Istanbul Technical University RoboSub 2021 Technical Design Report

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Abstract—The vehicle named Turquoise, which we designed as ITU AUV Team, has emerged as a result of long studies because of both financial inadequacy and lack of knowledge. Our vehicle, which could not participate in the RoboSub 2020 due to cancellation of the physical competition, gained a new look with the changes we made this year. Mechanical studies focused on reducing vehicle weight and increasing the strength of the vehicle. In electrical studies, previously designed cards have been improved and focused on the operation of the vehicle for a longer period of time. In software studies, previous software were improved and restructured for better debugging and portability as well as efficiency.

I. Competition Strategy

Although there are frequent restrictions in Turkey, due to the coronavirus, team members have tried to continue their preparations for the competition with social media platform such as Discord and Zoom. The Hull Design video was specially shot within the scope of the permissions obtained from ITU. Since the limitations within the scope of the competition were not clearly evident, the tasks given were made according to the limitations of the previous period.

Team members accomplished the tasks given below and took their videos.

- Start Gate
- Path
- Make The Grade
- Collecting
- Survive The Shootout
- Cash or Smash

The team plans on completing the start gate mission without penalty. To accomplish this task, a vehicle with appropriate dimensions is important. Our team paid attention to these details on the process of hull design. The box shaped frame design enables to use of the volume effectively. Our team kept in mind that any parts or tools places outside of the box shaped frame, might cause problems in the start gate mission as those parts might hit the gate. Also, this provides a safe enclosure for all actuators and sensors such as DVL, just in case. To perform a barrel roll for stylish movement and extra points, the difference of center of buoyancy and center of mass needed to be reduced in order to reduce the required torque while rolling. This required some modifications on the vehicle, and therefore some effort. These efforts kept minimal during the design and development process due to the limited time.

A camera was placed facing downward to detect path markers to localize the next mission. The detection is performed with OpenCV by applying an image color restoring method, color filtering, thresholding and contour detection. This enables the vehicle to obtain a heading angle to the mission. To save weight and prevent complexity, a Raspberry Pi camera used because of its dimensions, which enabled us to place the camera in the watertight enclosure. However, this required extra camera calibrations, as the image is lensed through the acrylic enclosure. Considering the fact that outside placement required an extra watertight enclosure, our team has decided machining such parts would take more effort compared to solving this problem by using camera calibration with a camera placed inside the main enclosure.

For the Make The Grade mission, a forward looking camera is used with our trained YOLO model for a tommy gun and a badge. Similar Guidance & Navigation methods were performed for this mission, enabling the vehicle to complete the mission without extra tools & steps. Due to lower complexity on this mission, our team implemented the Choose Your Side functionality, and thus enabled the vehicle to aim for the correct target and hit it.

Considering the requirements of the Collecting mission for full points award, our team has decided to not to lift the cover, therefore focus on dropping to the appropriate section. Again, similar algorithms were used with the bottom camera. Instead of lifting the cover, our team will use their effort and this competition time, for the Survive The Shootout mission, and therefore has spent efforts on developing acoustic signal processing system and torpedo launch system.

A torpedo launch system is designed with low complexity design ideas. Our team have had different approaches for launch system before, using electromagnetic forces. But due to complexity of electromagnetic launch system, and also after inspecting many other teams' reports and designs, our team has concluded on the pressurized pneumatic launch system for this mission.

II. Design Creativity

A. Mechanical

Our vehicle is 764mm long and 616mm wide and consists of three parts; tubes, bulkhead and chasis. Each part carries different kind of materials and equipments. To make our vehicle lighter, covers are emptied by carving in every suitable place and the bulkhead is largely empty from the inside.

Fig. 1. Turquoise From Upper Front View

- Tubes: The tubes acrylic cylinders and are used for covering our electronics completely. Each tube has a diameter of 172mm and are 298mm long. Tubes are connected to the bulkheads flanges with o-rings and make electronics completely safe from water.

