Purchased	Mechanical	Plain shaft bearing		49,20	12,45
Purchased	Mechanical	Plain shaft harrows bearing		271,15	68,62
Purchased	Mechanical	Plexiglas pipes		80,35	20,34
Purchased	Mechanical	Seals		6,46	1,63
Purchased	Mechanical	Steppers		690,17	174,67
Purchased	Mechanical	Wire holder		44,67	11,31
Purchased	Mechanical	Wormwheel		129,99	32,90
Purchased	Tooling	Combination pliers		44,34	11,22
Total ROV				**12199,77**	**3087,53**
Tools					
Donated	Tooling	Drill	Provided by BASS Polska (BASS Polar	355,00	89,84
Donated	Tooling	Polisher	Provided by BASS Polska (BASS Polar	120,00	30,37
Donated	Tooling	Grindstone	Provided by BASS Polska (BASS Polar	180,00	45,55
Donated	Tooling	Pliers	Provided by BASS Polska (BASS Polar	34,00	8,60
Donated	Tooling	Drill bits	Provided by BASS Polska (BASS Polar	40,00	10,12
Donated	Tooling	Wrenches	Provided by BASS Polska (BASS Polar	47,00	11,89
Donated	Tooling	Percussion drill	Provided by BASS Polska (BASS Polar	150,00	37,96
Donated	Tooling	Socket wrenches	Provided by BASS Polska (BASS Polar	280,00	70,86
Donated	Tooling	Magnetic tool pan	Provided by BASS Polska (BASS Polar	25,00	6,33
Donated	Tooling	Jigsaw	Provided by BASS Polska (BASS Polar	129,00	32,65
Donated	Tooling	Lamp	Provided by BASS Polska (BASS Polar	90,00	22,78
Total tools				**1450,00**	**366,97**
Registration for MATE ROV COMPETITION 2016					
Donation	General	Registration	Provided by the Dean of the Faculty of Pow	987,83	250,00
Total registration				**987,83**	**250,00**
TOTAL ALL				**14637,60**	**3704,50**

Figure 5 Budget: Project and ROV costing

INCOME							
Item	**Description/notes**	**Type**	**Quantity**	**Amount (PLN)**	**Amount ($)**	**Total (PLN)**	**Total ($)**
University Donation	Provided by Warsaw University of Technology	Cash	1	10000,00	2530,81	10000,00	2530,81
University Donation	Provided by Warsaw University of Technology – the Faculty of Power and Aeronautical Engineering	Cash for travel expenses	1	20000,00	5061,63	20000,00	5061,63
University Donation	Provided by Warsaw University of Technology	Cash for travel expenses	1	25000,00	6327,03	25000,00	6327,03
Fundraising	TechOcean - Technological Partner	Cash	1	8000,00	2024,65	8000,00	2024,65
Fundraising	Bass Poland	Tools	1	1450,00	366,97	1450,00	366,97
Employee Dues	Team Members Dues	Cash	7	110,00	27,84	770,00	194,87
					TOTAL	**65220,00**	**16505,96**

TRAVEL EXPENSES					
Item description	**Quantity**	**Amount (PLN)**	**Amount ($)**	**Total (PLN)**	**Total ($)**
Air fare	7	3500,00	885,78	24500,00	6200,49
Car rental	1	4262,50	1078,76	4262,50	1078,76
Accomodation	7	395,96	100,21	2771,72	701,47
Insurance	7	120,00	30,37	840,00	212,59
ROV transportation	1	3500,00	885,78	3500,00	885,78
Visa	5	630,00	160,00	3150,00	797,21
Food	7	790,26	200,00	5531,82	1400,00
			TOTAL	**44556,04**	**11276,30**

BUDGET	
Manufacturing Materials	**Value**
ROV expenses	3087,53
Donated tools	366,97
Registration for MATE ROV Competition 2016	250,00
Travel expenses	11276,30
Contingency	1500,00
Total expenses	**16480,80**
Total income	**16505,96**
BALANCE	**25,16**

$<->PLN Rate	
1 PLN to $	0,25
1 $ to PLN	3,9513

Figure 6 Budget: Income and travel expenses

DESIGN RATIONALE

V. DESIGN PROCESS OVERVIEW

After defining the basics (what we need, how does it work, what we need it for), the person responsible for a particular task was supposed to create a simple 2D/3D model using CAD software (in SURA we use *SolidWorks*), show possible methods of manufacturing, estimate the cost of production and perform basic engineering analysis (required thrust in case of propulsion system, maximum pressure the parts can withstand underwater etc.). At advanced level, FEM analysis (*ANSYS*, *FLUENT*) was also conducted (though as it turned out, analytic results were a good approximation in the majority of cases).

CAD models of some elements (like a ducted propeller) were imported to *CURA* software in order to generate G-Code, allowing us to manufacture it using 3D printing method.

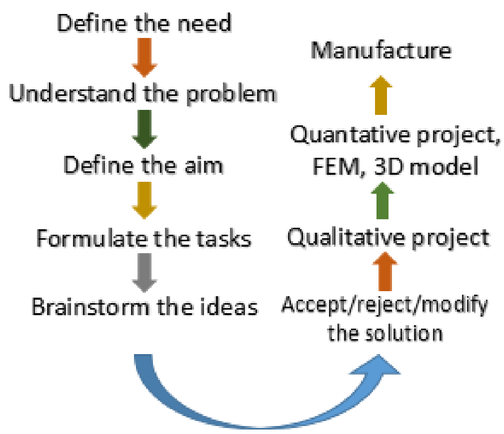


Figure 7 Design process scheme

VI. VEHICLE SYSTEMS

1. FRAME

The frame is the biggest part of our ROV and defines its gauge and overall shape and which acts as a spine of the vehicle, holding every other part together. Thanks to the modular nature of our ROV every unit can be easily removed from the frame for repairing or further development purposes.

The frame has dimensions 400x300x8 mm and has a shape of a rectangle with rounded edges. It is made of polycarbonate, which is a light and reliable material with very good mechanical properties. Its stiffness is comparable to that of the aluminum. The frame was made using CNC waterjet cutting machine in view of the importance of high-quality surface finish and of the accuracy of manufacture.

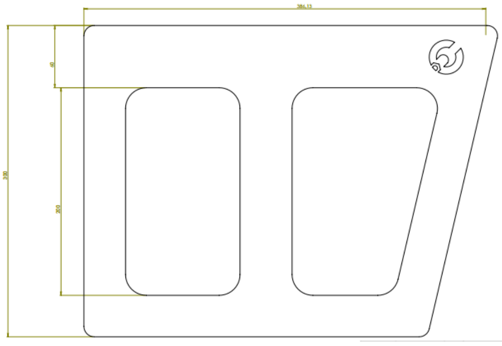


Figure 8 Frame's CAD drawing

2. FUSELAGE

Figure 9 Fuselage – reality (aluminum) and conception (acrylic glass)

The fuselage was, at the beginning of the design process, supposed to be made of acrylic glass (PPMA) in an hydrodynamic shape with relatively low drag coefficient and rounded edges to avoid concentration of shear forces. Unfortunately, the manufacture of such fuselage was really a hard issue to deal with, since bending acrylic sheets appeared to be very expensive, and glued connection was not really reliable when it comes to the water tightness. Since being impervious to water was our ultimate requirement we decided to design a second fuselage – very simple, yet reliable rectangular cuboid made of aluminum. We sacrificed the hydrodynamic characteristics on purpose, knowing that the vehicle is not supposed to operate quickly, allowing the electronics to be able to be easily inserted into the fuselage, and more importantly, allowing us to optimize the costs of the whole construction.

