Self-Powered Robots – A Survey

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Self-powered robots represent a significant advancement in autonomous robotics, leveraging renewable energy sources such as solar panels, thermoelectric generators, piezoelectric actuators, microbial fuel cells, and RF energy harvesting to operate independently of traditional power supplies. This study presents a comparative analysis of seven self-powered robotic systems, including the Crabbot, Thermoelectric Quadruped, MilliMobile, and Row-bot, evaluating their energy mechanisms, power consumption, control systems, and application domains. Notable findings include the Crabbot's 85 nm resolution and 150 V piezoelectric actuation for precision tasks, the Thermoelectric Quadruped's 703 J/m gait energy cost for geothermal monitoring, and MilliMobile's submillimeter-scale battery-free operation via RF harvesting. These robots are assessed based on critical parameters such as load-to-weight ratio, energy autonomy, and control architecture. The study highlights the growing role of miniaturized, energy-efficient designs in enabling real-world deployment across sectors like pipeline inspection, remote environmental sensing, and disaster response. By identifying performance benchmarks and gaps, this paper offers insight into next-generation, self-sufficient robotics aimed at sustainability, reliability, and broader societal impact.

Keywords: Autonomous Robots, Self-Powered Robots, Robotics, Energy Harvesting, Structural Health Monitoring, Pipeline Inspection

Introduction:

Equipped with intelligent algorithms and sensory systems, the autonomous robots can navigate and manipulate their surroundings with very little help from humans, revolutionizing manufacturing, healthcare, agriculture, and exploration. Much of the recent research in this direction has focused on increasing the autonomy and sustainability of such systems. Autonomous robots have pushed across conventional boundaries by using artificial intelligence and robotics to execute tasks that require minimal human intervention. The coming of battery-less autonomous robots marks great strides, as the systems use sources of energy in the environment, such as solar [1], vibrations [2], and thermal differentials [3] to power operations. This approach, as shown in Table 1, reduces dependence on finite sources of energy and enhances autonomy and lifetime of the robotic systems.

Objective:

The primary objective of this study is to conduct a comparative survey of modern self-powered robotic systems and evaluate their capabilities across energy harvesting mechanisms, structural design, autonomy levels, control architectures, and practical applications. The aim is to highlight the key technological features, performance, and limitations that define the current performance of self-powered robotics.

Novelty Statement:

This paper uniquely contributes to the field by offering a comprehensive evaluation of seven cutting-edge self-powered robotic platforms, including performance based on energy cost, resolution, size, load-bearing capacity, and control algorithms. This review provides a critical analysis of robots' design, highlighting application-specific advantages and disadvantages, laying the groundwork for future innovations in sustainable robotic autonomy. The study also introduces a comparative table that highlights the strengths and limitations of each robot, making it a valuable resource for future research work.

Recent developments in battery-less autonomous robots demonstrate the potential to work in a wide range of applications. For example, in [4], a new mechanism of energy harvesting by triboelectric nanogenerators (TENGs) has been proposed for the purpose of powering small robots and providing real-time environmental monitoring and surveillance. Here, this excludes traditional batteries, thus showing the scale and flexibility of energy harvesting technologies applied in robotics.

Another research highlights another type of autonomous robot, which avoids the use of classic sources of power, like batteries or an external power supply with cables. Such robots derive energy from the environment, such as light, heat, mechanical vibrations, and so on, to make their operations at least partly autonomous. The work presented a solar-powered crawling robot capable of performing autonomous locomotion without a battery, proving that energy harvesting methods can be effective and efficient for use in robotics [5].

Self-operating robots are highly autonomous, undertaking decisions and executing tasks independently based on environmental cues and predefined missions. More often than not, such robots incorporate cutting-edge AI algorithms, including machine learning and computer vision, to perceive, learn, and adapt in dynamic environments. In [6], an autonomous agricultural robot equipped with an AI-driven vision system for weed detection is demonstrated, and selective herbicide application mirrors potential autonomous robots in the quest for precision agriculture.