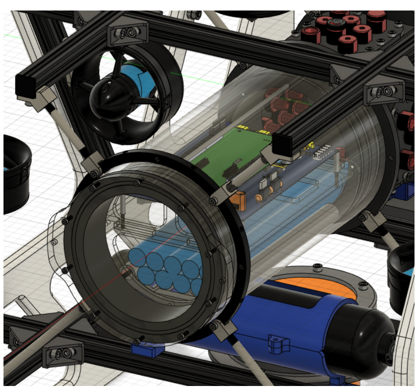

Fig. 2. One Of The Tubes With Electronics In It

- Bulkhead: The bulkhead is made of aluminium and in the shape of an octagonal cylinder. Four faces of the bulkhead have penetrator holes for letting cables in and out. Each of these four faces has 8 holes and enables 32 entries in total. Bulkhead has openings on two sides and these openings are covered with flange. There are o-ring seats on these flanges, which makes our vehicle waterproof when tubes are connected to flanges and compressing o-rings. It was essential to making bulkhead one solid material so a big aluminium cylinder bought and manufactured on a CNC machine. Thanks to aluminium the bulkhead is lighter than it seems.

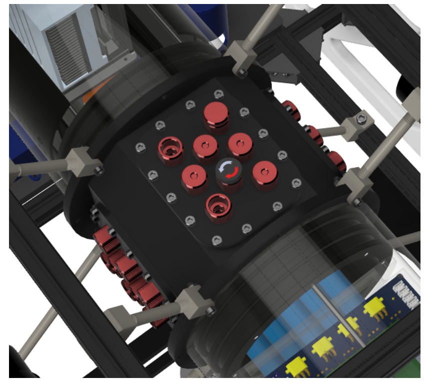

Fig. 3. Bulkhead Between Tubes

- Chasis: Every part of the vehicle is somehow connected to chasis. Chasis is the skeleton of the system. What makes chasis a thing is sigma profiles. Sigma profiles are connecting each other and together they make the chasis. Sigma profiles are very light and strong enough to carry more than AUV needs. Also, their shape makes us to use them as puzzle and assemble anything on them with little effort.

1) Mission Tools:

- Marker Dropper: Marker dropper is a tool for launching markers out of AUV. It works with gravity and a solenoid valve. Markers are conserved in droppers holding and when solenoid activated markers fall off themselves.

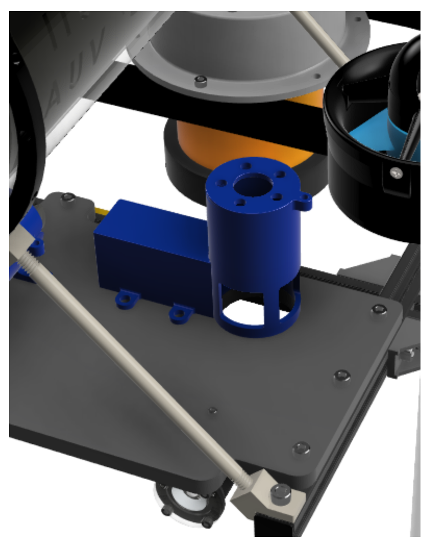

Fig. 4. One Of The Marker Droppers

- Torpedo Launcher: To launch our torpedo we have a pneumatic system. Launcher is located in the front of the vehicle and looking forwards. When compressed air pushes the piston torpedo launches off.

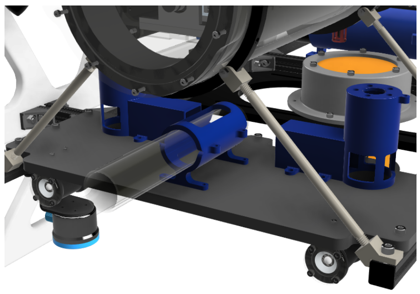

Fig. 5. Torpedo Launcher

- Manipulator: Our manipulator is also works with pneumatic system and located in the front of the vehicle as well. It's working principle with torpedo launcher is substantially same.

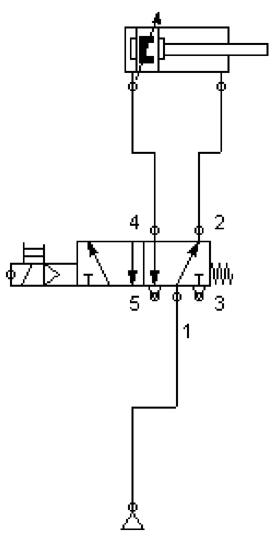

Fig. 6. Pneumatic System Diagram

B. Electrical

The design of the electrical system aims to be both supervised and allowed the microprocessors to communicate with the various sensors and motors on the vehicle, furthermore be regulated the power distribution within the vehicle.

