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Design and Application of Multifunctional Robots for Deep-Sea Exploration and Rescue Operations

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ABSTRACT

Despite ongoing advancements in science and technology, human casualties persist in deep-sea and subterranean environments due to hazardous conditions, limited accessibility, and insufficient safety measures. These risks are exacerbated by the lack of effective innovations in project execution and emergency response. The extreme depths of oceans and drilled wells often render direct human intervention impractical, especially for rescue, inspection, and maintenance tasks. This research presents the design and evaluation of a multifunctional robotic system capable of operating in high-risk environments where human access is restricted or unsafe. The robot is engineered to perform a wide range of tasks, including exploration beneath ocean ice, seabed data collection, geological and geotechnical analysis, rescue operations, sampling in toxic zones, and interventions in corrosive or contaminated conditions. Experimental results from three pilot projects—spanning water and wastewater systems, oil and gas wells, and underwater environments—demonstrated robot success rates ranging from 80% to 90%. The robot completed welding, cutting, and sampling operations within 1.5 to 2 hours, outperforming traditional methods in terms of safety, speed, and operational efficiency. These findings confirm the robot's reliability in environments characterized by high pressure, toxic exposure, and limited human accessibility. By replacing manual intervention with autonomous systems, this research highlights the transformative potential of robotics in bridging the gap between scientific theory and industrial practice. The proposed design contributes to safer, more efficient workflows and lays the foundation for future innovations in extreme-environment robotics.

1. Introduction

Deep wells—including water, gas, and abandoned wells—pose significant operational and safety challenges due to their extreme depths, limited accessibility and the presence of hazardous gases. These conditions often render conventional maintenance and equipment replacement impractical, as , as human access to the bottom of such wells is frequently impossible. In response to these constraints, researchers and engineers worldwide have proposed innovative solutions tailored to regional needs.

One promising approach involves the development and deployment of exploration robots designed for subsurface and rescue operations. These robotic systems are engineered to perform tasks traditionally carried out by human specialists, enabling remote intervention without exposing workers to life-threatening environments [4].

Parallel to terrestrial applications, the exploration of deep-sea environments presents similarly formidable challenges. Over 90% of marine biodiversity remains undiscovered and unclassified, and the deployment of sufficient oceanic sensors to monitor global phenomena with adequate temporal and spatial resolution remains a daunting task [10]. While underwater robotics has significantly advanced marine research, the vastness of the ocean and the limitations of individual robotic units constrain operational

efficiency. These robots, however, are uniquely capable of withstanding the extreme pressures of deep-sea environments, making them indispensable for tasks such as exploration, sampling, reconnaissance, and target search [11].

Recent studies have outlined a forward-looking trajectory for deep-sea robotics, emphasizing the potential integration of space-derived technologies across three key domains: biomimetic structural and energy systems, artificial intelligence (AI), and the miniaturization of life-detection sensors[12]. These interdisciplinary approaches aim to enhance the operational capabilities of underwater robots in extreme environments. In parallel, the rapid advancement of AI has prompted growing interest in its application to social robotics, particularly in contexts where human caregiving is insufficient [32]. However, scholars have also noted the inherent unpredictability of technological evolution, which often challenges the accuracy of long-term projections and invites critical reflection on the development paths of emerging innovations [33].

2. Problem Definition

Robotic systems have become essential tools for remote exploration and intervention in hazardous environments, particularly in deep-sea and subterranean settings. The robot discussed in this study is designed for a wide range of applications, including laboratory applications, , including laboratory research, welding and cutting operations on submerged objects, geological surveying, fault detection, and soil classification through sampling, photography, and videography. It is also capable of operating in high-risk wells—such as those lacking oxygen or containing explosive, toxic, or flammable gases—where human access is unsafe or impractical. Additional use cases include the retrieval of trapped humans or animals from collapsed wells and underwater locations, and the remote repairs of underground and submarine equipment [1].

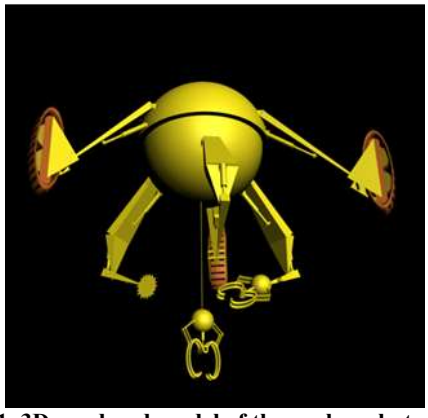


Figure. 1. 3D-rendered model of the probe robot, designed using 3ds Max software, showcasing its articulated arms and mechanical structure for deep-environment operations.

