PWr Diving Crew Technical Design Report (June 2021)

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***Abstract*—KN Robocik's latest AUV called "BlueNemo" is a new version of the club's most successful generation, which has already competed in RoboSub 2019 in San Diego. Since the last competition the main focus was to eliminate imperfections of the design. A lot of work was done to improve the vehicle's software and electronics. The team has reorganized the software architecture, designed a new outer frame and printed circuit boards. A new module - DVL is currently being integrated into vehicle. Also, the torpedo system has been greatly improved. Due to COVID-19 pandemic the major part of the project has been carried out remotely using various online tools that made the workflow more efficient.**

I. Competition Strategy

A. Overall strategy

Based on the team's experience from previous RoboSub competitions, it has been concluded which of the tasks could be potentially problematic. The main focus was on utilizing the strengths of the project. After studying previous years' tasks, a number of physical models were prepared. They were then used to train and test the artificial intelligence algorithms.

The first set of navigational tasks requires two key components: a camera for visual analysis of the environment and a motion control system able to position the vehicle precisely and quickly. YOLO V5 neural network is used to detect objects in the input image provided by two main navigational cameras: front and bottom.

For training the AI two main sources of data are used. First consists of real images taken in pools that are later labeled manually and second is generated using the simulator which outputs both images and labels. Dataset size has been also multiplied by additionally post-processing the images using effects such as blur, noise, flipping, offsets and distortions which should help recognize objects even in unfavorable conditions.

For tasks involving pingers, the output from two hydrophones is used after a denoising preprocessing step. However if audio input becomes unreliable or unnecessary it can be switched to using video input as a primary source of data, at any given time.

For *Survive the Shootout*, the team moved away from the compressed carbon dioxide propulsion and designed an electric drive to improve stability and range. This task also required a lot of variables that were configured through trial and error like torpedo launcher offset, method of checking for successful hit and a number of tries. Because of that it was crucial to enable quick reconfiguration even right next to the pool through a remote terminal.

Due to the limited ability to test solutions in a real environment, some tasks such as *Collecting (bins)* have been attempted to solve in the easiest way possible by designing a simple mechanism consisting of a basket and a servo to open it and drop the marker at the right time.

Previous manipulator designs have turned out to be too difficult to operate underwater, so this year a simple three-finger gripper was designed and it is attached directly to the vehicle construction. Thanks to that the *Cash or Smash* task can be undertaken without the need for complex control algorithms. Also this year a lot of effort was made to make sure that the gripper is correctly perceived by the vision system. It is covered by two cameras, partly by the main camera and by a gripper camera that is placed at an angle. First the AUV approaches the object using the main camera and then switches to the two-camera view. Output from two network instances running on cameras is combined in order to locate the object in relation to the gripper in three dimensional space which would be impossible with a single camera. Specifically it is done by comparing two bounding boxes from cameras against positions of cameras in relation to the gripper. What is also important is redundancy in the system which allows it to function even if the view from one camera is obscured for example by air bubbles or particles [1], [2].

Limited access to the pools during this year made it impossible to test out all solutions, so some of them have not been examined yet. The team however hopes that the time spent on research will bring us success in the future in on-the-spot competitions.

II. Design Creativity

A. Electronics

1) Data pipeline: The team's previous vehicles were based on the idea of using three processing units cooperating with each other. NVIDIA Jetson AGX Xavier was a GPU handling the image processing, neural network operations and general decision-making. Raspberry Pi was responsible for hydrophones, effector management as well as collecting other sensor data, while STM32 mainly operated the thrusters, lights and the torpedo launcher. In the present AUV generation it has been decided to simplify the dataflow and a decision was made to remove Raspberry Pi from the internal communication network. Not only does it lower the risk of potential data loss on the communication channels, but also allows us to optimize the space needed for electronic components inside the vehicle.

