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## UNMANNED SURFACE VEHICLE – TRITOR

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### Summary

This paper presents an unmanned surface vehicle Tritor that was developed, constructed, and tested within an innovative, multi-purpose, multidisciplinary, low-budget and environmentally friendly solution. The idea behind this work was trying to invent a new concept of a miniature surface vehicle that will be unmanned, remotely controlled and autonomous, with electric propulsion, and with an innovative Three Slender Cylinders Hull (3SCH) form gaining advantages in comparison to existing surface vehicles. This initial work is focused on vehicle prototype design, propulsion system development and optimization, control design, and trials, while research related to advantages of the vehicle in terms of naval architecture criteria such as drag and power, stability, seakeeping, and maneuverability will be investigated in further work. In addition, the paper intends to contribute to a new trend in developing vehicles with electrical propulsion that could use renewable sources of energy such as wind and solar energy. The potential usage of the vehicle can be civilian or military, and further work will be focused on larger models, improved based on the experience got during the development of the vehicle. Tritor vehicle was successfully designed, constructed, and tested in real environmental conditions. The preliminary results show that the vehicle has required performances and potential for improvements in the future. The main scientific contribution of this work is advanced surface vehicle development with a focus on a new hull form and the integration of electric propulsion in it.

*Key words: unmanned surface vehicle; autonomous; remote control*

### 1. Introduction

An Unmanned Surface Vehicle (USV) is a maritime platform that performs its missions on the surface of the water. It can be operated with different degree of autonomy that ranges from simple remote control to complete autonomous navigation, however, it is foreseen that such vehicles in the future will be fully autonomous without human control. USV development requires the hull and propulsion design, reliable communication, powerful control, guidance, and navigation systems. USV normally has dual civilian and military

purposes. USV platforms could be used for civilian needs in commercial shipping, maritime search and rescue, environmental monitoring of the sea, recording data on marine environmental parameters, monitoring of illegal activities in the Exclusive Economic Zone (EEZ), border patrol and surveillance, and control of ports and other maritime infrastructure. For military purposes, USV could be used for the protection of forces and seaports, patrols and reconnaissance, countermine operations, anti-submarine warfare, detection of Nuclear Biological Chemical (NBC) threats, hauling targets at sea, laying mines and depth charges, logistic support, assessment of destruction of forces after hostilities and reconnaissance of a certain area before the arrival of special and/or landing forces in that area. The main advantage of using such vehicles for these purposes over the use of conventional naval forces is a significant reduction in the cost of operations due to reduced staffing, low consumption of fuel and energy, increased efficiency of these operations, and what is the most important it does not endanger human lives during these military operations.

In the following text literature review in this area is presented.

Paper [1] presents a comprehensive literature review of recent progress in USVs development. It provides an overview of both historical and recent USVs development and some fundamental definitions. The existing USVs Guidance Navigation and Control (GNC) approaches are outlined and classified according to various criteria, such as their applications, methodologies, and challenges. An analysis of USV accomplishments worldwide, as well as the overall technical challenges of USVs, was given in [2]. A common description of USVs was provided along with their typical uses. The technical challenges of developing a USV include its intelligence level, control, high stability, and developmental cost minimization. Work [3] analyses the enabling technologies that have allowed USVs to appear like a feasible platform for marine applications. The work follows achievements in technology from initial systems developed by the author in 1993 through the latest progress and demonstration programs. Paper [4] analysis the possibilities and how US Navy might employ USVs identifying the US Navy's main missions and functions for which USVs are suitable.

Article [5] presents a remotely operated system developed by using a leisure-use fish finder and an unmanned watercraft to inspect water bottom topography and other data associated with bottom materials. The system is inexpensive, simple to use, and mobile. The system should be useful in inspecting areas that have been hard to explore, including remote, small, and shallow lakes, such as volcanic and glacial lakes. Paper [6] describes a design of a USV, which task was to control oxygen level, acidity, and the water temperature in rivers, lakes, inland waterways, and coastal waters. Work [7] presents the development of open-design catamaran-type USV that would be utilized for detection and identification of marine and lake waste. The aim of [8] research was the development of long range, autonomous USV for oceanographic measurements powered by wind and solar energy. Paper [9] presents the new design of a small solar-powered autonomous USV that was used for measurement of water parameters such as pH, purity, oxygen content, and turbidity. Work [10] explored the use of USV for bridge inspection focusing on USV design, selection of acoustic sensors, control and dynamic positioning of USV.

Research [11] presents the design of a prototype of a Trimaran Unmanned Surface Vehicle (TUSV). It was used as a purely academic research platform with a focus on the development of navigation and communication systems based on nonlinear control theories. Paper [12] provides the design and operation analysis of trimaran USV, with a focus mainly on propulsion system design and distribution of hydrodynamic and aerodynamic pressure. Research [13] shows a discussion of the advantages and disadvantages of different types of

forms of USV for oceanographic field missions e.g. comparison of trimaran to monohull and catamaran forms in terms of naval architecture.

Research [14] gives the analysis of the electric propulsion system for USV at different Pulse Width Modulation (PWM) values. Study [15] performed research in optimization of the propulsion system for electric propelled USV with the aim to reduce fuel consumption, and to make intelligent equipment selection. In [16] the three Degrees of Freedom (DOFs) dynamic and propeller thrust models of USV were developed. In the three-DOF model, the propulsion of the USV was completely provided by the resultant force generated by double thrusters and the rotational moment was related to the differential thrust. Field tests of a 4-meter-long, 180-kilogram, USV have been completed in [17] to evaluate the performance of station-keeping heading and position controllers in an outdoor marine environment disturbed by wind and current.

