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Implementation of a Robotic System on a USV Drone

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Abstract. This paper investigates the integration of robotic systems on autonomous maritime vehicles for the identification and neutralization of marine threats, with a focus on optimizing operational efficiency through the use of renewable energy sources. The study aims to develop an innovative and secure solution for eliminating naval hazards while significantly reducing human exposure to risks.
The analysis examines the evolution of mine clearance technologies, the classification of naval mines, and the design of an advanced robotic arm, mathematically modeled and optimized for tactical operations. Additionally, the research explores the implementation of renewable energy sources to power these autonomous systems, enhancing their operational autonomy and sustainability.
The prototype's design and testing were conducted using specialized software and 3D printing technology, with integration on an ARDUINO UNO platform. The results confirm the viability of this solution, offering prospects for further improvements in both military and civilian applications.
Keywords: Autonomous Maritime Vehicles. Renewable Energy, Tactical Operations, ARDUINO UNO, Maritime Security, Sustainable Energy Solutions Introduction (The first section in your paper)

1. Introduction

The growing dependence on non-renewable energy sources and their negative environmental impact necessitate the adoption of sustainable solutions, such as the use of renewable energy. In this context, powering autonomous maritime drones with renewable sources represents a viable solution for extending operational autonomy and reducing the environmental footprint of maritime security operations.[1], [2] The integration of sources such as solar, wind, and hydroelectric energy can significantly enhance the energy efficiency of these systems and reduce dependence on fossil fuels.[3]

At the same time, technological advancements in robotics have enabled the development of advanced autonomous systems used in various applications, including the detection and neutralization of maritime threats. Robotic arms mounted on unmanned surface vehicles (USVs[1]) can contribute to the safety of operations by handling explosives and other dangerous devices without exposing human personnel to direct risk.[4], [5], [6]

This paper analyzes the impact of using renewable energy to power maritime drones designed for neutralizing marine threats, highlighting the technological advantages, energy efficiency, and

[1] Unmanned Surface Vehicles

sustainability of this system[7], [8]. The study explores the integration of advanced technologies to optimize the performance of autonomous operations and contribute to the development of innovative solutions for maritime security.

2. Classification and Analysis of Renewable Energy Sources

Renewable energies are energy sources that regenerate naturally in a short period of time and are essential for sustainability. Here's a detailed classification:[9], [10]

1. **Solar energy:** Solar energy comes from solar radiation, captured through photovoltaic panels for electricity or solar thermal collectors for heating. It is an abundant and clean source, with no greenhouse gas emissions.
2. **Wind energy:** Wind energy is obtained from the movement of air, captured by wind turbines that convert the kinetic energy of the wind into electricity. It is efficient in regions with consistent winds and can be used both at a large scale and small scale.
3. **Hydroelectric energy:** Hydroelectric energy comes from the flow of water, used to move turbines that generate electricity. It is one of the oldest and most stable renewable energy sources, available throughout the year.
4. **Geothermal energy:** Geothermal energy comes from the Earth's internal heat and can be used for electricity generation or heating. It is available in regions with volcanic activity.
5. **Biomass energy:** Biomass energy is obtained by burning organic materials, such as wood or agricultural waste. It is a renewable source of heat and electricity and is considered carbon-neutral.
6. **Tidal and wave energy:** Tidal and wave energy is captured from the movement of ocean waters, converting mechanical energy into electricity. Although this is a developing technology, it holds great potential in coastal regions

3. Photovoltaic panels

Photovoltaic panels convert light into electrical energy. Some materials can absorb light photons, releasing electricity. The photovoltaic effect was first observed in 1839 by Edmund Bequerel.