a) Power Distribution: Components in the vehicle can operate with input power at different voltages. Therefore , a power distribution system was created. There is a high power requirement in the AUV because the underwater vehicles must have high mobility. For this , the vehicle is powered by a battery pack which specially designed by team members. This battery pack contains lithium-ion batteries. Each battery have an average voltage of 3.6V and a capacity of 3000mAh. The configuration of these batteries is 4S9P (4 series 9 parallel) and a total of 36 cells battery pack has 26100mAh capacity, 14.4V voltage and 375Wh energy. Considering the power requirement of the vehicle's eight engines and other electronic circuits, an 11AWG cable is used to satisfy the power consumption of approximately 20W in stagnant operation, approximately 70-80W in continuous operation and up to 500W in instant operation.For an average power consumption of 80W in continuous operation, this battery pack runs the vehicle for approximately 210 minutes (3.5 hours).

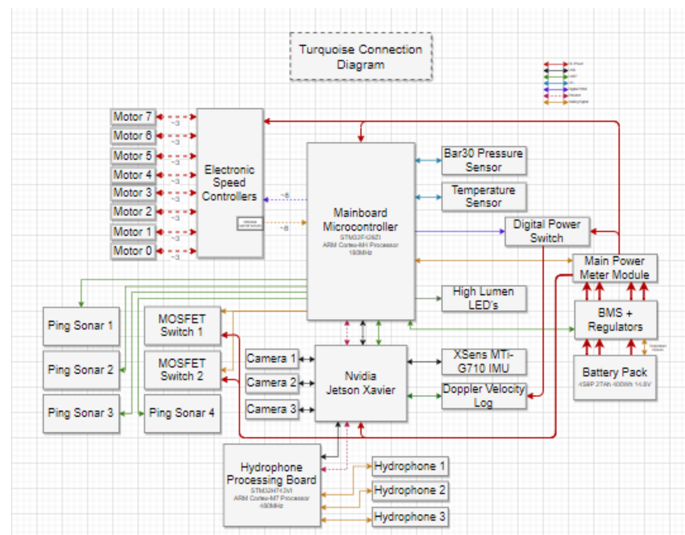

Fig. 7. Power Distribution Diagram

A Battery Management System (BMS) circuit in the battery pack ensures the charging safety of lithium-ion batteries, and a temperature sensor on this circuit provides security against heating problems. Moreover, the power inputs taken from the battery pack are protected against possible short circuits and overcurrents with the help of fuses on the PCB's.

b) Sensors: An Inertial Measurement Unit [1] (IMU) is used to determine angle of rotation, rate of rotation and linear acceleration.The selected inertia measurement unit is shown in Figure 8.

Fig. 8. XSens Mti-G-710 Inertia Measurement Unit

It was decided to use the pressure sensor [2] , considering its small dimensions and high sensitivity in order to

[1]shop.xsens.com
[2]bluerobotics.com

stabilize the depth of the vehicle during the missions. Even though the depth can be measured with the help of the pressure sensor, the mission might fail if the altitude of the vehicle (distance to the ground) is not measured precisely. In this context, due to its cost and small volume, 2 Ping Sonar [3] were used and the distance to the ground could be determined horizontally and vertically. It is important to know the location of the vehicle during the execution of the tasks. A Doppler Velocity Log [4] (DVL), which has a high operating frequency range and complies with the weight and size restrictions of the competition, was used in order to determine the position of the vehicle relative to the (x, y) axes. The selected DVL is shown in Figure 9.

Fig. 9. Navquest 600 Micro DVL

3 hydrophones will be used for the acoustic detection of the signal emitting pinger. A hydrophone is an underwater microphone obtained by covering a piezzo element with a waterproof material. In the selection of the hydrophone, a hydrophone[5] model, which stands out with its high sensitivity, small dimensions, and simplification of the amplification stage in the acoustic processing circuit designed with an amplifier circuit, was chosen. The selected hydrophone is shown in figure 10.

Fig. 10. Aquarian H2C Hydrophone

It is aimed to perform image processing tasks through a front-facing camera in the vehicle. For this reason, a Low-Light FHD USB Camera was preferred because it has an adjustable lens and has a wide viewing angle, making it easier to detect tasks.