Work [18] gives a preliminary study of the autopilot development of a USV. The catamaran autonomous vehicle is modeled as a two-input, single-output system while the autopilot selected is a genetic algorithm-based Model Predictive Controller (MPC). Simulation results showing the autopilot characteristics in response to changes in the desired course are demonstrated. Paper [19] shows the autonomous functionality of a boat appropriate for surveillance operations. Autonomous characteristic is achieved by applying the Ardupilot board along with the Arduover firmware which is part of it. The Mission Planner software allows getting the current Global Navigation Satellite System (GNSS) location and marking the waypoints, the boat then follows the waypoints path in order to finalize the setted mission. Thesis [20] presents techniques to advance the capability of two important parts that are significant for autonomous vehicles: a geo-positioning system, and remote control. Paper [21] is dealing with autonomy development of USV with a focus on perception, way-points path planning, guidance and control. Article [22] presents a solution for an effective communication network for the control of a number of distributed USVs.

ArduPilot [23] is an open-source autopilot software website for any kind of unmanned vehicle (air, ground, surface, or underwater). It gives instructions on how to download, install and use the software, and how to compose the vehicle, calibrate and tune it. The page is directed toward many hardware producers or specific drone components such as autopilot boards, communication systems radio control transmitters, etc. Reference [24] is a YouTube video stream of the vehicle Tritor during the trials.

This work aimed to develop a unmanned surface vehicle, which will be remotely controlled, perform autonomous missions and transmit required data from the vehicle to the ground control station and vice versa. The focus was on the new vehicle hull and propulsion system design while all other elements were taken from existing technical solutions. The main contribution of the paper is the development of a new 3SCH form and the integration of electric propulsion in it. After conducting the first part of the planned trials it showed a high level of stability, seakeeping performance, and maneuverability. Also, it is expected that drag of the form will be competitive in comparison to existing forms (monohull, catamaran, trimaran) This work will be continued through the carrying out of the second set of trials in a towing tank by comparison of 3SCH form with the existing forms. The development and integration of electric propulsion was a secondary goal, and it was successfully implemented.

After a brief introduction and literature review of this research area in paragraph 1, the development of a novel 3SCH form is presented in paragraph 2. The propulsion system of the vehicle and its integration within the hull form is shown in paragraph 3. USV Tritor control and navigation scheme are described in paragraph 4. The performed trials of the vehicle are presented in paragraph 5, and the conclusion in paragraph 6.

## 2. Unmanned surface vehicle Tritor design

The main idea of the vehicle was to be remotely controlled, autonomous, have electric propulsion, and have the advantage in comparison to classical ship forms in terms of naval characteristics such as stability, seakeeping, maneuverability, etc. One of the main goals was to have a vehicle that will be much better in stability and seakeeping than known comparable platforms. Based on mentioned requirements and the long process of developing the initial idea it was decided that the vehicle will be composed of three cylinders that would constitute a hydrodynamic base form and a deck that would be built on top of this base. The cylinders were arranged in a way that the mid cylinder was completely submerged, and two side cylinders were partially submerged in the water. The mid and side cylinders were connected by hydrodynamic lifting elements that had the function to connect the mid cylinder with the side cylinders and ensure a hydrodynamic lift on the vehicle. The two side cylinders were substantially shorter in comparison to the mid-cylinder, but they were widely spaced to ensure good transverse stability. The electric propulsion i.e. the motor was placed in the rear part of the mid cylinder, rudder was put on the mid cylinder behind the strut that was installed on the top of the mid cylinder, and above the propulsion system. The initial vehicle was constructed and tested by sailing it on the lake and observing the characteristics of the vehicle.

The main problems that were encountered during the development phase are described in the below text. The longitudinal stability of the vehicle was not adequate because the side cylinders were not long enough and could not ensure the required return moment on the vehicle at higher speeds. Due to the pitching of the vehicle at higher speeds there was an attempt at the bow of the vehicle to submerge due to hydrodynamic force on symmetric lifting elements. It was difficult to keep a watertight stern tube that wasn't initially firmly installed. On the other hand, during the trials of the initial model, a very good hydrodynamic response of the model was observed in calm and moderate waves in closed waters, the good response of the propulsion system, handling characteristics, reliability, and compatibility of commercially available electrical and electronic components.