3. PROPULSION SYSTEM

The propulsion system is one of the most important subsystems within the ROV. In order to have a great maneuverability and the ability to move in orthogonal three dimensional space freely, the propulsion system must have enough power to generate required thrust. Apart from that, it is important that the thrusters are located

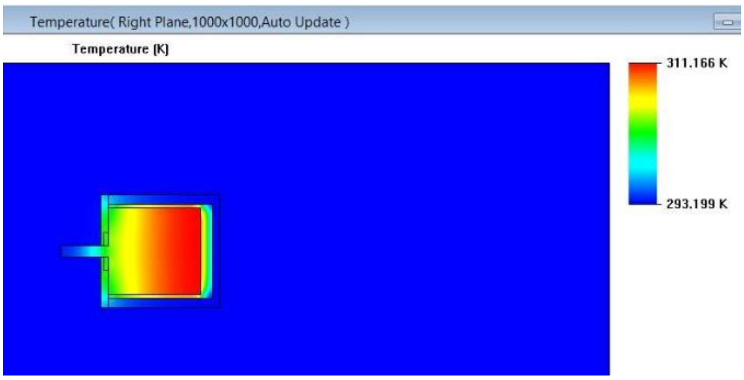


Figure 10 Simulation of the heat distribution within the motor

properly so that the turbulent water streams behind the thruster do not influence other pumps or does not strike other parts of the vehicle.

We therefore spent a lot of time on developing our thrusters. First of all, we had to define working conditions and decide what is the most important for the good mobility. Having an initial idea of the construction design, we estimated average vehicle's drag coefficient. The best solution was to use FOXY C22/20 BLDC Motors. The motors have 180W power, 12V DC while being simultaneously light and very small. In connection with our main idea (to minimalize the usage of metal) we made motors' cases using 3D Printing technology. To make cases waterproof, we used 100% fulfilment and protective surface made of an epoxy resin. RC Hub is clamped on the engine's shaft. The end of the hub is threaded with M5 thread. 32mm diameter propeller is screwed and protected against unscrewing with Loctite glue.

In order to improve efficiency as well as for safety purposes we have designed ducted propellers. The water circulation that occurs within the Kort nozzle results in forward force component having a positive impact upon the thrust (especially observable at low speeds). Kort nozzle was designed based on NACA 4415 airfoil (known for very good characteristics and its widespread use in the industry). For the sake of people's and cables' safety, on the top of the nozzle we have placed special grids, which prevent from contacting with rotating propellers.

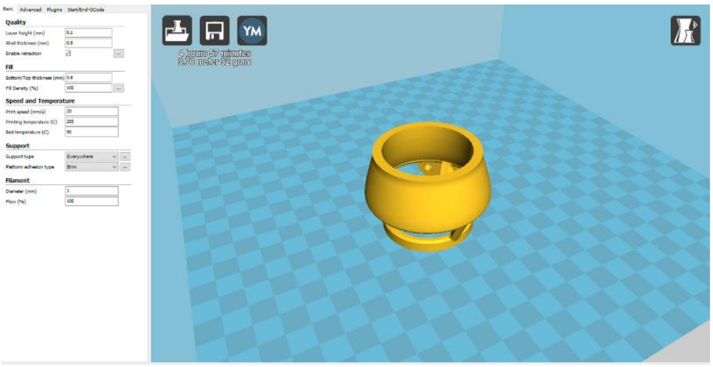


Figure 11 Kort Nozzle model in CURA software

During the design process, we used SolidWorks FLOW MANAGER and SolidWorks MECHANICAL MANAGER to optimize thrusters' performance. Stress calculations were conducted on various depths. 3D printed parts are designed to provide stable flow in both directions. Four of our six thrusters are mounted vertically, allowing AHTI to dive very quickly. The thrusters are placed in four corners of the frame, allowing us to tilt the robot in each direction. Two thruster are mounted horizontally, parallel to the plane of symmetry. During the tests we estimated the center of mass in frame's plane and drag forces on every part of the robot, which compared together let us find the best place for thrusters' position. That configuration provided us with good mobility forward – almost 1m/s.

4. TETHER

Our tether is twenty five meters long and consists of two wires – one used for power transmission and one used for control signals transmission. Wires are shrouded by a 2mm thick cover to avoid mechanical injuries. In order for the tether to be positively buoyant and work without tangling underwater during the vehicle's operation, polypropylene foam in the shape of cylindrical pieces was used and installed onto the tether.

5. CAMERAS

The robot is equipped with two HD USB and one HD Raspberry Pi dedicated wide-angle cameras pointing in three different directions, thus making the control more comfortable and allowing the operator to maneuver with great precision.

Figure 12 Theter with cylindical foam pieces

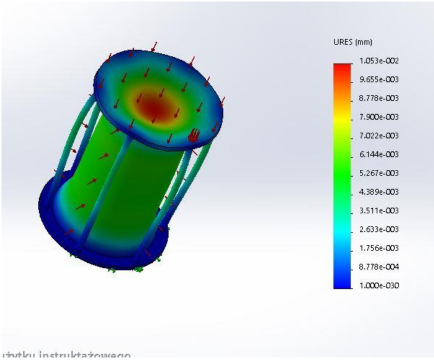


Figure 13 FEM Analysis of the camera's housing

Camera housing is made of cylindrical PMMA tube protected by metal plates and EPDM O-rings. The cable from camera passes through the waterproof connector placed at the bottom of cylinder. We made a stress analysis to choose optimal thickness of the pipe. The case was checked under 1,5 bar pressure and the results are shown in the figures. Finally, to provide a good visibility and enough strength, we have chosen the pipe with a wall thickness of 3 mm. The pipe was cut in 100mm pieces and the aluminum plates were attached. Six threaded rods were used to compress plates and the pipe inside. The camera was put inside the 3D printed frame which makes it stable. Acrylic glass has a good transparency, allowing us to rotate our cameras around the lateral axis. To make a vision the best possible, we installed a wide-angle camera on an arm, made of fiberglass. The arm is installed over the ROV, so the camera gives a clear view in front of the robot. Second set is placed under the body and gives the best view on the gripper. It is especially needed during the complicated manipulations.

6. LIGHTING

To provide a good visibility in almost every conditions, we installed the lightening on our ROV. There are two headlights, close to the cameras. Each headlight is made of small, 5V, white color LED, a diffuser, and a case. The case was designed in SolidWorks and printed on 3D printer. Inside the case there is a LED covered with a diffuser, made of glass. For safety reasons, we used epoxy resin to fill the case and prevent LED's from water. The lightening gives good quality visibility up to 2m in darkness.

7. MANIPULATOR

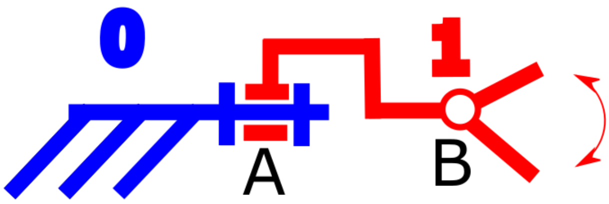


Figure 14 Kinematic chain of the manipulator

To complete all tasks during the competition AHTI utilizes a manipulator. Here is a setup of the bodies and joints:

Considering the low mass requirement in the competition it is decided to use only two degrees of freedom (DOF):

- **A** - to rotate the effector **1**,
- **B** – to open/close the effector.

The body **0** represents the part of the chain which is attached to the base of the robot. To maximize the usage of the device we have decided that for DOF **A** a stepper motor should be used. Thanks to self-locking from the worm gears there is no need for a brake in **B** as well.

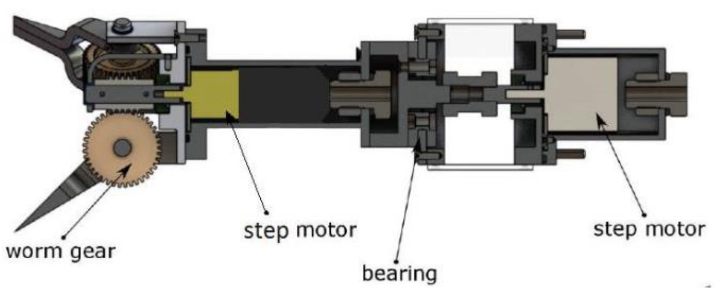


Figure 15 Cross section of the manipulator

The sealing of motors is done from two sides (one with the shaft and one with the wires). To seal shafts we used radial shaft seals. They are placed in plates with sockets. Plates are connected with motor housings. Such connection is sealed with O-ring.

To seal wires we used custom cable grommets. Their construction consist of a nut-screw connection sealed with O-ring under the screw head. The screw has a hole through which wires are routed. Such holes are sealed with butyl.