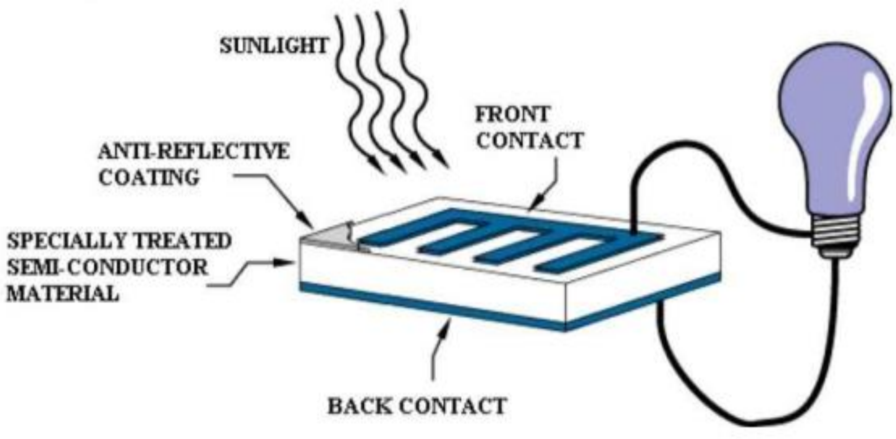


Figure 1: The operation of a photovoltaic cell[11]

The image above illustrates the operation of a photovoltaic cell. These cells are made from semiconductor materials, such as silicon. When light energy reaches the solar cell, electrons are released from the semiconductor material. A number of solar cells electrically connected to each other and mounted on a support form a photovoltaic module.[11], [12], [13]

4. The Drone Concept and Exploration of its Applications

Currently, unmanned surface vehicles (USVs) are used for various civilian purposes, such as law enforcement, climate monitoring, naval operations, submarine hunting, commercial applications, oceanographic research, and search-and-rescue missions, including hazardous operations.[14]

These USVs introduce an innovative element in the naval sector. They are robotic boats capable of operating without the need for a crew on board. Initially, surface vehicles were developed for military purposes and complex mission execution. In recent years, such technologies have advanced significantly. [15], [16]

- Military applications
- Marine applications
- Commercial applications
- Hydrographic applications

5. Mathematical Calculation for Arm Design

The kinematic evaluation of a robotic arm's movement involves identifying different coordinate frames for each joint to establish transformations that associate the joints with spatial coordinates. This process also determines the position and orientation of the end-effector relative to a reference frame.[17]

The use of rotation matrices provides a concise representation of the rotational motion of a rigid body. The analysis considers the rotation of a specific reference frame in relation to the global reference frame (rotation around the z-axis), as illustrated in the figure below.[18], [19]

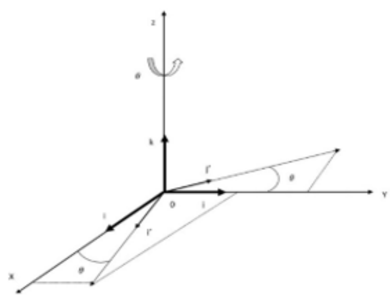


Figure2: Rotation of the (x', y', z') frame relative to the reference frame (x, y, z)

The 7-degree-of-freedom robotic arm consists of four rotational joints and five elements with lengths l_1 to l_5, as depicted in Figure 3.

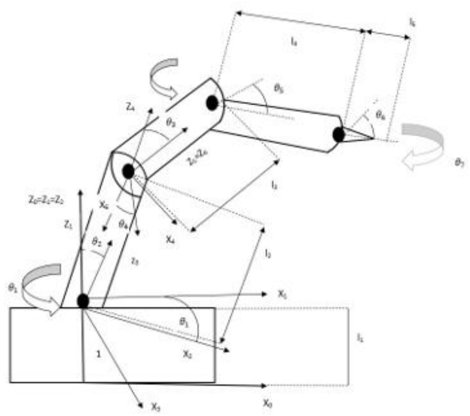


Figure 3: 7-degree-of-freedom arm

Seven stepper motors are considered for the rotation and translation of individual elements. Joints two and four can rotate around two axes, while all other joints can rotate around only one axis. The following notation is introduced: [18]

- θ_i = Generalized coordinates, i = 1, 2,...,7
- l_i = Length of element i, i = 1, 2,...,5