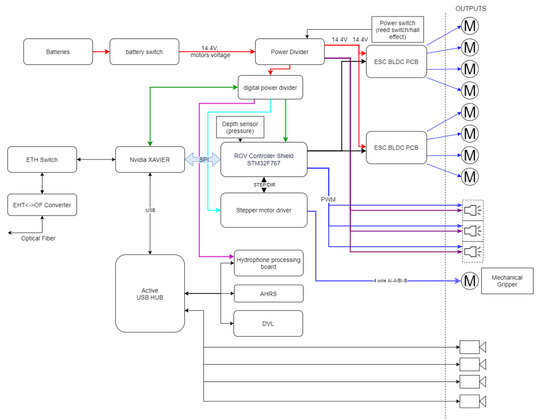

Fig. 1: Block diagram

2) PCB design: One of the major improvements in electronic design was a step towards modularity. The team has divided the previous PCB which was responsible for power as well as connecting ESC to the thrusters, into two smaller ones. As a result, the combined surface area of those PCBs has decreased by 25%.

3) Vision: For image processing, we used four cameras placed in three different places in the vehicle. The main module, which consists of two cameras, is located inside. One of them is placed above the other one and set to show the terrain at a different angle. Both are located behind a protective cover made of polycarbonate. Another camera is placed near the torpedo launcher to improve target visibility. The last camera is placed under the board to widen the view area which provides extra feedback to improve drone control.

All four cameras are connected to the mainboard via a USB interface. Every camera, excluding these inside the drone, has its own waterproof case which is attached to the drone frame.

The drone is illuminated by three LUMEN LIGHT R2 modules. These lights are specially constructed to work underwater, capable of operating at depths of up to 500m. The light distribution angle of 135 degrees and the light temperature of 6200K are parameters best fitted for the applications. The lighting system emits a total of 4500 Lumens, with a power consumption of 15W per module.

4) The hydrophone system: The system consists of two RESON TC4013-1 hydrophones by Teledyne Marine, connected to a dedicated PCB (Fig. 2), where signal processing takes place. A set of operational amplifiers and an audio codec are used to process the signal by subjecting it to bandpass filtration, and then converting it into digital data, which can be transmitted to the overriding controller, and further processed.

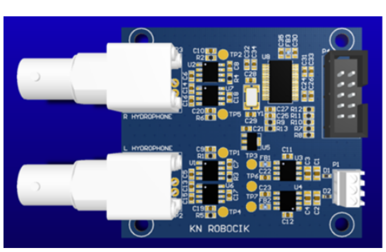

Fig. 2: Hydrophones printed circuit board

In the previous generation, information was sent to the Raspberry Pi using I2C and I2S protocols, but due to further development, it was decided to change Raspberry Pi to the NVIDIA Jetson AGX Xavier platform. As a result, it was possible to implement an improved signal analyzing program based on neural networks, thanks to which the accuracy of finding the localization of the sound source will increase [3].

5) CAN: Apart from the use of SPI, I2C, I2S, due to the operating environment loaded with numerous sources of electromagnetic interference (motors and converters), a more robust form of communication was needed. Therefore, it has been decided to use the Controller Area Network which provides reliable data transmission by using a differential bus, a message priority arbitration system and error detection. The CAN bus connects the NVIDIA Jetson AGX Xavier and the main onboard microcontroller, with several stand-alone data acquisition modules based on STM32. Since these devices are programmed in a large team, to facilitate cooperation, it has been decided to implement higher layers of network communication. As a result a simple client-server protocol named RoboCAN is under development. When finished it will greatly reduce the time needed to program any device that communicates over the bus, as it is going to take care of the whole low level configuration. All the programmer has to do is implement the desired behaviour. Additionally an idea has been proposed to use the CAN bus for programming individual devices without disassembling the whole construction, a bootloader that will make this possible is currently being developed [4].

6) DVL: Based on the previous experience and observations of other participants, the team deemed the improvement of velocity measurements necessary. That's where DVL – Doppler Velocity Log - comes into place. It allows for a very precise calculation of the relative velocity of the device in XYZ coordinates [5].

DVL operation principle is based on the doppler effect. It transmits multiple acoustic pulses that get reflected from the seabed. Then, they get processed to extract the information about the velocities.

