Development of a Sustainable Unmanned Surface Vehicle (USV) for Search and Rescue Operations

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Abstract—Unmanned surface vehicles (USVs) are marine crafts that are capable of unmanned operations in sea and oceans. Such missions are sea patrol, reconnaissance, search and rescue and marine data collection. They vary in degrees of autonomy, ranging from remote controlled vehicles to ones that are fully autonomous and can operate with minimal human intervention. Unmanned vehicle systems technology has been greatly improved with advancement in computer capabilities and advanced control methods. In this paper, a new USV prototype for search and rescue missions is presented. Mechanical design, Electrical control systems and developed software of the USV are presented. This USV is designed to be a sustainable marine craft and to operate using renewable energy such as wind and solar energy. Such capability greatly prolongs the mission time and decrease the expected power consumption from conventional batteries. Also, it is compact in size and light in weight. This vehicle can be operated manually and autonomously with Live camera and LIDAR feedback system.

Keywords—unmanned surface vehicle, obstacle avoidance, double hull, Mission Planner, sustainable marine craft.

I. Introduction

USV can be defined as unmanned vehicle that operates on the surface of the water and performs tasks in a variety of cluttered environments without any human intervention [1]. According to environmental changes, marine security and requirements of each individual, development of unmanned surface vehicles (USVs) is strongly demanded from many institutions. Unmanned surface vehicles (USVs) have attracted a great deal of interest for their ability to perform dangerous and time-consuming missions in marine environments while they are remotely operated by pilots from safe locations. A large number of marine workers are exposed to drowning annually. Statistics shows that drowning is the third leading cause of unintentional injury death, accounting for 7% of all injury-related deaths [2]. So, this USV can be used to rescue the lives of those people even in cases when they are drowning in regions where there is poor vision or it is hard to send rescue team.

Unmanned Surface Vehicles (USVs) were first developed in 1993 at the MIT Sea Grant College Program and were designed to be used in a wide range of missions. The first USV built at MIT Sea Grant was named ARTEMIS [3]. This vehicle was an identical scale of a fishing ship which was used for testing the navigation and control systems required by a USV. Later on, this USV was used to collect simple bathymetry data in the Charles River in Boston, USA.

Another USV named ACES (Autonomous Coastal Exploration System) was developed during 1996 and 1997 [4]. In order to enhance its performance, it was equipped with sensors to suit hydrographic surveys. It succeeded in accomplishing such a survey in Boston Harbor in December 1997. By January 1998, the USV ACES was returned to the lab for an important upgrade of its mechanical systems. Adjustments and design trials were tested through the summer of 2000 when the new USV platform was renamed AutoCat.

Generally, USVs can be categorized into three main types according to their hull structure. A hull can be defined as the main body of a ship, including the bottom, sides and deck. The three types of hull structure are: single hull structure, double hull structure and triple hull structure [5]. In the following paragraphs, examples of different USVs and their used control systems are mentioned for each type.

EchoBoat-240 USV is an example on the single hull USVs. It was made for marine survey applications. It uses AutoNav USV autopilot module, which allows the user to easily pre-plan a mission, upload the mission to the vessel, and launch for fully autonomous operation and it has the option for being wirelessly controlled through a remote-control unit that can operate at distances of up to 2km. It is 2.4 × 0.9m in size, its payload is 90.7 kg, its top speed is 4 knots and it operates using twin brushless DC outdrive motors [6].

C-Enduro USV is an example on the double hull USVs. It is a long endurance USV, ideal for any application where long-term remote data collection is required. It is capable of enduring missions up to 3 months in length because it has a solar panel system that generates a peak electrical power of 1200 Watts and a wind turbine system that generates a peak electrical power of 700 Watts. It has an autonomous control system and it communicates through satellite. It is 4.75 × 2.22m in size, its speed is 6.5 knots and it operates using two DC brushless motors [7].

Aquarius USV is an example on the triple hull USVs. It was developed to be cost-effective and to be used in many applications. Typical missions for this USV could include monitoring harbor pollution, oceanographic surveys, maritime park surveillance, port security, coastal border patrols and marine data collection. It is powered by a solar-electric hybrid marine power (HMP) solution. Its length is 5m and its beam is 8m. Its speed is 6 knots and it navigates using GPS [8].