[3]bluerobotics.com
[4]link-quest.com
[5]aquarianaudio.com

c) Motherboard: To operate all actuators and obtain data from all sensors, a motherboard is designed. The motherboard consists of 8 Electronic Speed Controllers (ESC), the power distribution infrastructure, STM32F4 type microcontroller and multiple connectors for sensor connections. Also, a current sensor is placed on the power line of each ESC to obtain the current draw of each thruster. This enables the microcontroller to estimate the thrust or to implement some safety features. The motherboard has been designed to reduce the complexity of cables by aiming for ease of use. There are 8 Electronic Speed Controllers (ESC) on the motherboard, 4 of which are on the bottom layer of the board where the vehicle's engines are controlled and 4 are on the top layer of the board. ESCs are mounted in their designated places on the motherboard and the connecting cables are shortened as much as possible, thus avoiding cable clutter and saving space. There is a microcontroller from the STM32F4 family on the board. It is connected to the relevant headers from the selected communication pins of this microcontroller. Communication with the sensors to be used is provided through these headers.

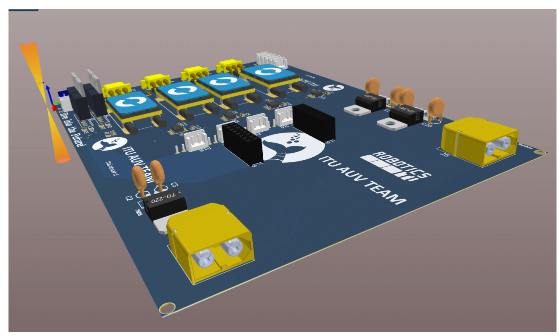

Fig. 11. Motherboard 3D View

The purpose of the embedded software on the motherboard is to control all electronic inputs and outputs (I/O) on the vehicle and to receive data from the sensors. Also, the software performs some safety measures by monitoring the critical system components such as battery or thrusters, and taking action when needed. This is primarily to prevent any damages to humans or environment in case of a catastrophic failure. Apart from a physical kill-switch that disconnects the battery from the vehicle components, the embedded software can also decide to power down the vehicle in case of an emergency.

The embedded software also creates an interface layer for the high level software to control vehicle or to collect sensor data by use of Rosserial[6]. This enables all features of the motherboard to be accessible on the ROS network. Thanks to this RTOS based embedded software, all such features can be prioritized and scheduled in the task

[6]wiki.ros.org

scheduler, to offer improved efficiency and a modular system.

d) Acoustic Signal Processing Board: To detect the azimuth of a sound wave, an acoustic signal processing board was designed. Due to the shape and limited space of the hydrophone housing, PCB split into 2 sections as lower section and upper section. The main task of the Acoustic Signal Processing Board is azimuth detection by use of phase difference of the signals emerging from 3 identical hydrophones. For superior anchorage of the signal emerging from the pinger, Sixth Order Chebyshev Band-Pass filter is used on the lower PCB section to permit signals to be passed in the range of 31.28kHz-61.73kHz. The signals are then passed through a digital programmable differential amplifier and a buffer amplifier, sequentially. The filtered signals are routed to the ADC inputs of a STM32H7 type microcontroller which can sample the signal with 16-bit resolution and 3.6MHz sample rate.

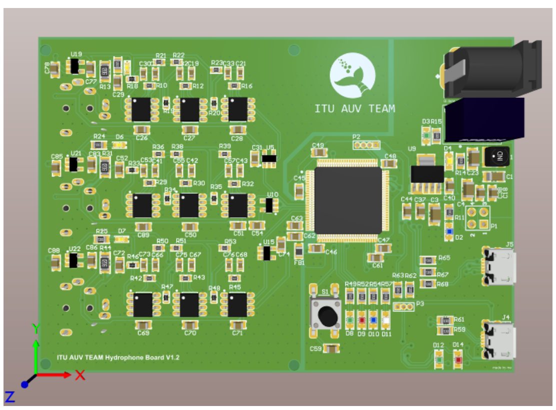

Fig. 12. Acoustic Signal Processing Board 3D View

WAVES [1] (Weighted Average of Signal Subspaces) algorithm is implemented in the microcontroller with C programming language to calculate the azimuth angle of an incoming ping.

C. Software

a) Control Navigation: To control the vehicle in all 6 axes, at first multiple PID controllers were used. But after switching to a Model Predictive Controller a cost based tuning was implied. This outperformed the previous best tuned PID controllers and also gave the opportunity to control the vehicle with a reference state trajectory, rather than static reference.