Currently, the electronics department is at the very end of the integration of the device with AUV. Once finished, it will provide a noticeable advancement in both: tracking the position of the AUV and setting the spatial positioning reference for the laser triangulation.

7) Triangulation based laser scanner: The laser triangulation module is a new feature that is planned for the next season. Its goal is to make the AUV able to determine the state of its surroundings not by image processing as it is done currently, but by a 3D point-cloud mesh of the environment obtained using a triangulation based laser scanner. Other use cases for the module might include precision scans of the sea floor or target recognition.

Future versions of the project are planned to use laser scanning directly with the DVL module, and as a result obtain the exact movement parameters of the vehicle as well as the 3D map of the environment.

At the current state of the research the functional scanner able to perform 3D scans of small objects has been built and is being tested. Next step of the research will be to adapt the scanner for underwater operations and to enlarge the scanning area.

B. Software

1) Object detection: In image object detection is performed by NVIDIA Jetson AGX Xavier so its processing power limitations had to be taken into account. YOLO V5 project offers a few different sizes of the prediction model, namely: small, medium, large and extra large. Each one slightly differs in architecture and has different performance. In the end though, a small model has been chosen as it needs to be evaluated in real time and it was the only reliable option able to meet performance expectations with data from a 30 FPS camera producing image analysed in 480x480 resolution. The fact that YOLO V5 is based on PyTorch allows for the use of this library's toolset and to take advantage of its automatic optimisations. It proved to be very easy to use, especially compared to the previous solution that used YOLO V3 dynamically loaded library through ctypes bindings [6].

Since both computer vision and sensor libraries were written in Python language, a decision has been made to use it as the main language for the controller program. Besides these reasons the language also provides a lot of metaprogramming utilities, is easy to read and its core utilities are cross platform. The main disadvantage of that language is its performance, however it plays a marginal role considering that AUV is limited primarily by its physical movement speed.

2) Caching: Very important concept that wasn't really utilised in previous competitions that the team took part in is caching. New software was developed in order to decide how often to fetch, analyse sensors, vision data and move the fetching into least computationally busy periods of time. This way it was possible to achieve almost indistinguishable results with less required computational power.

3) Gitlab: Version control system is a crucial tool in software development - the team uses a distributed Git system. The team used to use GitHub remote repositories for managing the code and keeping trace of the improvements, but recently decided to switch to another platform - Gitlab. Thanks to its' features, it is possible to create group projects corresponding to the software and electronics departments. Instead of working on the project individually, it is now assigned to the entire team. Gitlab also allows the automation of the testing process by CI/CD tools. It guarantees the higher reliability of the vehicle's software and helps us find errors more efficiently.

C. Construction

1) Thrusters: Over the years, the effect of making the propulsive thrusters responsible for moving the vehicle in the horizontal plane has been tested. Consideration was given to placing four thrusters parallel, rotated 45 degrees, and 30 degrees off the axis of the vehicle. Due to the predominantly forward motion of the vehicle, a solution with four thrusters on each side was decided upon, two rotated 30 degrees about the axis of the vehicle to provide smooth forward and side-to-side motion and two facing up for submerging [7].

2) Gripper: There are two distinct parts of the gripper - the cover of the electrical motor and the gripping part. For the cover, polyoxymethylene has been used, as it can be easily machined. This allows reaching the required surface finish as well as geometrical tolerances which are necessary for the elements to be waterproof. The claws of the gripper are 3D printed out of PLA [8]. This solution is easily modifiable and allows for complex geometry to be used as needed for efficient gripping. The parts are connected by a screw with an ACME thread that is powered by the motor and allows the fingers of the gripper to move.

