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AI-Integrated and Energy-Optimized Robotic Systems for Autonomous Water Surface Purification: A ComprehensiveSurvey

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Abstract

This comprehensive survey explores the advancements in AI-integrated and energy-optimized robotic systems designed for autonomous water surface purification. As water pollution continues to pose significant environmental challenges, innovative solutions that leverage artificial intelligence and robotics are becoming increasingly vital. This study reviews the current state of technology in robotic systems that utilize AI for efficient navigation, pollutant detection, and purification processes. We analyse various methodologies, energy consumption patterns, and the integration of renewable energy sources to enhance operational efficiency. Beyond water purification, industrial and service robots are transforming multiple sectors. Industrial robots such as articulated, SCARA, Delta, Cartesian, and collaborative robots (cobots) are revolutionizing manufacturing through precise and automated operations. Service and cleaning robots, meanwhile, are increasingly applied to tasks such as floor, window, and water surface cleaning, where advanced navigation, obstacle avoidance, and adaptive decision-making are critical. Artificial intelligence plays a central role by enabling computer vision, deep learning approaches such as Convolutional Neural Networks (CNNs) and Single Shot Detectors (SSDs), and real-time learning for dynamic environments. Additionally, Robots-as-a-Service (RaaS) models are making AI-powered robotic solutions more accessible and cost-effective, particularly for small and medium enterprises. By combining robotics with AI-driven autonomy and renewable energy optimization, these systems not only improve operational efficiency and reduce environmental hazards but also align with global sustainability goals. The findings highlight the transformative role of AI in enabling intelligent perception, decision-making, and energy-aware operations. This survey identifies challenges, research gaps, and future directions, providing a foundation for scalable and sustainable water purification technologies.

1. Introduction

Water is essential for life and plays a major role in our daily life and human body needs the certain amount of water to live and the basic uses for human. Here are some reasons of highlighting its importance: Hydration, Temperature Regulation, Skin Health, Agriculture and farming, Sanitation and Cooking and food Preparation and cleaning. Water pollution is the contamination of water bodies such as rivers, lakes, and oceans with harmful substances making them incapable of being used by [1,2,3,4,5]. It hurts aquatic lives, breaks up ecosystems, and causes health issues in humans. Common pollutants include chemicals, industrial waste, plastics, and sewage [6,7,8,9] Water pollution often leads to waterborne diseases, loss of biodiversity [10,11,12], and scarcity of clean water [13,14,15,16]. Human activities include improper waste disposal, deforestation, and overuse of pesticides [17,18,19].Machine learning offers powerful tools for predicting and optimizing solar energy systems [20,21,22]. Its integration enhances

