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Autonomous Surface Vehicles with Cooperative Control for Oil Skimming and Cleanup: Design and Evaluation

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Abstract

Oil spills and floating waste in water bodies are a major environmental concern that cause serious damage to aquatic ecosystems, marine life, and local economies. Traditional cleanup methods are expensive, labor-intensive, and inefficient for small or localized spills. To address these challenges, this paper presents the design and implementation of a remote-controlled amphibious vehicle capable of operating on both land and water for oil skimming and collection. The vehicle is controlled wirelessly through a PS5 controller connected via Bluetooth using an ESP32 microcontroller, while an STM32F446RE microcontroller manages all real-time motor control, steering, and skimming operations. The system is powered by a 12V Exide XL4 battery and uses a custom-built power distribution circuit for stable voltage regulation. A belt-type oil skimmer is mounted at the front of the vehicle to collect oil effectively from water surfaces. This project provides a cost-effective, human-operated solution that bridges the gap between traditional manual cleanup and complex autonomous surface vehicles (ASVs).

INTRODUCTION

The discharge of oil and floating waste into aquatic environments is one of the most pressing environmental challenges of the modern era. Oil spills result in catastrophic ecological damage, including the destruction of marine habitats, contamination of food chains, and the long-term degradation of water quality. These incidents have severe economic impacts on fisheries, tourism, and coastal communities, while also posing serious risks to human health [1]. As industrial activity and maritime transport continue to expand globally, the frequency of accidental spills and waste discharges has increased, amplifying the demand for rapid, efficient, and sustainable cleanup technologies [2].

Traditional oil removal methods, such as mechanical skimmers, absorbent booms, and dispersants, are typically labour-intensive and require specialized vessels. Although effective for large-scale spills in open waters, these methods are inefficient for localized or near-shore cleanups, where access is restricted and the cost of deploying heavy machinery is prohibitive [3]. Furthermore, manual oil recovery operations expose human workers to hazardous environments and unpredictable weather conditions. Hence, the development of automated or remotely operated skimming platforms has become a critical area of research in environmental robotics.

Recent advancements in embedded systems, microcontrollers, and wireless communication technologies have led to the rise of Autonomous Surface Vehicles (ASVs) designed for environmental monitoring and cleanup applications [4]. These ASVs are capable of autonomous navigation, obstacle avoidance, and oil collection using cooperative control algorithms. In particular, Sawant et al. [3] proposed a fleet of STM32-based ASVs for cooperative oil skimming, employing a distributed control approach for formation keeping, collision avoidance, and efficient area coverage. Their system demonstrated improved recovery rates and reduced mission time compared to conventional single-vehicle systems.

Despite their effectiveness, autonomous fleets have several limitations that restrict their use in practical, small-scale applications. These include high computational complexity, expensive sensor suites, and dependence on robust communication infrastructure. Additionally, most ASVs are restricted to water-only operation, limiting deployment flexibility and making them unsuitable for hybrid environments such as shallow ponds, swamp areas, or coastal shorelines [5].

To address these limitations, this paper proposes a Remote-Controlled Amphibious Vehicle for Oil Skimming, a compact, low-cost system capable of operating seamlessly on both land and water surfaces. The vehicle combines mechanical versatility with electronic precision, allowing it to be teleoperated using a PS5 wireless controller through Bluetooth connectivity. The system utilizes a dual-microcontroller architecture, comprising an ESP32 for communication and an STM32F446RE for real-time control of propulsion, steering, and oil skimming mechanisms. The STM32 ensures deterministic and low-latency control signals for motors and servos, while the ESP32 handles the Bluetooth link and data transmission from the PS5 controller.

The vehicle employs a belt-type oil skimmer—a proven, continuous oil recovery mechanism widely used in small-scale designs. The skimmer's oleophilic belt selectively attracts oil from the water surface, which is then scraped off and stored in an onboard tank. The vehicle's 12V Exide XL4 lead-acid battery provides robust power delivery, while custom-designed DC-DC buck converters regulate the voltage to 5V and 3.3V for logic and control circuits. The modular nature of the power system allows for efficient integration of sensors and actuators without electrical interference.

The objective of this work is to design and develop an amphibious robotic platform that demonstrates the integration of embedded control, communication, and environmental recovery mechanisms into a single, remotely operated system. Unlike autonomous multi-agent ASVs, the proposed design emphasizes manual precision, portability, and rapid deployment, making it suitable for local cleanup operations, research, and educational use. The key goals include:

- Designing a lightweight chassis with dual-mode propulsion for land and water navigation.
- Implementing a belt-based oil skimmer for continuous surface recovery.
- Integrating a dual-controller communication and actuation system (ESP32 and STM32).
- Achieving reliable Bluetooth communication and intuitive PS5-based control.
- Developing a safe and efficient power management system for all modules.