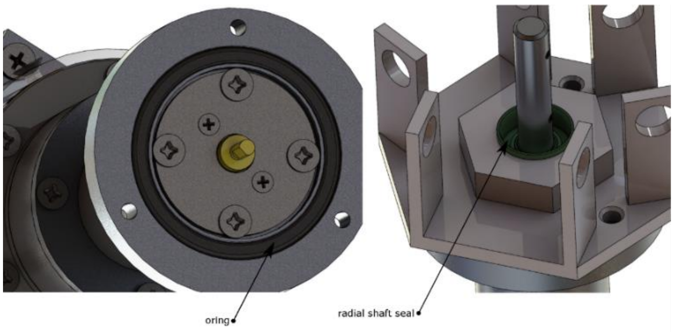


Figure 16 Shaft side sealing of the motor

Lessons learned:

One degree of freedom is not sufficient enough to allow the robot's operator a proper object manipulation, having more than two axes of grip rotation allows to hold objects with more strength.

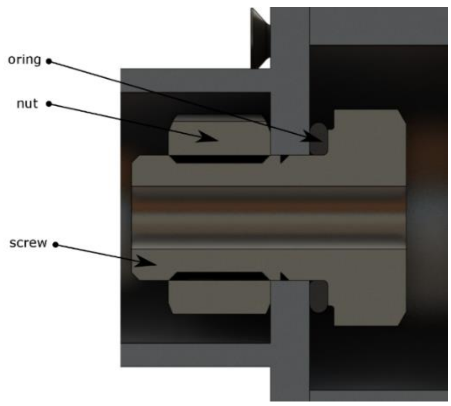


Figure 17 Wire side sealing of the motor

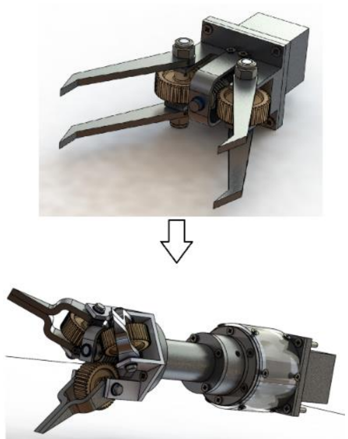


Figure 18 Comparison of the previous and current solution

8. SEALING

The success is dependent upon the tightness of vehicle's components. High pressures underwater trigger a rush of water into the smallest slits of the vehicle which requires a big effort in terms of sealing. Waterproof units are important for two main reasons: first and the most important is safety – electronics is very susceptible to water; even the smallest leakage can cause short circuit. Secondly, properly sealed components condition proper functioning of the system. In SURA we therefore put great emphasis on sealing and making our robot impermeable to water. This has been done using:

- O-rings and flat EPDM gaskets, placed between two parts that are in contact with each other (camera housing, manipulator). Their main advantage is their versatility, reliability, relatively low price, combined with the fact that their efficiency increases with pressure to which the vehicle is exposed.

- Radial shaft seal – used to seal rotary elements, for example the gripper's main shaft.

VII. ELECTRONICS

9. SYSTEM INTERCONNECTION DIAGRAM

Figure 1 and 2 show both ROV and Ground station System Interconnection Diagrams that depict power distribution and signals' connections. Ground station SID additionally shows the total power and main fuse calculations.

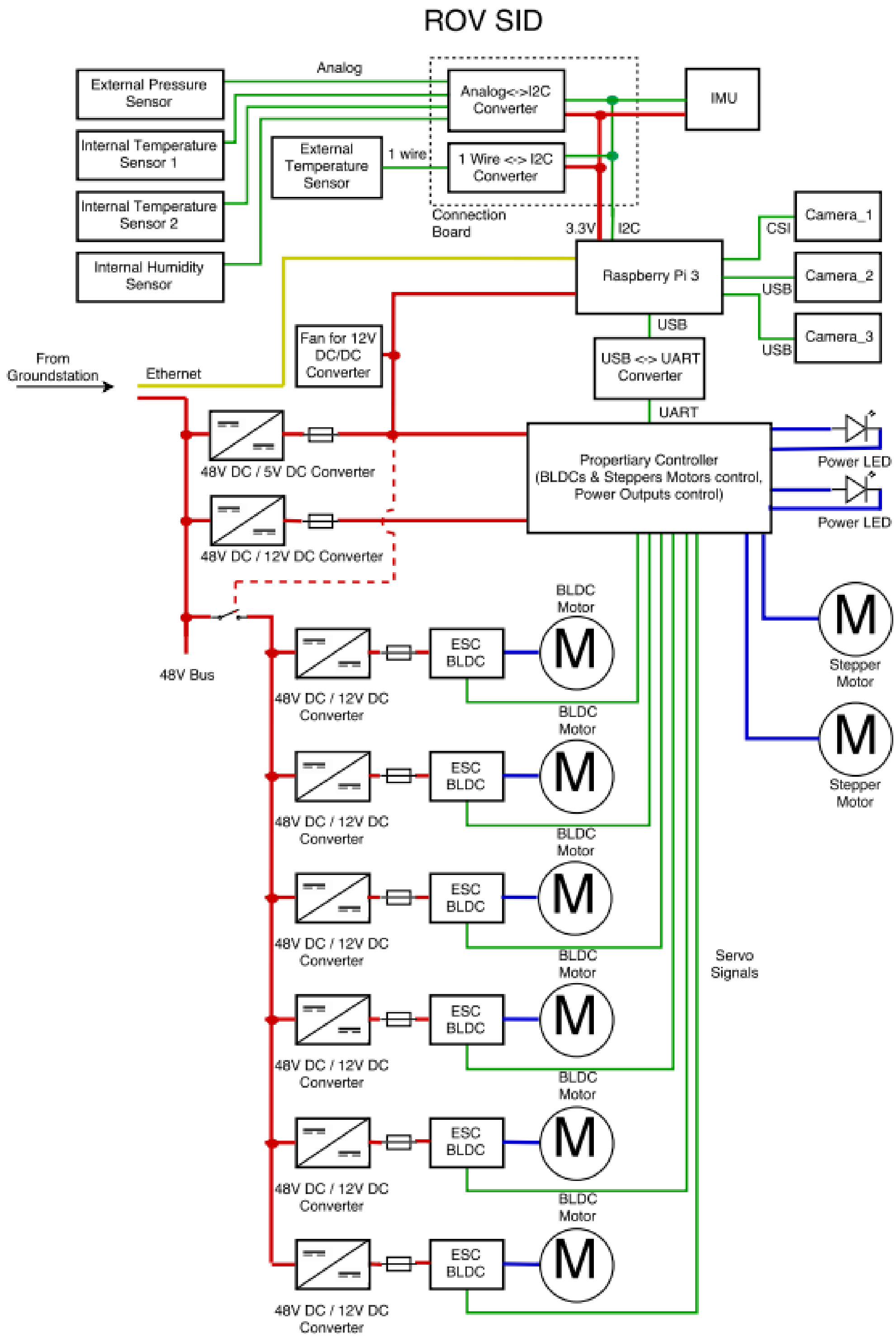
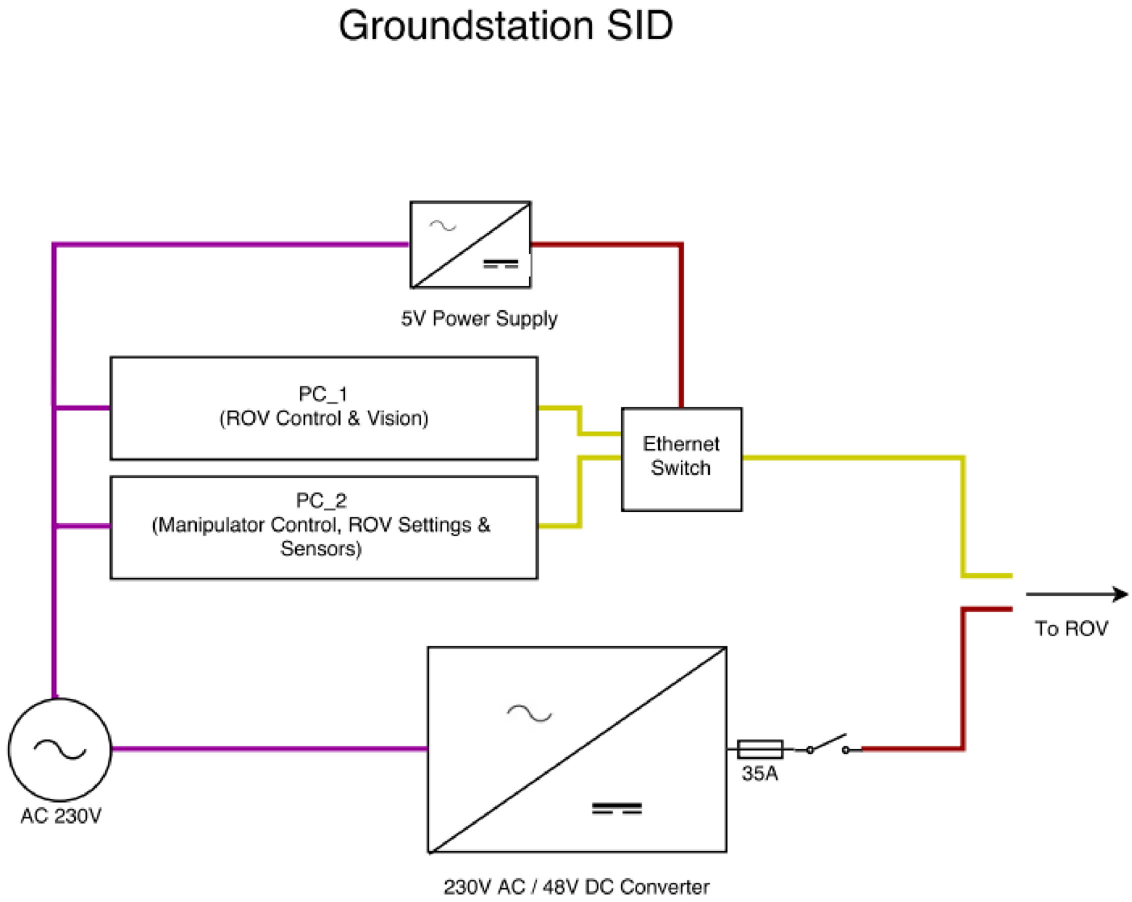