In deep sea and underground environments, equipment such as pipes structural components are often subject to damage from corrosion, erosion, cracking, and mechanical stress caused by tectonic activity or the cumulative weight of installed systems. These failures can lead to costly delays, safety hazards, and operational inefficiencies. Timely and reliable repair or replacement of such components is critical to minimizing project costs and protecting human lives [1].

The digital revolution has accelerated the development and deployment of robotic technologies, making them integral to both economic and scientific advancement. Robots now play a pivotal role in remote operations across domains such as space exploration, marine research, and industrial automation [25].



Figure 2. Deep-sea mobile robot equipped for exploration and maintenance tasks [25]

This particular robotic system is also designed for aquatic rescue missions, capable of retrieving both conscious and unconscious individuals without endangering the rescuer. Statistical data on water-related accident indicate that many fatalities occur during rescue attempts by untrained individuals. Consequently, recent research has emphasized the development of marine robotic systems to perform tasks that exceed human physical limits or pose significant safety risks [13].

Operationally, the robot is that the user or guide first places the robot at the top of the well (for operations inside the wells) or on platforms and marine vessels (for operations in deep waters), then using a “remote control device, guides it to the bottom of the well and the accident site or the ocean floor and performs the desired operation in the relevant project” [1, 9].

Operationally, the robot is deployed either at the mouth of a well or from marine platforms and vessels. It is then guided via remote control to the target site—whether within a well or on the ocean floor—where it performs the designated task in accordance with the project’s objectives [1], [9].



Figure 3. View of the probe robot model, featuring articulated arms and mechanical components for deep-environment operations.

3. Significance of Robotic Systems

The integration of advanced tools and robotic systems is increasingly vital across a range of industries, including civil engineering, water and wastewater management, marine operations, military applications, petrochemical processing, oil and gas extraction, nuclear facilities, and aerospace engineering. In these domains, replacing human intervention with robotic systems—particularly in research, laboratory work, welding, cutting, and rescue operations—offers significant advantages in terms of safety, efficiency, and precision. This is especially critical in high-risk environments such as deep-sea and well-based operations, where human access is limited or hazardous [5, 9].

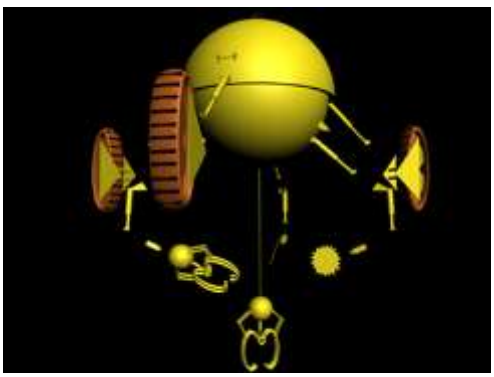


Figure 4. 3D MAX-rendered view of the probe robot, highlighting its symmetrical structure and mechanical components for advanced operational tasks.

4. Classification of Robots by Autonomy

Robotic autonomy determined by the system's ability to operate independently, which depends on the integration of sensors, computational hardware, and control algorithms. Based on their operational capabilities, robots can be classified into three categories:

- Non-autonomous: Fully dependent on human control.
- Semi-autonomous: Capable of performing certain tasks independently but still require human oversight.
- Fully autonomous: Operate independently across a range of tasks without human intervention [7].

The level of autonomy directly influences the complexity of the system design and the scope of its applications.

5. Robot Navigation and Movement Strategies

Path planning in unknown environments presents significant engineering challenges. methods of spatial exploration are often inefficient or impractical in dynamic marine settings. To address this, hybrid search algorithms have been proposed to enable efficient and adaptive pathfinding for underwater robots engaged in target search missions [26].

Underwater robots are increasingly deployed to perform complex tasks in environments that are inaccessible or dangerous for humans. . These include scientific exploration, industrial operations, and military missions. The robot's propulsion system plays a critical role in determining its maneuverability, endurance, and stealth concealment [27].

Structurally, underwater vehicles are categorized as:

- Remotely operated vehicles (ROVs : Tethered systems controlled from the surface.
- Autonomous underwater vehicles (AUVs): Untethered systems capable of independent operation [39, 40].

Functionally, they are further divided into: :

- Investigation robots: Used for observation, measurement, and sample collection.
- Operation robots: Designed for tasks such as underwater welding, pipe manipulation, construction, and underwater cutting, etc.) [39, 41].

Exploration of the Arctic seafloor remains remains a major challenge due to persistent ice cover, which limits the effectiveness of of oceanographic tools [14].

