

# Energy Management Techniques in Mobile Robots

G. Gurguze, I. Turkoglu

**Abstract**—Today, the developing features of technological tools with limited energy resources have made it necessary to use energy efficiently. Energy management techniques have emerged for this purpose. As with every field, energy management is vital for robots that are being used in many areas from industry to daily life and that are thought to take up more spaces in the future. Particularly, effective power management in autonomous and multi robots, which are getting more complicated and increasing day by day, will improve the performance and success. In this study, robot management algorithms, usage of renewable and hybrid energy sources, robot motion patterns, robot designs, sharing strategies of workloads in multiple robots, road and mission planning algorithms are discussed for efficient use of energy resources by mobile robots. These techniques have been evaluated in terms of efficient use of existing energy resources and energy management in robots.

**Keywords**—Energy management, mobile robot, robot administration, robot management, robot planning.

## I. INTRODUCTION

THE robot concept emerged in the early 20th century has become a part of our daily life with the rapid developments taking place in mechanical, electronic and computer fields. The first successful operation of today's robot was realized in 1961 on the production lines of an automobile factory [1]-[4]. Over time, together with the evolving technology, robots have begun to be used as mobile in many different areas requiring precision, speed, security and power [5], [6]. Over time, together with the evolving technology, robots have begun to be used as mobile in many different areas as requiring precision, speed, security and power as military, medicine, search and rescue [5]-[7].

In all applications, it is aimed that mobile robots perform their tasks in a fully autonomous structure. For mobile robots, autonomy is defined as being able to move on its own, avoid obstacles, get information about the environment, send information to necessary units, make decisions on its own, communicate with other units when necessary, and have own power unit. In particular, the need for autonomous energy resources is a key factor for mobile mobility in terms of sustainability of operations. Because, when mobile robots are dependent on an energy source outside their system during their tasks, their motion fields become narrower. [8]-[10].

Firstly, the robots used short-time power supplies. Then, rechargeable batteries came out. Despite the advantages of rechargeable batteries, manual or self-charging problems have

arisen. However, the length of charging times and the difficulty of these applications in real-world conditions have accelerated the development of batteries that can operate longer [11]. These batteries have been enough for simple tasks. However, over time, the expectation of mobile robots and the complexity of their equipment have increased the energy demands of robots. This situation has led to new studies for adequate and continuous energy [12]. After that, the idea of integrating mobile robots with renewable energy systems emerged. This idea enabled mobile robots to autonomously generate their own energy, sources such as sun, wind, heat and motion while on the move. However, the fact that these energy systems could not provide fast and adequate charging at optimal times has shown that these systems alone were not the solution [10], [14], [15]. In addition, the use of different power requirements in the same system has made hybrid systems necessary [12]. Hybrid systems are a strategy developed to supply different power needs with different power sources. In this way, correct use of power of the robot units is ensured and insufficient or unnecessary power consumption is prevented [16]. The development of hybrid systems, both hydraulically and electrically, has emerged as a successful solution, especially in hydraulic-based robots. However, there are difficulties in creating and using these systems [9], [10], [17].

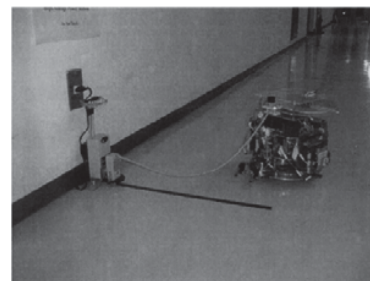


Fig. 1 Charging by outlet contact: HYPOS prototype [13]

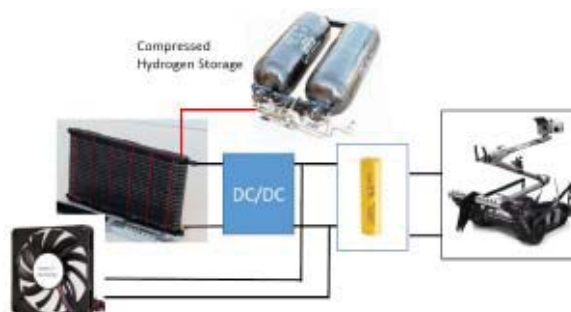


Fig. 2 Hybrid system [16]

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From past to present many power supply technologies have been developed for mobile robots, taking into consideration factors such as size, weight, power changes, mobility, hardware structures, tasks to be performed, working environment, working time. These include batteries, renewable batteries, photovoltaic cells or solar cells, super/ultracapacitors, thermoelectric, generators, hybrid structures.

Today, although many new technologies on energy resources are being developed, it is seen in applications that the limited energy of these systems presents difficulties in achieving the desired level of performance [18]. For example, the HUBO robot, developed with a high technology, can only work for about 60 minutes with the latest developed power supply. Honda can walk about 30 minutes on foot [19]. Difficulties in developing these limited power sources have made it important to develop approaches and techniques to extend the life span of existing ones. Implementation of efficient energy management techniques has been seen to save up to 40% of energy in some cases [20].