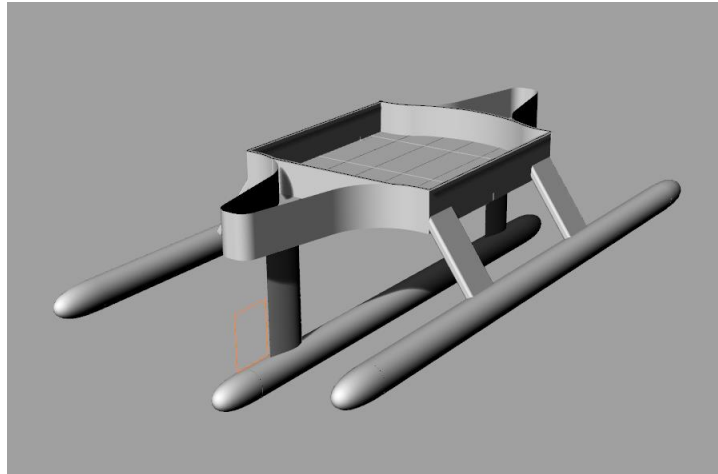
Based on these experiences and lessons learned the improved vehicle was constructed to eliminate shortfalls in the initial vehicle. Side cylinders were substantially extended to improve the longitudinal stability of the vehicle. Instead of hydrodynamic elements, vertical struts were introduced that connected the mid cylinder with the platform. In this way, the hydrodynamic lift could not be achieved, but the problem of submerging the bow of the vehicle was avoided. The deck was downsized in order not to compromise transverse stability, the bow and stern part of the platform was narrowed to keep longitudinal stability high. The vertical struts were symmetrical has a hydrodynamic shape and they were 3D printed. The propulsion system was better than on the initial vehicle, the propeller was designed and optimized using Openprop free software and 3D printed. The computer 3D design of the vehicle is presented in Fig. 1, a picture of the vehicle with components in the cradle in Fig. 2, and the vehicle on the water in Fig. 3. The main particulars of the vehicle are shown in Table 1, and the list of electronic equipment in Table 2. The material of the cylinders is PVC plastic with ends that are 3D printed from PLA consumables. The rear part of the middle cylinder is made of Al alloy for better cooling of the BLDC motor. The cylinder parts were connected using fiberglass tape and polyester resin. The vertical supports and rudder are also 3D printed from PLA plastic. The vehicle deck and its connections with side cylinders are wooden.

After sailing trials on the new version of the vehicle there are the following observations. The new version of the vehicle was compact and much better than the first one.

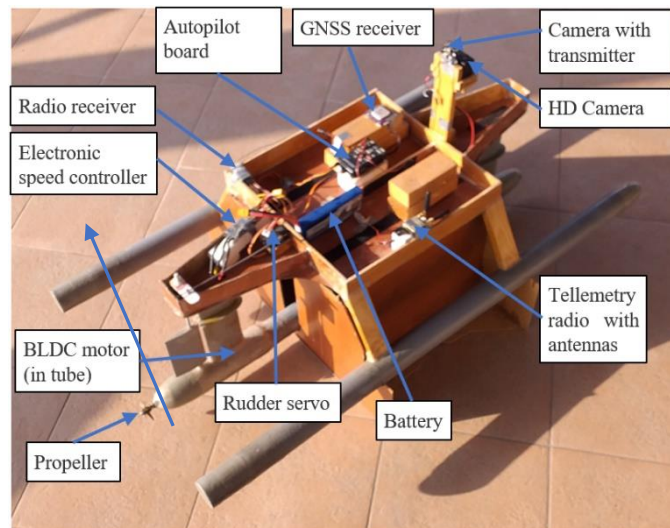
Transverse stability was observed exceptionally high because of the high distance between the side cylinders. Longitudinal stability was improved after the extension of the side cylinders. The angle of the heel during the turn of the vehicle was very low, it was observed that the vehicle is very maneuverable and has good directional stability. During sailing on waves, the vehicle showed exceptionally good seakeeping characteristics, relatively small roll and pitch amplitude, cylinders cut easily through the waves, and there was a negligible loss of speed on waves.

This concept vehicle represents a new kind of ship form called Three Slender Cylinders Hull. Another advantage of the vehicle was its simplicity to manufacture, there are no complicated forms as in other classical ship forms, just three cylinders that could be built from widely available commercial construction elements. It is foreseen that this kind of vehicle would be significantly lower in cost in comparison to classical vessel forms due to its simplicity. It was suitable to install electric propulsion in the rear part of the mid cylinder that was made from aluminum to achieve better cooling of the electric motor. During trials, it was observed that the advanced vehicle achieved higher speed than the initial one, and proved that it can operate at a wide range of speeds. For more details about the trials and the results see Section 5. It is foreseen that this kind of vehicle could be scaled to build bigger platforms used for many different purposes, not only for USV missions. The main disadvantage of the vehicle was its limited range due to the small capacity of the battery (4000 mAh). Using a cruising speed of 1.5 to 2.0 m/sec battery can last approximately 30 minutes. It can be extended to double capacity at the expense of a useful payload. Another disadvantage of the vehicle is the relatively small payload that can be carried. This can be improved by increasing the volume of cylinders, which results in gaining on displacement and at the same time useful payload. The payload/sensors for the current development of the vehicle are two cameras that were used during trials. The first one is HD camera with SD memory card, and the second one is a camera with a video transmitter that was used to transmit the video signal to the notebook to get first-person view. The vehicle has an additional capacity of approximately 1 kg, and it is planned to install an echo sounder that would be used for mapping the depth of lakes. Increasing the radius of the middle cylinder, the capacity of the vehicle could be increased and more sensors will be considered.

The following paragraph explains the comparison of 3SCH form with the classical trimaran form and emphasizes potential advantages. The 3SCH form compared to the stability/buoyancy of a classic trimaran hull is similar. Probably the stability could be better due to the fact that the side cylinders of the 3SCH shape can be placed wider. The main advantage of the 3SCH form compared to the classic trimaran is the lower drag of the form, and lower wave drag because the middle cylinder is underwater and does not create any wave resistance, which is important at high speeds. Wave interference between the side cylinders of the 3SCH shape is expected to be lower due to the fact that they are placed wider, have a small footprint, and produce lower waves. It is also expected that the vertical accelerations of the 3SCH form will be lower compared to the classic trimaran due to the fact that the central cylinder acts as a damping means and reduces the vertical acceleration. The directional stability of the 3SCH form is higher due to the hydrodynamically streamlined vertical supports. Also, there is no slamming of the bottom on the waves due to the fact that the middle cylinder is underwater.