The control objective consists of determining the joint parameters that ensure a desired position of the end-effector. This position is determined by the reference values of the x, y, z coordinates and the angles θ_6, θ_7, which govern the rotational configurations of the final joint. The position of the end-effector was determined according to the following equation: [20]

$$E = T_z(l_1)R_z(\theta_1)R_y(\theta_2)T_z(l_2)R_y(\theta_3)T_z(l_3)R_z(\theta_4)R_y(\theta_5)T_z(l_4)R_y(\theta_6)R_x(\theta_7)\begin{bmatrix}0 & 0 & l_5 & l\end{bmatrix}^T$$

$$T_z(l_1) = \begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 1 & l_1\\0 & 0 & 0 & 1\end{bmatrix} \tag{5.1}$$

$$T_z(l_2) = \begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 1 & l_2\\0 & 0 & 0 & 1\end{bmatrix} \tag{5.2}$$

$$T_z(l_3) = \begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 1 & l_3\\0 & 0 & 0 & 1\end{bmatrix} \tag{5.3}$$

$$T_z(l_1) = \begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 1 & l_4\\0 & 0 & 0 & 1\end{bmatrix} \tag{5.4}$$

$$R_z(\theta_1) = \begin{bmatrix}\cos(\theta_1) & -sin(\theta_1) & 0 & 0\\sin(\theta_1) & cos(\theta_1) & 0 & 0\\0 & 0 & 1 & 0\\0 & 0 & 0 & 1\end{bmatrix} \tag{5.5}$$

$$R_z(\theta_4) = \begin{bmatrix}\cos(\theta_4) & -sin(\theta_4) & 0 & 0\\sin(\theta_4) & cos(\theta_4) & 0 & 0\\0 & 0 & 1 & 0\\0 & 0 & 0 & 1\end{bmatrix} \tag{5.6}$$

$$R_y(\theta_2) = \begin{bmatrix}\cos(\theta_2) & 0 & sin(\theta_2) & 0\\0 & 1 & 0 & 0\\-sin(\theta_2) & 0 & cos(\theta_2) & 0\\0 & 0 & 0 & 1\end{bmatrix} \tag{5.7}$$

$$R_y(\theta_3) = \begin{bmatrix}\cos(\theta_3) & 0 & sin(\theta_3) & 0\\0 & 1 & 0 & 0\\-sin(\theta_3) & 0 & cos(\theta_3) & 0\\0 & 0 & 0 & 1\end{bmatrix} \tag{5.8}$$

$$R_y(\theta_5) = \begin{bmatrix}\cos(\theta_5) & 0 & sin(\theta_5) & 0\\0 & 1 & 0 & 0\\-sin(\theta_5) & 0 & cos(\theta_5) & 0\\0 & 0 & 0 & 1\end{bmatrix} \tag{5.9}$$

$$R_y(\theta_6) = \begin{bmatrix}\cos(\theta_6) & 0 & sin(\theta_6) & 0\\0 & 1 & 0 & 0\\-sin(\theta_6) & 0 & cos(\theta_6) & 0\\0 & 0 & 0 & 1\end{bmatrix} \tag{5.10}$$

$$R_x(\theta_7) = \begin{bmatrix}1 & 0 & 0\\0 & cos(\theta_7) & -sin(\theta_7)\\0 & sin(\theta_7) & cos(\theta_7)\end{bmatrix} \tag{5.11}$$

The calculation of the force for a robotic arm depends on several factors, such as the weight of the arm, the payload weight, the length of the arm, the range of motion, and the type of actuators used for moving the arm, as shown in Figure 5. [21]

Assuming these parameters are known, the following equation can be used to calculate the force required for a robotic arm:

$$F = \frac{m*g*d}{L*sin\theta+(\frac{m}{M}*cos\theta)} \tag{5.12}$$

- F- Required force
- m- Payload mass
- g- Acceleration due to gravity (9,8 m/s^2)
- d- Distance from the center of mass of the payload to the considered joint
- L- Length of the robotic arm
- θ- Angle between the arm and the horizontal axis
- M- Total mass of the robotic arm

This equation analyzes the weights of the payload, the arm itself, and its angle relative to the horizontal axis. It can also be used to calculate the required force at various points along the arm by adjusting the d and θ parameters. [22]