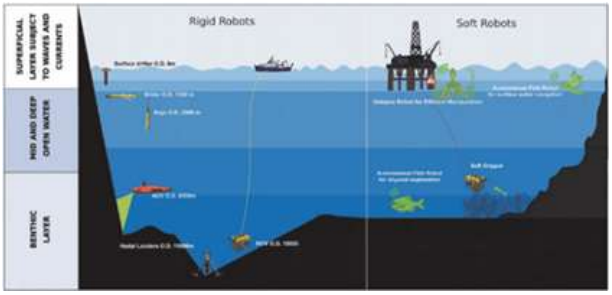


Figure 5. Overview of marine depth zones and the operational range of rigid and soft robots across ocean layers, from surface to hadal depths [14]

Only a few robot ic systems worldwide are capable of reaching depths of 6,000 meters, typically for seabed mapping and industrial surveys. These systems must follow predefined paths and be continuously

monitored, which restricts their flexibility and coverage [14, 31].

The Underwater Vehicle-Manipulator System (UVMS) has seen growing adoption for marine resource exploration. However, underwater environments pose substantial challenges for controll, navigating, and communication. These difficulties have driven ongoing technological innovation and made UVMS development a focal point of marine robotics research [20]. Recent advances in autonomy, sensor integration and robotic design have enabled deep-sea exploration capabilities that may one day be extended to extraterrestrial oceans, such as those on icy moons [12].

6. Robotic Welding and Cutting Applications

Welding robots are particularly, promising for use in steel structure construction. Manual methods methods face limitations in precision, efficiency, and safety, making the development of automated welding systems increasingly urgent. Robotic welding offers high-speed, consistent performance, contributing to industrial modernization[15-18].

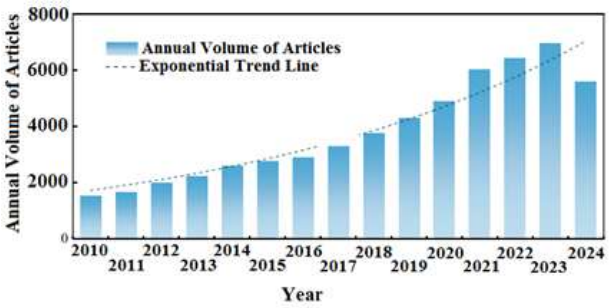


Figure 6. Annual publication volume of research articles on welding robots from 2010 to 2024, showing an overall exponential growth trend [19].

Moreover, traditional welding process often result in high energy consumption and the release of harmful emissions, including fumes and toxic gases. Robotic systems can mitigate these issues by precisely controlling welding parameters, optimizing paths, and employing advanced techniques. This not only improves environmental sustainability but also enhances worker safety [19].

7. Environmental and Structural Considerations

Deep-sea robots are typically enclosed in pressure-resistant structures, including metallic housings and pressure-compensation systems, to protect sensitive electronics and mechanical components from extreme underwater pressures [35]–[38].

Simultaneously, marine pollution poses a growing threat. An estimated 70% of marine litter sinks to the seabed, with p lastics compose over 60% of this debris. These materials degrade slowly and can enter the global carbon cycle, ultimately impacting human health. Effective investigation and retrieval of this litter are essential to prevent irreversible environmental damage [42, 43].

To address this, underwater robots are increasingly being used for large-scale, upward transport tasks such as sampling marine organisms and collecting submerged waste. These labor-intensive operations benefit significantly from robotic assistance, which can reduce human exposure and improve operational efficiency [42, 44].

8. Design Requirements

To ensure safe and effective operation in aquatic and subterranean environments, the robot must meet several critical design criteria:

- Waterproofing and Environmental Safety: All electrical components are housed within a sealed body, minimizing the number of moving parts to reduce potential points of water ingress. Mechanical joints between the body and moving components must be engineered to prevent leakage. Additionally, any materials in direct contact with water must be non-polluting and environmentally safe [8].



Figure 7. 3D MAX-rendered model of the probe robot, featuring symmetrical arms and mechanical joints for precision tasks in hazardous environments.

- Functional Versatility: The robot is designed to perform a wide range of tasks, including soil layer analysis, mechanical sampling data transmission from deep wells or underwater locations, and the welding or cutting of damaged metallic components. It also supports the transport of objects from the ocean floor to the surface. These capabilities require integration of diverse technologies and performance mechanisms to support field workers and advance project objectives. [1, 9].