**Fig. 1** Computer 3D design of the vehicle



**Fig. 2** Picture of the vehicle in the cradle



**Fig. 3** Picture of the vehicle on the water

**Table 1** The main particulars of the vehicle

Length [m]	1.07
Breadth [m]	0.55
Draft [m]	0.125
Displacement [kg]	5.04
Maximum payload [kg]	1.2

**Table 2** The list of electronic equipment on the vehicle

Item	Item type
Autopilot board	Pi Pixhawk 1
Electronic speed controller	Aero Star RVS 40 A
BLDC motor	350 W, 1350 kV, 3 cell battery (12V)
GNSS receiver	mRo u-Blox Neo-M8N Dual Compass LIS3MDL+ IST8310
Radio receiver	Radio Link
Battery	Turnigy 4000 mAh
Telemetry radios	SiK V3 433 MHz with antennas
HD camera	Lenco Sportcam-700
Camera with transmitter	Eachine TX03
Servo	Tower Pro MG995

### 3. USV Tritor propulsion system

The USV Tritor propulsion system is composed of a brushless direct current (BLDC) motor whose specifications are given in Table 2, 4 mm propulsion shaft, and three-blade propeller. The propulsion shaft is placed within the 10 mm stern tube with bearings and connected to the BLDC motor shaft by Cardan transmission. The stern tube was filled with special grease to enhance lubrication at the high rotation per minute (RPM) and prevent the ingress of water in the mid cylinder. The rear portion of the mid cylinder is from aluminum which improved the cooling of the BLDC motor. The initial propeller was a three-blade, left-handed, plastic 4.5 cm diameter propeller that was available on hand. It showed relatively good results, and the maximum speed was 3.75 m/sec (75% throttle). There was an intention to optimize the propulsion system by designing a new propeller using free software Openprop. First, a parametric study was performed to determine the optimal RPM of a propeller for a new propeller diameter of 6 cm. The diameter of 6 cm was chosen because the mid cylinder diameter at the rear was 6 cm, and also larger propeller would probably overload the BLDC motor. A parametric study showed that at 7500 RPM propeller had an efficiency of 0.71, and the BLDC motor can easily operate in that range. Using 7500 RPM, 6 cm diameter, and the assumption that the required thrust would be around 40 N, a new propeller was designed. The geometry of the propeller was imported within the 3D modeling tools, slightly adapted, and exported as a stereo-lithography (STL) file suitable for 3D printing and finally, 3D printed (see Fig. 4). The new propeller showed much better results, the maximum achieved speed of USV Tritor was about 4.2 m/sec (75% throttle), and it was observed that the vehicle achieves higher speed in the rear direction too. One of the main advantages of this propulsion system was that chosen BLDC motor was very light, with exceptionally small dimensions, and without reduction gears. The material that was used for the 3D printed propeller was PLA consumable. The 3D print was not perfect due to the nature of 3D printing using layers, therefore the propellers were smoothed using fine grinding paper. There is a

plan to use materials with better properties for the propellers in the future such as ABS filaments or consumables with carbon fibers. Cavitation was not observed during trials, nor was there mechanical damage to the propellers.



**Fig. 4** 3D printed propeller

#### **4. USV Tritor control and navigation**

One of the main requirements for the vehicle was to have both capability to be remotely controlled and to be autonomous. The aim of the designer was not to develop a new control and navigation system, but rather to use the existing one. Due to the fact that the authors had experience in using the ArduPilot autopilot system for the aerial vehicle, it was decided to use the same system for the USV Tritor. ArduPilot enables the creation and use of trusted, autonomous, vehicle systems. It provides a comprehensive suite of tools suitable for almost any vehicle and application. As an open-source project, it is constantly evolving based on rapid feedback from a large community of users. Ardupilot firmware works on a wide variety of different hardware to control unmanned vehicles of all types. Autopilot for a boat called Rover is an advanced system for guiding ground vehicles and boats. In the case of this work Rover firmware runs on autopilot board Pixhawk 1 which details can be seen in [25], and [26]. The main components of control and navigation of the vehicle are shown in Fig. 5.

Autopilot board is a controller or brain of the drone which monitors and controls everything the drone does. It is composed of hardware and software that control all sensors to determine the motion of the drone. The hardware usually comprises of high-speed processor, and different internal sensors such as an Inertial Measurement Unit (IMU), magnetometer, barometer, distance measurement sensor, etc. The autopilot board should ensure communication protocols with different sensors and toward the Ground Control Station (GCS) to exchange telemetry information and messages (commands) from the GCS. It takes inputs from the GNSS unit, compass, GCS, and the remote controller. The autopilot board processes it into information that is distributed to the electronic speed controller (ESC) to control the BLDC, and the servo to control the rudder. In this case, the autopilot board was Pixhawk 1, and the software was ArduPilot Rover which is used for controlling rovers and boats.

