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Power solutions for autonomous mobile robots: A survey

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ABSTRACT

Autonomous mobile robots are a special class of robotic systems that can move a payload from one location to the other or perform a specific task. They allow efficient, precise, and streamlined workflow that makes human work less arduous. The market and research work related to these robots is increasing in anticipation of industry 5.0, where humans and machines are expected to co-exist and co-work. The future mobile robots are desired to have clean and cost-effective energy sources to have longer operation times and compliance with environmental requirements to allow application in diverse fields. The research on mechanical design, perception, navigation and control has carved out many commercially viable solutions for mobile robots. However, their widespread application is still limited due to the lack of efficient power systems for use in diverse and largely unknown/uncontrolled environments. The current power solutions incur high initial costs and require recharging or refuelling, which makes them unsuitable for unattended long-haul worktimes and cost-effective applications. These drawbacks are major hurdles in the wider applicability of terrain-based mobile robots to new domains and daily life scenarios, which are possible with the existing mechanical, perception, and control technologies. Keeping in view the need for advancement in this field and to gain a better understanding of the current state of the art and future directions, this work summarizes and reviews the energy solutions presented in the literature and used in notable commercially available terrain-based mobile robots. The provided solutions are categorized and discussed while the prospects and research gaps are also highlighted. A comparison of discussed power techniques is also provided, which can serve as a guideline for selecting a robot's energy source according to the desired requirements.
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1. Introduction

Locomotion in a machine allows it to be robust, perform tasks at multiple sites, reposition and reinstall itself in a different workspace with minimal physical alterations and operate in unknown and inaccessible environments. Such mobility in robots provides flexibility to perform intricate, tiring, and repetitive tasks that are otherwise difficult or impossible for humans. Autonomous mobile robots (AMR) can navigate in partially known environments, which makes them useful in industry, agriculture, hospitals and homes [1]. They can be used for tasks like planting, construction, patrolling, cooking, cleaning, mining, monitoring, and control of other systems. The efficiency and productivity of AMR are the main reasons behind their success and rapid growth [2].

Initially, mobile robots were developed to demonstrate navigation and artificial intelligence (AI). Shakey, which was developed in the late 1960s at the Stanford Research Institute, was the first mobile robot to meet these objectives [3]. Moving on to the present, rigorous research and development of robots for different applications has made them an important part of industry 4.0 [4]. In 2021, the European Commission provided its vision of industry 5.0 to be human-centric, sustainable and resilient [5]. According to experts, industry 5.0 will bring back the human touch to the industry where the humans will guide the robots in carrying out more automated production processes [6].

Considerable efforts have been put into developing robots to carry out the required tasks and work in unknown dynamic environments. However, these efforts mainly focused on the mechanical and locomotion design [1,7], perception [8,9], navigation [10,11], cognition and control [4,12] of the AMR, while relatively small efforts were directed towards the development of energy supplies for these robots [13]. Thus, it is feared that energy supply can become a limiting factor in the application of robots to larger domains and hinder further scientific developments in the field [14]. For closer integration into human environments and to tackle the current climate crises, clean and energy-efficient solutions with low environmental impact are desired for future robots. Energy autonomous robots that can autonomously replenish themselves with cheap and readily available resources can be

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the ultimate target. The market for AMR is expected to grow from $19B in 2018 to $54B by 2023 [15]. By 2025, the anticipated number of robots will surpass 50 billion, out of which the majority will be industrial robots [16]. Providing power to these huge numbers of robots can become a problem, especially if environmental effects are considered [14]. If the issues of energy supply and operational longevity are solved, the future robots will not only become sustainable but could also be commercialized for new applications leading to further industrial expansion. Therefore, rigorous research is required to improve the currently available solutions and to explore new options for powering robots. In this regard, environment and task-specific solutions possibly be more desirable and practical as each task and environment put different constraints on the selection of the powering technology. Multiple solutions with different costs, operational times and hardware setups for similar tasks and working environments can allow commercialization of wider variety of robots targeting different customer demographics.

Currently, batteries, internal combustion engines and fuel cells are commonly used power supply methods for AMR [13]. According to the literature reported to date, the operation time of an AMR can be prolonged by two methods: software side power management and hardware-based solutions. Intensive research has been conducted in software side power management. For example, a genetic algorithm was implemented in coverage path planning to decrease energy consumption [17], an energy-aware power framework was developed for multi-robot systems [18], the travelling speed and on-board processor's frequency were optimized to improve the working time of an AMR [19], and speed optimization was used as a method for software-based power management [20,21]. All these solutions are robot specific and difficult to extend to other types of mobile robots. Moreover, such solutions are usually a trade-off between economy and function, with only a negligible impact on the cost of the robot.

The hardware-related solutions include replenishing or replacing the source, using dual-energy sources, increasing source longevity or simultaneous energy transmission, acquisition and operation. Although such methods can significantly improve the operational longevity of the robots and possibly decrease the energy supply costs, the amount of research devoted to their development has been relatively low. Furthermore, the development of such solutions can extend the applications of mobile robots to new domains and tasks. Therefore, in this work, we have concentrated on presenting hardware-based power solutions reported in the literature and used in prominent commercially available systems for terrain-based AMR. No review article to date has discussed the power techniques used in AMR. The contribution of this work is to bring together the major powering techniques and technologies used for terrain-based AMR and highlight the requirements and limitations that need to be overcome to achieve an energy-autonomous mobile robot. To maintain focus, provide a better comparison and ensure wider applicability in industrial environments, only terrain-based mobile robots were chosen while aerial and underwater mobile robots are excluded from this work.

The methodology used for literature search and selection is explained in the next section. Section 3 includes the different types of solutions presented in the literature, which are further categorized into sub-sections. The energy system, application and working environment of a few commercial robots available for military, search and rescue, agriculture, domestic and industrial use are presented in Section 4. Discussion, limitations of this work and prospects for future works are included in Section 5 while the conclusions drawn from this work are presented in Section 6.

2. Methodology

Most industrial robots (other than AMR) are stationary and use a direct and continuous energy supply. Whereas the mobility of AMR usually requires an onboard energy source that has limited capacity. The current operating times of AMR are limited, and the energy setup costs are high. That is why they are limited to special conserved environments for applications that can bear high-cost solutions. Future AMR are desired to have energy autonomy through low-cost energy solutions for applicability in vast domains. An AMR that can replenish its energy source while working or generate onboard power may be more productive for industrial or outdoor tasks and exploration. A cost-effective energy setup can result in AMR that is affordable for the general user. Currently, personal AMR is very expensive and a major portion of their price is dependent on the sensors and energy setup. The energy solutions for AMR are scarcely considered in the literature. Therefore, this review is an effort to highlight this shortcoming and stimulate further research. Also, no review article summarizes different types of energy sources applied in AMR.

The included literature was searched through 'Scopus' and 'IEEE Xplore' databases. The selected keywords were searched in the title, abstract and keywords of the published articles using the following search string; (mobile AND robot) OR (autonomous AND mobile AND robots) OR (automated AND guided AND vehicle) OR (agv) OR (amr) OR (field AND robot) AND ((alternative AND power) OR (power AND solutions) OR (power AND management) OR (energy AND solutions) OR (fuel-cell AND powered) OR (solar AND powered) OR (prolonged AND activity) OR (energy AND efficiency) OR (hybrid AND power) OR (biomass) OR (long AND working AND duration) OR (wind AND powered) OR (engine AND powered) or (biofuel)) AND NOT (traffic) AND NOT (drone) AND NOT (flight) AND NOT (humanoid) AND NOT (under AND water). The following selection criteria were used to further filter the searched articles.

1. Include only terrestrial robots with any type of locomotion (wheeled or legged etc.).
2. Exclude humanoid robots.
3. Include research articles only and exclude patents.
4. Include articles that present alternate energy solutions according to the working environment.
5. Include robots with the ability of navigation and autonomous motion.
6. Exclude power solutions for self-driving, human-driven and remote-controlled car-type systems.

No time limit was imposed in the search as this work is the first of its type to summarize the power solutions presented in the literature to date. Duplicate works, articles with minor contributions or improvements of already reported systems were excluded. The literature cited in the selected articles was also analysed and articles fulfilling the selection criteria were included. Fig. 1 shows the categories and highlights of the articles included in this work. The broad categories are based on the energy solution while sub-categorization is based on the classification of each energy solution. However, for solar-powered robots, this categorization is based on the application of the robot as the photovoltaic technology does not offer any significant offshoots.

3. Power solutions

3.1. Engine-powered AMR

In this section, the combustion-based solutions applied to power mobile robots are presented.