9. Research on Deep-Well Robotics

Deep wells are generally categorized into two types based on their internal structure:

Wells with rods or pipes: These typically contain structural elements for water supply, oil and gas extraction, or sewage transfer.

Wells without rods or pipes: These are more common in industries such as oil and gas, petrochemicals, and wastewater management. With diameters typically

ranging from 40 or 50 cm, such wells lack internal infrastructure, making manual intervention impractical or unsafe. Robotic systems offer a viable solution for inspection, maintenance, and operational tasks in these environments [1], [3], [9].

The concept of telepresence—the remote operation of devices as extensions of human capability—was first introduced in 1942 through science fiction literature. The story depicted an engineer controlling robotic tools remotely, a vision that has since influenced technological innovation and public imagination regarding human-machine interaction [22, 23].

One notable advancement inspired by this vision is the All-Round Six-Limbed Robotic Extraterrestrial Exploration (ATHLETE) platform, developed for planetary exploration. ATHLETE features six limbs with seven degrees of freedom, enabling both locomotion over rugged terrain and manipulation of tools. Each wheel contains an interface for instruments such as drills, clamps, and anchors, allowing the robot to interact dynamically with its environment [28]–[30].

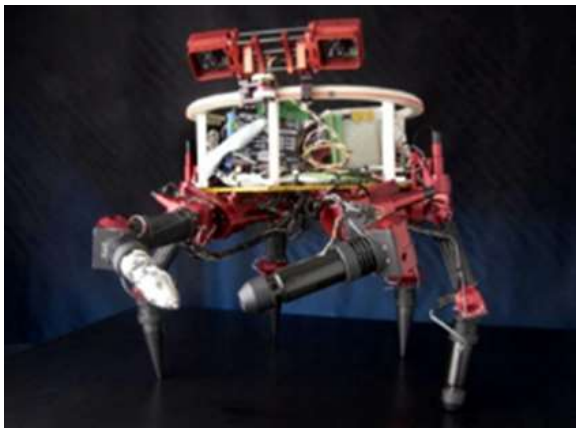


Figure 8. The Lemur robot, designed for space assembly, utilizes wrist-mounted tools to perform tasks such as drilling, bolt manipulation, and visual documentation [28]

10. Robot Mechanisms and Capabilities

Robotic systems designed for deep wells and underwater environments must possess a wide range of capabilities to perform complex and hazardous tasks. These include:

- Research and exploration: direct inspection of well interiors and seabed equipmentfor scientific and operational analysis.
- Maintenance and Repair: cutting and welding of damaged components located at the bottom of wells or the ocean floor, including inaccessible or angular positions.
- Object Retrieval: Extraction and transport of submerged objects to the surface, even from confined or irregular spaces.
- Infrastructure operations: Servicing of underground water and sewage pipelines, seabed conduits, and ocean-floor fiber optic cables.
- Hazardous Environment Deployment: Operation within oil and gas well containing flammable or toxins substances, as well as high-radiation zones such as heavy water ponds in nuclear power plants. In these contexts, robotic intervention is essential to minimize human exposure and risk [6], [9].

These robots are engineered to function `in environments where the electromagnetic spectrum technologies enable long-range imaging and high bandwidth communication. Despite the challenges posed by marine and extraterrestrial conditions, robotic systems have demonstrated cost- effective, high precision performance in these domains [45].

11. Marine Robotic Technologies

Recent analyses have identified key classes of robotic components used in marine sampling operations [46]:

- Manipulator claws:
  - Parallel fingers: Provide stable grip for flat or uniform objects.
  - Opposed/ intermeshed fingers: Offer enhanced dexterity for irregular shapes.
  - Grabber claw: Suitable for firm grasping of larger specimens.
  - Cage claw: Designed to enclose and secure delicate or mobile samples. details on each class are provided in Figure (9).

- Sampling gears:
  - Suction samplers: Ideal for collecting fine particles or small organisms.
  - Scoops and scoop-nets: Used for sediment and biological sampling.
  - Corers: Extract cylindrical samples from seabed layers.
  - Traps: Capture mobile marine organisms.
  - Water bottles: Collect water samples at specific depths.

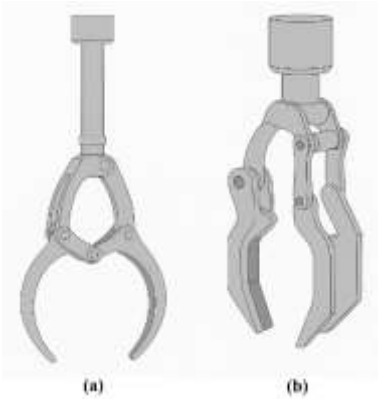


Figure 9. (a) Examples of parallel, intermeshed, and grab claw grippers, shown from left to right. (b) Cage-type gripper used in the ROV Liropus 2000 [46–48].