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efficiency, reliability, and innovation in solar technology applications are implemented the researchers are [23,24,25]. Water pollution arises from multiple sources, with industrial discharges from sectors such as mining and power generation releasing heavy metals and toxic pollutants into water bodies. Plastic waste, accumulating in rivers, lakes, and oceans, poses long-term ecological harm, while oil spills from ruptured pipelines, illegal discharges, and tanker accidents rank among the most devastating forms of contamination. Agricultural runoff further contributes by carrying nitrogen- and phosphorus-rich fertilizers into rivers and lakes, triggering algal blooms and eutrophication that deplete oxygen and threaten aquatic life [26,27,28]. Collectively, these pollutants severely damage ecosystems, endanger human health, and disrupt economies dependent on clean water resources. Water pollution causes severe ecosystem damage, threatening the survival and quality of natural habitats. It leads to biodiversity loss and disrupts the food chain, endangering ecological balance [29,30,31]. Water pollution poses serious health risks, including cancer, antibiotic resistance, skin and gastrointestinal disorders, hormonal imbalances, and developmental issues [32,33,34]. Industrial and oil-related discharges into rivers and lakes worsen these threats, limiting access to safe water. Solutions include physical filtration, chemical treatment, robotic cleaners, magnetic nanotechnology, reducing chemical use, and promoting clean water campaigns[35,36,37]. A robot is a programmable mechanical system that performs tasks autonomously or with minimal human intervention using sensors, software, and mechanical components [38,39]. The first industrial robot, created by George Devol in 1954, marked the rise of modern robotics. Today, robotics integrates mechanical engineering, electronics, computer science, and artificial intelligence to achieve precision and consistency[40, 41]. Robots are applied across industries to enhance efficiency, reduce risks, and perform tasks in hazardous environments [41,42,43,44]. They are widely used in industrial automation, healthcare, environmental protection, domestic services, space exploration, and defense. From factory assembly and medical surgeries to waste collection, home cleaning, and space missions, robots play a vital role in modern society. Convolutional Neural Networks (CNNs) enable water-cleaning robots to intelligently detect and classify floating waste using image processing and pattern recognition. The robot captures images via cameras, which are processed by a trained CNN to identify different types of contaminants such as plastics, algae, or organic debris. Based on this classification, the robot decides whether to collect or ignore each object [45,46]. The CNN is trained on labeled water surface images to recognize objects like plastics, leaves, or oil spills by extracting visual features such as color, shape, and texture. It enables the robot to accurately identify and collect waste in real time while minimizing false positives [47,48]. Additionally, CNNs offer flexibility, allowing retraining for different locations, seasons, or new types of debris. The SMURF robot is an autonomous, solar-powered water-cleaning robot that uses RGB cameras and a CNN-based classifier to detect and collect plastic litter from lakes and urban water bodies efficiently. Robots are machines capable of performing tasks automatically, completing work in a fraction of the time [49]. The first industrial robot was invented in 1954 by George Devol from Louisville, Kentucky, marking the beginning of modern robotics.

2. Different applications of robot

Robotics are basically bifurcated into industrial robots which are used in manufacturing something and service robots as in cleaning or healthcare or Personal/Home use. Each one is unique in that it gives a particular kind of performance for specific tasks, ranging from mechanized repetitive functions in factories to supplementary aid to humans in their daily endeavors. High-tech systems like personal robots are viewed as becoming an everyday human product similar to personal devices. Among these types of robots, practical application ones as well as those for scientific purposes will be developed for the purpose of multimodal communication as well as human-like interactions. Many people lose their lives due to diseases associated with safe water, and plastics have seriously impacted water bodies. Mechanical cleaning methods of the surface of water are based on human activity and from this perspective are ineffective as well as risky in this work. The autonomous robots can purposely employ appropriate cleanliness of water surfaces, some sections which are hard for humans to access due to risk factors involved. The new prototype is a self-propelled method of cleaning water surfaces moving through improved CPP and SSD for greater efficiency in the cleaning process.

2.1. Robot applications

Robots have found applications in various sectors including healthcare, manufacturing and environmental services. In the medical field, robots are utilized to transport supplies such as surgical tools, organs, medicines and samples in hospitals. They improve the efficiency of deliveries, reduce staff workload, and have ancillary features like temperature, and humidity control. Inspection and maintenance robots are used in infrastructure areas like power lines and pipelines. These are robots that are used to place-up bird diverters on power-lines or test pipelines for leakages. Many of their designs also include stabilization and multirotor systems for transport and deployment .General categories of robots in Figure 1:

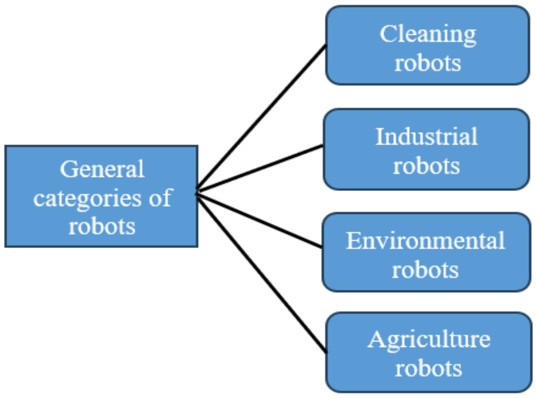

Figure 1. General Categories of Robot.