After reviewing different types of USVs according to their hull structure, the advantages and disadvantages of each type can be summarized in Table I.

TABLE I
COMPARISON BETWEEN DIFFERENT HULL STRUCTURES

	Single Hull USV	Double Hull USV	Triple Hull USV
Advantages	Tackles quickly. More manoeuvrable and faster to respond to the helm. Slice through water effortlessly. Easily manufactured.	Inherent stability. Faster than single hulls, particularly on downwind runs, reaches and broad reaches.	Faster than single hulls because their load is distributed across three hulls, not one. Reduces drag because each hull rides higher and means less boat in the water.
Disadvantages	Low stability. High drag force.	There can be slapping or pounding while underway in heavier seas, because a wide bridge deck is strapped between two hulls, More cost.	Takes a large space. Rougher ride in rough water because of the large surface at the bow. The outer hulls also might cause pounding.

Thus, after reviewing different types of USVs with different hull structures, double hull structure was chosen due to its stability, low drag force and high velocity.

II. MECHANICAL DESIGN AND MANUFACTURING

The system was designed through repeated process and multiple stages to achieve these requirements:

- The structure must resist the corrosion.
- The shape of the USV and its configuration must assure the stability of the system, the buoyancy and reduce the drag.
- The electronic components must be sealed and protected.
- The USV must have relatively good speed.
- Implementation of solar and wind energy capabilities are needed.

This section includes the mechanical design of the USV, floating and drag calculations, material selection and manufacturing processes.

A. Mechanical Design

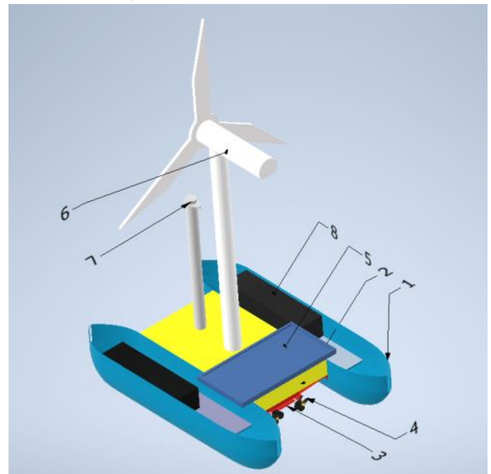


Fig. 1 CAD model for the assembled design of the USV.

The USV assembly with all of its main mechanical parts are demonstrated as can be seen in Fig. 1. They are summarized as:

1. The double hull that generates the needed buoyancy force and provides the needed stability.
2. A link between the two hulls to connect them together and support the components.
3. Frame to hold the thrusters and the propeller.
4. Thrusters and propeller.
5. Solar panel.
6. A column to support the wind turbine.
7. A column to support the LIDAR
8. A box to store the electronic components.

B. Floating and Drag Calculations

Additionally, floating and drag calculations are considered for stable operation and maneuvering. In order to calculate the buoyance force, the total weight of the boat and the onboard components had to be calculated as can be seen in Table II.

TABLE II
WEIGHTS OF MAIN USV PARTS

Part	**Weight**
Boat	15 kg
T-100 Thruster	2×0.156 kg
DC Motor	1.2 kg
Batteries	4×0.863 kg
Frame	1.8 kg
Solar Panel	4.2 kg

Wind Turbine	9 kg
Wind Turbine Holder	0.5 kg
Other Components	1 kg
Total	36.464

$$F_B = W \times g \quad (1)$$

The resulted buoyance force for a total weight of 36.464 was 357.712 N. This value is used to calculate the volume of both hulls using the following equation:

$$v = \frac{F_B}{\rho \times g \times no.of\ hulls} \qquad (2)$$

The resulted volume obtained from this equation was 0.036464 m³. This value is used to calculate the height of the part that is submerged in water.

$$Tc = \frac{v}{B \times Tc \times L_{WL}} \qquad (3)$$

Where Tc is the height of the submerged part in water, B is the width of the hull and L_{WL} is the length of water line. The resulted value from this equation is 0.187m which is an acceptable Tc value [9]. After this, the drag force is calculated in order to determine the power needed to overcome this force.

$$F_D = C_D \times 0.5 \times \rho \times 0.5 \times B \times Tc \times V^2 \times no.\ of\ hulls \quad (4)$$

Where C_D is the coefficient of drag according to the hull shape and V is the velocity of the boat and here it is assumed to be 4 m/s. The drag force resulted was 101.1 N. To calculate the needed power this equation was used:

$$P = F_D \times V \quad (5)$$

The resulted power needed is 404.4 Watts.