Details on each class of sampling gear are illustrated in Figure 10. Additionally, round-shaped manipulator fingers, typically configured with two jaws and three to

four fingers are specifically designed to gently enclose spherical or cylindrical specimens. This configuration is particularly effective for retrieving delicate samples or entire organisms without inflicting damage, making it well-suited for biological and ecological studies in sensitive marine environments [46].

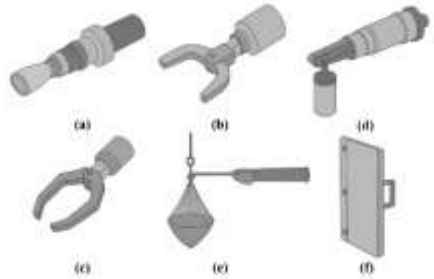


Figure 10. ROV collection tools used in marine sampling: (a) suction sampler, (b) scoop and net, (d) corer, (e) trap, and (f) Niskin bottle. Sources: (a–e) [46, 49, 50], Schmidt Ocean Institute; (f) [46, 21].

12. Research Hypotheses and Case Motivation

Deep oil wells similar subterranean structures are often inaccessible due to their extreme depth and narrow openings, rendering direct humans intervention impractical or impossible.. This limitation has prompted the development of robotic systems capable of performing complex operations remotely from the surface [1], [9].

The impetus for this research originated from a tragic incident in Iran involving an abandoned well.

Due to inadequate safety measures and poor oversight in sealing the well opening, a child fell into the narrow shaft. Rescue efforts were severely hindered by the confined dimensions of the well, highlighting the urgent need for a robotic solution capable of navigating and operating within such constrained environments.



Figure 11. Bottom view of the probe robot, modeled in 3ds Max, showing its mechanical limbs and structural layout for ground-level operations.

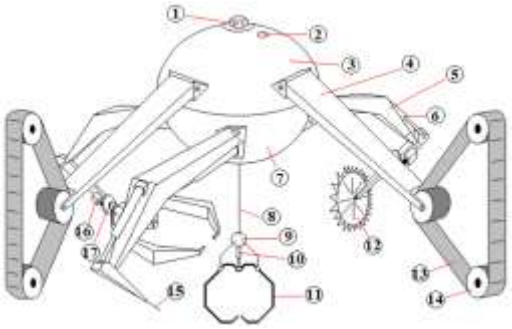
13. Materials and Methods

The initial design of this robot was completed in 2005 and officially registered in 2006 [2]. It was developed to perform complex operations in deep wells and underwater environments, including welding, cutting, sampling, and object retrieval. The system is remotely operated via radio control by a technician positioned above the well or offshore platform. Once deployed to the target site, the robot begins executing its assigned tasks [9].

Structurally, the robot consists of three large base units and three stainless steel arms, each equipped with pneumatic jacks and gears. The arms are capable of 360-degree rotation and are fitted with advanced tools for shearing, welding, lifting, and manipulating objects at various angles. The robot is designed to function in confined spaces and can retrieve heavy items from deep locations. It also includes CCTV cameras and a control interface for real-time monitoring and guidance.

The system incorporates 11 pneumatic jacks for vertical and rotational movement, 13 motorized reels powered by high- and low-power DC motors, and two half-spherical enclosures—one fixed and one rotatable—housing the robot's arms and lifting mechanisms. The motors are engineered to be waterproof, heat-resistant, corrosion-proof, and shock-resistant, ensuring durability in harsh environments. Additional features include imaging devices such as direct and indirect camcorders, a microscopic camera, and high-adhesion belts that allow the robot to grip various well surfaces, including metal, plastic, concrete, and stone.

The robot's mechanical and electrical components are distributed across upper and lower metal enclosures, connected by screws, nuts, and cable entry points. Figures 12 through 16 provide detailed schematics of the robot's design and layout.



Front view of the robot showing key structural and functional components, including the metal enclosures, pneumatic jacks, articulated arms, welding and cutting systems, and accessories for balance, mobility, and cable management. Components labeled 1–17 correspond to mechanical and electrical features integrated for deep-environment operations.

To model the robot's joint dynamics, Lagrangian mechanics is applied. The torque at each joint is calculated using:

$$\tau i = \frac{d}{dt}\left(\frac{\partial L}{\partial qi}\right) - \frac{\partial L}{\partial qi} \quad (1)$$

where L = K - P, with K representing kinetic energy and P potential energy. The variable q_i denotes the joint angle or displacement, and τ_i is the torque applied to joint i

.