2.2. Cleaning robots

A cleaning robot is a type of autonomous machine that is designed to clean with little or no human during the task. Operating based on the sophisticated, advanced technologies (such as sensors and artificial intelligence), the robot navigates throughout your various environments to perform general tasks such as vacuuming, scrubbing, or even sanitizing. These robots can use different methods like simultaneous localization and mapping (SLAM) to make maps of spaces, avoid situations objects during movement and get the most efficient cleaning route [54]. This robot scope is so wide that some are floor specific while other is window, pool or water body specific too. They are designed to be more efficient in the cleaning process, reduce human labor and function continuously; therefore, they are adaptable over a variety of surfaces or types of dirt. They clean the street using special tools like brushes or UV light to create a design. They are designed using specialized tools, such as brushes or UV light, for unique cleaning requirements in complex settings such as underwater or industrial environments. This is especially useful in maintaining hygiene standards in public spaces, industries, and environments where human cleaning is difficult or hazardous.[52]. Just as floor-cleaning robots can switch between vacuuming and mopping, water-cleaning robots might have modules for surface skimming (collecting floating waste) and deeper water filtration. Many water robots are solar-powered for extended operation times, which is both eco-friendly and practical, as they can recharge during daylight hours.

2.3. Industrial robots

The industrial robots are being utilized for manufacturing aspects. Industrial robots are however automated and programmable Industrial robots are multifunctional machines in modern manufacturing that facilitate functions such as material handling, welding, and precision work at high speeds. Industrial robots come in various types; each one designed for different purposes. For example, articulated robots have a resemblance to the human arm and their flexible range of motion makes them ideal when it comes to welding and assembly. Cartesian robots operate along linear axes, making them appropriate for applications including 3D printing. They can either save people from having to do repeating or dangerous tasks, which means rapidly reducing human effort and bringing evenness. The evolution of technology like artificial intelligence (AI) and machine learning has made industrial robots smarter, more flexible, and a little less intimidating to work alongside. In all, industrial robots have raised the bar for different industries by maximizing manufacturing opportunities and thus opening a door towards more interconnected and streamlined production systems.

2.4. Environmental robots

Environmental robots are very much at the forefront in the drive towards sustainability, with their focus mainly on conservation and resource management. One of the most important ways they have been used involves water-cleaning robots, which clean waste products, pollutants, and invasive species from many water bodies. This category of robot operates both at the surface and below the water and is designed to use sensors and collection mechanisms that capture debris, even down to microplastic levels. Robots also play an important role in managing waste-particularly in sorting and recycling materials to reduce landfills. In addition, air- and soil-quality-sensor-equipped robots can monitor pollutants, chemical levels, and other harmful substances in the air and soil environment. These monitor the changes in the parameter conditions, such as those from the levels of CO_2 and pH levels of the soil, for early detection of sources of pollution. Another important sector is biodiversity monitoring, where autonomous drones and ground robots monitor wildlife and plant species, habitat conditions, and so on. Such data gives credence to nature conservation, as scientists can study, among other things, migration patterns, biodiversity, and environmental health.

2.5. Limitations of the autonomous surface water cleaning robots paper

The paper on Autonomous Surface Water Cleaning Robots presents an innovative solution to water pollution, but it also has certain limitations that should be acknowledged 5 types: (i) Technological (ii) Dependence: The robot relies heavily on advanced sensor fusion and computer vision technologies for this navigation and waste identification. This could limit its performance in poor visibility or extreme weather conditions, thereby hindering the operational capabilities.(iii) Cost of Implementation: The cost of implementation is high, and though the design emphasizes sustainability, the initial costs of developing and deploying such advanced robotic systems may be high.Maintenance Requirements: Autonomous robotsrequire regular maintenance for proper functionality, which necessitates technical expertise that may pose limitations when utilized in remote locations. (iv) Limited Waste Types: Although the robot is designed to distinguish between different types of waste, it might not be able to handle all types of debris, especially heavy or submerged debris. This might limit its ability to clean various water bodies with different types of pollution. (v) Scalability Issues: The paper discusses that the robot covers large areas. However, a big operations scale for cleaning extended water bodies will pose logistical issues. Coordinating multiple robots and ensuring them to work with efficiency may raise deployment complications, while the paper presents a very promising solution for water pollution, it is absolutely necessary to point out these limits so that these challenges can be understood when one tries to translate this concept to practical autonomous robots for cleaning the water.