C. Material Selection

After going through different types of materials, it was settled to cover the USV MDF chassis with fiber glass. Because it is light in weight, has high strength and relatively low density. Also, it is sustainable, easy to work with, needs minimal maintenance, has relatively low cost and its dimensions does not get affected by water.

D. Manufacturing Process

The manufacturing process went through the following stages:

1. The CAD model was divided into planes to create sections to make it easier for manufacturing.
2. Assembly interference check was done on the CAD model using Autodesk Inventor.
3. CNC laser cutting machine was used to cut the MDF sheets into the designed sections.
4. The MDF sections were assembled to create the chassis as can be seen in Fig.2

Fig. 2 Assembled chassis.

5. The MDF sheets were covered with fibre glass material as can be seen in Fig.3.

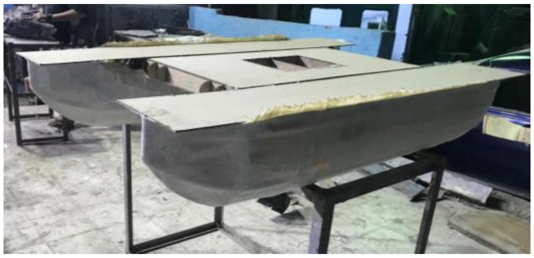


Fig. 3 Fabrication process.

6. An isolation material was painted and the USV was painted afterwards with the desired colours.
7. The parts were assembled and the components were mounted on the USV as can be seen in Fig.4.

Fig. 4 Real-life picture of the assembled USV.

III. Power Distribution System for Renewable Energy Utilization

The main electrical power concerns for the USV are related to the main power needs with the inclusion of the solar and wind energy charging of batteries. The proposed sustainable power system consists of solar panels and a wind turbine. Both renewable resources are used to charge the batteries that power the two T-100 thrusters using relays. This will result in increasing the duration of the working hours and the USV's endurance in the sea.

Hybrid solar-wind systems are combination of energy resources that are used for generating power. The solar panels generate 200 Watts of electrical power while the wind turbine generates 400 Watts. Both are connected to wind-solar controller to protect the batteries from over-charging [10] as can be seen in Fig.5.

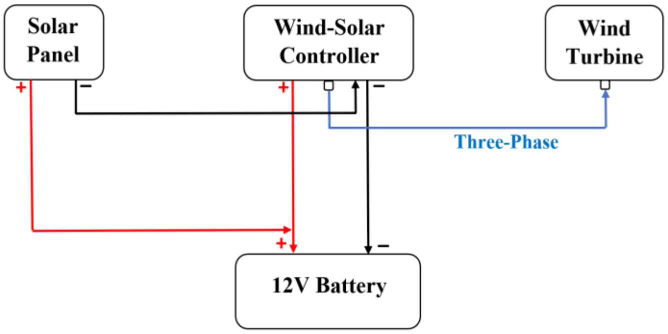


Fig. 5 Hybrid power system connections for the USV.

A switching circuit was designed to increase the mission's duration, by switching between two sets of batteries, each set contains three batteries connected in parallel as shown in Fig.6. First, two voltage sensors will be connected to each set to measure their voltage. If the voltage sensor measures that Set One is charged, then this set will be connected to the motor to drive it through Relay 2 and Set Two will be connected to the hybrid system through Relay 3 to be charged and vice versa. Relay 1 is used to switch between Relay 2 and Relay 3 depending on which set is charged and ready to drive the motor.