Figure 19 ROV's System Interconnection Diagram



	Voltage (V)	Current (I)	Power (W)	Quantity	Total Power (W)			
BLDC	12	12	177,8	6	1066,7		**DC/DC efficiency**	0,9
Stepper Motor	12	0,5	6,7	2	13,3		**BLDC driver efficiency**	0,9
LED	5	0,3	1,7	2	3,3			
Fan	5	0,3	1,7	1	1,7			
Raspberry + Camers + USB<->UART Converter	5	3	16,7	1	16,7			
Arduino Board	5	0,2	1,1	1	1,1		**ROV Total Power (W)**	1103,3
Sensors	5	0,1	0,6	1	0,6		**Fuse (A)**	34,5

Figure 20 Ground station's System Interconnection Diagram

10. POWER SYSTEMS

In order to properly function in the United States at 110V AC standards, we have bought the 110V / 230V transformer rated at 2000W with build-in fuse. Also, to provide an appropriate power supply for thrusters we designed our own PCB (fig. 15).

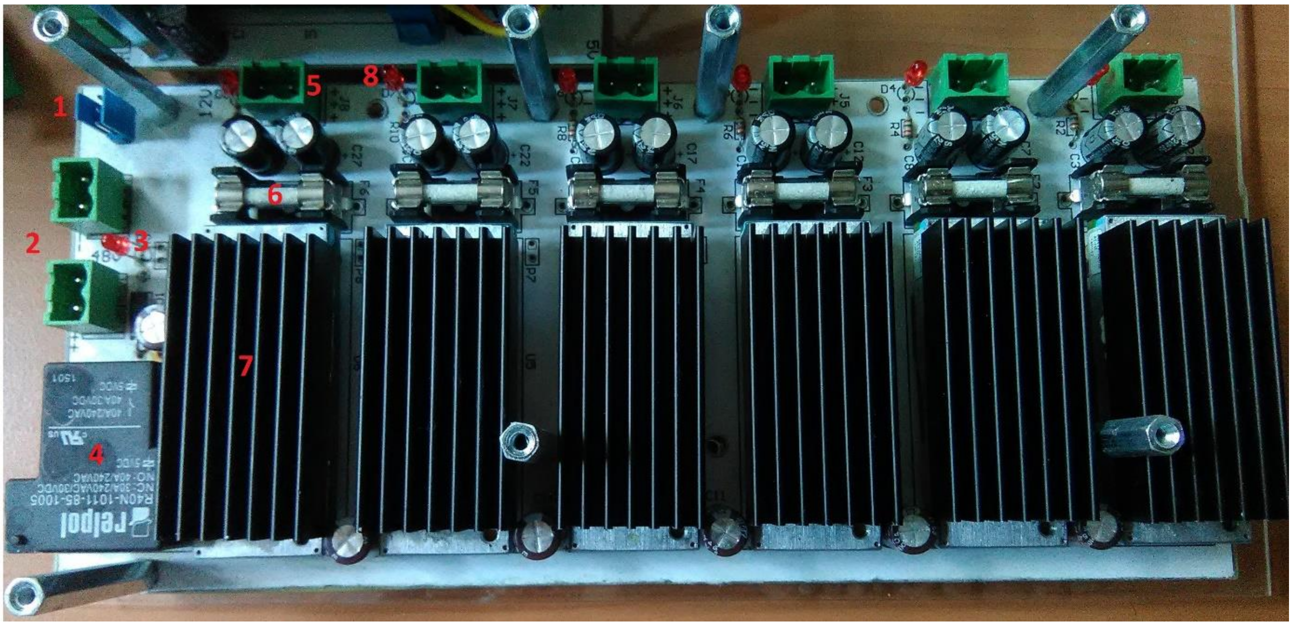


Figure 21 Power Supply for BLDC motors (thrusters).

There are 48V two-port input connector [2] and six power outputs connectors [5] rated at 12V and 20A maximum current. It has a lot of important features and properties:

- On/Off signal [1] that switches relay [4] connected with input voltage for PCB.
- Polarized high power connectors [2], [5].
- Led indicators for input and output voltages [3].
- Fuses on each power output [6].
- Radiators for heat dissipation [7].
- Holes for firm mounting [8].
- Graphical and text designations for clear connections.

Figure 22 Gripper's power supply

These elements make it easy for possible disfucntions detection, and are, most importantly, safe and reliable.

We also designed a power supply PCB for our manipulator (fig. 15) and onboard logic systems.

They both have similar properties as the power supply for BLDC motors:

- Polarized high power connectors [2], [8].
- Led indicators for output voltage [7].
- Fuses on power output [6].
- Radiators for heat dissipation [3].
- Holes for firm mounting [5].
- Graphical and text designations for clear connections [1], [9], [10].

11. LOGIC CONTROLLERS AND DRIVERS

Raspberry Pi 3 was used as a main onboard computer (fig. 8). It is very attractive because of its price and performance, possibility to run Linux operating system and useful for low-level communication interfaces (CSI, I2C). It also is equipped with both Ethernet and USB interfaces.

For low-level control where timing is critical, we have designed a proprietary controller based on Arduino. It can generate 6 PWM (Pulse Width Modulation) servo signal for BLDC drivers, drive up to 4 stepper motors (based on Allegro A4988) and is equipped with a 3 MOSFET power outputs (5V or 12V, maximum 3A). It has communication based on UART and Modbus-RTU protocol.

