About the Automation of an Autonomous Sail-propelled Search Drone

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ABSTRACT

The paper presents the prototype of an autonomous sail-propelled vehicle, powered by sails and equipped with mini solar panels, intended for the surveillance of maritime space. Hardware and software aspects regarding the automation of this unmanned boat are addressed. Conceptual solutions have been identified to ensure short manufacturing times, component accessibility (price and availability on the free market), and high system reliability. The paper proposes an original solution to respond to at least two imperative needs: the safety and security of commercial and military navigation in the Black Sea area (faced with a tense geo-political climate) and the increased need to integrate European and global policies on reducing pollution and promoting renewable energy principles.

Keywords-Arduino; autonomous vehicle; microcontroller; WiFi module; photovoltaic cell

I. INTRODUCTION

As early as 2007, in response to the Commission's Green Deal on the future of the European Union's maritime policy, the Parliament adopted a resolution supporting an integrated approach to maritime policy, with a safe and secure marine environment being essential for the development of marine economic activities. In the current geo-political context of the Black Sea region, the safety of maritime space has become a priority, with earlier detection of dangerous situations and / or obstacles being of paramount importance, along with increasing the reaction and intervention capacity within specific missions regarding the monitoring of maritime traffic, securing civil and military infrastructure, search and rescue operations, and protecting the marine environment. Unmanned surveillance systems (airborne, on the water surface, underwater, and on shore) operating independently of the ship with minimal human intervention quickly highlighted their potential to create an adaptable and interconnected network that will ensure ship protection, secure shipping routes, and allow access to dangerous areas for vessels with crews onboard. The current paper aims to present an integrated prototype to the concept of "blue energies": an automated, very small, unmanned vessel, powered by sails and equipped with mini solar panels. Launched near ships or coastal and port areas, this autonomous vessel can have multiple functions: monitoring the marine environment, gathering information (scientific, commercial, tactical), identifying obstacles (navigation or combat), perform early identification, monitoring, deterrence and, eventually, destroying threats in the navigation area. Given the increased destruction potential of these unmanned surveillance systems operating on the water surface, in the open sea, conceptual solutions (design and construction) are sought that ensure short manufacturing times, component accessibility (price and availability on the open market) and high system reliability [1-2]. Describing the concept of automation originated from the notion of modifying a device or one of its components in a manner that would enable independent operation without much human intervention, by achieving automated control over specific processes. Automation has been brought into effect through a range of methods, encompassing mechanical, hydraulic, pneumatic, electrical, electronic, and computational devices, often used in combination. Complex systems such as contemporary factories, aircrafts, and ships typically integrate all these techniques. The benefits of automation encompass reduced labor requirements, savings in electricity consumption and material costs, and enhancements in precision and quality [3-5]. The broad-ranging advantages attributed to automation encompass heightened production quotas and augmented productivity, optimized material employment, superior product quality, elevated safety measures, condensed working hours, and reduced production timelines. Consequently, the imminent prospect for automation technologies holds the promise of fostering a progressively expanding socio-economic milieu, where individuals can relish an elevated and enriched standard of living [6-9]. The concept of Autonomous Surface Vehicles (ASVs) or Unmanned Surface Vehicles (USVs) emerged as a practical response to the need for creating compact waterborne vessels capable of functioning on the surface without requiring crew presence. This concept was initially put into practice towards the conclusion of World War II. These USVs found application in military contexts, including tasks like mine detection, reconnaissance, surveillance, intelligence gathering, surface warfare, and safeguarding strategic installations [9-13]. The potential of ASVs extends to serving as force multipliers in different naval operational domains due to their adaptable structures and capability to transport various payloads. With the integration of Artificial Intelligence (AI) into fully mature ASVs, it is foreseen that by the conclusion of 2025, ASVs will seamlessly operate within naval task groups, collaborating with crewed vessels [12-16]. The development and construction of ASVs poses intricate challenges for builders and developers alike. To optimize their functionality, designers aim to substitute human interface elements with remote interfaces, allowing control from mobile units, command centers, and floating platforms [17-18]. Thanks to advancements in USV control systems and continually evolving navigation technologies, unmanned vessels now function at various levels of autonomy. These range from remotely controlled USVs to partially and fully autonomous USVs that adhere to the International Regulations for Preventing Collisions at Sea (COLREG). ASVs are making significant headway in multiple research sectors, encompassing environmental monitoring, seabed mapping, commercial transport, surveillance, and especially military and naval operations [18-20]. Central to the construction of pilotless surface vehicles are microcontrollers that act as command-and-control hubs. These microcontrollers underpin control and communication software, integrating collision avoidance sensors and other relevant sensor systems. To maximize the processing of sensor data and minimize latency, ASVs incorporate cutting-edge data analysis and transmission technologies [20]. ASV power sources vary, contingent on factors such as design, size, and mission scope. Options encompass diesel, gasoline, electric hybrids, batteries, and renewable energy sources like solar and wind power. Nonetheless, battery-powered, or renewables-driven systems are most prevalent, given the challenges inherent in managing autonomy functions for internal combustion engines on unmanned vessels [14, 21-22]. Concerning the payloads of these ASVs, they predominantly encompass communication apparatuses for ship-to-ship coordination and data sharing with crewed or uncrewed platforms. The composition of an ASV's payload depends on its intended role and mission profile. It might involve cameras, optical sensors, infrared sensors, hydro-meteorological sensors, and various forms of sonars such as single-beam, multi-beam, side-scan, and synthetic aperture sonars. These sensors play a pivotal role in mine countermeasures, anti-submarine warfare, and survey operations. The employment of sensors can be individual or combined, dependent on the specific application [9, 25]. Given its remarkable performance in maritime contexts, this technology has rapidly captured the attention of naval forces globally. ASVs have evolved into indispensable tools for data acquisition, lure deployment, surveillance, mine clearance, submarine detection, and the protection of capital ships. Naval forces and defense industry entities worldwide are increasingly investing in ASV technologies [10, 25].