2.6. How the robot identifies different pollutants

The self-sustaining water cleaning robot utilizes various modern technologies to identify different types of pollutants in water bodies. The main methods
that the robot employs are: Sensor Fusion: The robot is equipped with multiple sensors that work together to gather comprehensive data about the environment. Sensor fusion allows the robot to combine information from various sources, such as cameras and environmental sensors, to create a detailed understanding of its surroundings. This capability is crucial for accurately identifying different types of waste and pollutants present on the water surface. Computer Vision Technologies: This robot uses computer vision to examine visual data it captures through cameras. The use of computer vision allows the robot to identify and categorize plastics, biomedical wastes, and other debris. Images are processed by the robot as it identifies the patterns to classify different pollutants accurately. Machine Learning Algorithms: Although the paper does not provide explicit detail about the application of machine learning algorithms, most autonomous robots employ machine learning algorithms in classification applications. The robot could be trained with a labeled image dataset containing images of different types of pollutant so that, when in operation, it could learn to classify and distinguish among them.

2.7. Real-time data processing

The robot structure should contain facilities for the real-time processing of all the sensor data coming to it onsite. This could enable instant in immediate identification of all the impurities that were detected during its operations followed by appropriate measures being taken to effectively handle those impurities. In short, the pollution types are identified through sensor fusion, computer vision technology, and probably machine learning algorithms. This, in turn, makes the robot independent, yet effective at cleaning water surfaces to specific types of waste [52]. This paper makes various key contributions to the field of environmental management and robotics. Especially in the war against water pollution. The contributions are as follows: Integration of Advanced Technologies: It uses sensor fusion, computer vision technologies to make the robot operate in an autonomous mode and navigates through floating garbage and waste collecting wastes effectively.

2.8. Sustainability focus

There has been focus on sustainability aspects through the employment of green products and energy consuming parts. From the perspective of renewable sources such as solar, the robot produces less carbon by aligning to global initiatives set up for this purpose of having sustainable activities reduce climate change influences.Proactive Solution to Water Pollution: The autonomous water cleaning robot is, therefore, one proactive solution meant to curb the increasing water pollution caused by irresponsible waste disposal practices. Its potential to work twenty-four hours in a day with the coverage of large areas consisting of water bodies further contributes more to effective and efficient cleaning operations that fulfill this urgent need to improve waste management.

3. Future works

The paper outlines several potential future works that could enhance the capabilities and effectiveness of the autonomous water cleaning robot. Here are the key suggestions: Improvement of Sensor Technologies: Future research could focus on enhancing the sensor technologies used in the robot. This may involve developing more advanced sensors that can detect a wider range of pollutants, including microplastics and chemical contaminants, thereby improving the robot's cleaning efficiency and effectiveness in diverse environments.

3.1. Integration of artificial intelligence

The incorporation of more sophisticated artificial intelligence (AI) algorithms could be explored. This would enable the robot to learn from its experiences and improve its decision-making processes over time, allowing for better navigation and waste identification in complex water bodies.The paper suggests exploring the potential for collaboration with other technologies, such as drones or stationary monitoring systems. This could create a more comprehensive approach to water pollution management, where different systems work together to monitor and clean water bodies more effectively. Conducting extensive field tests in various aquatic environments would be essential for validating the robot's performance. Future works could focus on deploying the robot in real-world scenarios to gather data on its effectiveness and make necessary adjustments based on practical observations.

3.2. Problem statements for cleaning robots

Environmental and Safety Challenges: In high-risk environments like power lines, human workers face dangers such as high altitudes and exposure to voltage. Cleaning and maintenance robots address these risks by performing tasks traditionally done by humans, reducing the need for direct human interaction. Current medical delivery robots face the challenge of needing adaptable features to meet varied demands (e.g., temperature-sensitive organ transport or aseptic drug delivery). The modular design of these robots allows for flexible configurations to suit different hospital needs. In water cleaning operations, energy conservation is critical due to limited battery or solar reserves. Figure 2 highlights a practical approach to minimize unnecessary movements. Robots follow energy-efficient global paths and activate local processing units only when waste is detected. This behavior is typically controlled using lightweight AI models like Tiny YOLO or Mobile Net, capable of real-time inference on edge devices with minimal power draw. By maintaining the robot in passive mode during non-critical operations and activating full systems only during collection phases, energy usage is drastically reduced, allowing longer operation times, particularly for solar- or wave-powered robots.