Table 1. Key Parameters of Energy Harvesting Methods for Robotics

EH Method	Output Voltage	Output Power (µW)	Energy Density	Integration Complexity	Material Flexibility	Key Applications	References
Piezoelectric	10–100 V	0.1 – 10000	Medium (2–10 mJ/cm²)	Moderate	Medium	Vibration-driven robots, wearables	[7]
Triboelectric	100–500 V	0.1 – 5000	High (up to 20 mJ/cm²)	High	High	Self-powered sensors, soft robotics	[8]
Thermoelectric	1–5 V	1000 – 100000	Low (0.5–2 mJ/cm²)	Low	Low	Body-heat-powered devices	[9]
Photovoltaic	0.5–3 V	1000 – 1000000	High (20–100 mJ/cm²)	Low	High	Solar-powered UAVs, field robots	[10]
Biochemical	<1 V	0.01 – 100	Low (1–5 mJ/cm²)	High	High	In vivo systems, medical implants	[11]
Hybrid Systems	Variable	0.1 – 10000000	Very High	High	Medium–High	Long-duration exploratory systems	[12]

Table 2. Performance and parametric analysis of self-powered Robots

Attribute	Crabbot [20]	Thermoelectric Quadruped	Milli Mobile	Smart Spider	Row-bot	Battery-Less Soft Millirobot	Solar Powered Autonomous RC Robot
Power Source	Piezoelectric actuators	Thermoelectric generator, batteries	RF energy harvesting	Internal battery, autonomous	Microbial fuel cell	Magnetic and piezoelectric effects	Solar panels
Operating Voltage	150 V	Servos: 7.2 V; Electronics: 6 V	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable	Varies, depending on solar cells
Power Consumption	Voltage of elongation unit: 15 V	4 cm gait: 703 J/meter; 8 cm gait: 600 J/meter	Average power consumption: low	8-10 hours of continuous operation	Energy from organic matter in water	Harvests energy from the environment	Varies with solar intensity
Weight	0.35 kg	Data Unavailable	Lightweight	Data Unavailable	Data Unavailable	Data Unavailable	1.5 kg
Size	50 x 54 x 86 mm	Not explicitly detailed	Submillimeter scale	Compact size to fit in pipes	Small, waterborne	Millimeter scale	Standard RC car size
Load Capacity	High load-to-weight ratio	Not mentioned	Limited due to small size	High load capacity	Capable of moving in water	High relative to its size	Varies based on design

Resolution	85 nm	Data Unavailable	Sub-millimeter precision	High resolution for inspection tasks	Data Unavailable	Data Unavailable	Data Unavailable
Sensor Types	Data Unavailable	Bump sensors, infrared cliff sensors, and a camera	Data Unavailable	Cameras, ultrasonic sensors	Data Unavailable	Data Unavailable	Light sensors, obstacle detection
Control System	Pololu 24-channel servo controller, Arduino	Pololu 24-channel servo controller, Arduino	Autonomous control	Remote and autonomous control	Autonomous	Autonomous	Microcontroller-based
Material	Aluminum plate and channels, acrylic legs	Aluminum body, acrylic legs	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable	Lightweight, durable materials
Algorithm Used	Denavit-Hartenberg parameters	Denavit-Hartenberg parameters	Autonomous navigation	Autonomous inspection algorithms	Data Unavailable	Data Unavailable	Obstacle avoidance, path planning
Special Features	Power-off clamping, flexible piezoelectric stacks	Sustainable energy from geothermal steam	Battery-free operation	Versatile pipeline inspection	Energetically autonomous	Remote movement and communication	Renewable energy use
Applications	Pole climbing, precise movement	Geothermal garden monitoring	Micro-scale tasks	Pipeline inspection	Water quality monitoring	Movement and sensing in constrained spaces	Remote control, autonomous navigation

It makes battery-less autonomous robots extremely useful in missions where entry into areas without power sources or tricky access to the same is restricted or not feasible, such as space exploration missions, disaster zones, and remote areas. For example, [13] introduced a solar-powered rover for extraterrestrial exploration, further enhancing the prospect of energy-autonomous robotic systems working in extreme environments. In this regard, author have designed a kinetic energy harvesting mechanism for underwater robots, hence allowing their perpetual operation in difficult aquatic environments without external power sources.

The types of battery-less autonomous robots vary from application to application and operational constraints. These include robots moving on land for exploration and surveillance, flying drones above for reconnaissance and monitoring, and underwater robots for marine research and exploration. In addition, advances in swarm robotics have further helped in developing collaborative ad hoc networks of autonomous robots with no batteries, particularly in the areas of collective decision-making and executing coordination acts in complex environments [14].