For gripping operations, the total force exerted by the robot's gripper is modeled as:

$$F_{grip} = \sum_{i=1}^{n} Ti \,.\sin(\theta) \quad (3)$$

Here, $Ti$is the torque at joint i, θi is the angle of that joint to the main axis. This equation accounts for the effective torque components that contribute to linear gripping force at the fingertips.

A gripper consists of several mechanical fingers, each with several joints. Each joint generates a torques (e.g. by a motor or actuator). These torques, when transmitted through the joints to the fingertip, create a linear force. Depending on their angle, that grips the object. The above formula calculates the sum of all effective components of the torque in gripping the object. Since only the component of the torque that is in the direction of gripping the object is effective, it must be multiplied.

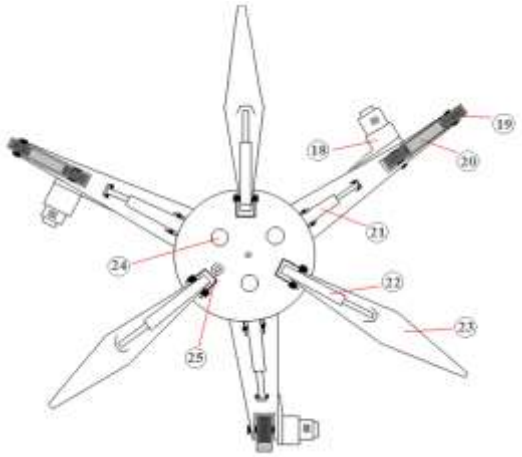


Figure 13. Bottom view of the robot showing key accessories, including wheel chain alternator, pneumatic jacks, rubber mobility components, lighting mounts, and CCTV installation point. Components 18–25 illustrate the mechanical and sensory systems supporting vertical movement and environmental monitoring.

The robot's vertical movement via chain drive is governed by:

$$\nu = \frac{r.\tau}{I+m.r2} \quad (4)$$

where ν is the velocity, r the radius of the chain wheel, τ the motor torque, I the moment of inertia, and m the total mass of the robot. This formula helps determine the optimal motor specifications and wheel-chain configurations for vertical mobility.

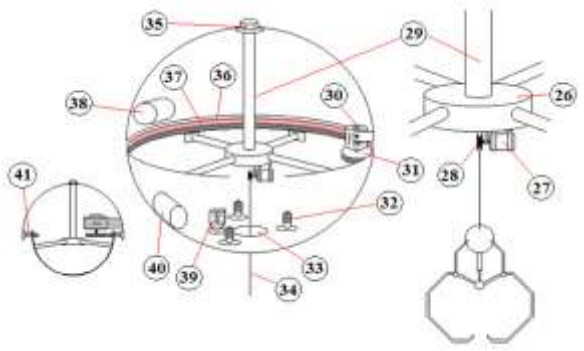


Figure 14. Internal view of the robot showing mechanical and electrical components, including alternators, pneumatic jacks, wiring systems, support structures, and integrated CCTV for operational monitoring. Accessories labeled 26–41 illustrate the robot's internal architecture and functional layout.

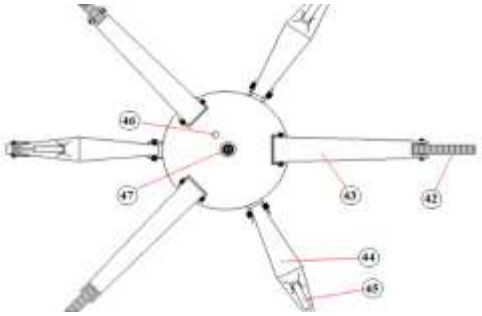


Figure 15. Upper view of the robot showing structural and functional components, including rubber bands, arm bases, pneumatic jacks, wire entry points, and fastening elements connecting the upper and lower enclosures.

For cutting operations, the required torque is calculated using:

$$\tau_{cut} = F_{cut}.\, r_{blade} \quad (5)$$

This equation relates the cutting force (F_{cut}) to the blade radius (r_{blade}), allowing engineers to select motors capable of delivering sufficient torque for material penetration.



Figure 16. Perspective view of the robot featuring cable-free mechanical grippers, designed for precision handling and autonomous operation in constrained environments.