Another promising strategy for extending operational lifespan involves adaptive power management systems that monitor the robot's energy state in real time and dynamically adjust task scheduling. For instance, during periods of low sunlight or high energy demand, the robot can prioritize essential cleaning functions while deferring secondary tasks such as detailed mapping or high-resolution data logging (**Figure 3**). This type of energy-aware scheduling ensures that the robot remains active for longer durations without complete shutdowns. Additionally, researchers are exploring the use of modular energy storage units, which allow robots to switch between battery packs or integrate hybrid storage systems combining supercapacitors and rechargeable cells. Such designs provide rapid charging during peak solar conditions and stable discharge when sunlight is unavailable. Another emerging trend is the use of collaborative multi-robot systems that share workload and energy demand. For example, one robot equipped with larger solar panels can act as a mobile charging station, transferring energy wirelessly to smaller robots performing localized cleaning tasks. This cooperative model not only reduces downtime but also allows large water bodies to be covered more efficiently. Finally, predictive energy optimization algorithms powered by machine learning are being integrated into robotic platforms. These algorithms analyse the environmental data such as sunlight intensity, wave patterns, and pollutant density to forecast energy consumption and adapt robot behaviour proactively. By combining prediction with adaptive control, robots can plan cleaning routes that balance waste collection with minimal energy expenditure, ensuring sustainable and continuous operations. Validation of AI-integrated water cleaning robots requires a critical comparison of existing approaches to understand their efficiency, limitations, and applicability in real-world scenarios. Many robotic systems have been proposed for water surface purification, yet their performance varies depending on navigation strategy, power optimization, sensing technologies, and environmental adaptability. Artificial intelligence has become a central driver in this domain by enabling the real-time decision-making, adaptive navigation, and intelligent waste detection. For example, lightweight deep learning models such as Tiny YOLO, Mobile Net, and SSD allow robots to detect floating debris with high accuracy while consuming minimal computational energy. Similarly, reinforcement learning-based control policies are increasingly being used to optimize path planning, where robots learn from their environment and adapt movements to maximize coverage while reducing redundant energy expenditure. Energy management is another validation criterion, as many robots depend on limited solar or battery reserves. Some studies highlight the integration of hybrid systems combining solar panels with rechargeable batteries, while others explore innovative solutions such as wave-energy harvesting. These strategies directly influence the duration of autonomous operations and the scalability of deployments across larger water bodies. Furthermore, the degree of autonomy and collaboration also plays a key role in validation. Single-robot systems are often limited in the coverage, whereas multi-robot swarms demonstrate better efficiency by distributing workload and sharing energy resources. However, this introduces challenges such as inter-robot communication, collision avoidance, and cooperative task allocation, which are still evolving areas of research. It is reviewing these dimensions, AI-powered perception, adaptive navigation, energy optimization, and scalability, researchers can better assess the strengths and weaknesses of different approaches. The comparative analysis presented in the following table provides an overview of selected recent studies, focusing on their methodologies, energy strategies, and identified limitations (Table 1). This structured validation not only highlights the progress in the field but also underscores the gaps that future research must address to develop scalable and sustainable water purification technologies.