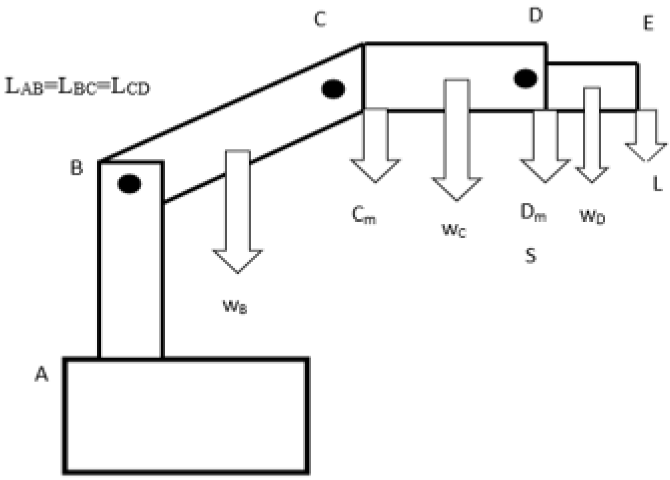


Figure 4: Force Diagram of the Arm

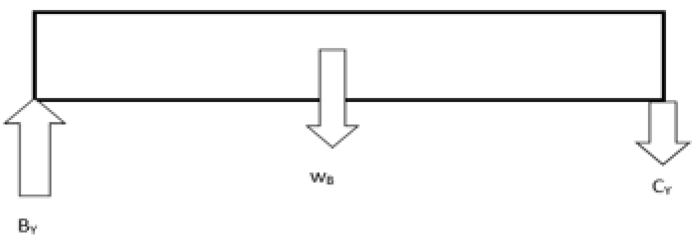


Figure 5: Force Diagram at Points CB

Summing the forces along the Y-axis using the loads as shown in Figure 5. Similarly, summing the moments around point C and point B to obtain the torque at C and B.

$$\sum F_y = (L + W_d + D_m + W_c + C_m)g - C_Y = 0 \tag{5.13}$$

$$\sum F_y = (L + W_d + D_m + W_c + C_m)g - C_B = 0 \tag{5.14}$$

$$\sum M_C = -\left(\frac{W_C L_{CD}}{2}\right) - W_D\left(L_{CD} + \frac{L_{DE}}{2}\right) \quad (5.15)$$

$$\sum M_B = -L(L_{BC} + L_{CD} + L_{DE}) - W_D\left(L_{BC} + L_{CD} + \frac{L_{DE}}{2}\right) - D_m(L_{BC} + L_{CD}) - W_C\left(L_{BC} + \frac{L_{CD}}{2}\right) - C_m(L_{BC}) - W_B\left(\frac{L_{BC}}{2}\right) + M_B = 0 \quad (5.16)$$

- W_d= Weight of joint DE
- W_c= Weight of joint CD
- W_b= Weight of joint CB
- L_{BC}= Length of joint BC
- L_{CD}= Length of joint CD
- L_{DE}=Length of joint DE

C_m=D_m= Weight of the servo motor

6. Presentation of the Drone Concept for Neutralizing Merine Threats

The proposed project aims to develop and implement a highly complex solution for the elimination of naval mines through an Unmanned Surface Vehicle (USV) equipped with a web camera for live transmission and a robotic system with three degrees of freedom, remotely controlled using the ARDUINO UNO development board.

The primary objective of the project is to utilize the robotic arm, with its ability to manipulate explosives, for placing them on identified naval mines. The system operates under remote control, allowing for precise and safe handling of the device. The core function of the project lies in the transport, placement, and detonation of explosives, with the ultimate goal of neutralizing identified naval mines.

The image below illustrates the complete robotic system developed within the Robotics Laboratory of the “Mircea cel Bătrân” Naval Academy.