The model was designed and implemented on MPC with 13 states which are described in Table I.

b) State Machine: The flow of the missions is operated by state machines. A state machine is a behavior model that comprises a finite number of states. According to the present state and a given data, the machine enforms state transitions and produces outputs. The goal of finite state machines, which are designed one by one for each task, is to perform the task as soon as possible and to continue the task by making accurate decisions in the face of possible problems.

State	Description
p_x	Position x
p_y	Position y
p_z	Position z
q_w	Quaternion w
q_x	Quaternion x
q_y	Quaternion y
q_z	Quaternion z
v_x	Velocity x
v_y	Velocity y
v_z	Velocity z
w_x	Angular Rate x
w_y	Angular Rate y
w_z	Angular Rate z

TABLE I
Model Predictive Controller States

c) Simulation: To observe and quickly test the mission algorithms, object detection, and hydrodynamic / hydrostatic effects on the Turquoise; a simulation using the uuv_simulator [2] package was developed. The simulation is Gazebo based and ROS compatible for easy to use modularity. Thanks to this simulation, the testing phase of the algorithms, and therefore process of production and development of the algorithms has been accelerated.

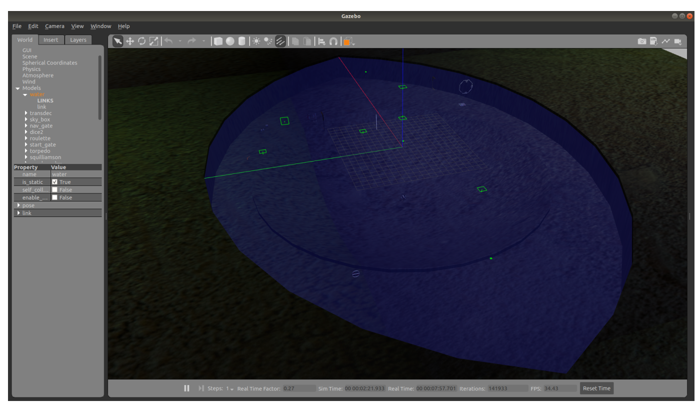

Fig. 13. Simulation of Robosub Test Environment

In order for the simulation to be realistic, the vehicle features and parameters were taken from Autodesk Fusion 360 (CAD Software), Ansys (CFD analysis software) and some real-world test results. Also, all sensors on the vehicle (IMU, Magnetometer, Depth/Pressure Sensors and Ping Sonars), cameras and thrusters have been modeled in the simulation by their parameters. In addition, a kinematic and dynamic model equations in ”Underwater Vehicle Dynamic Modeling” [3] were taken as reference in the mathematical modeling of Turquoise.

Fig. 14. Example of Some Mission Objects in Simulation

Additonally, a software called "Fake Battery System" was developed to predict energy consumption in the BMS simulation environment, which is mentioned in the field of electronics. By separating the static and dynamic forces on the vehicle, the estimation algorithm was developed based on the power per 1 millisecond. A virtual battery management system, which detects the energy consumed and the remaining energy from the battery, was obtained.

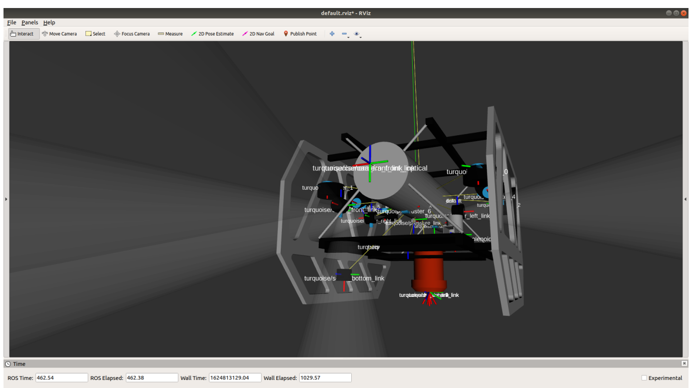

Fig. 15. 3D Visualization of Turquoise on RViz With Topic Names

d) Computer Vision: Computer vision covers an important part of the competition. Our main priority has been to achieve the most accurate and desired results in a minimum time. First of all, a classical approach using OpenCV [4] has been developed to detecting objects with color correction, masking, getting borders and center. Secondly, the data set is prepared and the collected data is replicated by data augmentation. Then, these collected data sets were examined in different algorithms with speed and accuracy criteria. It has been determined that YOLOv4 [5] has priority in real-time detection and speed. It has been observed that the accuracy rate is high as well as the detection speed. Our other option is Faster R-CNN [6]. This algorithm is both supported by TensorFlow Object Detection API [7] and is the fastest in training. Moreover, it was thought to work on different filters to eliminate some mistakes while detecting. For instance, Kalman Filter [8].