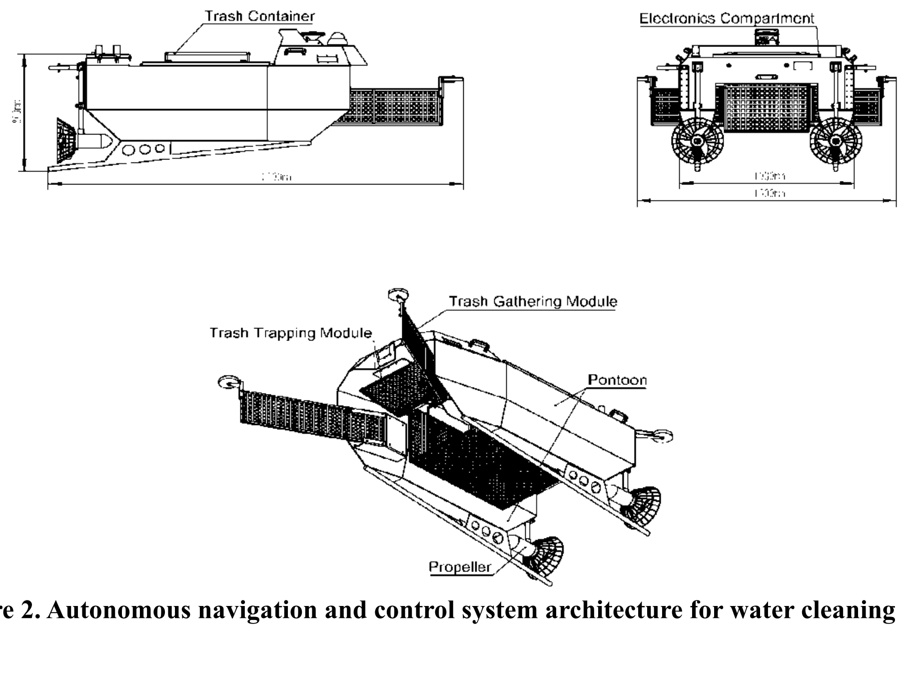

Figure 2. Autonomous navigation and control system architecture for water cleaning robot.

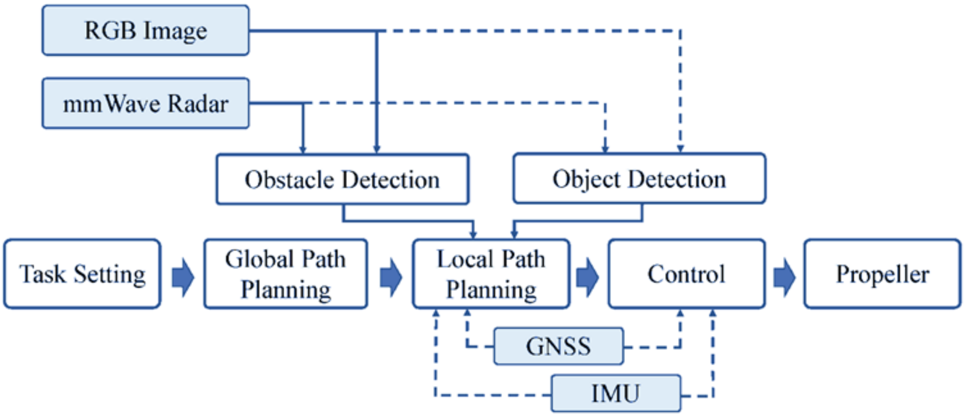

Figure 3. Adaptive trash detection and path switching in real-time.

Table 1. LIST of various methodologies and applications of robot

Paper title	Methodology	Where they tested it	Applications
Role of trust in customer attitude and behavior formation towards social service robots [58].	The study analyzes how trust in AI and social service robots influences customer attitudes and behavior using quantitative surveys and statistical modeling.	The research was conducted in hospitality settings like hotels and airports to assess customer interactions with service robots.	The findings help improve customer acceptance of service robots, optimize robot design for hospitality, and guide businesses in enhancing AI-driven services.
In-water surface cleaning robot: Concept, locomotion, and stability [55].	The paper introduces a flexible crawling mechanism using suction cups and water jets for stable adhesion and cleaning of underwater surfaces.	The robot was evaluated for stability and locomotion on different underwater surfaces, including ship hulls and industrial installations.	It is used for underwater cleaning, bio-fouling removal, and maintenance of submerged structures like ships and power plants.
Modeling and Experiments of Rotary Percussive Drilling for Robotic Civil Infrastructure Rehabilitation [57].	The study develops a mathematical model for rotary percussive drilling, incorporating dry friction and nonlinear elements to optimize robotic drilling performance for civil infrastructure repair.	The system was tested on bridge decks and concrete structures, using an in-situ force measurement system to validate drilling performance.	The robotic drilling system is used for automated infrastructure repair, specifically for bridge decks, tunnels, and civil engineering structures requiring non-destructive rehabilitation.
Robotics: Enabler and inhibitor of the Sustainable Development Goals [53].	The study uses a consensus-based expert elicitation process to assess how robotics enables or inhibits achieving UN Sustainable Development Goals (SDGs) by analyzing scientific literature and expert insights.	The study reviews robotics applications worldwide, covering economic, societal, and environmental impacts across multiple industries.	Robotics contributes to sustainable industry, environmental monitoring, automation, and economic growth but may also exacerbate inequalities and ethical concerns in some cases.
An improved single short detection method for smart vision-based water garbage cleaning robot [51].	The robot uses an improved SSD-based vision system with ResNet-50 for accurate waste detection and collection.	The system was tested on various water bodies, including lakes, coastal areas, and inland streams.	The robot is used for autonomous water cleaning, garbage collection, and environmental monitoring.