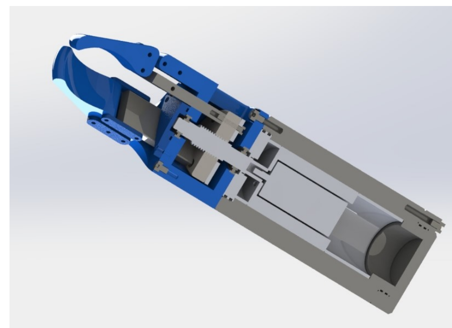

Fig. 3: 3D model of mechanical gripper (section view)

3) Torpedo: New concept for the torpedo system is based on a propeller powered with a small DC motor, sealed inside the housing. In a previous design, which considered using CO2 cartridges to drive the torpedoes, some problems with safety and accuracy were encountered. It was decided to create a concept with solutions already tested. Simple electronic circuit is responsible for controlling the DC motor and it is activated through a reed switch, making it a more efficient solution. DC motor and battery small dimensions helped create a new torpedo design just as small as the previous one. Still a lot of improvements need to be made in order to make the torpedo system reliable and repetitive.

III. Experimental Results

The most reliable form of testing is running the controller program in a fully assembled AUV in a pool. Even though there were some limitations caused by the pandemic it was still manageable to assemble a group of people that performed the tests and provided necessary data. Singular elements of the AUV such as hydrophones and sonars have been tested in the pool, though most of the work has been done using either collected data or in various levels of simulation.

Due to the current situation, it became important to develop a comprehensive and reliable underwater simulation environment that can be run on a low-end laptop. The solution was created in the Unity3D engine and can be connected to the controller program running on the same computer through the ML-Agents toolkit [9], [10]. This allows team members to test and develop the main controller program from anywhere, although the disadvantage is that the simulated environment is idealized and doesn't cover all of the real-life cases.

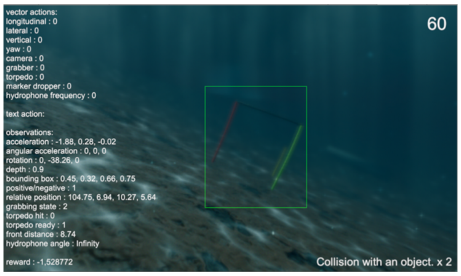

Fig. 4: Debug view of the simulation showing exchanged data

All sensors and thrusters of the current vehicle are simulated through various geometric calculations and external libraries. Most of the free packages for simulating water buoyancy and current did not meet the team's expectations in terms of efficiency, setup ease, and sensible defaults. Therefore, it was decided to create a tailored Unity3D module that uses the NVIDIA PhysX engine as a foundation.

For graphics visualization, Aura 2 library was used to introduce volumetric lighting, as well as a combination of procedural noise, particles, rendering surface distortions, and random blurring which results in very realistic effects in real-time. The rendering module of the simulator is also used to collect data for object detection. This allows one to generate a diverse dataset without the need to label the data manually or modify the images to create more variation.

Fig. 5: Samples from the dataset generated by the simulator

Collection of dataset for the artificial intelligence algorithms has been achieved through physical models that are built according to the instructions of given tasks. Those props are then submerged in the pool and are recorded either by AUV's camera or through a handheld one. After that, the recordings and pictures are uploaded to a private labelling server with a Computer Vision Annotation Tool on it. The data could be labelled by every member of the team. This solution allows for fast and effortless creation of large datasets.

1) Hydrophones - testing: For proper control of the vehicle an algorithm calculating the direction of the signal from the hydrophones has been implemented. First version was meant to determine phase shift between signals received by each of the hydrophones. Unfortunately after some testing it came out not to be a good way of finding required information.

A second algorithm, which is still in use, was based on measuring the time in which sound gets from one hydrophone to the other. First test confirmed that this method could be used with success, so the research in that direction was continued. It was decided that the best solution for interpreting the hydrophones' signal would be a neural network. To collect a dataset for said network a dedicated stand, with precise angle alignment was made and the measurements at the pool were taken.