The robot's dual-chamber design enhances its operational flexibility. The upper chamber remains fixed, while the lower chamber rotates freely, enabling full-range manipulation of tools and equipment. Arms mounted on the lower chamber are equipped with multifunctional tools for metal removal, welding (oxygen/gas), and milling. Finite element analysis confirms that flexible joints outperform rigid ones in underwater conditions, offering greater range of motion and improved maneuverability. The control module, equipped with advanced sensors and a CPU, manages the dynamic behavior of these joints, ensuring precise and responsive operation [34].

14. Applications of the Robot

The robot is engineered to perform a wide range of operations in extreme and hazardous environments, making it suitable for deployment across various industrial and scientific domains. One of its core capabilities is executing welding and cutting tasks in deep wells and corrosive settings, including environments contaminated with toxic chemicals, microbial agents, or explosive gases. This includes applications in water and wastewater systems, oil and gas extraction, petrochemical facilities, and marine infrastructure [9].

Its mechanical design enables precise manipulation and movement of objects in all directions and orientations, even within confined or irregular spaces. This flexibility supports geological exploration, soil mechanics research, and the classification of subsurface layers through sampling, surveying, and marking [9].

The robot is equipped with CCTV cameras capable of capturing high-resolution images and video in environments containing suffocating gases, acidic compounds, and other hazardous substances. This visual capability is essential for inspection, documentation, and remote decision-making in inaccessible or life-threatening conditions [9].

In rescue scenarios, the robot can identify and retrieve injured individuals from deep wells or submerged locations, minimizing human exposure to danger. Its operational range is robust across temperature extremes, functioning reliably in gaseous environments from –30°C to +30°C, and in liquid environments from –15°C to +45°C [9].

The system is also adaptable for use in vacuum or gas-free environments, making it suitable for space research and extraterrestrial exploration. Its modular architecture allows for self-repair and reconfiguration, enabling the robot to restore damaged components and rearm itself autonomously [9].

Constructed from lightweight and durable materials—including compact aluminum, stainless steel with zinc coatings, and corrosion-resistant nano-polymers—the robot maintains structural integrity under mechanical stress and chemical exposure. Its design includes a rotatable semicircular chamber and a base platform capable of 360-degree horizontal rotation deep underground. The arms themselves are engineered to rotate freely in all directions, allowing full spatial coverage during operations [9].

Additionally, the robot demonstrates a high degree of waterproofing and resistance to corrosion in acidic environments, with optimal performance in pH ranges between 5 and 7. This ensures long-term reliability in chemically aggressive settings and supports sustained deployment in industrial and research applications [9].

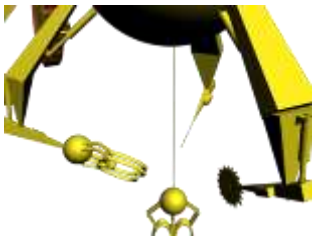


Figure 17. Front view of the robot rendered in 3ds Max, highlighting its mechanical accessories and structural layout for operational deployment.



Figure 18. Front view of the robot rendered in 3ds Max, illustrating its structural components and integrated accessories for advanced operational functionality.

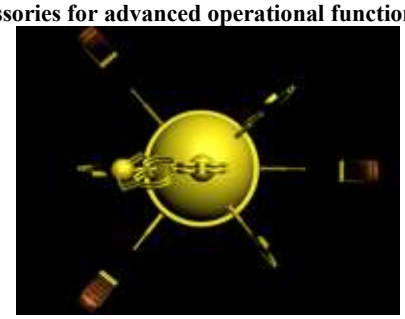


Figure 19. Upper view of the robot rendered in 3ds Max, showcasing its structural components and accessory layout designed for advanced mechanical operations.

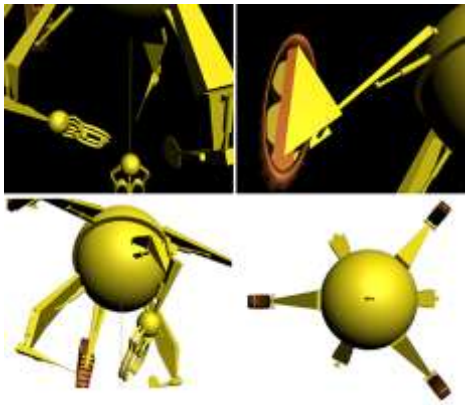


Figure 20. Demonstration of the probe robot's welding and cutting operations across all angles, rendered in 3ds Max to showcase its full-range articulation and multifunctional tool deployment.

15. Results and Discussion

The performance of the proposed robotic system was evaluated across three distinct project domains: water and wastewater, oil and gas operations, exploring deep underground and seabed exploration. Tables 1 and 2 summarize the results of these tests, highlighting operational efficiency, execution time , and comparative advantages over traditional human-led methods. [9].