Approaching Robotics and Autonomous Systems as an Integrated Materials, Energy, and Control Problem [50].	The approach integrates materials science, energy management, and control to create dynamic robotic systems, with interdisciplinary collaboration in design, fabrication, and testing.	Includes laboratory-based testing, as well as applications across industrial, defense, and research settings, often specific to the environment being simulated	Autonomous systems for industrial tasks, healthcare, defense, agriculture, and exploration, focusing on adaptability and energy efficiency in varied environments
SMURF: A Fully Autonomous Water Surface Cleaning Robot with A Novel Coverage Path Planning Method [52].	The paper introduces a fully autonomous water surface cleaning robot named SMURF. It uses a novel Coverage Path Planning (CPP) method that adapts to irregular boundaries and obstacles, along with an improved nonlinear model predictive controller (NMPC) for precise path tracking. The system integrates sensors, including RGB cameras and mmWave radar, to perceive the environment and optimize cleaning operations.	SMURF was tested in real-world environments, including inland waterways, lakes, and coastal areas, under various weather conditions.	SMURF is designed for cleaning floating debris in various water bodies, including inland waterways, lakes, coastal areas, and marinas. It aims to replace dangerous and inefficient manual operations for water surface cleaning.
Design of a new composite underwater hull cleaning robot [54].	The robot integrates mechanical cleaning with cavitation jet cleaning. The design includes a rolling brush module for initial cleaning and a cavitation jet module for deeper, non-destructive cleaning. Testing involved structural simulations using SolidWorks and fluid simulations with Fluent.	Testing and simulations were conducted virtually to assess structural integrity and fluid dynamics	Primarily for ship hull cleaning in various marine environments, especially useful in ports, docks, and shipyards. The robot's technology helps reduce marine fouling, improving fuel efficiency and reducing corrosion.
A Water Surface Cleaning Robot[56]	This robot, designed for collecting floating debris, has a pontoon-shaped hull for stability and a motor-driven arm for waste collection. Controlled remotely using an XBee-based system, it can maneuver in tight spaces and is equipped with a differential drive for easy movement.	Tested in a controlled water area to confirm stability, functionality, and load capacity.	Effective for clearing debris in water bodies, helping prevent clogging and flooding. Potential future uses include monitoring water quality and removing algae.

4. Results

The look at those self-cleaning water robots shows some serious progress in how they're built, how smart they are, and how they're all about keeping things green and clean. The study's findings are well-supported by the data.Robots like SMURF and those using ResNet-50 and SSD models nailed it when it came to spotting and sorting out floating trash like plastic, leaves, and algae. These robots were pretty good at using color cameras and smart computer programs to figure stuff out in real places like city lakes and beach areas.Most systems were built to be power saving, using solar energy and lightweight AI models like MobileNet or TinyYOLO. This means the robots can handle data on the fly without guzzling too much power, so they're great for tasks that go on for a while. Using a mix of RGB cameras, sensors that check the environment, and mm Wave radar, the robots got better at spotting trash and could handle different lighting or visibility situations.Robots use smart techniques like Coverage Path Planning and Nonlinear model; they use Predictive Control to navigate around stuff without bumping into things and make the cleaning path as efficient as possible.Robots got put to the test in all sorts of water places like rivers, lakes, shipyards, and coastal areas.