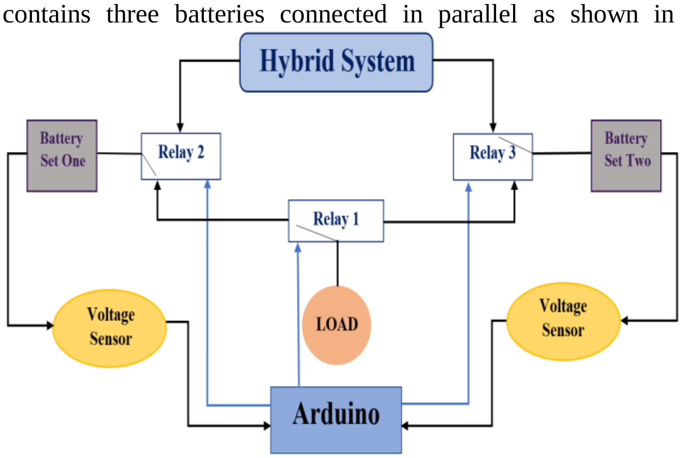


Fig. 6 Power Switching system of the USV

Total power needed to power the two T-100 thrusters used for steering was 168 Watts. The total power provided by the three batteries is 540 Watts and this was sufficient to overcome the needed power and to increase the duration. Lithium-Ion batteries were used according to these specifications:

- Battery Weight: 680 gm.
- Cpacity:15000 mAh.
- Volt:12V.

To calculate the batteries run-time, equation 6 was used:

$$Battery\ Run\ Time = \frac{Power\ of\ Batteries\ [Wh]}{Power\ of\ Load\ [Watts]} \quad (6)$$

The run-time of the batteries resulted from equation 6 was 3.2 hours. Then, the charging time of the batteries had to be calculated using this equation:

$$Battery\ Run\ Time = \frac{Power\ of\ Batteries\ [Wh]}{Power\ of\ Hybrid\ System\ [Watts]}$$

The charging time resulted was 2.7 hours.

IV. CONTROL SYSTEM OF USV

Since USVs are custom platforms, they can be designed to be equipped with various sensors and actuators to perform different tasks. As mentioned before, this USV was made for search and recue applications. Both manual and autonomous navigation modes are available with the ability for obstacle avoidance in the sea. In addition, a ground station for monitoring surveillance and control is established on a PC. The live Camera, LIDAR and GPS feedbacks of the USV are monitored continuously.

In order to explain the control system capabilities of the USV, a rescue mission scenario is explained in which a human in distress is lost in sea. The person in distress has a mobile GPS module which is connected to the ground station. The ground station is also connected to the USV and guides its navigation in the sea using another GPS module mounted on the USV. Obstacle avoidance is automatically triggered during the USV mission using the LIDAR sensor in addition to the camera feedback. A detailed explanation for the rescues mission scenario and the control system behaviour is explained in the following subsections.

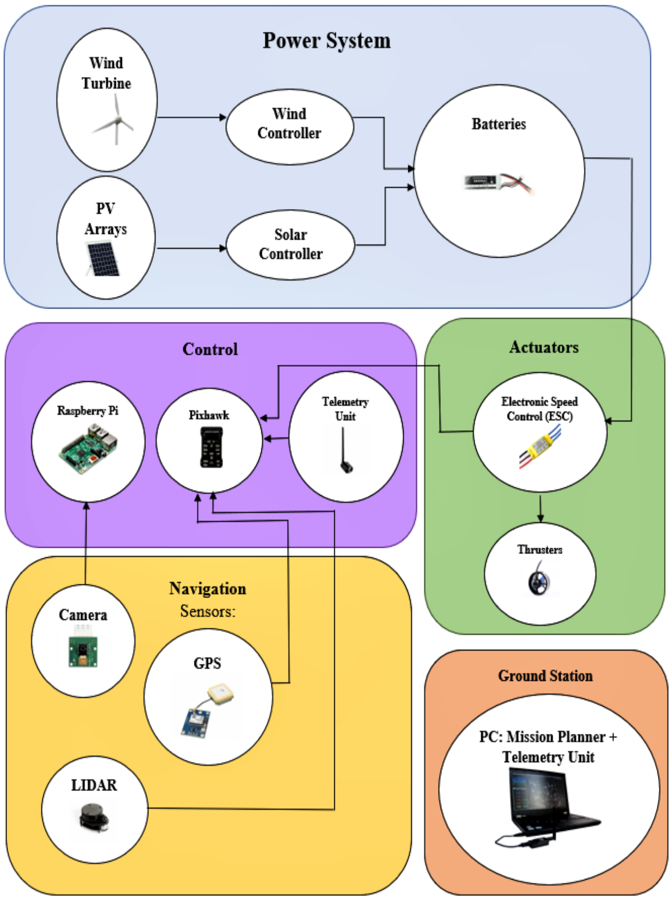
A. Rescue Mission Scenario

The mission starts with the person in distress who will be wearing a bracelet that has a GPS module and a button that sends the coordinates of his location to the station whenever he pushes this button. The coordinates of his location will be sent to the ground control station on the PC that will transmit these data to the USV through wireless communication that includes two telemetry units (antennas). One of them is fixed in the PC and the other one is fixed in the Autopilot system of the USV. The USV will move directly towards the target using DC motor for forward thrust and two T-100 thrusters for steering.