Global Navigation Satellite Systems/Compass (GNSS/COM) unit provides position information received from the navigation satellites. This information in combination with



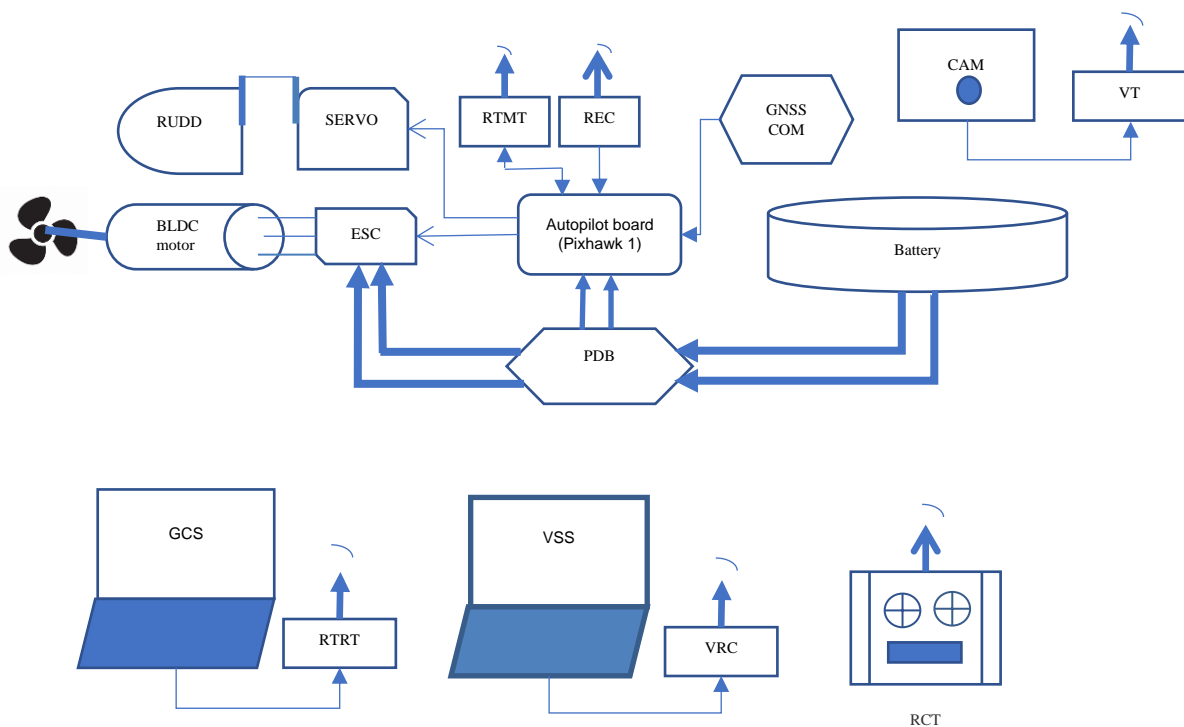
bearings got from the compass unit is used for the determination of headings of the vehicle in autonomous sail from one waypoint to another.

The battery provides power for the propulsion system and all other electronic components onboard. Power Distribution Board (PDB) monitors the power coming from the battery and distributes it to ESC and the autopilot board. Electronic Speed Controller (ESC) is connected to the battery through a power distribution board and the autopilot board. The ESC receives a signal from the controller that changes the amount of power given to the brushless direct current (BLDC) motor and controls its speed. BLDC turns the propeller based on the received signal from the ESC. Servo is a direct current (DC) electric motor used for turning the rudder based on a signal received from the controller.

Radio Control Transmitter (RCT) is unit used for remote control of the vehicle. It sends signals or related commands to the vehicle via the receiver. It can have several channels, each for a specific command such as throttle strength, turn of the rudder, go forward or backward, or turn on/off a specific switch. It controls the mode of driving the vehicle such as manual, autonomous, and guided. Receiver receives a radio signal from RCT or related command of throttle strength for the BLDC motor, required angle for the rudder, mode of driving the vehicle, etc.

Ground Control Station (GCS) is software that is running on the laptop or desktop computer that provides communication with the vehicle. It receives the telemetry data from the vehicle, shows it, or stores it as a log file for later analysis. It can be used for sending the command to the vehicle for example to change the mode of driving or to go to a specific geolocation. It is usually used for mission planning that can be stored or sent to the vehicle for execution. GCS is also used for checking or changing the parameters of the vehicle before starting the mission, for calibrating different sensors such as magnetometers, accelerometers, RCT sticks, etc. During the first drive, it is used for tuning specific controller components such as speed and throttle, turn rate, navigation, cruise throttle, cruise speed, etc. Software for GCS for this vehicle was Mission Planner (MP) which details can be seen at [27]. The main screen of the MP is shown in Fig. 6. Radio Telemetry Module Transmitter (RTMT) is unit used for the transmission of telemetry data from the vehicle to GCS. The telemetry data represent information about the status of certain sensors and electronic equipment on board, as well as information about speed, the direction of the vehicle, motions (roll, pitch), accelerations, etc. Radio Telemetry Receiver/Transmitter (RTRT) with an antenna that receives telemetry data or sends specific commands to the vehicle for execution.

Video Streaming Station (VSS) is ground station for video streaming received from the vehicle. It can be a notebook or a video display, but it can also be part of the GCS. Video receiver (VRC) receives the video signal from the vehicle. Camera (CAM) is placed on the vehicle for video capture. Video Transmitter (VT) transmits a video signal from the vehicle to GCS or VSS.