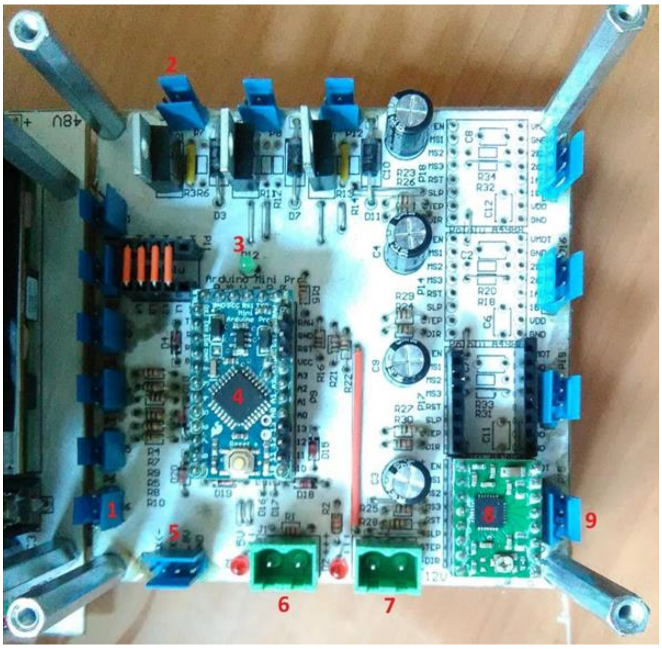


Figure 23 Proprietary low level controller

1 – Servo signal output

2 – Power switch output

3 – Led, blinks when modbus data received

4 – Arduino mini pro

5 – UART communication port

6 – 5V power supply

7 – 12V power supply

8 – Stepper motor driver

9 – Stepper motor connector

The drivers for BLDC motors have been bought as ready components (fig. 10). These are standard model ESC (electronic speed controllers) controlled by servo signal (50Hz PWM). Each driver handle the motor up to 40A (information from the manufacturer datasheet).

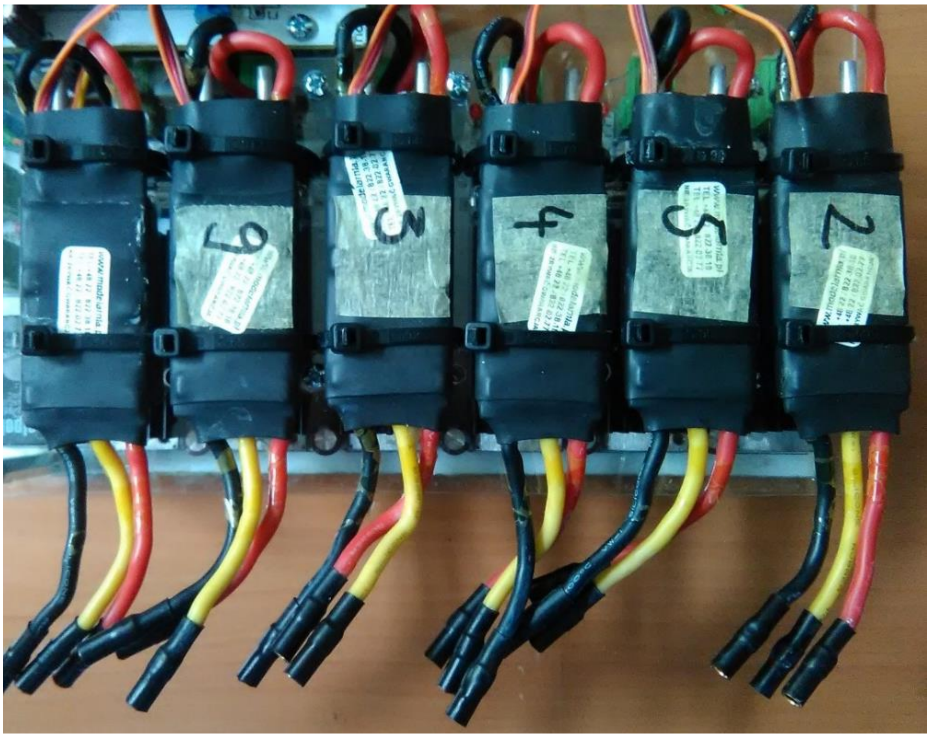


Figure 24 BLDC motor drivers

12. SENSORS

Our onboard sensors include:

- IMU (Inertial Measurement Unit) with I2C interface,
- External pressure sensor with analog interface,
- External temperature sensor with 1-wire interface,
- Internal temperature sensors with analog interface
- Internal humidity sensor with analog interface

As the IMU we have decided to use a module based on BNO055 absolute position sensor (fig. 12) that helps us with the ROV control. For environmental measurements we use two external probes – for temperature (based on Maxim-Dallas DS18B20 – fig. 11) and pressure (based on Honeywell ABPLLNT010BGAA5). Because of the high power electronics closed in a small box we decided to measure the temperature with two internal sensors (based on Honeywell TD5A). Internal humidity sensor is used to detect a leakage (based on PCB electrodes – fig. 13). There was a necessity to use some external translators and converters to connect sensors to onboard computer. We use an analog-to-digital converter based on Microchip MCP3424-E/SL and translator between 1-wire and I2C protocol based on Maxim-Dallas DS2483R+U.

VIII. SOFTWARE AND ALGORITHMS

The robot is controlled by three applications running on laptop with Ubuntu 14.04. The first program receives information from camera, the second one collects data from measurements and the last one controls motors and manipulator axes. The reason, why we have made three programs instead of one is the unexpected crash of one application will not stop others.
The goal during development was to create intuitive interface to safe, fast and comfortable controlling of Ahti.

13. CAMERA APPLICATION

The application, which receives image from camera was written in C++, using QtCreator and OpenCV. The application communicates with underwater computer via TCP. It sets image parameters: resolution, fps and sends order to start streaming. Image streaming goes via UDP. After receiving data, the program decompresses and displays them. The application also allows user to stop streaming, change resolution, fps, the level of compression, record images (to .avi file) and make snapshots. Usually, three instances of camera program are alive, one for each camera.

14. MEASURES COLLECTING APPLICATION

This application was written in Python, with PyQt libraries. It consists of two threads: first one sends messages asking for current measures to underwater gateway periodically, then receives them and passes to the second thread, which handles GUI. On the graphical interface, there are displayed current parameters values and drawn a graph. For the safety of data, all measurements results are saved in file. If some parameter has inappropriate value, because of unexpected malfunction, the red alert is shown.

15. MOTORS AND MANIPULATION CONTROL

The robot is controlled with two gamepads (one for motors, and one for manipulator) and application's GUI. The program was written in Python with PyQt and PyGame libraries. For safety, Ahti can start only after pressing special button for arming (either on gamepad or in GUI). Before that, the robot does not react to messages. Analog joysticks have adjustable dead zone to prevent Ahti from spinning motors or manipulator axes, when their position is near zero. Controlling robot's and axes' position is achieved by manipulating buttons and joysticks. The application also allows to set parameters for controlling algorithm during robot's work. and shows current motors' and axes' velocity.

16. ONBOARD COMPUTER

We use Raspberry Pi 3 as a main onboard computer (later called the underwater gateway) with Ubuntu 16 LTS as an operating system. The main purpose of the gateway is to communicate with a controller PC (located on the side of the pool) and with low-level electronics. It also performs some measurements (temperature, pressure) and provides ROV's stabilization.

The software is written in C++ with Qt and additional libraries (OpenCV, libmodbus, udp-image-streaming, WiringPi). The source code is periodically uploaded to Github. With this we can easily collaborate, review new modifications or roll back to older version in case something stopped working.

The software is divided into modules to create ability of easy service creating (see attached UML class diagram). Each service consists of TcpServer, FrameParsesr and at least one Handler. Thanks to FrameParser frame format is independent from other classes, so it can be easily replaced. The same is with TcpServer – if we ever needed another form of communication (UDP, Profibus, UART and so on) we would replace only this one class.