5. Discussion

The implications lead towards the potential contribution of independent water cleaning robots towards mitigating increasing instances of water pollution. While remarkable in their work towards collecting surface wastage, there are some other numerous significant factors that should also be given due attention:Limitations of Technology: The robots, so effective at detecting and picking up floating litter, remain short of detecting and capturing submerged and dissolved pollutants. Use of image-based models restricts their power to deal with subsurface pollution.Limitations of the Environment: Real-time detection apparatuses fail in extreme environments like low illumination, polluted water, or high turbidity, compromising camera and sensor accuracy.Scalability and Coordination Challenges: Numerous robots would need to be deployed at once to effectively cover lengths of water efficiently. It is a tricky problem coordinating their route of navigation and communication among units.Real-World Test Requirement: In spite of the fact that most systems were tested under controlled or semi-controlled conditions, long-term operation in real-world environments with uncertainty, high contamination, or high biological richness must still be demonstrated convincingly.Integration with Larger Systems: Next-generation projects can be enabled by integrating water-cleaning robots with stationary sensor stations, drones, or satellite systems for cross-scales environmental sensing and response.In brief, although existing autonomous water-cleaning robots represent a milestone in environmental robotics, practical use at scale requires refinement in adaptability, affordability, and inter-system cooperation.

5. Conclusion

The increasing prevalence of water pollution due to industrial discharges, plastic waste, oil spills, and agricultural runoff has led to severe consequences for ecosystems, human health, and economies. These adverse effects underscore an urgent need for innovative solutions that reduce human risk and improve cleaning efficiency in water bodies. This study on autonomous robotic systems,

particularly water-cleaning robots, highlights a promising avenue for addressing these challenges. Equipped with advanced sensors, artificial intelligence, and navigation systems, these robots can autonomously clean lakes, rivers, coastal areas, and other water bodies. Their ability to operate without human intervention allows them to reach hazardous areas and handle difficult cleaning tasks that are otherwise inefficient or dangerous for humans. Advanced technology and human ingenuity are required to control water pollution. System for example, the SMURF robot collected debris efficiently with the help of CPP, RGB cameras and mmWave radar. Human inspection has never gone out of the window with all these innovations. Durability, navigation accuracy, and complex water conditions call for collaboration in engineering, scientific, and community efforts. Sustainable practices are built into an integrated system by building efficiency in solar energy, hence reducing the impact on the environment.

Future developments will include arming robots with water-quality sensors and fine-tuning navigation with human expertise. Involvement of human wisdom is at its best because technology cannot tackle all problems alone. Ideal solutions for cleaning water are proper balances between automation and human wisdom. In collaboration, engineers and scientists with communities can design scaling systems that keep water clean and biodiversity intact. Shared responsibility will ensure a sustainable future for ecosystems. For water-cleaning robots to be as effective as possible, it is necessary to consider how and when they utilize energy. Much thought must go into developing operating systems for water-cleaning robots that prioritize long-term environmental sustainability - this might be especially true if we are talking about a robot in a remote area or large body of water. Strategies like installing solar panels, building with lightweight materials, employing energy-efficient electronics, keeping the robot in one area - these measures will help lessen the burden on the battery system and human staff. Some designs are so advanced that they attempt to harvest naturally occurring energy, harvesting wave and solar energy for self-recharging and extended hours of output. Beyond energy aware implementations, intelligent decision-making is another important dimension to robot performance that has been promising to address. With onboard processing, the robot can better and quicker pick-up waste and better plan its direction. For example, upon spotting an item of debris, the robot can adjust its path in real-time, thus becoming more efficient with the time and energy it consumes. It will also continue evaluate "successful" and "unsuccessful" patterns to react even better to the changing surroundings. The combination of energy aware systems and intelligent route-driving systems will produce strong operational tensions for a robotic cleaning program that–instead of needing to be constantly teleoperated or follow robotic patterns – are positioned better position to clean.

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