As technologies continue to reach the frontiers of innovation, they can be expected to cope with the ever-increasing challenges to society, enhance environmental sustainability, and open new frontiers in exploration and discovery. Autonomous robots could handle environmental, industrial, domestic, and community challenges. This paper reviews the development and application of autonomous and self-powered robots worldwide in the fields of healthcare and environmental monitoring.

Literature Review:

In [15], a highly advanced robotic system is presented that integrates solar power and autonomous operation for agricultural applications. It operates on a 12V system powered by a 30W monocrystalline silicon solar panel and a 12V, 2.6Ah rechargeable lead-acid battery. The robot runs for about 18 minutes with a 10 kg payload, though power availability drops with increased load, as battery voltage falls from 11.9V to 10.8V. The SPARB system features a compact frame (50 × 27 × 80 cm), weighs 3 kg, and can carry up to 10 kg. A four-wheeled drive with 6 cm ground clearance enables mobility across agricultural terrain. It uses ultrasonic sensors for obstacle detection and navigation, controlled by a Raspberry Pi 4B microcontroller. Both automatic and manual modes are supported via the Blynk application. A load cell and LCD are included to show the weight of collected produce. The system demonstrates efficient solar utilization and modern sensor technology, contributing to agricultural automation and improved operational efficiency. Figures 1(a) and 1(b) show the proposed and developed robot. The SPARB robot effectively harnesses solar energy and automation for precision farming; however, its short 18-minute runtime and voltage drop under load constrain scalability and long-duration field performance.

In [16], a Battery-Less Soft Millirobot that can move, sense, and communicate remotely by coupling magnetic and piezoelectric effects is introduced. It opens new frontiers in autonomous robotics through combined magnetic actuation and piezoelectric energy harvesting. The robot requires no external power supply; instead, it uses an external magnetic field to deform piezoelectric elements embedded in a thin multilayer structure, generating voltage signals. A piezoceramic composite film enables both energy recovery and actuation, allowing full battery-less operation. This self-energy scavenging through motion ensures efficient power use, making the robot highly suitable for various applications. Its soft, flexible structure allows stretching, bending, and twisting without failure. The multilayer film supports both locomotion and wireless communication, making it ideal for in vivo biomedical tasks like diagnosis, monitoring, and low-invasive surgery. With a size under 10×30 mm² and the ability to carry loads 100 times its weight, the robot demonstrates excellent efficiency and adaptability. However, design details such as cost, control algorithms, and implementation are not specified. The robot's unique combination of magnetic actuation and piezoelectric harvesting holds great promise for biomedical sensing, but the lack of data on software control, fabrication cost, and deployment limits its reproducibility and industrial application.

In [17], the robot called "Row-bot" is a more advanced example of energetically autonomous robotics, featuring a bio-inspired design and energy harvesting techniques tailored for aquatic environments. Mimicking the water boatman beetle, it incorporates propelling features based on hind leg motion. It uses a microbial fuel cell (MFC) to convert electrochemical energy from the surrounding fluid into electricity, eliminating the need for conventional batteries. Power is stored in capacitors such as 0.33 F (charged to 4.1 V) and 0.18 F (charged to 5.5 V), with the latter offering better efficiency. However, energy consumption analysis reveals that the feeding mechanism alone consumes 1.8 J, while overall servo demands exceed MFC output, creating a bottleneck. Figure 1(d) shows the Row-bot with its mouth open. The robot, measuring 70 × 124.7 × 63.2 mm and 3D-printed, consists of modular subsystems for propulsion, feeding, and energy generation. Customizable oars optimize thrust, enhancing movement in fluid environments. It's closed-loop energetic autonomy reduces system complexity and increases robustness. Future improvements target drag reduction, material stiffness, and propulsion refinement. Applications include underwater robotics and bio-matter-rich fluidic environments**.** Row-bot's use of MFCs for continuous energy generation is innovative; however, insufficient power for all servos and a lack of details on weight, cost, and sensors limit system scalability and optimization.