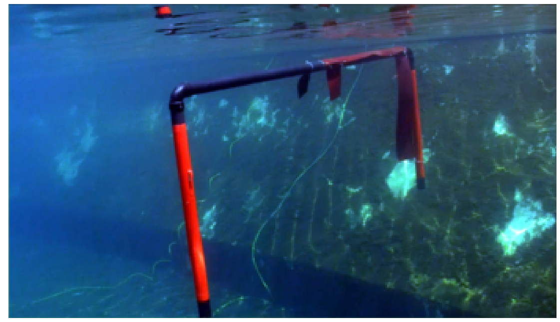

Fig. 16. Clarified Gate After Image Processing

III. Experimental Results

- In order to keep the vehicle stable at a certain depth, the algorithm written by our team was rearranged and the vehicle was stabilized. Thanks to this algorithm, the collision of the vehicle with any place during close passes, possible reverse movements during torpedo shots were prevented, and it was determined in the experiments that it accomplished its tasks by consuming less energy than before.

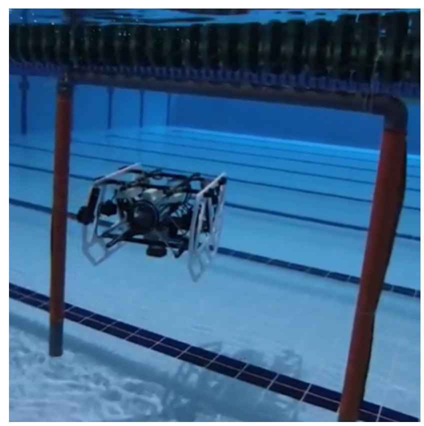

Fig. 17. Real World Test

- In pandemic conditions, where it was difficult for the whole team to come together and go to the real world test, the simulation made a great contribution. Specially, the ability of testing the image processing algorithms and competition strategy in simulation has accelerated the team.
- Our data set, which is masked and edited with image processing, is expanded with data augmentation. YOLOv4 and Faster R-CNN algorithms are trained with the expanded dataset. As a result of the tests, the accuracy rate of YOLOv4 is between 95-99 percent and the accuracy rate of faster R-CNN is between 97.0-99.5 percent .In addition to detecting objects, centres of objects are also detected. Although physical tests could not be done adequately due to the pandemic, many tests are carried out on simulation and computer.

- Stability tests frequently done on Turquoise as new materials added and olds removed. These tests were done in the circulation tanks and olympic pools in our campus. During these tests it is observed that vehicles stability continously changing with every thing done on equipments. Trim of the vehicle have fixed everytime with added weights or buoyant foams.
- Turquoise used to have 6 thrusters and couldn't done all of the 6 DOF motions. To make Turquoise more mobile, 2 more thrusters have been added to the design. These extra 2 thruster were located in the Y direction and let the Turquoise make sway motion.
- During the Acoustic Signal Processing Board experiments, the copper paths of PCB were not kept equal for each hydrophone data, thus unwanted phase angles emerged.The copper paths are adjusted equally in order to prevent this situation and unwanted phase angles are prevented.
- Since the voltage follower was not placed in the voltage divider circuit, 1.65V DC voltage received was not stable. After the situation was noticed, a voltage follower was placed in the circuit and stability was ensured.
- Hydrophones were directly connected to 5V DC voltage and were grounded in common. For this reason, unwanted noise has occurred and damaged the received data. Later, a separate DC/DC Converter was used for each hydrophone and the grounding was made separately for each hydrophone to correct this situation. In this way,noise is prevented.
- During the placement of the cables in the vehicle,the distance between the cables which draw high current and the cables which transmit the sensor data were became very close and the data which emerge in sensors damaged. The cables that draw high current were coated with aluminum in order to prevent this situation.