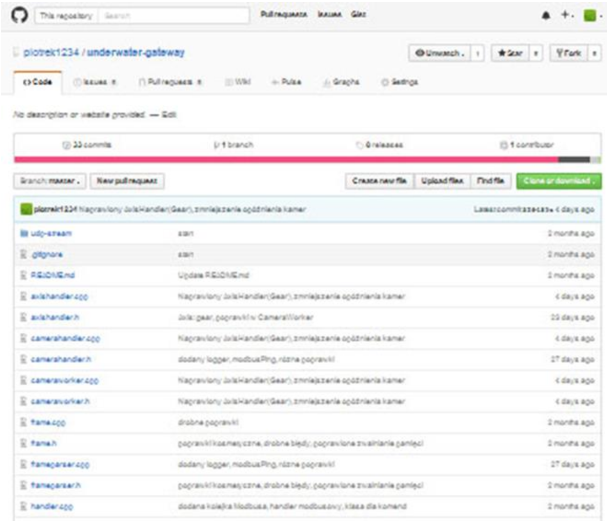


Figure 25 Source code on Github

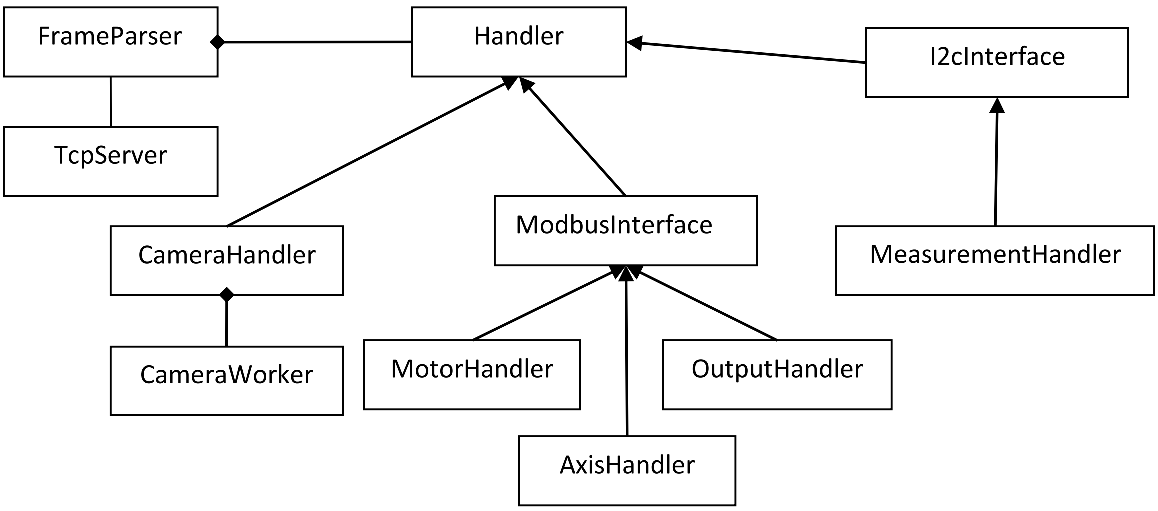


Figure 26 UML class diagram

17. COMMUNICATION WITH CONTROLLER PC

Communication is performed via TCP. There are 3 independent services: camera control, motors/gripper control and measurements. Each of them is run on separate thread (additionally, each camera has its own thread).

Camera control is used to capture live video stream from the cameras, compress data and send it via UDP to one of the controller PCs. The parameters for each camera (such as a resolution, frame rate, compression ratio) can be set independently. Camera control service is configurable with one out of two applications: firs one is automatic, displays image and records video, the second one provides more manual control but doesn't support recording (this app is used to debug software). Due to the need of compression and sending image through Ethernet there is a slight lag between live and received image, about 150 milliseconds.

The server supports simple debugging. Connecting with gateway via SSH gives us a possibility to see what frames are received and what the responses are. Frames are constructed in a way that human can easily understand: left bracket, main command, handler or service abbreviation, specific command, command parameters, right bracket. All of these are separated by a comma. Example frames or responses:

$(S, C, H, 192.168.1.1)$ – set camera host to 192.168.1.1,

$(G, T, 0)$ – get temperature 0 value,

$(S, S, m, 0)$ – disarm all motors,

$(R, C, 0{,}640{,}480{,}15{,}1{,}1111)$ – camera 0 is on with resolution 640x480 at 15 fps,

$(R, A, s, *, 360{,}240{,}10)$ – Axis speed is set to 360 (axis 0), 240 (axis 1) and 10 (axis 2),

$(S, M, 4{,}80)$ – set setpoint for 4th motor to 80%.

18. MOTORS/GRIPPERS/OUTPUTS CONTROL

M/G/O control is used to receive orders from a pilot. It handles desired motors/gripper set points and performs communication with motors' controllers. Thanks to IMU and barometer the service is able to perform auto leveling and maintaining fixed depth. There are some switchable modes:

- manual mode – each motor can be controlled separately,
- auto-leveling – ROV tries to keep the horizon,
- level-hold – ROV tries to keep fixed depth,
- and combination of these modes.

The service can control binary outputs. As for now, they are used to power LEDs.

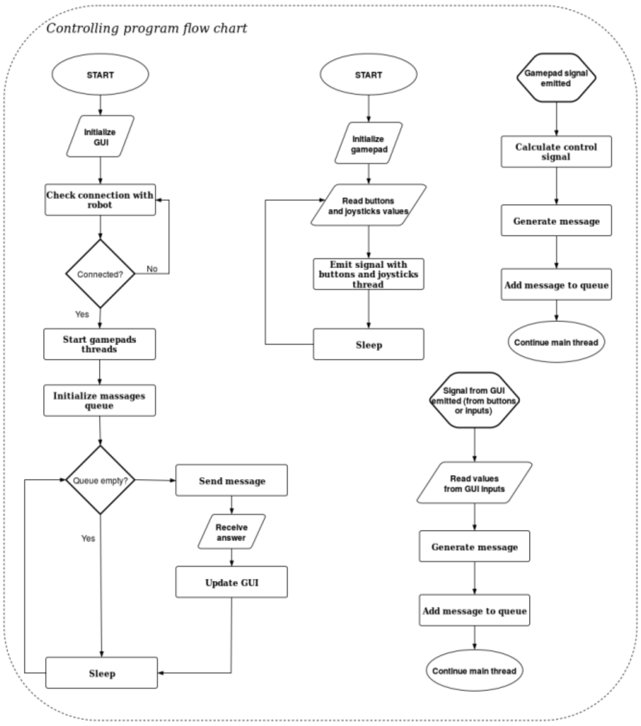


Figure 27 Controlling program flow chart

For safety reasons packets received from controller PC are marked with creation time and can expire. This way there is no problem with overfilling the commands queue. If the command requires read or write operation to Modbus controller, it is put into Modbus queue and processed one by one with fixed time period.

Communication with motor and power outputs controllers uses Modbus RTU.

19. MEASUREMENTS

The sensors are connected directly (or with simple adapters) to Raspberry Pi, so the measurements can be performed with high frequency. All of the measurements are performed periodically, filtered and exported to be used by underwater gateway's services.