In [18], a Mobile Autonomous Battery-free Wireless Microrobot called the millibot is presented, which is a step-ahead approach in autonomous robotics, with a concentration on battery-free operations and power efficiency. MilliMobile harvests solar and RF power and works with a voltage regulator at 2.5V, consuming below 100 μW of power. It also has a power system, which includes an array of thin-film solar cells and a capacitor storing up to 1 mJ of energy, and is capable of intermittent movement with a maximum speed of 5.5 mm/s. Its design also integrated a compact chassis of 10x10 mm from lightweight carbon fiber and polyimide, fabricated through precise laser micromachining techniques. Careful placement of components reduces weight, further allowing the integration of sensors, including temperature, humidity, and photodiodes. This pioneering robot signals major strides in low-power autonomous systems. The MilliMobile has no traditional battery; it challenges conventional wisdom on how robots should look and be powered, carrying a sensor payload three times its weight and performing a host of environmental sensing tasks. In this respect, the fact that it can transmit data wirelessly at distances larger than 200 meters and perform with a high degree of effectiveness on different surfaces brings about considerable enablement in its practical application. The MilliMobile, generally, is a new frontier of power harvesting and actuation efficiency with a fully integrated sensor set heralding a future for autonomous micro robotics. Figure 1 (e) shows the exploded view of the millibot showing all the major components. MilliMobile demonstrates exceptional energy efficiency and lightweight design, successfully integrating energy harvesting and sensing. However, its limited motion speed and intermittent operation pose constraints for continuous or high-speed tasks.

Materials and methods:

The "Solar Powered 10 mg Silicon Robot" presented in [19] represents a new frontier in micro robotics, powered by solar energy alone to perform self-contained operations. Although only 560 pm x 2050 pm x 200 pm in size, it is ultra-compact and lightweight at 10.2 mg, yet it works, powered by solar cells; the sequencer works nominally at 22 nW. Although the robot was effective in energy conversion, it lost around 40% of the produced power through leakage currents. On the positive side, the robot was able to hold its weight and move with the help of its electrostatic inchworm motors. However, its movement in the forward direction remains quite unpredictable because of low contact friction and issues of clutch slipping at high voltage. The design focuses on solar power and advanced chip technology for control and motion. Solar cells, coupled with high-voltage circuits, enable the harvesting of energy and efficient signal conversion to drive actuators. Despite operational difficulties, increased leakage impacts functionality, and reliable forward motion is problematic, the robot shows that autonomous microrobots can be powered by renewable energy. Hence, this approach does address the potential of developments in micro robotics by enhancing multi-degree-of-freedom movement, intelligent sensors, and energy efficiency in the confined and energy-limited environment. Figure 1 (f shows the diagram of the proposed three-chip working robot. The robot proves that ultra-miniaturization and solar energy can coexist effectively. However, high energy leakage and erratic motion limit its current usability and suggest a need for improved energy management and locomotion control mechanisms.