II. MAIN HARDWARE COMPONENTS

A. Arduino UNO

The Arduino UNO is the most well-known and widely used open-source processing board, built on a simple, flexible, and user-friendly hardware and software foundation, suitable even for beginners. The board features 20 digital and analog input/output pins that can be connected to various expansion boards (shields). It provides 14 digital pins (6 of which can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. It encompasses everything needed to support the ATmega328P microcontroller and deliver the desired results to the user [23, 24, 26]. When utilizing an Arduino development environment, all connections are programmed through serial connections. The implementation varies based on the hardware version. Several Arduino modules have integrated level shifters to facilitate the conversion between RS-232 and TTL logic levels. Current Arduino boards are programmed via USB and include USB-serial converters, such as the FTDI FT232. Some newer UNO models include a separate AVR chip programmed to function as a USB-serial converter, which can be reprogrammed through an ICSP interface [26]. Other models, like the Arduino Mini and official Boarduino, use detachable USB-serial adapters, cables, Bluetooth, or other methods [26].

B. Electric Servo Motors

The proposed autonomous sail-propelled vessel utilizes two different types of servo motors (Figure 1) for controlling the sails and the rudder. The movement of the sails from one side to the other is achieved by a standard quarter-scale servo motor, which has a 180-degree rotation in both directions, to a total of 360 degrees. On the other hand, the rudder is controlled by a standard micro servo motor, which has a 90-degree rotation in both directions, to a total of 180 degrees.

C. Ultrasonic Distance Sensor HC-SR04

The HC-SR04 ultrasonic distance sensor is a component used for distance measurement, compatible with Arduino boards. It consists of a receiver, a transmitter, and a control circuit. The underlying principle of its operation is straightforward: the sensor automatically sends a series of 8 pulses at a frequency of 40 Hz and measures the time taken from the transmission to the reception of the wave [27].