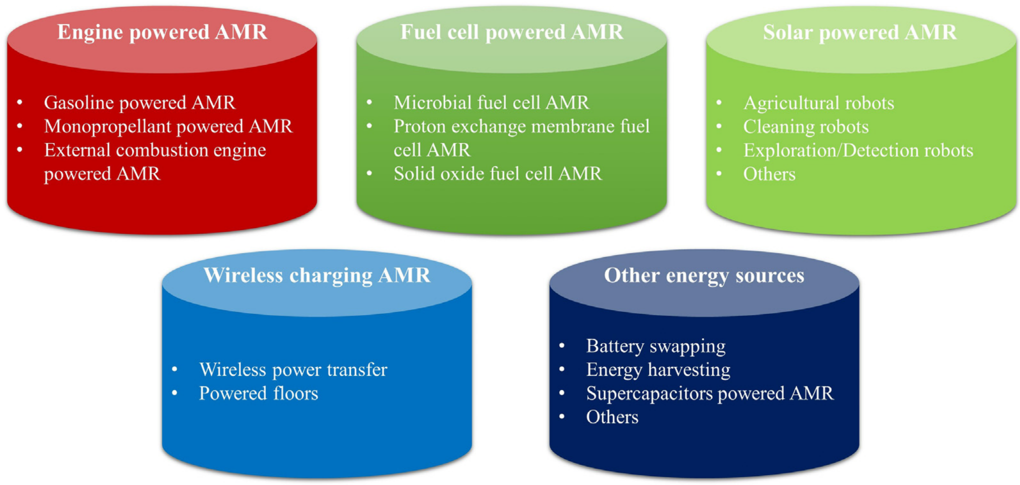

Fig. 1. Categories and highlights of the works included in this work.

3.1.1. Gasoline-powered AMR

A decade ago, gasoline-powered robots were popular because of their quick replenishment with easily available fuel and the reliability of their power supply method. These robots are suited for outdoor recurrent applications where energy replenishing time can significantly reduce the effectiveness of a mobile robot. The gasoline-powered engines produce rotary power that is not directly useable for the majority of robots. Therefore, according to requirements, the engines are coupled with power conversion units like hydraulic pumps or electrical generators, which increases the overall weight of the robot and reduces the power-to-weight ratio. The other drawbacks of such systems include noise, pollution and the requirement of an operator for refuelling.

AMRU 3 (Autonomy of Mobile Robots in Unstructured environments) was a six-legged teleoperated robot with hydraulic actuators for automatic inspection of large mechanical structures [22]. A piston engine was used to power the robot while an alternator and a car battery were used to start the engine and power the onboard electronics. The T4 shown in Fig. 2(d) was an omnidirectional robot developed for the US Army-Tank-Automotive and Armaments Command's Intelligent Mobility Program [23]. It had a 16 hp gasoline engine to power its hydraulic actuators and electrical components. The robot could operate on roads with gradients of around 17%. The main objective of T4 was the inspection of suspected vehicles in parking lots and the deployment of an omnidirectional inspection vehicle ODIS from the underside of the robot.

A hydroelectric unit is an energy supply system that has an engine to power a hydraulic pump to drive the robot actuators and an alternator to power the electrical instruments. In [24], different commercially available two and four-stroke engines were evaluated using Ragone plots for application in a hydroelectric unit for field and service robots. Based on the results, gasoline-powered units were recommended as the most viable energy solution. Ragone plots were proposed to design the power unit and optimize its mass and characteristics according to the desired operation time. A ZDZ-80 hydroelectric unit was termed to be the most sophisticated one. It had a 2-stroke gasoline engine and provided 2.3 kW of hydraulic and 220 W of electrical power with an overall efficiency of only 8.1%.

Sadeghi et al. proposed the hybrid snow blower mobile robot shown in Fig. 2(a) [25]. It used a 196cc 5.5 hp Loncin gasoline engine with batteries. Most of the energy from the engine was used for blowing the snow while the rest drove the alternator to power the motors and other electrical components. It was demonstrated that mobile robots requiring 5 hp or more can be developed with a hybrid power system with 10.65 times less weight than a solely battery-powered robot.

The state-of-charge (SoC, which stands for currently available battery power given as a percentage) in a dual power source using an internal combustion engine and a lead–acid battery was modelled using type-II and type-III fuzzy frameworks [26]. The robot was battery-powered while the engine charged the battery when the SoC fell below a certain level. Two scenarios; a fixed SoC of 70% and a variable SoC, were simulated with the requirement-based control and the latter showed better results.

BigDog from Boston Dynamics (now a part of Hyundai Motor Group) was a quadruped robot developed to walk through rough terrains and slopes in outdoor environments, as shown in Fig. 2(b) [27]. It had hydraulic actuators and a 15 hp two-stroke internal combustion engine. The human operator used IP radios to communicate with the robot for instructions like squat, walk, trot, stand up, start or stop the engine etc. The later version named Alpha Dog, shown in Fig. 2(c), used a gasoline-powered engine with onboard batteries that not only powered the electronics but also provided an energy reservoir to charge handheld devices, radios and laptops. It could trek 32 km in 24 h with a 181 kg payload before requiring refuelling [28]. Alpha Dog had sensors mounted on its head to follow a human leader and was intended to assist soldiers on a battlefield. The latest iteration of the concept, called Spot, is battery-operated with a run time of only 90 min [29]. Jinpoong was a similar quadruped robot with hydraulic actuators and a 30 hp two-stroke engine, shown in Fig. 2(f) [30]. The robot was less susceptible to the leg dynamics than BigDog due to a smaller distance between its centre of gravity and its physical centre.

Nomad (shown in Fig. 2(e)) was a wheeled mobile robot for meteorite exploration in Antarctica [31]. It had sensors to identify different types of meteorites and rocks. A 3-DOF manipulator could pick samples and the maximum speed of the robot was 1.8 km/hr.

3.1.2. Monopropellant-powered AMR

Gasoline and diesel are high-energy chemicals suited for high-power applications like cars or aeroplanes. They may be unsuitable for AMR because of the low energy demand of robots, the environmental impact and the low efficiency of small horsepower engines. Therefore, low-energy chemicals like hydrogen peroxide and propane have also been investigated for robots.

A free piston compressor internal combustion engine working on propane was proposed in [32]. The free piston acted as an air pump and the engine converted the chemical energy of

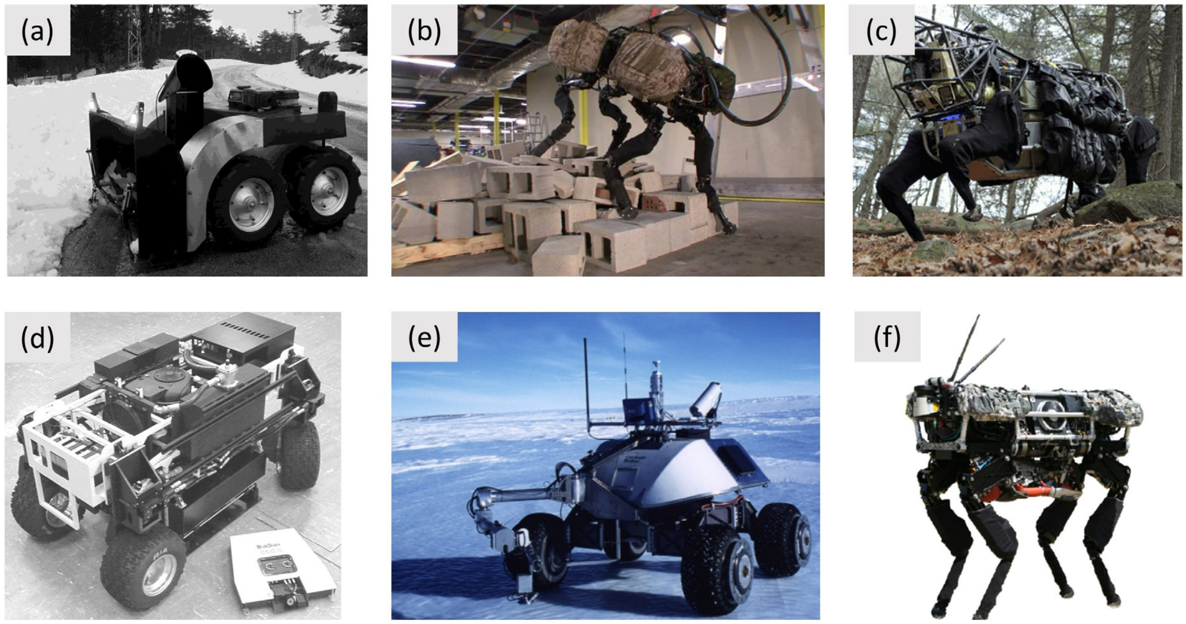

Fig. 2. Engine-powered mobile robots: (a) Snow blower robot [25], (b) BigDog [27], (c) Alpha Dog [28], (d) T4 and ODIS (the omnidirectional robot) [23], (e) Nomad [31] and (f) Jinpoong [30].

propane into the pneumatic potential energy of compressed air. The motivation was to develop a portable power supply source that provides pneumatic power for untethered mobile robots. The developed device could start on-demand and produced less noise and exhaust gases than comparable conventional internal combustion engines. It had an energy density of 46350 kJ/kg of propane. A similar pneumatic power supply used a catalytic reaction of liquid hydrogen peroxide (H_2O_2) to provide an energy density of 288k J/kg of liquid [33]. The mechanical work was extracted from the heat generated by the reaction. A free piston hydraulic pump to power a robot in anaerobic conditions used hydrogen peroxide and hydrazine (N_2H_4) with a similar working mechanism [34]. Both fuels provided an efficiency of 20% and had energy densities less than that of lithium-ion batteries. The works reported in [32–34] presented only the power supply system without any integration with a robot.