20. FLOW DIAGRAMS

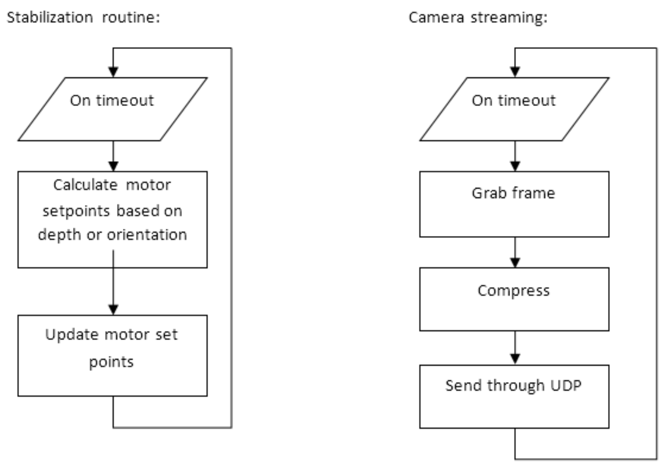


Figure 28 Stabilization routine and camera streaming flow diagrams

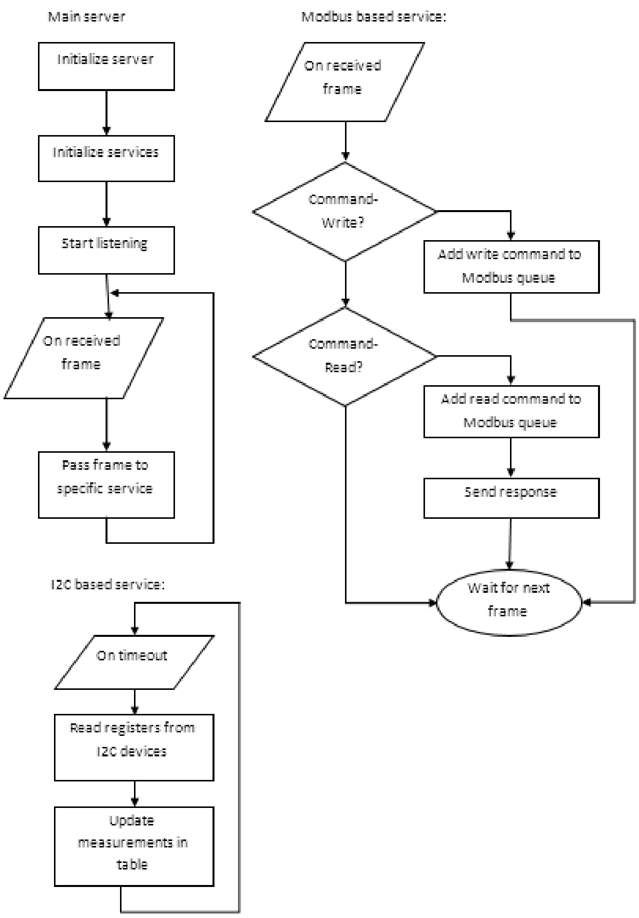


Figure 29 Main server and Modbus based service flow diagrams

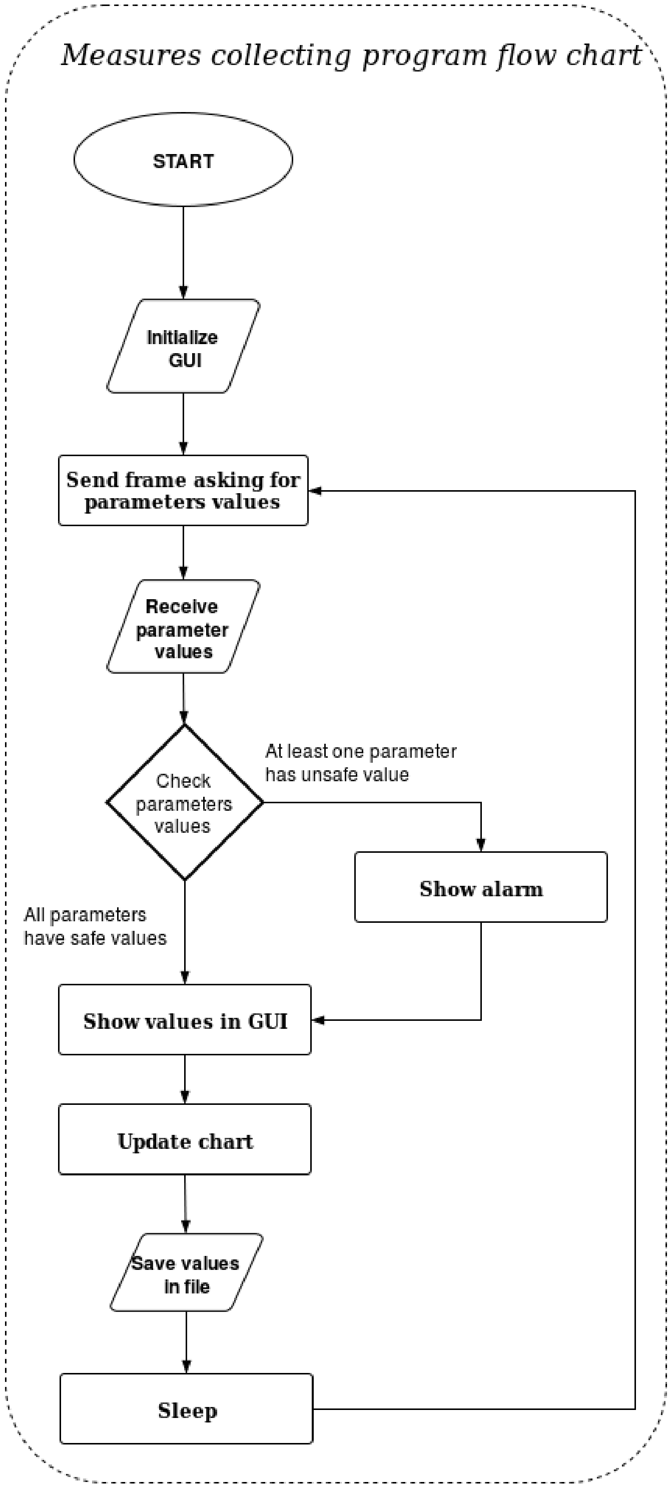


Figure 30 Measures collecting program flow chart

SAFETY

When designing and developing our robot, we have paid a particular attention to our team and co-workers' safety. We wanted to enjoy our project and learn as much as possible, also in this topic.

As newly created organization, we had to set many procedures connected not only with design, but also with manufacturing. Having great experience from previous organizations and jobs, we were aware of the risk, and we knew what to do to minimalize it.

After receiving equipment from our sponsor, the first thing we did after unpacking was reading user manual. That gave us basic knowledge about handling and let us to prepare appropriate procedures. We did it with every electrical equipment and with tools with sharp edges. Our procedures contained general instructions concerning:

Figure 31 Marek during the workshop

- outfit – gloves, long-sleeved shirts, goggles, prohibition of wearing watches, necklaces or other thing that might be accidentally hooked
- working – always in the presence of another person, after preliminary inspection of the equipment's condition. Workpieces always mounted in holders, ban on holding anything in arm while working.
- environment – work area cleaned up before using, each unnecessary thing removed
- chemical substances – mixing epoxy resin always in special mask, in well ventilated room, leftovers placed in special bin. Gloves always on. Substances stored in special room.

We have full procedures attached to the tools in workshop, so everyone can see them. We bought spare equipment, like additional goggles and gloves. We care about safety not only during manufacturing, but also during tests. On the swimming pool, we were always secured by lifeguard. Every electrical components were transported in special, waterproof box. Installation of electronics in robot is always done in dry conditions, to avoid increased humidity inside. We reduced the amount of moving parts which are uncovered. Safety grids in thrusters protect propellers without negative impact on performance.

To provide maximum reliability of our electronic modules, appropriate safety procedures were imposed. We used ESD safety tweezers for sensitive electronic components. We also used soldering station with the temperature control (fig. 33). We also pay a great attention to use a fume extrator while soldering PCB elements or cables.

On the ground station we do use a reliable 48V military class power supply.

Figure 32 Soldering station

We also have a lot of features that can improve power safety directly on our ROV:

Figure 33 Fume extractor

- On/Off signal of BLDC power module is connected to logic power supply. It provides appropriate power startup sequence (logic first, then high power systems) and thrusters power supply cut-off when failure on logic power supply occurs.
- All power supplies have a fuse on output.
- All power supplies have a LED indicator (important at test phase)
- All power connectors is polarized, that prevents reverse power supply connections.
- All power supply modules are clearly marked – input / output voltages, polarization.
- All DC/DC converters have radiators for easier heat dissipation
- All power supply modules have minimum 4 holes for firm mounting
- Two onboard temperature sensors
- Fan on manipulator power module
- All power supply modules have a built-in overheated protection

There are also safety features on control signals.

- Operator can read a startup time from proprietary controller and reset it remotely
- Proprietary controller stops all motors and turn off power outputs if there is no modbus frame within 300ms
- ESC stops BLDC motor if it lost its control servo signal

Connectors and cables

All connectors and sockets are polarized - there is only one correct position allowing for connection. All signals connectors have a latch. Cable are color marked and they are protected with heat shrink tubes. Power cable are twisted and kept as short as possible to limit the ROV EMI (electromagnetic interference) inside the ROV.