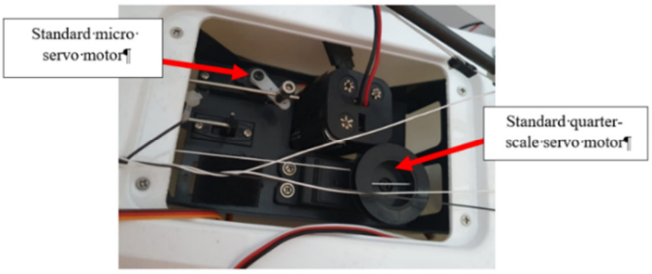

Fig. 1. Placement of the servo motors on the boat's board.

D. WiFi Module ESP8266

The ESP8266 Wi-Fi module is an integrated System-on-Chip (SoC) with an embedded TCP/IP protocol stack, providing Wi-Fi connectivity to any microcontroller. The ESP8266 can act as a host for an application or take over all Wi-Fi networking functions from another application processor. The module comes pre-programmed with AT command firmware and possesses processing and storage capabilities powerful enough to be integrated with specific sensors and devices through GPIO pins. ESP8266 supports APSD for VoIP applications, interfaces with Bluetooth, and features a self-calibrating RF unit that allows it to operate effectively in various conditions [28].

E. GPS Shield Logger

The device is based on a GP3906-TLP GPS module, comprising a 66-channel GPS receiver with a refresh rate of up to 10 Hz. The GPS module will transmit constant position updates via a simple UART serial connection, which we can subsequently utilize in the boat's position tracking process. This component includes a switch that enables us to choose the GPS module's UART interface between hardware and software ports. It also features a µSD card slot that operates through a hardware SPI port compatible with most Arduino boards, along with additional space for adding other components [29].

F. Compact Board MinIMU-9 v5

MinIMU-9 v5 is a compact board that integrates a 3-axis gyroscope (LSM6DS33), a 3-axis accelerometer, and a 3-axis magnetometer (LIS3MDL) to form an Inertial Measurement Unit (IMU). The I2C interface facilitates nine separate measurements for rotation, acceleration, and magnetism, enabling the calculation of the sensor's absolute orientation. These readings provide the necessary data to establish a suitable reference system in terms of direction and altitude for the autonomous sail-propelled boat. The board employs new MEMS sensors that offer increased precision, resulting in lower noise levels and improved zero-rate compensation [30]. This technology contributes to the development and implementation of advanced control and navigation solutions, essential in achieving superior performance in the field of autonomous navigation.

G. Electrical Power Supply of the Circuit

The electrical power supply for the entire circuit is ensured by connecting two Li-ion cells to two photovoltaic cells in a series configuration. This setup is reminiscent of a miniature off-grid circuit. To maintain a stable voltage level, a DC-DC voltage converter has been employed (Figures 2-3). This converter plays a pivotal role in regulating the output voltage, guaranteeing a consistent voltage level devoid of fluctuations at the terminals of the circuit. This configuration underscores the use of renewable energy sources to maintain the functionality of the circuit, without impacting the surrounding environment.

H. Block Diagram and Final Components Assembly

In this section, we aim to present the block diagram of the electrical circuit and the final layout of the electrical components (Figures 2-3).

The block diagram (Figure 2) provides an overview of how the components are interconnected, while the final assembly describes how the components have been physically positioned and interconnected on the circuit board or within the system's enclosure. Details pertaining to connections and assembly will be discussed to provide a clear understanding of how the electrical circuit was practically implemented. This was made possible with the assistance of the Fritzing software. Fritzing is an open-source hardware initiative that enables electronics to be used as a creative medium by anyone. Our offerings include a software tool, a community platform, and services reminiscent of Processing and Arduino. This ecosystem nurtures creativity by empowering users to document their prototypes, collaborate with others, facilitate electronics education in classrooms, and design and produce professional-grade PCBs [31]. The equipment described above was installed on a model vessel purchased on the free market, whose main technical characteristics are: length – 650 mm, width – 116.5 mm, mast height – 915 mm, total height – 1388 mm, total weight is about 1500 g, sail surface is 2226 cm^2. In Figure 4, the positioning of the electric circuit dedicated to the automation of the unmanned boat can be discerned on board.