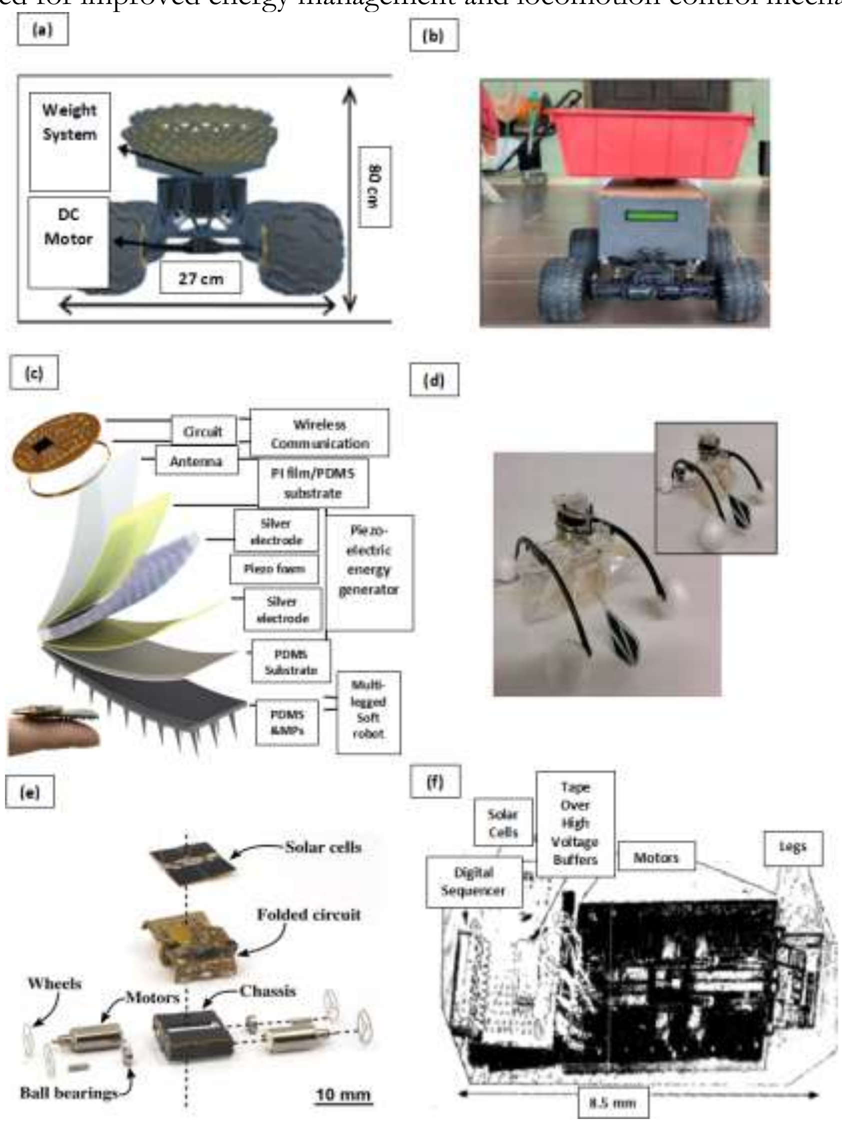

Figure 1. (a): Proposed Prototype; (b): Developed prototype [15]; (c) Schematic diagram of the untethered milli-scale soft robot with a RFID based battery-less sensing system [16]; (d) Row-bot with mouth open [17]; (e) An exploded view of the millibot [18]; (f)Three-chip working robot [19]

The "Crabbot", presented in [20], is an innovative pole-climbing robot utilizing piezoelectric actuators for high precision in a compact design. Driven by 150 V applied to piezoelectric stacks, it activates clamping and elongation units. Measuring 50 × 54 × 86 mm and weighing 0.35 kg, it achieves impressive load-to-weight ratios on horizontal and vertical poles of 1.42 and 0.57, respectively. It firmly grasps and climbs poles of 35 mm – 40 mm diameter. The robot achieves an 85 nm resolution for precise motion, reaching a maximum speed of 100.9 μm/s at optimal voltage and frequency. Most power is used by the elongation and clamping units, yet overall consumption remains low. Its minimal use of peripheral components enhances autonomy and maneuverability. Replacing traditional motors with piezoelectric drives simplifies the mechanism and improves efficiency. Tests show it maintains a deviation of only 0.85 μm across various pole shapes and angles, demonstrating suitability for tasks requiring fine, stable movement. Future enhancements could address backward motion and inter-pole transition. While cost and algorithmic details are lacking, Crabbot represents a novel, efficient solution in climbing robotics. Figure 2(a) shows its experimental setup. Crabbot provides ultra-fine motion resolution and pole adaptability using piezoelectric stacks, a key strength for vertical automation. However, limited information on cost, control algorithms, and low movement speed restricts broader applicability.

In [21], a fully autonomous, remotely monitored robot system is presented for a geothermal-heated garden in Iceland. Powered by a patented thermoelectric generator, it offers a novel approach to sustainable agricultural practices, producing up to 6 watts of steady power without conventional sources by harnessing geothermal steam. The robot's body is made from lightweight aluminum, and its translucent acrylic legs ensure durability and mobility. Equipped with bump sensors, infrared cliff sensors, and an accelerometer, it can navigate the garden autonomously without falling or veering off course. A Sony PlayStation Eye camera enhances its monitoring capabilities.