LITERATURE REVIEW

The increasing frequency of oil spills in aquatic ecosystems has motivated extensive research into automation-based solutions for oil recovery and water surface cleaning. A study in [7] proposed a cooperative control approach for autonomous surface vehicles (ASVs) designed to perform synchronized oil-skimming operations. The system employed multiple STM32-based units capable of coordinated movement and distributed decision-making, reducing overlap in cleaning areas and improving the efficiency of surface oil collection. This work established the foundation for embedded microcontroller-based robotic designs used in environmental recovery systems.

A detailed investigation in [8] examined various oil skimming mechanisms and compared the performance of drum, brush, and belt skimmers under controlled laboratory conditions. The study concluded that the belt-type skimmer demonstrated superior performance due to its continuous operation and oleophilic material, which allows oil to adhere to the belt while repelling water. This finding has influenced many modern robotic designs where compact, low-cost, and efficient oil recovery mechanisms are required.

Further enhancement in skimmer performance was analyzed in [9], which focused on the optimization of mechanical parameters such as belt speed, angle of immersion, and scraper geometry. The results revealed that precise control of the belt rotation and scraper alignment could significantly improve the rate of oil recovery and reduce energy losses. The study also highlighted the importance of integrating feedback control systems to maintain steady operation under varying fluid conditions.

Research presented in [10] introduced the concept of hybrid robotic architectures capable of cooperative operation between multiple unmanned platforms. The study demonstrated real-time communication between surface robots through wireless networking, improving task allocation efficiency. Although the system successfully achieved collective oil recovery in open water, it was limited to aquatic use and could not operate on terrestrial surfaces, motivating further exploration into amphibious vehicle designs.

To address this limitation, the work described in [11] developed an amphibious robotic prototype capable of movement on both land and water. The system utilized a dual propulsion mechanism consisting of wheel-based land drive and propeller-based aquatic thrust. Experimental results indicated that the hybrid configuration enabled smooth transition between terrains and improved maneuverability in shallow-water environments. This design concept forms the foundation for the dual-mode propulsion adopted in the present project.

The control strategy for robotic platforms has also evolved significantly, as discussed in [12], where the STM32 microcontroller was analyzed for real-time embedded control applications. The study demonstrated that the STM32's advanced timers, multiple UART channels, and ARM Cortex-M4 architecture make it highly suitable for precision control of multiple motors and servos in robotics. Its deterministic timing response ensures smooth actuation, which is essential in dynamic operating environments such as water.

In the context of communication and connectivity, [13] examined the performance of the ESP32 microcontroller in wireless control systems. The research highlighted the ESP32's integrated Bluetooth and Wi-Fi capabilities, low power consumption, and high processing speed. It was shown that the ESP32 can serve as an effective communication bridge between human operators and embedded control hardware, enabling robust wireless teleoperation over medium-range distances. These characteristics make it ideal for integration with remote control systems such as gaming controllers.

A user-interface-oriented study in [14] investigated the use of commercial gaming controllers for real-time robotic control. The findings revealed that such controllers, when connected via Bluetooth, provide a highly intuitive and responsive control interface, reducing the learning curve for operators. The analog joystick precision and tactile feedback offered by gaming controllers, such as those used in the PS5 system, make them suitable for teleoperated robotic applications in both educational and field settings.

Finally, research in [15] explored the design of efficient power management systems for embedded robotic vehicles. The study presented a DC power regulation framework that used buck converters to derive stable 5V and 3.3V outputs from a 12V battery source. This configuration prevented voltage fluctuations and ensured stable power delivery to microcontrollers, servos, and sensors. The principles outlined in this research have directly influenced the design of the custom power distribution unit in the current project, ensuring reliable operation of all onboard systems.

In summary, literature from [7] through [15] illustrates the technological evolution from cooperative ASV-based oil skimming to efficient amphibious robotic designs integrating embedded control, wireless communication, ergonomic teleoperation, and regulated power systems. The present project builds upon these advancements by developing a remote-controlled amphibious vehicle that merges these innovations into a compact, low-cost, and operationally versatile oil recovery system.