**Fig. 5** USV Tritor control and navigation scheme

## 5. USV Tritor field trials

Before the trials took place RCT, RTRT module, autopilot board, BLDC motor, and servo were calibrated. It was done through MP initial setup option. RCT calibration comprises calibration of remotely control sticks for throttle, rudder, and switches that control driving mode, and option for driving forward or backward. Calibration of RTRT module sets up parameters of communication parameters of RTRT such as transmitter power, communication protocol, the frequency used, etc. Autopilot board calibration comprises accelerometer and magnetometer calibration.

Another important preparation before the first drive of the vehicle was tuning of speed and throttle controller, and turn rate controller. All mentioned controllers are based on the PID (proportional, integrative, derivative) general controllers. During the tuning process, these three component parameters are changed until the vehicle behaves just as it is expected to do. The PID parameters for steering rate of the vehicle were as follows:  $P=2.0$ ,  $I=1.78$ ,  $D=0$ . The same parameters for throttle rate were:  $P=0.42$ ,  $I=0.23$ , and  $D=0$ .

The first test of the vehicle was just to try to drive the vehicle in remote control mode and see how it is behaving on the water. This was done on several occasions and all initial problems with the vehicle were fixed such as increasing of tightness of the stern tube that initially was not tight enough. Another improvement was related to the installation of sleeves on the vertical struts to avoid the overwhelming rising of water that pulled the vehicle down and increased resistance. Also, initially, the rear of the surface cylinders was rounded, which caused the submergence of the rear part of the vehicle during high speed and turns, therefore it was decided to change it into cut ends. The vehicle was driving on still water and on the waves. It was observed that the vehicle had very good seakeeping characteristics, the vehicle had a low roll angle during turns, and the angles of roll and pitch were relatively low on

waves that were significant high for the size of the vehicle. Also, the vehicle did not lose much speed on the waves, and the vehicle was easily cut through the waves due to its torpedo kind of form.

The next test was to check the maximum speed of the vehicle and its endurance with a current LiPo battery of 4000 mAh. Initially, the vehicle had a propeller of 4.5 cm diameter that was available on hand, and the maximum achieved speed at 75% throttle was 3.75 m/sec. After optimization of the propeller using free software Openprop and getting a 3D printed propeller of 6 cm in diameter, the maximum speed was increased to 4.2 m/sec. It was observed that the vehicle drives much faster in a backward direction too. The endurance of the vehicle on the economy speed of 2 m/sec was approximately 30 minutes, and it could be significantly increased by using a battery of 8000 or 10000 mAh. It is foreseen that the vehicle could achieve a speed of 5 m/sec if 100% throttle was used, but it was decided not to overload the BLDC motor.

One of the most important trials was to drive the vehicle in autonomous mode. Preparation for auto mode was done in MP where waypoints are determined on the map, saved in a file, and loaded to the autopilot board. To be successful in driving the vehicle in this mode all tuning procedure mentioned above was prerequisite. The start of the auto mission is done by the RCT switch that is determined for this mode, the vehicle starts the mission, follows the predetermined path through all set waypoints, and finally ends the mission at the last waypoint. This test was repeated several times using different waypoint paths, from the simplest one to one with very complex shapes. The test was successful, the vehicle followed the paths and did smooth turns on the waypoints. The example of one preplanned auto mission on MP is shown in Fig. 6.