3.1.3. External combustion engine-powered AMR

A linear control technique to control the instability of the gas-powered free piston Stirling engine was proposed in [35]. The simulations showed that it could be used for small robots requiring less than 1 kW power. A combination of the free piston Stirling engine and the linear alternator was studied at NASA's department of energy to realize a power supply for mobile robots intended for use in space [36]. It was proposed as an alternative to radioisotope thermoelectric generators to decrease the cost, hazards and risks of the mission.

3.2. Fuel cell-powered AMR

Devices that convert chemical energy from the source (usually a fuel) directly to electricity are called fuel cells. They can be categorized depending on their types of catalysts, electrodes or operating temperatures [37]. This section discusses the robots and power supplies that use different types of fuel cells.

3.2.1. Microbial fuel cell AMR

Microbial fuel cells (MFC) are a type of biofuel cells that use organic waste as fuel and living microorganisms as catalysts to produce electricity [38]. The operating temperatures of these devices are in the range of 20–60 °C. Such fuel cells do not require precious metal catalysts. However, they provide low current density with efficiency in the range of 15%–65%.

Gastronome, shown in Fig. 3(a), was a food-eating robot belonging to a class of robots called Gastrobots. It used a MFC to convert food into electrical energy to charge the onboard batteries and provide power to drive the robot [39]. It had three wagons with a front wagon hosting electrical components, motors and a feeding mechanism, the middle wagon housed a 6-cell stacked-plate MFC and the last wagon carried an oxidant tank and rechargeable batteries. The food was manually fed to the robot and it could perform basic motions with the motor.

EcoBot-III had 48 stacked MFC to build a robot with an artificial digestive system, as shown in Fig. 3(b) [40]. It was designed to feed on insects (flies) or liquid feedstock. A UV lamp and bait were installed to attract the flies. The artificial stomach digested the food and egested the waste materials. EcoBot-III worked consecutively for 7 days until a mechanical failure forced it to stop. However, these experiments were performed in a very controlled environment.

SlugBot (shown in Fig. 3(c)) was a MFC-based predator robot designed to feed on slugs commonly found on agricultural land [41]. It had image sensors and a gripper mounted on a long extendable arm. Images from the sensors were used to locate the slugs, which were picked up by the gripper and placed in a container that supplied them to the MFC for energy generation. The robot design was optimized to use less power. It detected slugs with an accuracy of 70% but could only pick 13% of them due to issues related to the gripper.

3.2.2. Proton exchange membrane fuel cell AMR

Polymer electrolyte (PE) fuel cell, solid polymer electrolyte (SPE) fuel cell or proton exchange membrane (PEM) fuel cell are different names for the same type of fuel cell that processes hydrogen to generate electric current [37]. An anode extracts an electron from the hydrogen atom and converts it into a proton. The extracted electron travels through the polymer electrolyte membrane and reacts with oxygen at the cathode to generate electricity and produce water as a waste product. The operating temperatures of such fuel cells are usually less than 100 °C. They

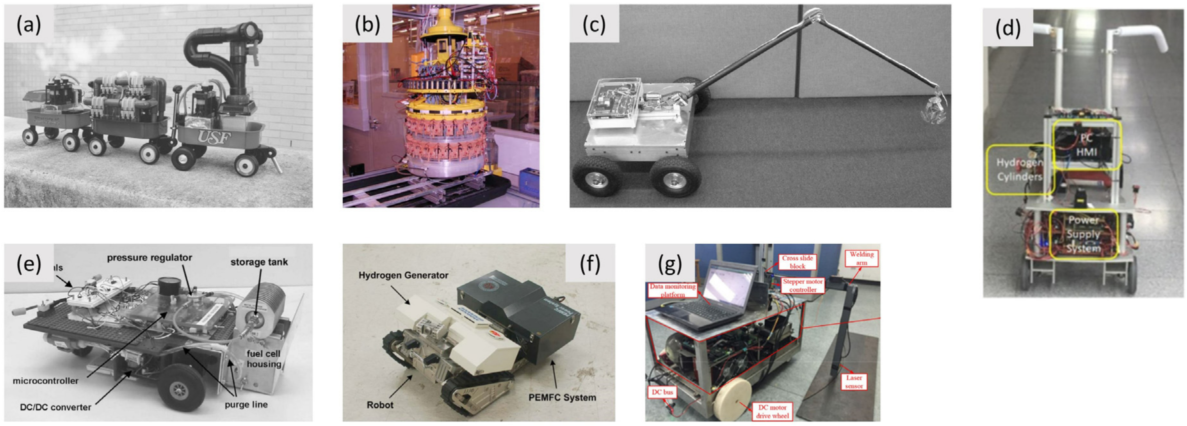

Fig. 3. Fuel cell powered robots: (a) Gastronome [39], (b) EcoBot-III [40], (c) SlugBot [41], (d) Co-walk robot [42], (e) MechBot [43], (f) Lee et al. robot [44], (g) Welding robot [45].

have a quick start and stop ability and have an efficiency in the range of 40%–60%. However, they use precious metal catalysts like platinum.

MechBot, shown in Fig. 3(e) [43], was a small-sized mobile robot used at Queen's University Canada for study projects. Its batteries were replaced with a PEM fuel cell and the robot demonstrated similar performance and work time of around 2 h with both sources. In a similar work, the battery of a small-sized Dedalo 2.0 robot was replaced by a fuel cell and supercapacitors [46]. Actively controlled DC/DC converters were used in this system and a regulation strategy managed power distribution.

A power supply system comprising dual lithium-ion batteries with a PEM fuel cell was used in the Co-walk mobile robot [42]. The robot (shown in Fig. 3(d)) was powered by batteries while the fuel cell was used to charge them. A charging logic was implemented so that one battery was charged while the other was discharged (supplying power to the robot). Experiments showed that implementation of the logic doubled the operation time to 5.9 h.

Lee et al. proposed a small-sized robot with a PEM fuel cell and battery for hazardous missions shown in Fig. 3(f) [44]. In this system, Nafion 211 membrane was used as a humidifier to decrease the size of the PEM fuel cell and the performance evaluation showed the results were similar to conventional humidifiers. In addition, $NaBH_4$ was used to generate onboard hydrogen to replenish the hydrogen tank and prolong operation time. A power management system allowed fast start-up, but a few minutes were required to stabilize the hydrogen generation.

A small-sized PEM fuel cell-based power supply was developed for small robots weighing 5–20 kg [47]. In this setup, a water-activated powder of lithium hydride (LiH) generated hydrogen using the water produced by the fuel cell. It was intended to reduce the hydrogen storage tank size for small robots. Simulations showed a continuous working time of 44 days.

A combination of PEM fuel cells and solar cells was used to power a toy robot [48]. Energy from the solar cells was used to produce hydrogen that was stored in the tanks for later use in an effort to realize an energy-autonomous robot. Using this system, 6026 min of operation was achieved with a litre of hydrogen at an initial gas tank pressure of 0.18 N/m^2.

A numerical model of a hybrid power supply for an automated guided vehicle (AGV) using a PE fuel cell stack and lithium-ion battery was proposed in [49]. Supercapacitors and a battery were used as energy buffers to store energy from the fuel cell, balance the output during fuel cell output fluctuations and help in meeting higher energy demands. The model was developed for the commercially available Formica-1 AGV manufactured by AIUT, Poland.

The working of a power system with a fuel cell and battery was optimized using a rule-based control method and energy management system [45]. This power model was developed for a 600 W self-humidifying fuel cell mounted on a welding robot, as shown in Fig. 3(g). Unidirectional and bidirectional DC/DC converters were deployed to manage the energy flow (charge batteries during idling and braking, and supplement power during motion). An adaptive mutation swarm optimization algorithm was also proposed. The results showed improved load power distribution with reduced equivalent hydrogen consumption and output power fluctuations.

3.2.3. Solid oxide fuel cell

With an operating temperature of 800–1000 °C, solid oxide (SO) fuel cells do not require precious metal catalysts [38]. A cathode donates electrons to an oxygen atom to convert it into an anion (O^{2-}) that travels to the anode and reacts with the fuel (usually hydrogen) to give its electrons to the anode. The energy efficiency of SO fuel cells is generally in the range of 55%–65%, but it can go up to 85% in the case of cogeneration. However, such fuel cells suffer from slow start-up and stoppage and require expensive interconnection materials that can withstand high temperatures.