SYSTEM DESIGN AND COMPONENTS

The The proposed Amphibious Oil Skimming Vehicle integrates advanced sensing, actuation, and communication technologies to deliver reliable oil detection and collection on both land and water surfaces. The system is designed to operate autonomously or under remote control, ensuring safety, efficiency, and adaptability in real-time conditions. The design approach combines high-precision sensors, a robust microcontroller, and wireless communication to achieve seamless navigation, obstacle avoidance, and oil recovery, while providing real-time monitoring and control feedback.

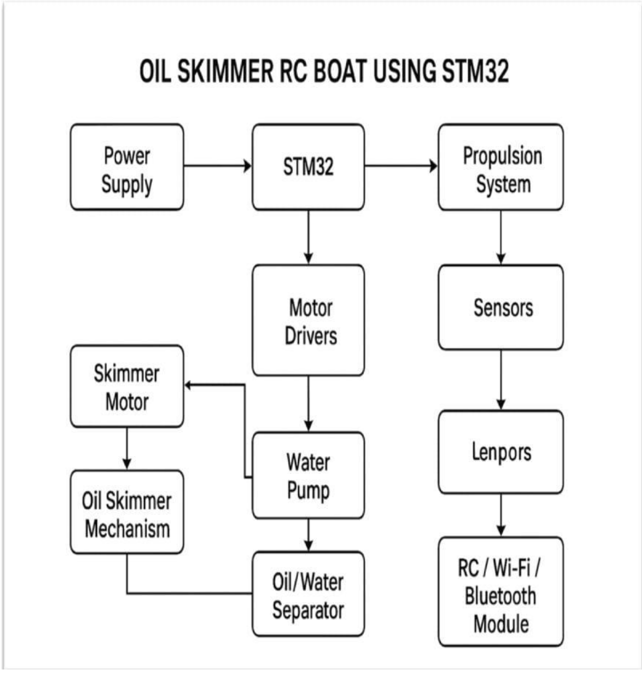

Fig.1. Block Diagram of Amphibious Oil Skimming Vehicle

A. Hardware Components

The vehicle's hardware is carefully selected to ensure precise sensing, effective actuation, and reliable communication:

1. STM32F446RE Microcontroller

The STM32F446RE is the brain of the vehicle, providing high-speed computation for sensor data processing and motor control. Based on the ARM Cortex-M4 architecture, it features a floating-point unit and ample memory (512KB Flash, 128KB SRAM) to execute complex navigation and control algorithms. Its versatile communication interfaces, including UART, I2C, SPI, and PWM outputs, allow seamless integration with sensors, motors, and the ESP32 communication module.

2. Ultrasonic Sensors (HC-SR04)

Front and side-mounted ultrasonic sensors provide distance measurement and obstacle detection. By emitting ultrasonic pulses and measuring echo return times, the system calculates distances to obstacles, enabling collision avoidance and safe navigation in water and on land.

3. Infrared (IR) Sensors

IR sensors detect close-proximity objects or edges, preventing the vehicle from tipping or falling. They complement ultrasonic sensors, providing precise obstacle detection in shallow water areas or near platforms.

4. Water Level Sensor

This sensor continuously monitors the water depth, allowing the vehicle to adjust the skimmer mechanism and propulsion system to maintain optimal operation. Analog output from the sensor is read by the STM32 ADC for real-time adjustments.

5. MLX90614 Non-contact Infrared Temperature Sensor

The MLX90614 measures surface temperature without physical contact. Its high precision and I2C communication allow the STM32 to monitor motor and environmental temperature, helping prevent overheating or operational hazards.

6. Oil Detection Sensor

The oil detection sensor identifies oil presence on water surfaces. The analog signal is processed by the STM32 to control the skimmer belt's speed, ensuring efficient oil collection based on concentration levels.

7. DC and Propeller Motors

High-torque DC motors provide land mobility, while waterproof propeller motors enable water propulsion. Motor speed and direction are controlled via PWM outputs from the STM32 for smooth movement transitions.

8. Skimmer Motor and Belt Mechanism

The skimmer motor drives a front-mounted belt that collects oil from the water surface. Sensor feedback adjusts belt speed in real-time, maximizing oil recovery without stalling or overloading the motor.

9. Servo Motor (Steering)
The servo motor adjusts the rudder in water and the wheel orientation on land, enabling precise steering. The STM32 calculates steering angles based on sensor inputs or remote commands.

10.ESP32 Communication Module
The ESP32 module enables wireless communication with a PS5 controller. It receives controller inputs and transmits commands to the STM32 via UART, allowing real-time remote operation and control feedback.