The USV will be equipped with camera for feedback and LIDAR sensor for obstacles avoidance. The camera will be connected to Raspberry Pi and its feedback will be viewed on the PC on the ground station. The LIDAR will be connected to the Autopilot and that will allow locating the obstacle to avoid it.

B. Main Electronic Scheme

The wiring connection chart of the control system shown



in Fig.7. On the bottom there is the ground station which includes the PC, that has the ground control station software. Mission Planner software is developed and supports a wireless MAVLink connection between the PC and the vehicle. There are two telemetry units; one fixed on the PC and the other fixed on the autopilot hardware which is the Pixhawk board. Both telemetry units communicate through UART protocol. The Pixhawk has a GPS module connected to it in order to determine and track the location of the vehicle. Moreover, the LIDAR is connected to the Pixhawk through telemetry ports.

Fig. 7 Control Scheme for the USV.

A camera was used for monitoring and for determining the state of the drowning person. This camera is connected to Raspberry Pi which communicates wirelessly with the PC that supports WIFI protocol in order to give live feedback.

Furthermore, the thrusters and the batteries are connected to the Pixhawk through electronic speed controllers (ESCs). Those ESCs are used to control the speed of the thrusters. Finally, a hybrid solar-wind system is used to charge the batteries to increase the duration of the operating time of the vehicle.

C. Communication Protocols

The communication protocols used in the control system are: Two-Wire communication protocol (I2C), WiFi protocol, UART protocol and MAVLink protocol.

The I2C communication bus is very popular and broadly used by many electronic devices because it can be easily implemented in many electronic designs. Only two wires are required for communication between up to almost 128 devices when using 7 bits addressing. The two wires are: Serial Clock (SCL) and Serial Data (SDA).

Wi-Fi protocol is a family of wireless network protocols which are commonly used for local area networking of devices and internet access.

MAVlink protocol is simply a communication protocol that allows an unmanned vehicle like a copter, a drone or a rover to communicate with the ground station, so the vehicle will send messages to the ground station that allows the ground station to monitor its status. For example, follow the position of the vehicle, send messages to the vehicle in order to perform some actions such as moving from one point to another. This protocol basically specifies a set of messages called MAVproxy, their structure, format and how they are exchanged between the vehicle and the ground station [11].

UART is a hardware communication protocol that uses asynchronous serial communication with configurable speed. Asynchronous means there is no clock signal to synchronize the output bits from the transmitting device going to the receiving end.

D. Software and Waypoint Map Generation

The ground control station software used with USV is Mission Planner Software. It is a ground control station software for any kind of unmanned vehicle. Mission Planner allows controlling any robot vehicle positioned at ground, sky or sea. It allows you to setup, configure, and tune any robot vehicle launched for its best performance [12]. Also, it makes it easier to prepare plans, save and load completely independent missions or operations into any autopilot robot vehicle with simple way points entry on the downloaded map, and finally to be ready to interface with a PC boat simulator.

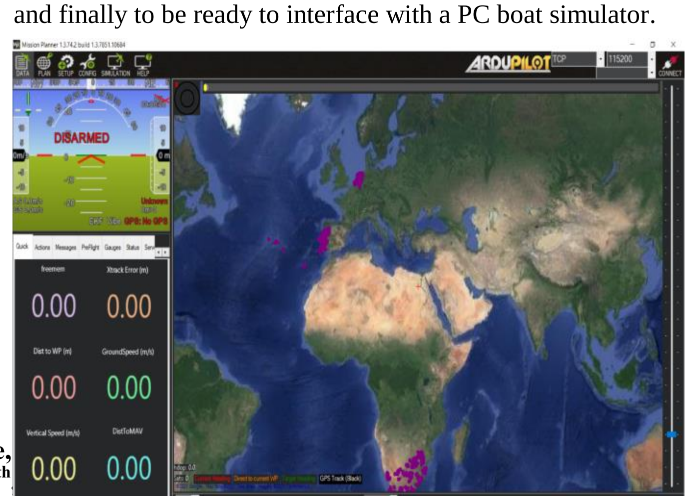


Fig. 8 Mission Planner Software.