A hybrid power supply system was studied for the iRobot Packbot [50]. Two power supplies were built using compressed propane-powered SO fuel cells and hydrogen-powered PEM fuel cells. Both types of fuel cells were used with a battery and their performances were compared. The experiments involved driving and scouting missions. The results showed that the SO fuel cell had a longer start-up and shutdown time. A control strategy was implemented to drive the robot using only the battery power during those long durations. It also had a lower energy density with an efficiency of around 15% compared to the PEM fuel cell's efficiency of around 48%. The hybrid power system increased the 4 h battery-powered operation time to more than 11 h.

Different control frameworks for an unmanned ground vehicle using SO fuel cell and battery were proposed in [51]. Switching of power sources, different operating regimes, SoC, temperature and output power were the main factors in these frameworks. Individual components were modelled and missions were simulated to investigate the energy losses and thermal response of the battery. In general, the maintenance of high operating temperatures in SO fuel cells is difficult and affects the overall efficiency.

3.3. Solar-powered AMR

Sunlight is a clean source of energy that can be directly converted to electricity using photovoltaic (PV) cells. When sunlight strikes the PV cells, electrons in the substrate become free, thus producing electricity. PV cells can be manufactured from monocrystalline, polycrystalline or multi-junction materials [52]. Monocrystalline cells are usually expensive and provide higher efficiencies as compared to cheaper polycrystalline PV cells. The output of the PV systems is dependent on multiple factors, such as temperature, irradiation, dirt deposition, battery type, charge converters etc. PV cells are considered a clean source of energy for producing direct current (DC) that can be used in AMR without conversion. The robots reported in the literature that utilize PV cells for energy supply are discussed in this section.

3.3.1. Agricultural robots

Ladybird, shown in Fig. 4(b), was an autonomous agricultural robot built by the University of Sydney [53]. It was developed for surveillance and monitoring of agricultural fields and used machine learning algorithms to detect and segment objects. Powered by batteries, a continuous operation of 20 h at a speed of 0.5 m/s was possible before requiring a recharge. Solar panels were installed on top of the robot body to charge the onboard batteries. On a clear day, it could work without any net power loss during daylight hours.

The smart farming robot was developed for irrigation and pesticide spraying, as shown in Fig. 4(a) [54]. It had photovoltaic cells to charge the batteries, but the presented version used electricity from the grid to meet peak power requirements. The robot was developed as an IoT device that can schedule water sprinkling and pesticide spraying according to weather conditions and requirements.

AgBotII, shown in Fig. 4(c), was a vehicle-sized weeding robot for agricultural fields [55]. It was powered by two battery packs and had a solar docking station where it could replenish its batteries from the electricity generated by PV cells. It used computer vision algorithms to detect different types of weeds with an accuracy of more than 90% and applied a mechanical or chemical solution depending on the type of weed. Some other prototypes of solar-powered farming or grass-cutting robots were also reported in [56–59].

3.3.2. Cleaning robots

A solar tracker for increasing the operation time of a cleaning robot was presented in [60]. It used four light sensors to track the direction of the sun. The addition of this tracker increased operation time from 18 min and 15 s to 25 min and 32 s. A cost-effective solar-powered cleaning robot was reported in [61]. It could travel 1.8 km on one charge that lasted for 2.8 h. The batteries were fully charged in 3.5 h using solar panels. The robot, shown in Fig. 4(g), was intended for cleaning roadways and had a dust collection capacity of 800 g. A conceptual design of a solar-powered smart waste bin (e-TapOn) with a robotic garbage collector was proposed in [62].

3.3.3. Exploration/detection robots

The cool robot was a solar-powered autonomous robot for exploration missions during the summertime in Antarctica and Greenland [63]. The top and sides of the robot were covered with solar panels, as shown in Fig. 4(d). It was able to drive in the soft snow at a speed of 0.78 m/s for 5–8 h. Hyperion was a solar-powered robot for exploration missions in the Canadian Arctic [64]. It had sun-synchronous navigation to avoid shadows and track the sun while moving at a speed of 2 km/h. A hybrid power supply system for a mobile robot that used solar and wind power was proposed in [65]. It could gather satellite data and was designed for polar expeditions.

Muhida et al. proposed a remotely operated solar-charged robot for imaging and sample collection from a disaster-struck region, as shown in Fig. 4(h) [66]. A 2-DOF robotic arm and a gripper were mounted on the robot to collect samples weighing around 250 g with an accuracy of 85%. The robot could work in tropical regions and climb a maximum slope of 30°.

A light sensor-based collector tracking system for extra-terrestrial rovers was designed for ARES (Advanced Robot Exploration System) in an effort to develop self-sufficient mobile robots [67]. The accumulator charged fully in 21 h and 25 min and the use of the tracker increased the generated power by 44% of the actual ARES power.

A small-sized mobile robot to detect gas leakage near industries was reported in [68]. As shown in Fig. 4(i), it used batteries and solar panels in conjunction to prolong the operating time from 55 min to 70 min. GPS and compass were integrated with the robot for navigation in outdoor environments. Another robot developed for a similar purpose had tilted solar panels for effective electricity production [69]. It had a camera for teleoperated control and a gas sensing module.

3.3.4. Others

Sulaiman et al. presented a hybrid solar-fuel cell energy system for a mobile robot [70]. Photovoltaic cells produced electricity to charge the batteries and the surplus electricity produced during the sunlight hours was used in the electrolysis process to produce hydrogen. During the intermittent hours, the hydrogen was used by the fuel cell to generate electricity. This method is similar to [48] but here the hydrogen was stored in the form of metal hydrides, instead of hydrogen cylinders.

The MarXbot shown in Fig. 4(f) utilized the light energy available in the house to recharge its batteries [71]. The robot had solar panels and used a phototaxis strategy where locomotion was driven by the stimulus of light. However, it took 130 h to recharge a 40 Wh battery.

A small-sized two-wheeled mobile robot with solar cells and a capacitor bank was introduced in [72] and shown in Fig. 4(e). Solar cells charged the capacitors which provided power to the robot. The highest charging voltage for a day in a five-day test was 4.96 V.

The Tribot shown in Fig. 4(j) was a robot with whegs; a hybrid combination of wheels and legs [73]. It had NiMH and Li-Po batteries to drive the actuators and embedded electronics, respectively. A power supply was designed with photovoltaic cells to prolong the operating time from 2 h to 4 h and 30 min. A step-down battery charger was the core of the power supply that allowed fast maximum power point tracking.

In [74], a Simulink model of a solar-powered power supply system was proposed. It could estimate the power consumption and power production for a task. The path providing more irradiance to photovoltaic cells could be chosen and the performance of the overall system could be estimated by the model.

3.4. Untethered power transfer

Mechanisms to transfer power to the mobile robot during operation to prolong its operation time without a wire or cable are presented in this section. It includes systems that wirelessly transfer energy to a robot in a non-contact assembly or loosely constrained systems (powered floors) which require continuous connection to the charging floor. The technique of wireless power transfer is quite old, and a lot of research has been done on various systems and methods. A comprehensive review of different technologies is also available in the literature [75]. Here, only