Acknowledgment

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APPENDIX A
COMPONENT SPECIFICATIONS

Component	Vendor	Model/Type	Specs	Cost (if new)	Status
Buoyancy Control	-	-	-	-	-
Frame	Wimarol - machining	Developed by team	POM	Reused	Installed
Waterproof Housing	CNC Kramet - machining	Developed by team	AW-6060	Reused	Installed
Waterproof Connectors	TopService - machining	Developed by team	AW-6060	170 $ (650 PLN)	Installed
Thrusters	Blue Robotics	T200	T200 spec.	Reused	Installed
Motor Control	Blue Robotics	Basic ESC	ESC spec.	Reused	Installed
High Level Control	-	Custom	PID	-	Done
Actuators	Pololu	4822 0.12 Nm	Pololu 4822 spec.	35 $	Work in progress
Propellers	Blue Robotics	included with T200 thruster	T200 spec.	Reused	Installed
Battery	GRALMarine	2x 23,8 Ah; 1x 6,8 Ah	Battery spec.	Reused	Installed
Regulator	Murata; Recom	UWE-12/10-Q12; RPA60-2405SFW;	UWE-Q12 spec.; RPA60-2405SFW	Reused	Installed
CPU	ST;	Nucleo-F767ZI MPU;	STM32 Nucelo F767ZI spec.;	35 $;	Installed
	NVIDIA	Jetson AGX Xavier 16GB SoC	NVIDIA AGX Xavier spec.	Reused	
Internal Comm Network	Texas Instruments	CAN bus transceivers	SN65HVD230D spec.	20 $	Installed
External Comm Interface	Helukabel	TCP/IP 1000base Ethernet via F-FTP 450 CAT6	Helukat 450 spec.	Reused	Installed
Compass	Xsens	AHRS included	MTI series X-sens spec.	Reused	Installed
Inertial Measurement Unit (IMU)	Xsens	MTI-30	MTI series X-sens spec.	Reused	Installed
Doppler Velocity Log (DVL)	Teledyne Marine	Wayfinder DVL	Wayfinder spec.	11029 $ (42127 PLN)	Installed
Vision	Logitech	C922 Pro Stream Full HD	Logitech C922 Pro spec.	Reused	Installed
Acoustics	Teledyne RESON	TC4013	TC4013 spec.	Reused	Installed
Manipulator	CNC Kramet - machining	Developed by team	three-finger or two-finger configuration	150$ (570 PLN)	Work in progress
Algorithms: vision	-	-	Convolutional neural nets, edge and colour detection, Hough transform	-	Done
Algorithms: acoustics	-	-	Phase difference	-	Work in progress
Algorithms: localization and mapping	-	-	-	-	-
Algorithms: autonomy	-	-	YOLO V5 PyTorch Implementation	-	Work in progress
Open source software	-	-	YOLO V5 PyTorch Implementation, Unity ML Agents Toolkit, Pytest framework	-	Work in progress
Team Size (number of people)	-	-	36	-	-
Expertise ratio (hardware vs. software)	-	-	02:01	-	-
Testing time: simulation	-	-	200+ h	-	-
Testing time: in-water	-	-	20 h	-	-
Inter-vehicle communication	-	-	-	-	-
Programming Language(s)	-	-	Main: Python; auxiliary: C/C++/C#/HLSL	-	-

APPENDIX B
OUTREACH ACTIVITIES (OPTIONAL)

The project couldn't exist without the team members. It was necessary during the pandemic to take care of the team spirit. It is important as well as finishing the project to create an atmosphere for everybody to unleash their potential. The team participated in various integrations via Zoom and other activities. We focused on emphasizing outreach activities as well.

Fig. 6: Members of the team during work

A. DFN

The Lower Silesian Science Festival is an annual science event held in our region - its aim is to promote science, encourage local communities to discover technological wonders and to present young talented scientists. As our goal is to share passion towards the underwater world and its exploration, we decided to engage in the festival by giving lectures on AUVs and ROVs. Although the remote formula of the festival seemed to be a challenge, we were thrilled to see the enthusiasm of our young audience. This year, we are going to participate in another edition, hoping for a in-person participation

B. National Conference on Composites (Ogólnopolska Konferencja o Kompozytach)

In May 2021, we had the pleasure of co-facilitating a national conference about composites together with another science club "Kompozytywni". The online event lasted two days and featured 20 guest speakers, who represented various technical fields. The conference attracted almost 130 participants and we were pleased to be a part of it.

Fig. 7: Our Conference on Composites