The robot supports multiple gaits, each with different power demands, allowing it to move at varied speeds while balancing energy efficiency and operational effectiveness. An Arduino microcontroller and a Pololu 24-channel servo controller provide precise motion control, guided by algorithms based on Denavit-Hartenberg parameters. This allows stable posture and traversal of challenging terrain with minimal soil disturbance, important in delicate agricultural settings. This system highlights the promise of renewable energy in agricultural robotics, particularly for geothermal cultivation and maintenance in hard-to-reach areas. Figure 2(b) shows the proposed quadruped robot. The geothermal-powered quadruped effectively demonstrates renewable energy in field robotics; however, its dependence on specific geothermal infrastructure and limited portability reduces its broader deployment potential.

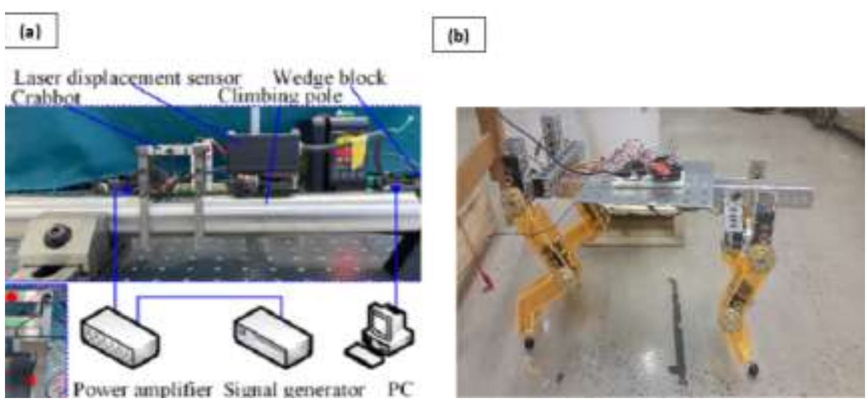

Figure 2. (a): Proposed prototype and its experimental setup [20]; and (b) Proposed quadruped robot [21]

Comparative and Critical Analysis of Self-Powered Robotic Systems:

The review of self-powered robotic prototypes reveals significant progress in energy autonomy, environmental adaptability, and application-specific optimization. The Crabbot and Thermoelectric Quadruped stand out as two of the most technically advanced and functionally refined systems due to their integration of precision control, high load capacity, and sustainable power sources.

The Crabbot utilizes piezoelectric actuators with a high operating voltage (150 V) and exceptional resolution of 85 nm, making it highly suitable for tasks requiring micron-scale accuracy, such as pole climbing or surface inspection. Its lightweight body (0.35 kg) and high load-to-weight ratio further optimize it for vertical or suspended operations. The power-off clamping feature enhances safety in critical conditions, making the Crabbot ideal for structurally constrained environments with minimal energy access.

In contrast, the Thermoelectric Quadruped Robot is geared towards agricultural applications**,** especially in remote geothermal fields, where it harvests steam-based thermal energy. It demonstrates relatively efficient energy usage (600–703 J/meter gait) and is supported by a control system integrating Arduino and Pololu servo controllers, along with motion algorithms such as Denavit-Hartenberg parameters. While lacking detailed dimensions and load specifications, its design for low soil disturbance and environmental compatibility distinguishes it in sustainability-sensitive domains.

The MilliMobile**,** leveraging RF energy harvesting, represents a leap toward battery-less micro-scale autonomy**.** Its submillimeter size and low power consumption make it ideal for sensitive environments, such as biomedical or confined inspection tasks. However, its load capacity is limited, and the absence of detailed control or sensing data restricts its practical evaluation.

The Battery-Less Soft Millirobot, which combines magnetic and piezoelectric effects, expands on this concept by achieving remote communication and movement with relatively high load-bearing for its size. Though still lacking specifics in weight and size, its hybrid actuation method suggests better adaptability in low-energy, space-constrained scenarios.

The Smart Spider is a robust solution for pipeline inspection, offering high load capacity**,** compactness, and multi-sensor integration (cameras, ultrasonic sensors). Its autonomous/remote control options and inspection algorithms give it an edge in hazardous environments, where human intervention is risky or inefficient.

The Row-bot features an innovative microbial fuel cell that converts organic matter in water into energy, providing it with true energetic autonomy. This makes it especially suitable for environmental monitoring and water quality analysis, though its precision and sensor capabilities are not clearly stated.