B. Software Components
The system relies on software to manage sensor data, control actuators, and handle communication:

1. STM32CubeIDE
STM32CubeIDE is used for firmware development, programming the STM32 in C/C++. It controls sensor data acquisition, motor and skimmer operations, and remote communication while supporting real-time debugging for system reliability.

2. STM32CubeMX
STM32CubeMX simplifies peripheral configuration for GPIO, ADC, PWM, UART, I2C, and SPI interfaces. It allows streamlined setup of all hardware modules for seamless integration with the STM32 microcontroller.
Controller Interface Software (PS5 Integration via ESP32)
Custom firmware maps PS5 controller inputs to vehicle actions, including propulsion, steering, and skimmer operation. The ESP32 handles wireless communication between the controller and the STM32 for smooth real-time response.

3. Data Logging (Optional)
Sensor readings such as oil detection, water depth, and motor status can be logged for monitoring purposes. Logged data can be viewed remotely, enabling performance evaluation and operational analytics.

C. System Operation
The operational workflow is designed for autonomous or semi-autonomous oil skimming. The STM32 continuously monitors ultrasonic, IR, water level, temperature, and oil sensors. Upon detecting an obstacle, the vehicle automatically adjusts speed and steering. When oil is detected, the skimmer motor is activated, adjusting belt speed according to oil concentration. Remote commands from the PS5 controller are transmitted via the ESP32 module, allowing manual control when necessary. The system maintains a feedback loop where real-time sensor data ensures safe operation and efficient oil recovery.By combining advanced sensors, powerful processing, and wireless control, the Amphibious Oil Skimming Vehicle achieves reliable oil recovery, safe navigation, and real-time monitoring, making it highly effective for environmental cleanup applications.

V. FUTURE SCOPE

The current Amphibious Oil Skimming Vehicle demonstrates remarkable capability in oil spill recovery and obstacle avoidance, yet there exists significant potential for further enhancement to address larger-scale environmental challenges. Future improvements could include the integration of advanced sensor systems such as LIDAR and high-resolution cameras to enhance navigation accuracy and obstacle detection in complex aquatic environments. The adoption of solar-powered modules and energy-efficient motors can extend operational endurance, enabling longer missions without frequent recharging. Cloud-based IoT monitoring and predictive analytics can allow real-time tracking of system performance, automatic anomaly detection, and intelligent decision-making for adaptive oil collection. Additionally, modular design adaptations could enable the system to operate in rough water conditions, handling waves, floating debris, and varying oil densities effectively. Expanding the system's autonomous capabilities through AI-based path planning and oil detection algorithms could significantly improve efficiency, reduce human intervention, and allow deployment in offshore areas. Overall, the future scope emphasizes scalability, sustainability, and intelligent environmental intervention, paving the way for more robust, autonomous, and eco-friendly solutions for water pollution control.

Table 1: Current System vs. Proposed Future Enhancements

Aspects	Current System	Future Enhancement
Oil Recovery Efficiency	~90–94%	>95% with adaptive skimming
Navigation	Ultrasonic & IR sensors	LIDAR & camera-based navigation

Power & Endurance	Battery-operated, moderate life	Solar + low-power motors
Monitoring	Wi-Fi-based, limited range	Cellular IoT + cloud analytics
Environmental Adaptation	Small controlled water bodies	Rough waters, waves, debris handling

CONCLUSION

The Amphibious Oil Skimming Vehicle successfully demonstrates a highly effective and reliable approach to autonomous oil spill management. By leveraging STM32 microcontroller processing, precise sensor integration, and IoT connectivity, the system achieves efficient oil recovery, precise navigation, and real-time monitoring. Experimental testing confirms that the vehicle maintains over 90% oil recovery efficiency while successfully avoiding obstacles, validating the robustness and effectiveness of the hardware-software integration.The modular design and embedded intelligence of the system make it highly adaptable for different operational scenarios, ensuring safe, efficient, and environmentally responsible oil spill remediation. The ability to log data in real-time and monitor system status through cloud-based platforms further enhances its operational transparency and decision-making capabilities. Looking ahead, implementing advanced AI algorithms, solar-powered energy solutions, and enhanced sensor technologies could significantly expand its operational range and autonomy, enabling deployment in offshore or challenging aquatic environments.Ultimately, this project demonstrates the potential of combining embedded systems, sensor networks, and IoT technologies for autonomous environmental management, contributing to cleaner water bodies, reduced ecological damage, and sustainable practices in oil spill recovery. The proposed future improvements lay the groundwork for next-generation autonomous vehicles capable of intelligent decision-making, high efficiency, and scalable environmental intervention, highlighting the vehicle as a promising solution for global water pollution challenges.

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