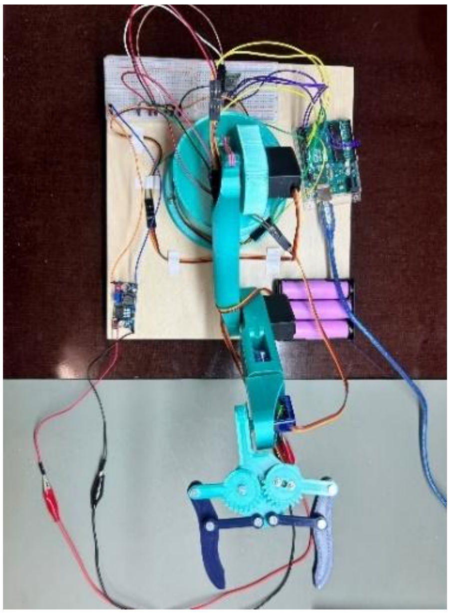


Figure 6: Complete assembly of the robotic system

7. Using Components for Building the Robotic System

To build the entire robotic system, a relatively large number of components were required. For their presentation, the schematic shown below was created. The Fritzing software was used to design the block diagram. This is an open-source program intended for electronic circuit design; however, it offers a user-friendly interface that allows users to construct electrical schematics and visualize their projects intuitively.

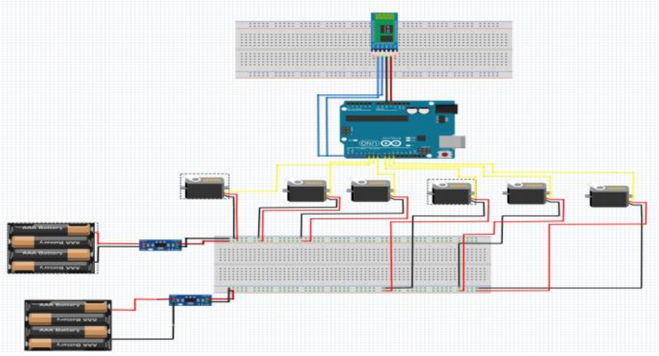


Figure 7: Block diagram for component connection

In the schematic above (Figure 7), we can identify:

1. Two power sources with four Lithium-ion batteries
2. Six servomotors (three MG996R servomotors and three SG90 servomotors)
3. Two voltage step-down modules (one for powering SG90 servomotors at 5V and one for powering MG996R servomotors at 6V)
4. Two breadboard modules
5. Arduino UNO programming board
6. HC-05 Bluetooth module

8. Control of the Robotic System

The RemoteXY Pro application was used to control the robotic system. This application, installed from the Google Play Store, enables the creation of a graphical interface where buttons are arranged in a matrix. This matrix is then inserted into the final code for programming.

Once the byte matrix is finalized, the buttons remain saved and can be used to control the servomotors.

Figure 3 presents the graphical interface of the application for connecting the HC-05 module. After pairing the module with the mobile application, it remains connected as a functional button within the graphical interface.

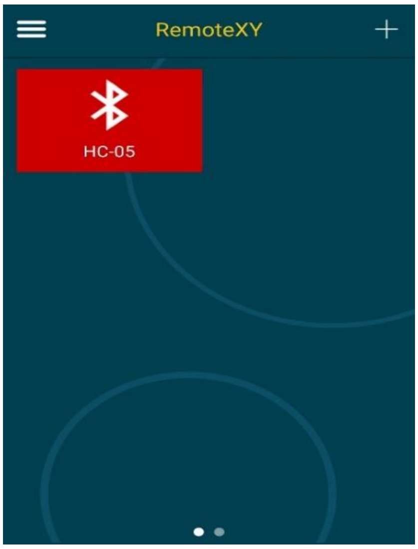


Figure 8: Graphical interface for connecting to the HC-05 Bluetooth module

Figure 9 presents the application interface with the buttons assigned for controlling the six servomotors.