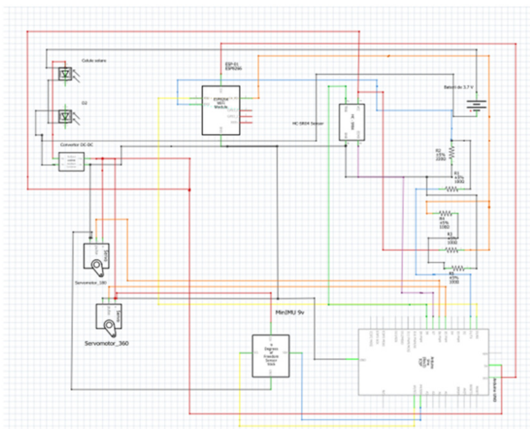

Fig. 2. The block diagram of the electrical components.

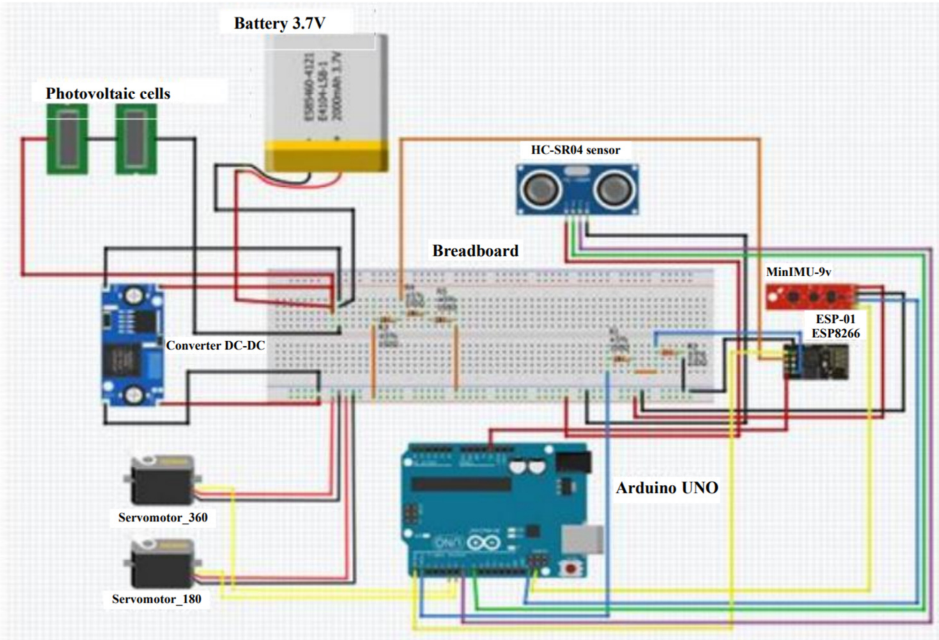

Fig. 3. The final layout of the electrical components.

Fig. 4. Automation of the sail-propelled boat.

III. SOFTWARE COMPONENT

The software component constitutes an amalgamation of data, libraries, instructions, and interfaces that dictate the operational behavior of the hardware component. Subsequently, a general overview of the employed development environments, the operational algorithm, source code, and concluding remarks are presented.

A. Arduino IDE

The Arduino IDE is an integrated development environment (cross-platform application) written in the Java programming language. It incorporates a code editor with features such as cut and paste, find and replace, automatic indentation, bracket matching, and syntax highlighting. It offers straightforward mechanisms for compiling and uploading programs to an Arduino board with a simple click. Additionally, it encompasses a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions, and a range of menus. It connects to Arduino hardware for program uploading and communication [32]. Any Arduino code is divided into two sections. The first section, "setup," is executed only once (when the board is powered or the "Restart" button is pressed), while the second section, "loop," is run in a continuous loop if the board is powered. Therefore, the "setup" section contains only the initialization code, while the "loop" section contains the execution program [32]. Furthermore, the development environment can be expanded through libraries. These offer additional functionalities in sketch usage. Upon installing the IDE, a minimal number of libraries are also installed [32]. Libraries are included at the beginning of the program using the syntax "#include <Library Name>" or "#include "Library Name.h". These libraries have been developed by companies producing devices compatible with the Arduino IDE development environment, aiming to facilitate the use of components. The following libraries from the Arduino IDE development environment were used in the program's coding:

1. Library NeoSWSerial.h - designed to enable serial communication on other digital pins of the microcontroller, emulating software functionality. Serial communication supports transfer rates of up to 9600 bps.
2. Library Servo.h - used to control servo motors.
3. Library TinyGPS++.h - designed to parse NMEA strings sent by the GPS module and provide insightful GPS information on the serial monitor.
4. Library ESP8266WiFi.h - intended for configuring and operating the ESP8266 module in station and/or soft access point mode.

5. Library RemoteXY.h - used to facilitate communication between the ESP8266 module and the Remote XY application.
6. Library Wire.h - used for communication with I2C/TWI devices.
7. Library Ticker.h - employed to replace the delay () function.

B. Remote XY

For interfacing the program on smartphones or laptops, the Remote XY application was used. This application is a well-designed "constructor" of interfaces, which allowed the development of dashboards for projects where widgets could be arranged to remotely control hardware, display sensor data, store and visualize data, and perform many other interesting tasks. In the Remote XY application, three widgets were created to input values such as: wind direction, desired coordinates point with latitude and longitude, and respectively, to display values such as the ship's coordinates point, speed, heading, number of satellites connected to the GPS, and the direction the vessel needs to navigate to reach the entered coordinates point. This connects via the Wi-Fi module to the drone and the Arduino board.

C. The Operating Algorithm

The Arduino Uno microcontroller will receive input data such as wind direction and real-time ship's coordinates (latitude and longitude), transmitted by the operator through the Remote XY application using the Wi-Fi module. Based on the provided data, Arduino will control servo motors, which in turn will adjust the sail and rudder to an optimal position for autonomous vehicle movement according to the wind direction. The ultrasonic sensor will emit and receive signals. When an obstacle appears in front of the vessel, it measures the distance to it and returns the value. If the returned distance is equal to the initially set 50 cm distance, the drone will actuate the servo motors and change its course.

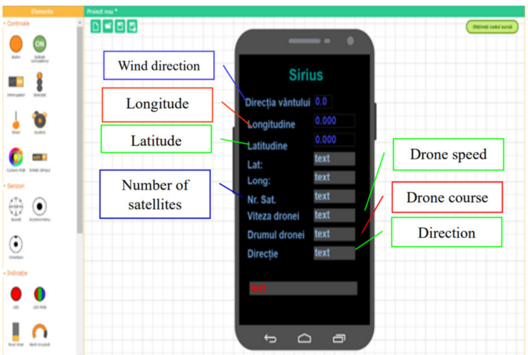

Fig. 5. The Remote XY application interface.

The ship's heading is determined using the MinIMU board as well as the GPS module. Additionally, if there is no obstacle ahead, the boat will continue moving until it reaches the latitude and longitude values set at the beginning. Once the vessel reaches the operator's desired coordinates, Arduino will activate the servo motors to turn the vessel back to the launch point. Simultaneously, the GPS module receives data about longitude, latitude, speed, and the number of connected satellites. It transmits this data through the Wi-Fi module to the Remote XY application (Figure 5) for display of the obtained values.

D. The Coding Algorithm

For programming and commanding the Arduino UNO board, the programming facilities of C and C++ were used, and the lines of code were written in the Arduinno IDE development environment.

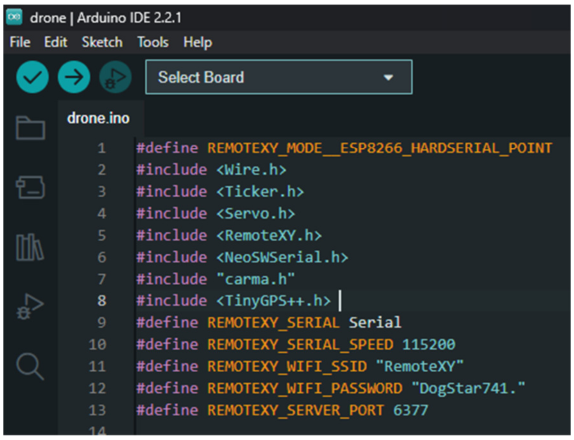

Fig. 6. Library selection.