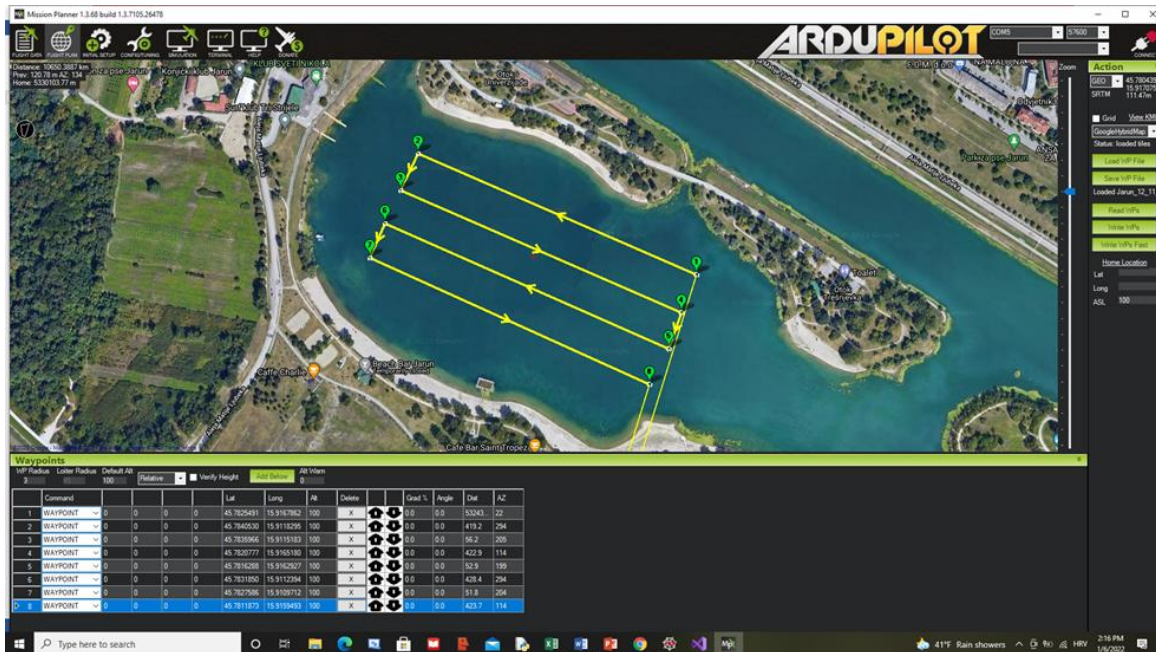


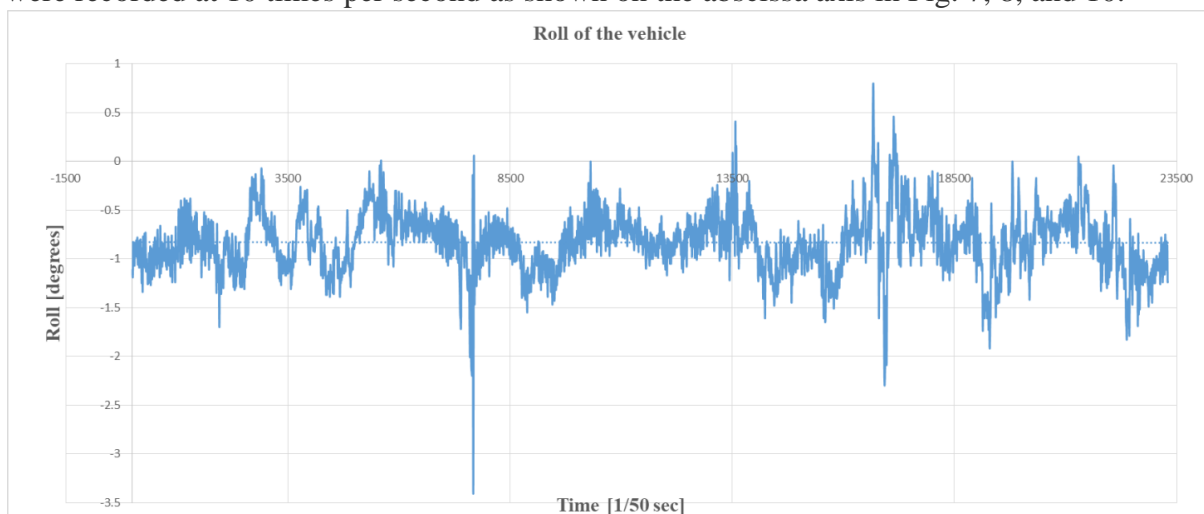
Fig. 6 Mission planner main screen and preplanned auto mission of USV Tritor

In addition, the vehicle was driving in guided mode. The command for this mode is executed through GSC in MP, it is done just by clicking at the specific point in the map where you want the vehicle to drive, and the vehicle starts to drive toward that point. The final

driving mode was loitering mode. In this mode, the vehicle just did turn around a specific point set through GCS in MP.

Initial trials including the calibration of the vehicle sensors were done on the lake near Zagreb in a place called Otok Svibovski. Maximum speed, autonomous, and guided mode trials were performed several times on the lake near town Dugo Selo. Remote control driving was also performed on Kupa river near the place called Letovanić. Environmental conditions were usually calm water with one exception with trials on Dugo Selo lake where the vehicle experienced very harsh conditions with strong wind and significant wave heights that were approximately 1/10 of the vehicle length. Significant portions of all these trials can be seen on the youtube video [24]. All trials were performed during the second half of 2021.

Some numerical results and graphs from the trials are presented in this paragraph. Fig. 7 and Fig. 8 are plots of the roll and pitch of the vehicle that are extracted from log files from the autopilot board. The actual trial was conducted in calm conditions, but there were lots of turns of the vehicle during the trial, and waves were produced by the vehicle. The trajectory plot of the trial is presented in Fig. 9. The mean value of GNSS horizontal accuracy was 0.427 meters. The speed plot of the vehicle is presented in Fig. 10. The numerical results are summarized in Table 3 which shows the average values, root mean square, and significant 1/3 values of roll and pitch. It can be concluded that mentioned significant value for roll supports the thesis of the authors that the vehicle has exceptionally high stability which was one of the main goals of the new 3SCH form. The significant value for pitch is within expected values. The roll and pitch angle samples were recorded at 50 times per second, while speed samples were recorded at 10 times per second as shown on the abscissa axis in Fig. 7, 8, and 10.