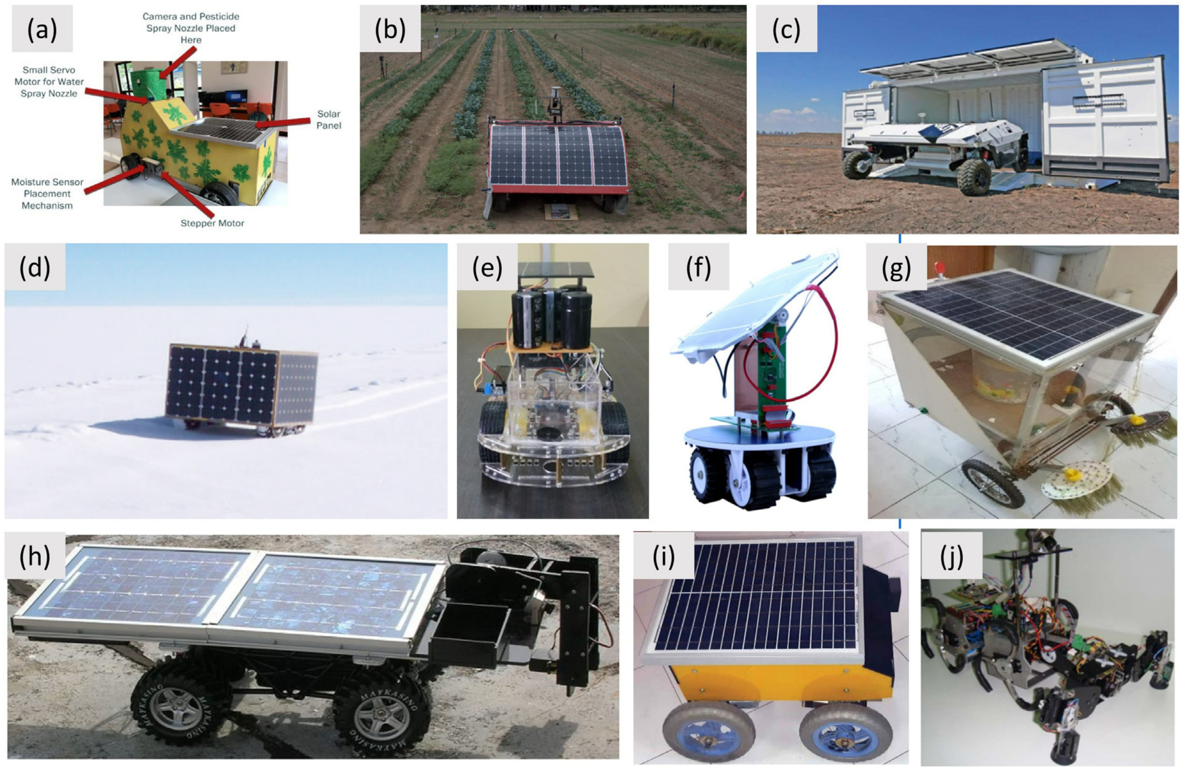

Fig. 4. Solar-powered mobile robots: (a) smart farming robot [54], (b) Ladybird [53], (c) AgBotII recharging its batteries at a solar-powered docking station [55], (d) Cool robot [63], (e) solar cell and capacitor powered robot [72], (f) MarXbot [71], (g) roadways cleaning robot [61], (h) robot for disaster struck regions [66], (i) gas leakage detecting robot [68] and (j) Tribot [73].

the literature related to the implementation of wireless power transfer for terrestrial mobile robots is included. Moreover, the works dedicated to dynamic charging (simultaneous working and charging) are included while the ones focusing on static untethered power transfer (where a robot stops working and charges wirelessly on a docking station) are excluded.

3.4.1. Wireless power transfer

Generally, wireless power transfer is divided into Inductive power transfer (IPT) and Conductive Power Transfer (CPT) [76]. IPT uses a pair of coils and the phenomenon of mutual induction to transfer power from a current-carrying coil to a load coil. IPT systems can have higher frequencies, longer transfer distances and high-power capacities. CPT uses capacitive coupling to transfer power through the action of electric fields. They are usually cheaper but offer lower frequencies, smaller transfer distances (usually in millimetres) and low power capacities. IPT is mostly used in non-contact charging of electronic devices and commercial AGVs. Current-carrying coils usually called primary coils are installed on the tracks of an AGV. The load coils, termed secondary coils, are attached to the lower side of the robot to receive power from the primary coils. Rectifiers are used at the secondary coil outputs to convert the induced AC into DC, which is then used to charge the batteries. Since IPT systems use the same principles as transformers, airgaps, misalignment of coils and coil structure are a few of the factors that affect their efficiency.

Multiphase quadrature pickup coils for AGVs were designed in [77,78]. They could capture both vertical and horizontal components of the magnetic field with two different pick-up coils around an IPT track. The solution was validated for both single-phase and three-phase bipolar tracks. The pickup efficiency for a fleet of 20 AGVs was 84%, including the shared standing loss. DDQP (double D quadrature pad) [79] and BPP (bi-polar pad) [80] are two other types of pads devised to increase the flux of an IPT system and replace the conventional circular pads. A comparison of both DDQP and BPP is given in [81].

An AGV charging mechanism for a tightly coupled IPT system was proposed in [82]. In this system, the issues of airgap variation, low voltage and high output current were solved using an LCC compensation circuit. The design could accommodate variations of 5 mm to 25 mm in the airgap without any significant efficiency loss. It could provide a charging current of 73.8 A for a 24 V battery across a 15 mm airgap resulting in a power transfer of 1.78 kW with an efficiency of 86.1%.

An energy pickup scheme for dynamic wireless charging of inspection robots was proposed in [83]. Centralized and decentralized energy pickup schemes were investigated for robots operating at low speeds on a pre-defined path. The decentralized scheme was implemented with two pickup coils and had higher efficiency and receiving power. A positioning strategy based on imitative relaying coil structure was also proposed. A switching control strategy combined with the decentralized energy pickup scheme and the positioning strategy provided higher efficiency and receiving power.

An AGV-mounted power transformer was designed to enhance mutual inductance in wireless charging coils [84]. The scheme was developed for Meidensha Corporation MCAT AGV to remove its batteries and improve operation. The secondary coil had a staircase arrangement, and a model was developed to consider the voltage drop across the diodes in the rectifier. This system achieved a power transfer of 100 W with an efficiency of 80%.

Energy logistics was another untethered method proposed to power a mobile robot developed to work in a living space with humans [85,86]. The power cable was replaced with a power delivery robot that would wirelessly charge the working robot and other electronic devices used by the humans.

A battery-less mobile robot operated on the dynamic wireless power transfer [87]. A synchronous buck converter acted as a virtual current source. The system cost was reduced as both the primary and secondary coils did not use a ferrite core. The mobile robot was mounted on a long rail and received power of 32 W at the secondary coil.

A dynamic AGV charging system with a single receiver and multiple transmitters was optimized using circuit theory [88]. The optimal current at a fixed number of transmitters was determined by the Lagrangian multiplier method to maximize the power delivered to the robot. Circuit theory was also used in an impedance matching method to wirelessly charge a line inspection robot [89]. The output power of the wireless transfer system was modelled, and the power efficiency was more than 30% at a 70 cm distance.

A wireless power transfer system was implemented with a small-sized mobile robot [90]. It had overhead and under-the-track testbed settings for continuous charging. A 2 cm distance between the transmitter and receiver was found to be optimal for both under the track and overhead type testbeds.

An interoperable power adjustment mechanism for wireless power transfer provided better transmission, efficiency, and savings [91]. The mapped impedance on the side of the primary coil and position of the AGV was used to adjust the output of each transmission module. The duty cycle control was improved, which accelerated the charging for scenarios with aligned coils. Changes in output current and voltage were negligible for misalignments of up to 20 mm.

The single-layer coils were replaced with double-layered coils in [92] for wireless charging of robots. The ferrite shielding design was optimized and the proposed hollow type design saved energy, decreased weight, and improved the cost-effectiveness of the coils. The experimental results showed a power transfer of 50 W over a distance of 100 mm with an efficiency higher than 50%.

An on-the-fly wireless charging system for a swarm of small-sized mobile robots was presented in [93]. Developed for evolutionary or research-related robots, the system allowed long-term testing of robotic swarms without the need for battery replacement or recharging. A 12-cell charging pad was implemented for the Mona mobile robot. Supercapacitors were used to avoid damage to the battery due to continuous charging.

A wireless charging system with a core-less transmitter for dynamic charging of multiple mobile robots has also been reported [94]. It was devised as a cost-effective alternative for AGVs used in small businesses. The energy transfer efficiency was 93%, excluding the gate losses in the inverter. The system had an unknown error below 50 W and had a maximum power transfer limit of 1 kW.

A model of a 1.5 kW wireless power transfer system was formulated in [95]. It used a PI-PBC (proportional–integral passivity-based control) passive control strategy that removed the steady-state error and showed better performance than a normal PI control strategy.

3.4.2. Powered floors

In systems designed to use powered floors, supernumerary sliding contacts on a robot are organized in a rigid contact array that interacts with a floor composed of alternating polarity bands connected to a power source. Such systems provide constant power. However, the geometry of the contact arrays and polarity bands is quite important for seamless operation. The robot receives power if at least one of its contacts is on a positive polarity band and at least one contact is on a negative polarity band.

A framework for the design and analysis of powered floors and contact arrays was proposed in [96]. Discrete and continuous methodologies were implemented, with the latter being more robust to uncertainties and errors. An octagon-shaped contact array and a powered floor were designed for the Elisa-3 robot. Monte Carlo simulations and experimental results showed that a polygon with 8 sides or more will always allow 100% contact.

In [97], a differential evolution algorithm was used to automatically find the location of contact points on a robot for energy transfer using a powered floor. The algorithm ensured that the robot would receive power in any position and orientation. The model was verified for determining the location of contact points on three small-sized mobile robots (Thymio II, mBot and Elisa-3). The results suggest the width of conductive strips attached to the robot is directly proportional to the distance between contacts.

NanoWalkers were small-sized three-legged robots with scanning microscopes to operate at a subatomic scale for drug and material characterization [98]. They worked on powered floors and used piezoceramic actuators to achieve maximum and minimum step sizes of 50 μm and 20 nm, respectively. Droplet was a ping-pong ball-sized robot that work using a powered floor [99]. It was an open-source platform to study swarm robotics and was actuated with vibrational DC motors.