Acknowledgment

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TABLE II
Component Specifications

Component	Vendor	Model/Type	Specs	Cost(if new)	Status
Buoyancy Control	-	-	-	-	-
Frame	-	Aluminium Sigma Profiles	-	25$	installed
Waterproof Housing	BlueRobotics	Cast Acrylic Tube 6”	link	98$	installed
Waterproof Connectors	BlueRobotics	Penetrator	-	0	installed
Thrusters	BlueRobotics	T100	link	169$	installed
Motor Control	BlueRobotics	Basic ESC	link	27$	installed
High Level Control	ITU AUV Team	Model Predictive Controller	-	-	-
Actuators	ITU AUV Team	Torpedo & Bin Dropper	-	-	installed
Propellers	Built-in w/Thrusters	-	-	-	installed
Battery	Sony	US18650VTC6 Custom Pack	link	250$	installed
Converter	Analog Devices	LTC3780	link	16$	installed
Regulator	-	-	-	-	-
CPU	Nvidia	Jetson Xavier	link	750$	installed
Internal Comm Network	TP-Link	TL-SF1005D	link	7$	installed
External Comm Interface	BlueRobotics	Fathom X	link	159$	installed
Compass	Built-in w/IMU	-	-	-	installed
Inertial Measurement Unit (IMU)	XSens	MTi-G-710	link	4500$	installed
Doppler Velocity Log (DVL)	Navquest	600 Micro	link	10500$	installed
Vision	Sony	IMX219 (Raspberry Pi Camera v2)	link	50$	installed
Stereo Vision	StereoLabs	ZED	link	350$	installed
Acoustics	Aquarian Audio	H2C Hydrophones	link	120$	installed
Sonars	BlueRobotics	Ping Sonar	link	279$	installed
Pressure Sensor	BlueRobotics	Bar30	link	72$	installed
Light(s)	BlueRobotics	Lumen SubSea Light v2	link	119$	installed
Mainpulator	-	-	-	-	installed
Algorithms: vision	YOLOv3	-	-	-	installed
Algorithms: acoustics	WAVES	-	-	-	installed
Algorithms: localization and mapping	robot_localization & ORB-SLAM	-	-	-	installed
Algorithms: autonomy	ITU AUV Team	-	-	-	installed
Open source software	OpenCV & ROS & FreeRTOS	-	-	-	installed
Team Size (number of people)	39	-	-	-	installed
Expertise ratio (hardware vs. software)	H: 20, S: 19	-	-	-	installed
Testing time: simulation	300-350h	-	-	-	installed
Testing time: in-water	150h	-	-	-	installed
Inter-vehicle communication	-	-	-	-	installed
Programming Language(s)	C & C++ & Python	-	-	-	installed

Appendix B: Outreach Activities

As the ITU AUV Team, we are aware of the importance of transferring knowledge to future generations, and we have participated in many activities to interact with STEM students and Robotics interests. In the last two years, 2020 Boat Show, Inovatim and as ITU Project teams, we had the opportunity to meet with Robotics-related students from Beşiktaş Anatolian High School.

In the 2020 Boat Show, we came together with lots of underwater admirers and had a chance to meet them. From the first minute, we were greeted enthusiastically. Our stand has aroused great interest in people as came to our stand and examined the vehicle and asked questions. For both us and the participants, it was one of the most productive activities. We had the opportunity to meet a lot of new people and exchange information, thanks to this event. In conclusion, with more networks we were provided, it was easier to access the sponsors we needed for our vehicle.

Fig. 18. Photograph From Boat Show

We also took a part in Inovatim's activity, Innovation Week in 2019. Inovatim, which is a subsidiary of the Turkish Exporters Assembly, tries to instill innovation in young people and to develop innovation studies in Turkey. Thanks to Inovatim, we had a chance to open our stand at this event. We had the opportunity to chat on many topics, from what materials other teams use to how the team works. Thus, we had the chance to look not only from our own point of view but also from other aspects. We topped this event off with the award we received by participating in a competition within the event.

Other than our generation, for inspiring the future STEM students the best way to introduce the underwater world is by meeting with the high schools. In this matter, we went to the Beşiktaş Anatolian High School and met with lots of students. We think that we have attracted many students about the submarine engines, from the slightly interested to the very interested, furthermore, we invited them to our school. We have shown that we have destroyed the stereotypes in the minds of many students who want to become engineers and have shown new areas in engineering for them.

Fig. 19. Our Team in Inovatim

Fig. 20. Our Stand in Beşiktaş Anatolian High School