**Fig. 7** Roll plot of the vehicle from trials

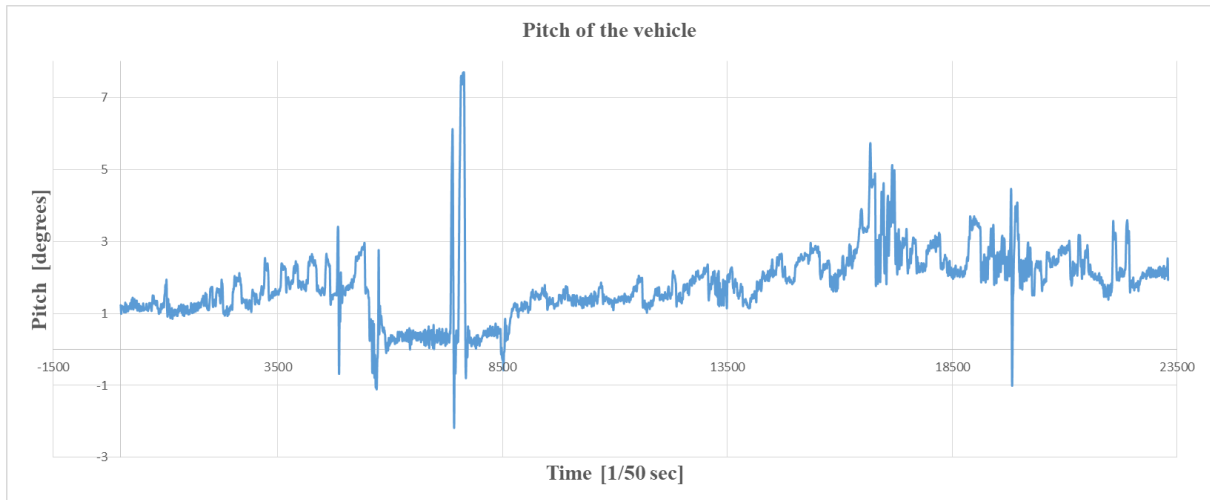
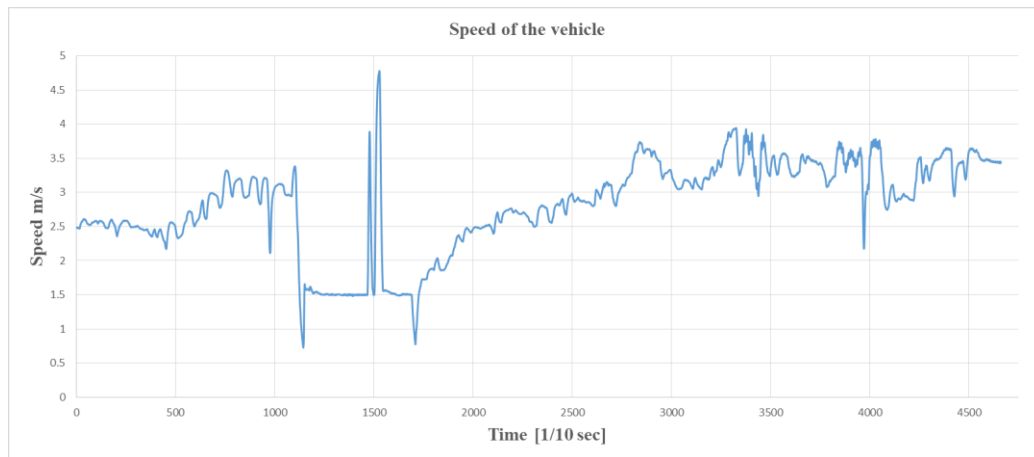


Fig. 8 Pitch plot of the vehicle from trials



Fig. 9 Trajectory plot of the vehicle from trials



**Fig. 10** Speed plot of the vehicle from trials

**Table 3** Numerical results for roll and pitch of the vehicle from trials

	Mean value [degrees]	Root mean square value, rms [degrees]	Significant 1/3 values [degrees]
Roll	-0.829	0.306	0.611
Pitch	1.789	0.952	1.905

## 6. Conclusion

The main goal of this work was achieved, the remotely controlled and autonomous vehicle was designed, built, and tested. This concept vehicle represents a new kind of ship form called Three Slender Cylinders Hull that showed high performance in stability, maneuverability, and seakeeping area. Regarding the control and navigation of the vehicle, it achieved good results in terms of using ArduPilot freeware for autonomous driving including remote control and getting all telemetry data at the GCS. Video stream in real-time was achieved that can be used for first-person view driving. There is much space for improvement of the vehicle such as increasing the payload by using the larger diameter of cylinders or by building a larger vehicle. The autonomy of the vehicle could be substantially higher using the bigger capacity battery. Although the vehicle is a prototype authors conclude that in this configuration it can be used for many civilian or military purposes. The vehicle as a platform showed through all performed trials that probably has a high potential to be used not only as a USV platform but also for other usages with promising naval characteristics. The future work in this area will be in building a bigger platform in size, improving control and navigation of the vehicle to integrate it into the internet network. Also, this platform will be further investigated in a towing tank to measure resistance, seakeeping, and maneuverability characteristic and compare it with other platforms to prove its advantage.

## NOMENCLATURE

BLDC – Brushless Direct Current  
 CAM – Camera  
 COM – Compass  
 DC – Direct Current  
 DOF – Degree of Freedom  
 EEZ – Exclusive Economic Zone

ESC – Electronic Speed Controller  
 GCS – Ground Control Station  
 GNC – Guidance Navigation and Control  
 GNSS – Global Navigation Satellite System  
 GPS – Geographical Positioning System  
 GUI – Graphic User Interface  
 IMU – Inertial Measurement Unit  
 LiPo – Lithium Polimer  
 mAh – mili Amper hours  
 MP – Mission Planner  
 MPC – Model Predictive Controller  
 NBC – Nuclear Biological Chemical  
 PID – Proportional, integrative, derivative  
 PVC – Polyvinyl Chloride  
 PDB – Power Distribution Board  
 PWM – Pulse Width Modulation  
 RCT – Radio Control Transmitter  
 REC - Receiver  
 RPM – Rotation per minute  
 RTMT – Radio Telemetry Module Transmitter  
 RTRT – Radio Telemetry Receiver Transmitter  
 RUDD - Rudder  
 3SCH – Three Slender Cylinders Hull  
 SD – Secure Digital (memory card)  
 STL – Stereolithography  
 TUSV – Trimaran Unmanned Surface Vehicle  
 USV – Unmanned Surface Vehicle  
 VR – Virtual Reality  
 VRC – Video Receiver  
 VSS – Video Streaming Station  
 VT – Video Transmitter

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