Table 1 presents the success rates and contextual challenges associated with each test scenario. In experimental and workshop settings, the robot achieved an 80% success rate, demonstrating its ability to operate in deep, inaccessible locations. In geological sampling missions conducted on the seafloor, the robot reached a 90% success rate, significantly mitigating the risks typically faced by human divers, such as exposure to toxic substances and physical hazards. In high-pressure fluid environments, the robot maintained an 85% success rate, outperforming human capabilities in conditions prone to marine animal interference and physiological stress [9].

Table 2 outlines the operational merits of using the robot in real-world scenarios. In a 25-meter-deep water well in Tehran, the robot completed welding and cutting tasks in 1.5 hours, eliminating the need for manual labor and reducing capital expenditure. In a dry well of similar depth, the robot conducted soil mechanics and geological investigations over a two-hour period, avoiding reliance on outdated tools and minimizing operational losses. In a corrosive and toxic underwater environment, the robot performed welding and cutting tasks within 1.5 hours, removing the necessity for divers and specialized equipment [9].

Table 1. Report No. (A): Robot Efficiency and Human Limitations

Row	Project success rate	Type of Test	Disadvantages Without Robots
1	% 80	Experimental and Workshop	Inaccessibility of deep, impassable areas
2	% 90	Seafloor geological sampling	High-risk environments in wells and seas
3	% 85	High-pressure, viscous fluid operations	Marine animal threats, , physical strain, vital sign compromise

Table 2. Report No. (B): Operational Merits of Robots

Row	Merits of Robotic Operation	Duration	Location	Type of the Operation
1	No labor or large capital needed	1.5 hrs	25m deep water well (Tehran)	Welding and cutting
2	Avoids outdated tools and losses	2 hrs	25m deep dry well (Tehran)	Soil samplings and geological analysis
3	No need for divers or underwater gear	1.5 hrs	6m deep pool (Tehran)	Welding and cutting in corrosive/toxic conditions

These results collectively demonstrate the robot's versatility, reliability, and efficiency across diverse and hazardous environments. The system not only reduces human risk but also streamlines operational workflows, offering a scalable solution for industrial and research applications. The comparative analysis underscores the robot's superiority in terms of safety, precision, and adaptability, validating its role as a viable alternative to human intervention in high-risk scenarios.

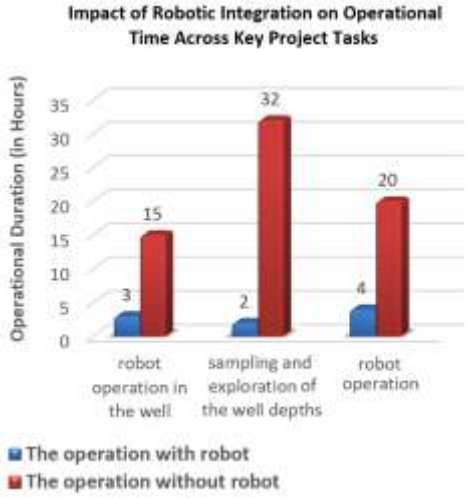


Figure 21. Comparative analysis of operational time and efficiency fluctuations between robotic and human-led methods across various projects, demonstrating the enhanced performance and time savings achieved through robotic implementation [9].

16. Conclusion

This research has demonstrated the effectiveness and continuity of operational methods involving robotic systems compared to traditional mechanisms. The integration of advanced robotics into industrial applications—particularly in water and wastewater management, oil and gas exploration, and deep-sea or underground operations—marks a significant leap forward in both technological innovation and practical execution.

The adoption of such technologies not only enhances economic efficiency by reducing labor costs and operational risks, but also fosters a robust scientific foundation for future advancements. Robots enable access to environments that are hazardous or inaccessible to humans, thereby accelerating data collection, improving precision, and minimizing human exposure to danger.

Moreover, the deployment of robotic systems bridges the gap between theoretical research and real-world application. It catalyzes the development of new inventions, supports interdisciplinary collaboration, and transforms abstract scientific concepts into tangible solutions. As industries continue to evolve, the role of robotics will be pivotal in shaping a future where knowledge, safety, and efficiency converge seamlessly.

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Statements and Declarations

Conflicts of interest

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Data availability

The datasets generated and analyzed during the present study were collected in Iran and are available from the lead author upon request.

Author contributions

The entire research process was done by myself as the responsible author: Data curation; Investigation in Civil Engineering-Structure; and mechanic and mechatronic Formal analysis; Writing – original draft; Supervision, Validation; Writing – review and editing.

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