3.5. Other energy sources

Energy solutions implemented for mobile robots that do not fall in any of the above-mentioned categories are discussed in this section.

3.5.1. Battery swapping

A battery swapping mechanism to replace the used battery with a charged one was introduced in [100]. The robot (shown in Fig. 5(a)) was for household environments. A 6-DOF manipulator was mounted on the mobile robot to remove the used battery, mount it on a wireless charging station and plug in the charged battery. The attached camera provided live feedback to the teleoperator who could replace the battery in about 1 min.

An autonomous battery swapping and docking mechanism were reported in [101]. The docking station could tolerate misalignment of $\pm 9^{\circ}$ and used optical sensors and magnetic tape to align the robot. The arms of the docking station removed the used battery from the robot and inserted a charged one. It could replace batteries in 45 s.

In [102], a support robot carrying charged batteries replaced batteries in work robots when their charge level fell below the specified threshold. CCD camera and LEDs were used to align and dock the robots for battery replacement as shown in Fig. 5(d). The mechanism automatically removed and replaced the two 12 V batteries that powered the work robot with an average battery swapping time of 100 s. A battery station was built with a similar configuration to the robots to charge the used batteries and provide fresh pairs to the robots. A flexible docking misalignment of $\pm 45^{\circ}$ and 120 cm was possible. The system provided robust and quick battery swapping and allowed prolonged working durations for work robots.

CISSBOTs were energy-sharing multi-robot systems that could replace batteries during operation [103]. A probabilistic model determined the exchange by considering remaining energy, the relative distance between robots, absolute distance to the charging station, workload and work history. Two CISSBOTs performing a battery exchange can be seen in Fig. 5(c). Experiments validated working in indoor industry or office-like environments.

Simulations on multi-robot systems with a tanker robot responsible for charging the work robots were presented in [104]. An uninterrupted power supply system to power the robot during the battery removal procedure was introduced in [105].

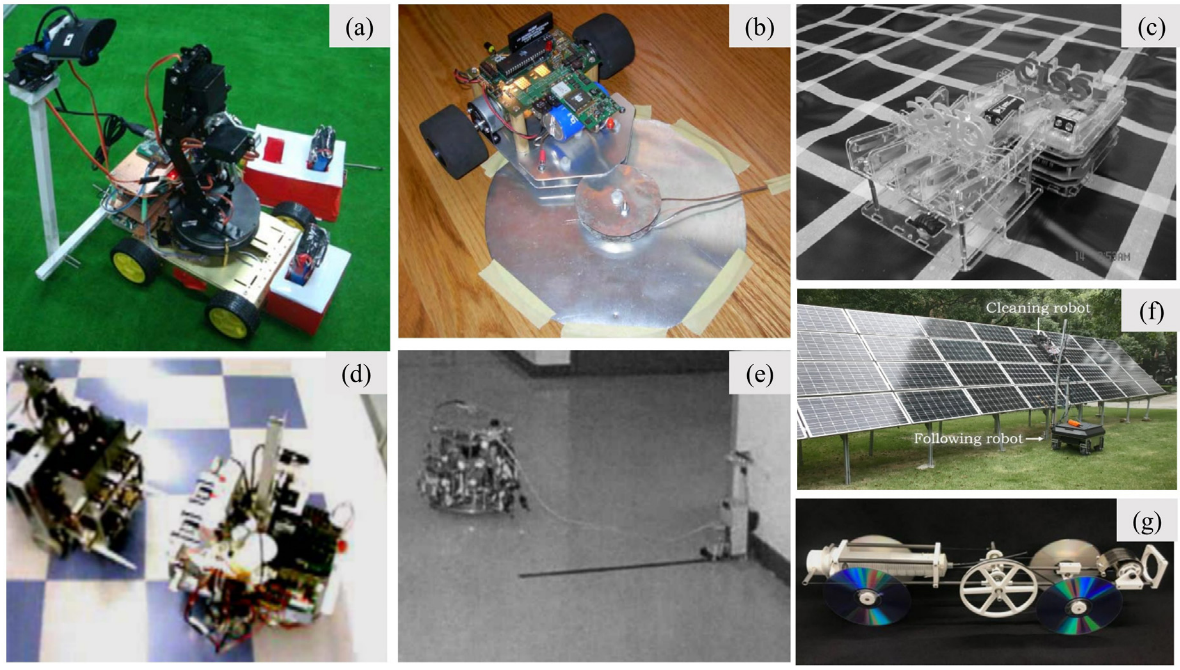

Fig. 5. (a) A mobile robot with a 6-DOF manipulator for battery replacement [100], (b) a supercapacitor-powered robot charging at a docking station [110], (c) two CISSBOTs replacing batteries [103], (d) a support robot providing fresh pair of batteries to a worker robot [102], (e) an indoor floor-sweeping mobile robot [111], (f) multi-robot system for solar panel cleaning [112] and (g) a wheeled vehicle powered by temporal temperature gradients harvested using butane and iso-butane [106].

3.5.2. Energy harvesting

Energy harvesting or energy scavenging usually refers to the conversion of a source present in the environment, such as vibrations, temperature gradients, light etc. to a useable power which can be in the form of mechanical work or electricity. The energy harvesting wheeled vehicle proposed in [106] utilized the temporal temperature gradients to harvest energy from the vaporization of the working fluids to power the actuators. The working principle was similar to the 17th-century clocks. The wheeled prototype shown in Fig. 5(h) used butane and iso-butane as the working fluids. It produced a work of 4.9 J and moved the vehicle 10 m at a temperature differential of 16° C.

A spherical energy harvesting mobile robot for polar expeditions had pipeline-type power generators [107]. They worked on electromagnetic induction and different types of pipeline systems were implemented to check the feasibility in robotic applications.

Ajala et al. proposed a gas-powered self-sufficient firefighting robot [108]. It worked on the sublimation of dry ice into carbon dioxide in the presence of a hot water catalyst. Pneumatic actuators converted the energy from the pressurized carbon dioxide into mechanical energy. Later, the work was extended to a hydraulically powered carbon dioxide-propelled firefighting robot [109]. It had 10 legs and wheels, which allowed it to climb stairs and move on flat surfaces. Only the theoretical design and empirical study were presented.

3.5.3. Supercapacitors-powered AMR

The small-sized robot shown in Fig. 5(b) was powered using supercapacitors [110]. Due to the small energy density of supercapacitors, frequent charging was required, which was done using a docking station. The robot could be charged in less than 90 s and worked for around eight minutes, thus providing a longer drive time than charge time.

Artal et al. converted the power source of a small robot from a battery to supercapacitors [113]. A mathematical model for a hybrid battery and supercapacitor power supply was introduced in [114]. It was designed to handle current buffering during different conditions to improve battery discharge.

3.5.4. Others

A power supply system was developed for floor-sweeping mobile robots operating in indoor environments [111]. It used battery power for navigation and autonomous motion and direct electricity to perform the cleaning task, as shown in Fig. 5(e). The robot had an infrared sensor to search for the power socket and an electromagnetic plug that could automatically connect to the socket via a magnetic field. A cord winding mechanism was also installed to avoid over tension or tangling of the wire during motion. With this system, the robot's operation time was increased from 25 min to 1 h and 45 min.

Solar panel cleaning robots are desired to be lightweight for easy movement and to avoid damage to the panels. A multi-robot system with a cleaner and follower robot for solar panel cleaning is shown in Fig. 5(f) [112]. The follower robot had optoelectronic sensors to identify the edge of the solar panel and a control mechanism to stay in place and keep the power line stationary for the cleaning robot. It could operate the cleaning robot for around 5.5 h and both robots required external assistance to switch panel arrays.

A power packet technology to share power between the different modules of a robot was proposed in [115]. Experiments were performed for a single power source and multiple power destinations on a four-wheeled rover while demonstrations were presented for multiple power sources and multiple consumer modules (see Table 1).

ARMEx (Autonomous Remote Methane Explorer) was a mobile robot developed for olfaction [116]. It used a husky robot base, 2D and 3D LiDAR and a spectroscopy-based gas sensor. The robot used batteries and the gas sensor could be oriented with 2-DOF. A decentralized market-based optimization technique was used for the navigation of mobile robots in an environment with static and dynamic obstacles [117].

Table 1
Comparison of the reviewed robots.