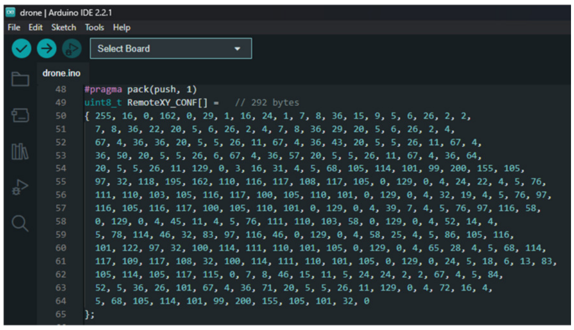

Fig. 7. Remote XY configuration.

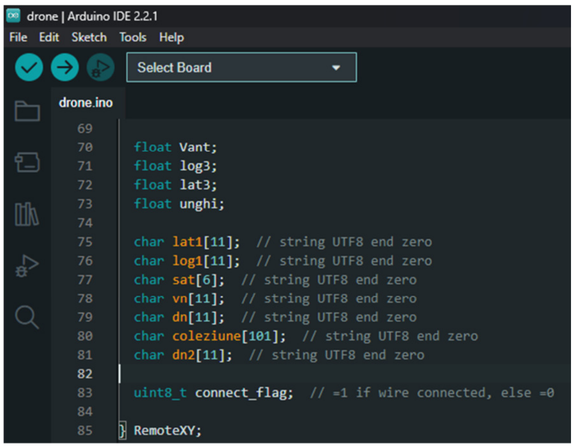

Fig. 8. Variable definition.

Some suggestive elements showing how the writing of program lines was carried out can be seen in Figures 6-8. The selection of libraries and communication module with Remote XY, selection of the GPS library, and settings for connecting with Remote XY are illustrated in Figure 6. The configuration of Remote XY is suggestively illustrated in Figure 7. The definition of variables (input and output) in the Remote XY application is shown in Figure 8.

IV. DISCUSSIONS AND FUTURE DEVELOPMENT

The current paper proposes the development of a system for automating a sail-powered autonomous vessel in response to at least two imperative needs:

- Safety and security of civil and military navigation in the Black Sea area, in the face of increased dangers in the context of political tensions and armed conflicts. Solutions are needed for surveillance of maritime space, for the identification, monitoring and destruction of hazards. These solutions must be almost immediate (which means very short manufacturing times, permanent component availability, and the lowest possible costs) without affecting performance, efficiency and reliability.
- The increased need to integrate European and global policies to drastically reduce pollution. Renewable energy principles involve the diversification of energy sources (solar energy, wind energy, ocean and hydroelectric energy, biomass, and biofuels) to ensure energy security and efficiency.

The prototype, whose final shape is shown in Figure 9, is an automated, autonomous, very small boat, powered by sails and equipped with mini solar panels.

Fig. 9. Automated sail-propelled research boat in the test basin.

Note*:* in Figures 4, 9, automation equipment is displayed exclusively for the reader to observe. During ship's operation, however, the automation equipment is naturally placed inside the ship's body to protect it from the marine environment.

The preliminary testing activities (carried out in the test tank) of the prototype of the sail-powered ship demonstrated the feasibility and functionality of the proposed solution. Future research efforts will focus on improving the nautical qualities of the ship drone (mainly its stability and functionality in somewhat harsher hydrometeorological conditions). Also, it must be noted that Figure 3 illustrates how the connections between the microcontroller used in the system and each required component were was established, highlighting how each element was interfaced with the microcontroller. The software and applications used enabled the automation of the sail and rudder to create a propulsion system powered solely by wind power and electrically charged by solar energy. In the future, this constructive approach could be improved by integrating an on-board anemometer, which would allow the ship to autonomously acquire wind direction and speed to achieve optimal travel speed. Furthermore, the ultrasonic sensor for obstacle avoidance could be replaced with a deliberate ship avoidance system at a higher level to re-plan the waypoint route for maintaining a safe distance from larger vessels.