Ardu-Rover firmware has to be installed and booted correctly from scratch. The appropriate icon that matches the needed framework has to be selected. Ardu-Rover firmware was selected as it is the most suitable for operating the USV.

Firmware is a software program or set of instructions programmed on a hardware device. There are some basic hardware setups that has to be done, such as calibrating the accel of the Pixhawk, and making sure the GPS is compatible with the Mission Planner. Also, motor configuration has to be done. The pins of the ESCs are connected to the Pixhawk and are assigned on the Mission Planner as servo outputs. Each ESC is assigned to a servo number. One for right throttling and the other for left throttling.

Furthermore, a relay switch was used to control the DC motor. Its parameters have to be adjusted on Mission Planner. The relay has two pins, one gives "low" signal (0) and the other one gives "high" signal (1). Each one of them is connected to the AUX pins of the Pixhawk. The relays can be controlled with the auxiliary switches.

Finally, the LIDAR should be mounted horizontally on the top or bottom of the vehicle. The sensor's view must not be interrupted by any portion of the vehicle. The LIDAR can be connected to the autopilot's serial input. Telem1 (Serial1) should be used because it is more capable of providing the required 1.5A. The TX is connected to Serial 1 Rx, and the LIDAR's Rx to the Serial 1 Tx, and the motor control should be connected to the VCC of the Pixhawk. After that, the parameters have to be checked from the full parameters list.

E. Acquiring the Person's Location and Starting the Mission

A message will be sent with the coordinates to the ground station whenever the person pushes the button in his bracelet. The screenshot for the sent SMS to the ground station can be seen in Fig.9.

Fig. 9 SMS message with the coordinates

The coordinates will be logged manually into the Mission Planner to specify the waypoints in order to draw the path to the person's location so that the mission starts. It starts with clicking on the "Plan" section. "Add Below" button is pressed from the last waypoint command in the list. Then, a new command WAYPOINT command should appear at the bottom of the list where the word WAYPOINT will be changed to the command "RETURN TO LAUNCH". After that, the mission will be uploaded to the autopilot using the "Write WPs" button. And finally, the boat will be able to drive itself. The summary of the rescue mission is clearly demonstrated in the following figures (Fig.10,11 and 12).

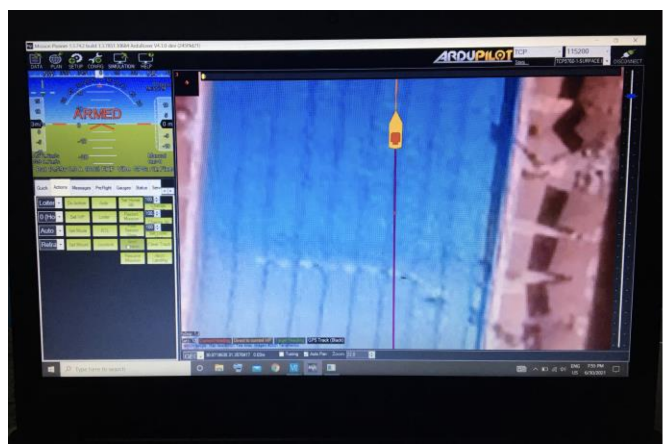


Fig. 10 Setting WAYPOINTS on the Mission Planner software.

Fig. 11 Real-Life Picture of the USV heading towards the human in distress.

Fig. 12 The path created by the WAYPOINTS on Mission Planner window.

V. Conclusion and Future Work

In conclusion, a new unmanned surface vehicle (USV) is presented for search and rescue operations. The mechanical design is realized after justified calculations and material selection. The cost, materials and availability of components were taken into consideration while building this USV. The implementation of renewable energy in the USV operation is achieved through a relay control system and a solar-wind controller. Thus, the expected USV mission is prolonged significantly. An automatic navigation system is developed for the USV in which obstacle avoidance, continuous monitoring, and wireless communication are utilized. A hardware validation of the USV control system is achieved through a rescue mission scenario and the USV achieved its objective successfully. This USV can be modified to suit many applications rather than search and rescue applications such marine data collection, sea exploration, sea patrol and reconnaissance.

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