Reference	Robot	Energy source	Environment	Work time	Comments
Riofrio et al. [32]	–	ICE/Propane	–	–	3 times more mechanical work than batteries
Gogola et al. [33]	–	Pneumatic/H_2O_2	–	–	5 times the energy density of batteries
Raade et al. [34]	–	Hydraulic/H_2O_2	Celestial	–	Conversion efficiency of 1.5%
Sadeghi et al. [25]	Snowblower	ICE	Outdoor	10 h	Simple lightweight robot
Wood et al. [23]	T4	ICE	Outdoor	8 h	Work on 17% slopes
Raibert et al. [27]	BigDog	ICE	Outdoor	2.5 h	Trekked 10 km in one charge
Bloss [28]	AlphaDog	ICE	Outdoor	24 h	Trekked 32 km in one charge
Cho et al. [30]	Jinpoong	ICE	Outdoor	–	Overall centre of gravity was closer to the centre of the robot
Apostolopoulos et al. [31]	Nomad	ICE	Outdoor	16 h	Mounted with a 3-DOF manipulator for sample collection
Wilkinson [39]	Gastronome	Microbial fuel cell	Outdoor	–	Low power density
Ieropoulos et al. [40]	EcoBot-III	Microbial fuel cell	Outdoor	7 days	Fed MFC every 30 min
Kelly [41]	SlugBot	Microbial fuel cell	Outdoor	–	Slugs are available for a limited time
Pa et al. [48]	–	PEM Fuel cell	Outdoor	100.4 h	A toy-sized robot
Wilhelm et al. [43]	MechBot	PEM Fuel cell	Indoor	2 h	Similar work time with fuel cell & battery
Artal et al. [46]	Dedalo 2.0	PEM Fuel cell	Indoor	–	Supercapacitors stored energy
Song et al. [42]	Co-walk	PEM Fuel cell	Indoor	5.9 h	A two-fold increase in working time
Lee et al. [44]	–	PEM Fuel cell	Outdoor	–	On-board hydrogen generation to get rid of the storage tank
Siegel et al. [50]	iRobot Packbot	PEM & SO Fuel cell	Outdoor	11 h	Two types of fuel cells were analysed
Bender et al. [53]	Ladybird	Photovoltaic cell	Outdoor	20 h	No net power loss on a clear day
Bawden et al. [55]	AgBot-II	Batteries	Outdoor	11 h	Solar docking station for charging
Tonmoy et al. [61]	–	Photovoltaic cell	Outdoor	2.8 h	Cost-effective design
Muhdia et al. [66]	–	Photovoltaic cell	Outdoor	–	Specialized design for tropical areas
Dewi et al. [72]	–	Photovoltaic cell	Indoor	–	Small-sized prototype robot
Watiasih et al. [68]	–	Photovoltaic cell	Outdoor	70 min	Used a waypoint navigation system
Sulaiman et al. [70]	–	Photovoltaic + fuel cell	Indoor	–	Solar energy is stored as hydrogen and used by fuel cell
Vaussard et al. [71]	MarXbot	Photovoltaic cell	Indoor	–	Charges from indoor lights
Ray et al. [63]	Cool robot	Photovoltaic cell	Outdoor	8 h	Operates in harsh polar environments
Wettergreen et al. [64]	Hyperion	Photovoltaic cell	Outdoor	–	Sun-synchronous navigation
Marco et al. [73]	Tribot	Photovoltaic cell	Outdoor	4 h 30 min	Specialized power supply
Muffoletto et al. [110]	–	Supercapacitor	Indoor	8 min	Drive time was 4 times more than the charging time
Wattanasin et al. [111]	HYPOS	Batteries	Indoor	1 h 45 min	The overall efficiency was 73.6%
Li et al. [112]	–	Batteries	Outdoor	5.5 h	Limited mobility of follower robot
Arain et al. [116]	ARMEx	Batteries	Indoor + Outdoor	–	Provided gas maps showing the presence of different gases

4. Commercially available robots

Terrestrial mobile robots are available for many commercial applications and the majority of them use batteries. Here, a few examples of such robots marketed for military, industrial and domestic use are presented to provide an overview of the available technologies, prospective usage, working environment and operation times.

Throwbot® 2 from Recon robotics is a military robot for audio–video reconnaissance in indoor and outdoor environments [118]. It is designed to be thrown into a hazardous environment and has the ability to crawl and climb in order to explore its environment and gather data. The robot has batteries that provide a run-time of up to 1 h. Andros F6A is an explosive ordnance disposal robot with dual mobility achieved using pneumatic wheels and an articulating track [119]. The robot can climb stairs, overcome trenches and kerbs, reduce its width for confined spaces, and has an integrated dexterous 7-DoF arm to handle high payloads. It is battery powered and has a mission time of 3–4 h.

Bulldog is a tracked robot for search and rescue, surveillance, bomb disposal and patrolling of hazardous areas [120]. It has a multi-degree of freedom arm for manipulation and is powered by batteries that provide a run-time of up to 8 h. The robot can climb stairs and obstacles and has flipper arms to lift and stabilize the robot. The robotics manufacturer Fiberscope has introduced a number of wheeled robots for pipe inspection [121], which are powered either through a tether connected to an external power source or through on-board batteries.

Thorvald-II is a commercially available autonomous wheeled robot for agricultural applications [122]. It has a modular structure and traction system to operate in polytunnels, open fields and vineyards, and is powered by either one 70 Ah or two of 35 Ah lithium-ion batteries. A rugged wheeled robot for the phenotyping of fields is marketed by EarthSense [123]. It has onboard cameras and long-range transmission systems, and its on-board batteries provide a working time of around 3 h.

A number of commercial weeding and lawn mower robots for domestic use like the Tertill robot [124], Vitirover [125], Landroid [126] and RK2000 [127] have also been marketed. Both Tertill and Vitirover are powered by a combination of solar panels and batteries, while Landroid and RK2000 are powered only by batteries. Another domestic application of AMR is in the field of indoor cleaning where systems like the ILIFE V5s Pro [128] and Roomba® i3 [129] can be considered as representative examples. Such robots use on-board batteries and have a docking station for charging; however, their operation time for one battery cycle is usually less than two hours.

There are numerous mobile robots available in the market for industrial automation, payload mobility and retailing applications. They usually use batteries and have different payload capacities and operating times. For example, the operating times of the Robotnik, MiR and Aethon mobile robots are 8–10 h [130], 10–14 h [131] and 10 h [132], respectively. The recent growth

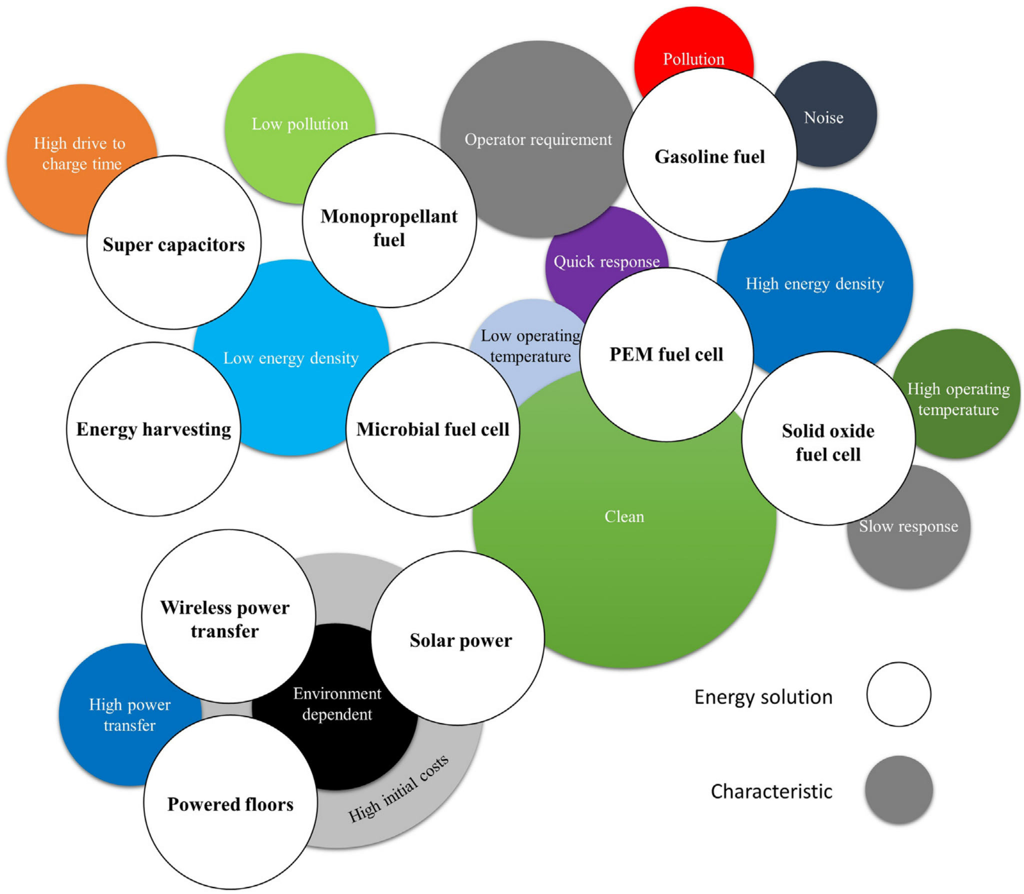

Fig. 6. (a) Comparison of the characteristics of the different power solutions discussed in this work. The power solutions are represented using white circles while their characteristics are marked by the different coloured circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in E-commerce has accelerated the development of last-mile delivery robots. Starship technologies [133], TeleRetail [134], Relay Robotics [135] etc. have introduced battery-operated wheeled delivery robots that are currently operational only in limited areas.