Employing Unmanned Surface Vehicles (USVs) for maritime research, search and rescue operations, and surveillance activities offers economic and safety benefits. Using USVs in lieu of manned vessels in hazardous areas safeguards crew's well-being, the ships integrity and security of the area. Consequently, on a small scale, the automation of a sail-powered ship offers a viable solution for researching, surveilling, and protecting areas of high potential danger.

V. CONCLUSIONS

An automated, sail-propelled, energy-autonomous vessel with efficient recharging capabilities, benefiting from a favorable cost-quality balance, relatively easy and quick to assemble with equipment available on the free market, could serve commercial and military fleets to meet the needs of surveillance of maritime space and navigation routes. Regarding the original contributions, prospects for further development and limitations of achievement presented in this paper, three perspectives can be approached:

- Economic perspective: the proposed unmanned vessel model is made exclusively with components existing on the free market, the price of the prototype being 750 euros (the cost of the model vessel is 500 euros), the assembly time of the boat was about 24 hr, the boat is completely energy independent, the propulsion being provided by wind, and the electricity supply of the electronic components is made with the help of mini solar panels (photovoltaic cells). When solar radiation is not present, the boat uses electricity stored in batteries. The small dimensions of the prototype, recommend it only for use on calm water, no more than grade one, the ship being capable of a cruising speed of 2 knots. As far as autonomy is concerned, it can be practically unlimited, conditioning being dictated only by the presence of solar radiation;
- Civil perspective of use: this autonomous sail-propelled vehicle can be operated in coastal and port areas for various surveillance, monitoring, control, data collection and sampling activities. The vessel is able to be used for search and rescue operations and for anti-terrorist monitoring operations. Obviously, the endowment with equipment must be correlated with the assumed mission, the

interchangeability of components being one of the elements of originality of the boat (easy changes in programmable memory; ease of adjusting electrical connections within the control system);

- Military perspective of use: the unmanned vessel developed and presented in this paper represents an innovative solution, being able to perform patrol, surveillance and intelligence gathering missions in the vicinity of military ships on mission, to which it can provide real-time data on possible dangers. The sailing propulsion gives it an almost zero acoustic fingerprint (the only source of noise being the waves hitting the drone body), which makes it invisible to hydro location sensors (hydroacoustic buoys, sonars, etc.). Its small size also ensures its invisibility to navigation or research radars, the vessel being able to provide information from a certain monitoring sector without disclosing its position.

The research presented in this paper represents only the first phase of a project funded by the Romanian Navy which is interested, in these times characterized by particularly accelerated risk dynamics, to identify its own possibility of building a type of low-cost surface drone intended for surveillance of marine space, identification, and destruction of navigational hazards.

The proposed ship drone is a demonstrator for a large-scale sailing yacht with autonomous surveillance capabilities in Romanian's territorial waters from Black Sea (which will be built in the second phase of the project). It was compulsory to develop this initial stage, which involved making a small-scale model, on the one hand to test the validity of the proposed solutions and, on the other hand, to reduce costs.

It should be noted that, according to the best of our knowledge, there are no ready-to-purchase autonomous sailing drones. We used a remote-controlled small sailing boat which was transformed in an autonomous vessel. In this paper, the readers can study the proposed method of hardware upgrade and software development for autonomous transformation.

The main tactical advantage of a sailing yacht drone is that it can easily be confused with a civilian yacht. Also, because it is constructed from non-metal materials it has a low radar reflection and it is hard to be detected and monitored by other states. But, its most innovative aspect might be that it can survey very dangerous waters, like mine fields or mine drifting waters, without exposing navy combat ships or personnel to risk. In the future, the autonomous system will be installed on second-hand low-cost full scale sailing yachts. In conclusion, the purpose of the current research was to test the opportunity and identify the possibilities of modifying a classic sailing yacht and transforming it into an autonomous surveillance one.

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