The solar-powered RC robot combines solar panels with obstacle detection and light sensors, offering a scalable, environment-friendly solution for general navigation and remote tasks. With a standard RC car size and microcontroller-based system, it is highly adaptable to educational, surveillance, or lightweight delivery applications. However, its performance is highly dependent on solar intensity, and the precision and load capacity vary with the design**.**

Table 2 highlights comparison parameters, or attributes, of these robotic systems concerning the power source, operating voltage, power consumption, weight, size, load capacity, resolution, sensor types, control systems, materials, and algorithms used, special features, and applications. All the above aspects have been systematically compared to bring out the special strengths and capabilities of the Crabbot, Thermoelectric Quadruped Robot, MilliMobile, Smart Spider, Row-bot, Battery-Less Soft Millirobot, and Solar Powered Autonomous RC Robot.

These cases of robotic systems show how the field of robotics has grown vastly, with very diverse applications and innovative designs. Each robot in itself speaks to unique capabilities that have potential uses, hence advancing technology in various environments. Sustainable sources of energy, precise algorithms for movement, and advanced sensors are what make these robots capable of performing specialized tasks efficiently, hence increasing their suitability for a wide range of applications.

Challenges:

Despite recent progress in the development of self-powered autonomous robots, several technical challenges continue to limit their scalability, robustness, and deployment across diverse environments. One major issue is the inconsistency of energy harvesting (EH) sources, such as solar, thermal, or microbial systems, which depend heavily on environmental conditions. This variability hinders uninterrupted operation, especially in dynamically changing or energy-scarce environments. Moreover, many existing systems exhibit limited operational runtime, low energy conversion efficiency, and constrained payload capacities, which significantly reduce their utility in real-world applications such as agriculture, medical monitoring, or industrial automation.

Another critical limitation is the lack of integration between energy harvesting modules and intelligent control architectures. Most reviewed robots rely on fixed actuation and control mechanisms with minimal adaptability to energy availability or task complexity. There is also insufficient incorporation of machine learning or AI-based algorithms for real-time decision-making, adaptive locomotion, or predictive energy budgeting. Without these capabilities, self-powered robots remain reactive rather than proactive, diminishing their autonomous functionality in unstructured environments.

Furthermore, the current designs often lack modularity and reconfigurability, which limits their applicability across various tasks or terrains. Miniaturization also introduces complexities in fabrication, actuation, and communication, particularly in soft or micro-scale robots. Wireless data transmission under constrained power budgets also remains a challenge, especially when real-time sensing or feedback loops are required.

Conclusion:

This study reviewed various self-powered robots designed for specific tasks and environments, highlighting innovations in autonomy, power management, and application-driven design. The Crabbot, with an operating voltage of 150 V and precision of 85 nm, demonstrates high-resolution movement for pole climbing. In contrast, the Thermoelectric Quadruped uses geothermal energy with energy consumption as low as 600 J/m per 8 cm gait, showcasing sustainable monitoring in harsh terrains. The comparison reveals that robots differ significantly in size from submillimeter scale in Milli Mobile to standard RC car size in solar-powered robots, as well as in power sources, ranging from microbial fuel cells (Row-bot) to solar and piezoelectric systems. Load capacity, control systems, and sensor integration vary according to intended use, whether for pipeline inspection, remote agricultural monitoring, or aquatic navigation. These trends underscore the increasing convergence of renewable energy harvesting, adaptive control, and task-specific mechanics, moving toward robust, self-sufficient robots for challenging environments.

Future Recommendations:

Future research should focus on the development of hybrid energy harvesting systems that combine multiple sources (e.g., solar, RF, piezoelectric, and thermoelectric) to ensure consistent power availability under varying conditions. Integration of adaptive power management systems that dynamically allocate energy based on task priority and environmental inputs can further optimize efficiency. The incorporation of AI-driven control strategies will allow for energy-aware planning, autonomous fault detection, and intelligent navigation even in complex scenarios. In addition, modular and scalable designs that can be easily customized for different tasks, environments, and form factors will play a pivotal role in enhancing versatility. Standardization of energy harvesting interfaces, compact storage solutions, and ultra-low-power sensors will also be key to promoting widespread adoption of self-powered robotics in industry, healthcare, and environmental monitoring.

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