5. Discussion

The mobility of mobile robots makes energy supply an area of key concern. This work was a summarization of the energy solutions presented and adopted in the literature and used in commercially available robots. The concentrated research efforts to improve design, perception, control and navigation in mobile robots have led to fleets of AMR operating worldwide. With the number of AMR expected to grow in the coming years [16], powering these robots may raise some important issues. Energy autonomy, power system costs and operational longevity are the major issues that can hinder further scientific research on mobile robots and inhibit their applications in other domains [14].

A comparison of the characteristics of the power solutions discussed in this work is given in Fig. 6. It is evident that the power solution selection is mostly dictated by the task and operating environment. Alpha Dog [28] and BigDog [27] had gasoline-powered engines because of their outdoor application and high payload capacity, but their recent Spot [29] variant, which is mostly used in indoor environments for demonstrations, is powered by batteries. The other gasoline-powered robots like Jinpoong [30], T4 [23], Nomad [31] and snow blower robots [25] were also used outdoors. Gasoline-powered solutions can be quickly replenished, which is the major criterion in their selection along with higher power, payload capacities and operation times. However, noise, pollution and low efficiencies are major limiting factors for this energy source. The monopropellant fuels can be a better solution for such outdoor mobile robots as they can provide the advantages of gasoline-powered solutions while decreasing the disadvantages related to them. But these monopropellants also have disadvantages like volatility, corrosiveness and toxicity, and require special handling. Power supplies using such fuels were reported [32–34] but a working prototype with a robot is still missing. Collectively, the exhausts and high temperatures of engine-powered robots make them unsuitable for closed or sensitive environments.

Fuel cells are a clean but expensive energy source. The hydrogen required for PEM and SO fuel cells is also not readily available. PEM fuel cell-based robots are more promising because of their high energy density, low operating temperatures and quick start and stop ability as compared to other fuel cell types. The operating temperatures (800°-1000 °C) of SO fuel cells can be a limiting factor for their practical applications. A comparative study of PEM and SO fuel cells for robot power supply reported similar findings [50]. MFC-powered robots like Gastronome [39], EcoBot-III [40] and SlugBot [41] were demonstrated in literature but an AMR for performing useful work can be difficult with MFC due to its low energy density, complex reactions and fuel and waste management. In short, MFC power technology can be explored for smaller robots to provide cost-effective and waste-consuming power supplies while PEM fuel cell-powered robots can be viable for high-cost applications and outdoor environments.

Sunlight is another clean power source, but its harvesting requires high initial costs. A large surface area is required on the robot for photovoltaic cells, which limits its usage to bigger robots. It is an environment-dependent solution, meaning it is feasible for outdoor robots that only need to operate during the daytime. A battery-solar combination is required for energy storage and intermittent hour operation. Ladybird [53], AgBotII [55], Cool robot [63] etc. were a few of the successful implementations of solar-powered robots. Most of their applications were focused on agriculture and exploration tasks. The concept of a solar charging station (like the one reported in [55]) for a fleet of robots can be a more flexible, greener and energy-efficient solution.

Wireless power transfer [77–79] is a practical solution implemented commercially and intensive research has been focused on its improvement. The powered floors [96–99] are suited for small robots, especially for testing swarm technologies. Both types of systems allow high power transfers but require high initial costs. Moreover, they are also environment-dependent solutions and robots with such power supplies are confined to their specified workspace.

The battery swapping methods [100–105] proposed in the literature can be a viable solution for robots requiring long-haul operation times. Instead of continuous power transfer, battery replacement can replenish the source quickly. This can avoid the need to prepare a specific working environment and the workspace confinement of the robots. Environment and task-specific solutions like [27,55,63,112] may also be an option for future robots.

5.1. Limitations

The current work is a scoping review discussing different powering techniques developed or deployed for AMR and has the following limitations. It is focused on terrestrial mobile robots and excludes aerial and aquatic mobile robots. Among the terrestrial AMR, the systems that can have autonomous or teleoperated motion were included while steered-type systems were excluded. The generalized improvements in the engine, battery, pneumatic, solar, fuel cell or wireless power transfers were not included in this work. Only the applications of these technologies reported for AMR systems were included. The energy conservation solutions based on mapping, navigation and control were also excluded as these are usually robot-specific and are mostly a trade-off between operation time and operational efficiency. Power techniques introduced in patents were also not a part of this work. The above-mentioned limitations mean that energy solutions for the field of non-terrestrial mobile robots and software-based energy conservation techniques remain open topics for similar future works.

5.2. Future prospects

Abstractly, future research for AMR power techniques may focus on increasing operation time, decreasing costs and formulating environment-specific solutions. The currently available and discussed power solutions have two major drawbacks: (1) low operation time and (2) high costs. The selection of a powering technique is mainly based on two factors: (1) operating environment and (2) task. For example, a mobile robot designed to operate outdoors for 10 h or more may use an engine, but if stealth is required then solar or fuel cell-based solutions may be better options. Similarly, a carrier robot for indoor logistics moving in a predefined environment can use wireless power transfer. A more complex task like indoor product search, retrieval, and last-mile delivery to the consumer location would require operation in known indoor and partially known outdoor environments. Such a robot will need a long-haul battery or a dual power source capable of replenishment in an indoor or outdoor environment during operation. A dual-energy source can be a better option for robots requiring longer working time in complex environments. Cost-effective power supplies are also required to expand applications of AMR to new domains. Currently, AMR are limited to arduous, complicated, and exorbitant tasks. If they are to find their way into simple daily life tasks requiring mobility, a cost-effective power solution will be required to develop affordable and task-specific solutions.

A new battery revolution is expected to happen with the lithium–sulphur batteries that are expected to offer more charge density at potentially similar prices to currently available lithium-ion batteries [136]. Commercialization of lithium–sulphur batteries may reduce the longer operation time issues. However, even such high-capacity batteries will need to be recharged or replaced. Therefore, the requirement for technologies to give power autonomy to robots will remain. Nuclear powered propulsion systems can be a feasible option for fulfilling this requirement as they can provide higher energy densities, resulting in longer operation times for AMR. The research on such energy solutions is currently limited to extra-terrestrial rovers and interplanetary robots. An NTP (Nuclear Thermal Propulsion) engine has been termed a game changer by NASA for deep space exploration [137]. Nuclear thermal propulsion or nuclear electric propulsion systems have the potential to power robots on earth but require rigorous research and development. The fuel cost, fuel handling complexity and safety are key concerns when considering the application of nuclear propulsion technologies to terrestrial mobile robots. The other power techniques for AMR that may hold potential are discussed below. A prototype of a jumping robot was powered by a butane and oxygen mixture [138]. These monopropellant-based power supplies can be useful for low-power requiring robots. A small-sized controllable untethered vehicle actuated by eutectic gallium indium wheels in an aqueous solution was reported in [139]. The possibility of powering a robot with sound waves was discussed in [140]. An energy recycling approach using springs and clutches to recycle the elastic energy was presented in [141]. Energy harvesting solutions (like [106]) can also be potential candidates for alternative energy sources. All these solutions can be topics for future research as they are currently in the preliminary stages of development and need further research to realize their application in an AMR. In short, rigorous future research is required in the field of power solutions for mobile robots to ensure continued expansion and applications in new domains.

6. Conclusion

Energy supply is one of the limiting factors in the expansion of mobile robots to new domains and with the increasing number of robots, appropriate power supply technologies can be an area of concern for future robots. As we approach the era of industry 5.0; clean, robust and long-haul power solutions will be required. The low operation time and high costs of currently available solutions make them feasible for exorbitant applications. Until now, individual research on the energy supply for mobile robots was limited and most of the research focused only on the design, perception, navigation, and control of such robots. The presented work summarized and discussed the power solutions reported in the literature and used in commercial terrestrial mobile robots. Engines, fuel cells, photovoltaic solar cells, wireless power transfer and battery swapping mechanisms were the major reported solutions. A comparison of the advantages and disadvantages of such solutions was also presented. Cost-effective, long working time, dual-energy source and environment-specific power solutions can be areas for future research. Monopropellants, energy harvesting, and energy recycling can be a few of the prospective solutions. In the end, rigorous research is required to achieve a self-sufficient, cost-effective, and clean solution for future generations of robots.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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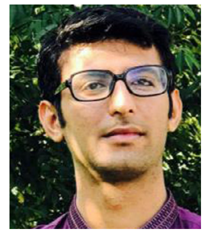

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