Mission procedure:

We also described a mission procedure to be conducted when testing the ROV on the swimming pool:

Start mission procedure:
- clean the operating area
- set control position:
  - switch on transformer
  - switch on extension cord in transformer
  - switch on control laptop in extension cord
  - pads connected to laptop
  - switch connected to laptop
- ROV preparation:
  - check condition of 6 thrusters
  - check 6 safety grids
  - check 3 camera cases
  - check body sealing
  - check body 24 body screws
  - check body's 14 cable-penetrators
  - check manipulator (gripper)
- switch on tether in switch
- switch on power cable in power supply
- all team members ready
- call out "ENABLING"
- tests:
  - call out "thrusters", thrusters test, count from 1 to 6 during test
  - call out "cameras", cameras test, one person in front of robot
  - call out "lightening", lightening test
  - call out "manipulator", manipulator test
  - call out "ROV ready"
- crew supervisor call out "mission start"
- crew member handle robot, call "ready"
- operator call out "ready"
- put robot into water
- check out thrusters, cameras, light, manipulator again
- if any issues, power off, take robot out using tether immediately

/mission/
- operator call out "end of mission"
- operator call out "out of water", thrusters killed
- crew member take ROV out

Figure 34 Mission procedure

CONCLUSION AND EVALUATION

IX. CHALLENGES

Obviously, during the design process we have encountered many challenges that required a creative approach and sometimes ingenious solutions. To the greatest challenges we include:

Heat dissipation

DC/DC converters get very hot after a short time of working – this made an activation of the built-in overheated protection possible. To avoid such situations, we applied the radiators with silicone thermal paste. The thrusters also experienced a great energy dissipation without IMU.

ROV control

During the test phase on the swimming pool (before implementing the inertial measurement unit) we found our control system to be very inaccurate. Manual control, without any automatic feedback was proved to be very problematic, especially, while doing precise operations with the use of gripper.

That was the main reason to implement an IMU that has built-in algorithms to calculate the orientation and velocity, based on acceleration and gyroscope sensors. That allowed us to design a feedback-loop controller to stabilize the orientation of the robot.

Vision system

Vision system was the second thing that we wanted to improve after the test phase. The main problem was the orientation of the operator. Cameras from the ROV show only a little section of the scene, so very often the operator could not find where he actually was. To avoid this kind of situation we added an additional wide angle camera that allow the operator for quicker recognition of the ROV's position underwater.

Software

The biggest problem when developing software was that most of the applications have to be written before finishing the robot construction and electronics in order to complete the project on time. This was in our case very difficult because, we could not test many functionalities and settings. This challenge was overcame by creating graphical interfaces with possibility to quickly adjust almost all settings like interval of sending messages to robot or dead zone of gamepad joysticks.

X. LESSONS LEARNED

Design process

In order to efficiently integrate the electronic components with the mechanical construction and to accelerate design process itself, we used an advanced EDA program – Altium Designer 15.1. This made the design of PCB very quick (fig. 16) and allowed us to generate the 3D models (fig. 17) of our electronics that helped a lot with the space management inside the fuselage.

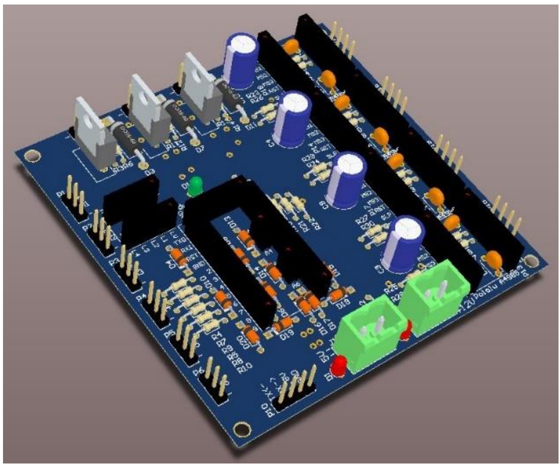


Figure 35 Altium - PCB model view

Control algorithms

We learned a lot about how to use feedback data from sensors to build regulator to improve control systems. We experienced control system without feedback and regulators and see how hard it is to control that kind of object without many hours of practice.

Safety

We put a lot of effort to perform a high safety robot system. We have met some big failures, like a fuselage leakage, which gave us a signal to invest our time on real time diagnostic systems, like onboard leakage sensor, onboard temperatures sensors etc. Thereby we have made an early failure detection system that gives us the opportunity to detect failures before they become dangerous.

Management and cooperation with media

Last but not least, our organization has been existing for about six months now. We started from zero and therefore learned how to manage the team, appear in the media and how to encourage investors to invest money in our project. We have surely improved our entrepreneur skills.

XI. FUTURE IMPROVEMENTS

Transparent fuselage – next year we are aiming at creating a completely transparent and durable fuselage, in order to be able to see the electronics while testing. This gives the team the possibility to see any leakage or a diode showing the inappropriate work of the component. Our outmost objective is to make the fuselage more aerodynamic and with all edges blended.

Six degrees of freedom – Currently our robot does not have any “side thrusters”, which makes it able to move in two directions (up/down, front/back) and tilt in three planes. There is no possibility to move left/right, what could have been a very good ability when dealing with manual tasks with the use of gripper.

Better controlling device

The gamepad, which we are using now, is quite uncomfortable. It was necessary to set wide dead zone on joysticks, what cause less precise controlling. We could try to use drone controller next year.

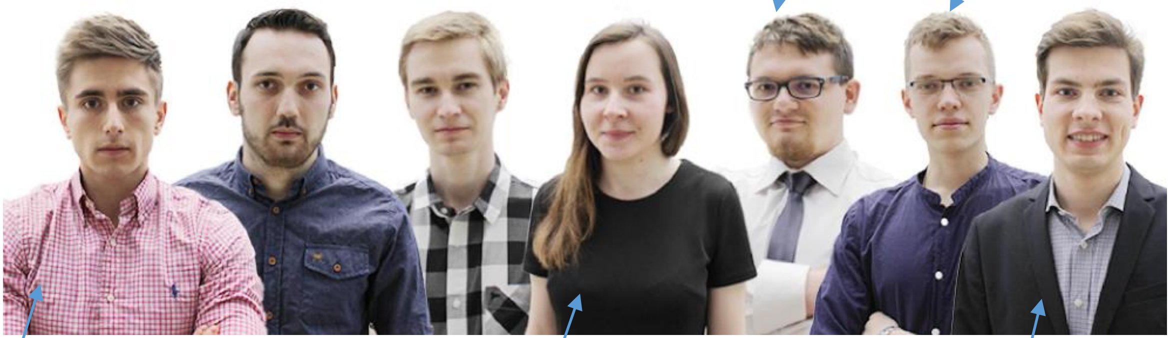
XII. REFLECTIONS

One requires the nerves of steel to reconcile the requirements of the mechanical engineers and the abilities of software engineers. My task was, apart from electronics, to be a compiler between those two.

Always be prepared to expect the unexpected, especially when you work both on software and hardware. I have learned to pay attention to every little detail so it wouldn't surprise me in least appropriate moment.

I learned that sometimes less is more. For a ROV which can maneuver almost freely two DOF's for the manipulator are surely sufficient.

As a CEO, the most challenging thing of the project for me, was multitasking. Not only had I to distribute the tasks, supervise the team, but also I had to think about the team budget, marketing and upcoming deadlines. It was a great lesson of self-discipline.



As a person responsible for the organizational issues and management I have learned, that managing a small company can be a very demanding task, as it requires a good time-management, strong analytical and critical thinking skills to solve problems at different structure levels (engineering, management, planning).

When constructing Ahti, I have gained a lot of experience, not only technical but also soft skills. I have improved the ability to work in group, to manage my time and to solve unexpected problems. Finally, I really enjoyed working with people full of passion and commitment.

When a team is relevantly small, it is essential to ensure a good internal and external communication. There are times when roles are becoming very dynamic and Team Members have to bear the responsibilities of a different company portfolios. Also, the press and business connections that have been established should be looked after by your company, as they might be a significant support with fundraising and the development of your project.

„ The SURA is a team of young, energetic and well-gifted people from the Warsaw University of Technology, who work very hard to accomplish their objectives. I believe that their efforts, combined with the ability to self-improvement, may be recipes for their success at the MATE competition and beyond. My team is very successful and brings many profits. I wish them all the best in their future endeavors!".
Paweł Malczyk, Mentor

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- DPS Software – for supporting us with SolidWorks licenses
- 3D Kombi – for 3D printed elements

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