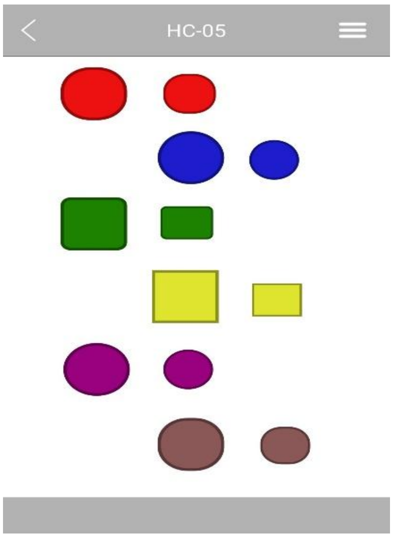
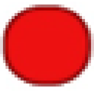
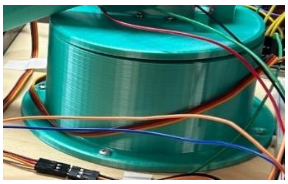
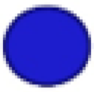
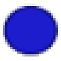
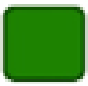
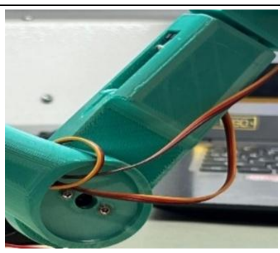


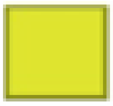
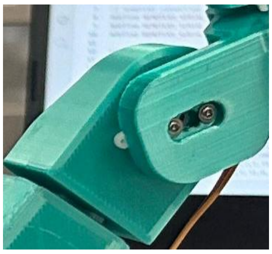
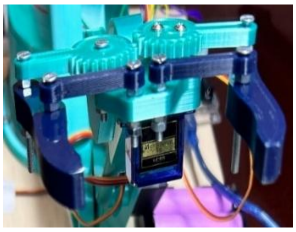
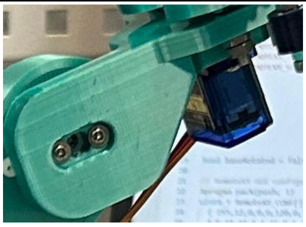
Figure 9: Graphical interface with buttons for arm control

9. Control of the Robotic System Using the Application

Table 1 presents the legend for the functionality of the buttons used to control the robotic arm within the application, as well as the component actuated by each button and its description.

Tabel 1: Button Functionality, Actuated Component, and Description

No.	Button Symbol	Actuated Component	Button Description
1.			Rotates the base to the left, movement occurs gradually, degree by degree.
2.			Rotates the base to the right, movement occurs gradually, degree by degree.
3.			Raises Arm 3.
4.			Lowers Arm 3.
5.			Moves Arm 2 upwards, gradually, degree by degree.
6.			Moves Arm 3 downwards gradually, as long as the button is pressed.

7.			Rotates Arm 3 to the left, degree by degree.
8.			Rotates Arm 3 to the right, degree by degree.
9.			Opens the gripper to allow manipulation of different-sized objects.
10.			Closes the gripper for securing smaller objects; for larger objects, ensures a better grip.
11.			Moves the gripper base upwards, gradually, degree by degree.
12.			Moves the gripper base downwards.

10. Conclusion

Due to the advancement of technology and the increasing demand for energy sustainability, the integration of renewable energy sources into autonomous maritime systems represents the most secure strategic development direction. The use of solar panels, along with other renewable energy conversion solutions, can significantly extend the autonomy of USVs.

Currently, the naval mine destruction system used by the Romanian Naval Forces relies on traditional methods, posing significant risks to military personnel. This study proposes the implementation of an advanced robotic system integrated into a USV, capable of executing maritime threat neutralization operations efficiently and safely.

Another innovative aspect explored in this project is the integration of renewable energy-based power solutions, such as solar panels and other energy conversion technologies. These solutions can significantly improve the autonomy of surface drones while reducing CO_2 emissions, thus contributing to environmental protection.

The implementation of such an innovative robotic system on USV platforms would represent a significant technological advancement in the combat doctrine of the Romanian Naval Forces, while also enhancing the safety of personnel involved in demining operations. This project paves the way for a new generation of autonomous maritime technologies with great potential for application not only in military operations but also in civilian maritime infrastructure and security missions.

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