Fig. 3 Shortest path planning

## II. RELATED WORKS

In this work, some examples from the past on the power sources used on a daily basis, their usage patterns, developments and management strategies are summarized.

In the early days of mobile robot work, power sources that provide short-term energy and require continuously charging have been used. The disadvantages of manual charging of mobile robots, which require independent operation, accelerated self-charging robot research [21]. First, in 1950, Walter charged the robot tortoises he developed with a light charging unit. In 1960, at Hopkins University, robots were developed that can be recharged by integrating into the electric socket with photocell [22]. At the beginning of the 1990s and early 2000s some studies with infrared sensors and laser distance sensors related to connecting to electrical outlets or other power units were successful. This achievement sheds light on how Zebrowski et al. have developed a study on the energy transfer of "mother" robots to "worker" robots, such as tanker aircraft fueling other aircraft. The mother robot records the positions of the other worker robots and acts as a charge source by going to that position when requested [11]. In recent years a similar work has been developed by the Wattanas et al. in a hybrid approach. This system is a hybrid system called HYPOS which is used both for normal rechargeable batteries and for batteries that can be recharged by home electricity. It

was seen that this hybrid system could be charged in a short time like 2 hours by being integrated into the electrical outlet. It provides an important alternative for systems requiring high energy. Thus, the power requirements of large mobile robots used in agricultural areas, homes, offices and hotels are provided by AC sources, reducing the need for different apparatus, technology or system [13].

Another idea emerging outside of wired charging is wireless power transmission. This idea was discovered by Tesla in 1890. It is aimed to wirelessly charge batteries in mobile robots. Wireless power transmission has not gone beyond just a few lamps with low power transmissions at short distances, except for systems that require high power. However, the use of mobile robots with equipment that can operate with little energy over time allows wireless power transmission to work. In this regard, the disadvantages of cable charging in mobile robots and the problems of clamping power units caused Tsumura et al. conducted study on uninterruptible power supplies. It was developed on the basis of electric transmission through a line fixed by electromagnetic induction [23]. The successes of this work later shed light on the work done in this regard. In recent years, when we look at the SubCultron project in 2016, artificial mussel AMussel robots can recharge by establishing a wireless connection with APADs standing on the surface of the water for recharging. At the same time, in these robots, unnecessary power consumption is prevented by using sleep mode for low energy regime [24]. Gao and Yan have offered a solution that provides wireless power transmission with inductive coupling approach to charge drop and recharge requirement, which prevents the operation of a capsule robot used in medical field. With this work, it is desirable to prevent the voltage-sensitive cameras and sensors in the capsule robot from making incorrect measurements and evaluations [25].

Dung et al. have offered an alternative application in which robots can exchange rechargeable batteries among themselves instead of recharging rechargeable batteries from another power source. However, apart from the laboratory environment, it has been found that such mechanisms are difficult to operate in the real world [11].

Another method, which is considered necessary in some systems in terms of energy management, is hybrid systems. The combination of different power requirements such as low energy, high energy, hydraulic power requirements in systems has made it necessary for energy management to have several different power supply combinations together. In a mobile robot, different power requirements, such as low energy, high energy, and hydraulic power, have made it necessary for different power supply types to coexist in terms of energy management. Raade et al. have developed a free piston hydraulic pump for hydraulic power requirements. In this way, the power supply used can distribute the electrical energy to other units for longer periods of time [9]. Amundson et al. talked about a hybrid system called HEPU. It aimed to save energy from the electric power of the mobile robot by ensuring that the hydraulic system produces its own energy [17]. Ahmad Ghaderi and his colleagues have argued that the

developing abilities of mobile robots cause different power demands. They have suggested using more than one energy source to meet different power demands. At the same time, they emphasized that the speed control of the engine will provide the correct power consumption if done according to the incoming power [26]. Guohu Wang and his colleagues have proposed a hybrid system of super capacitor with Li-Fe batteries. The purpose of this hybrid system is to provide both high energy and low energy requirements in a short time while the mobile robot is moving. Thus, the system is intended to work longer [27]. Carlos Arantes and his colleagues presented a hybrid approach to using the batteries together with ultracapacitors to ensure that the power supply was charged in a very short time [21]. Jason B. Siegel and colleagues present a hybrid approach to combining a lithium ion battery with a solid oxide fuel cell (SOFC) for a system that requires two different usage profiles that require high and low power. Thus, in case of sudden power changes, performance and savings are achieved by using the necessary resources [16].

One of the important issues in mobile robots is the integration with renewable energy systems. At this point, the design of fully autonomous mobile robots has become possible. Successful applications have been made in space, military, search and rescue areas. The Rocky 7 Mars Discovery robot used in space studies is one of the most popular applications developed with solar panels [13]. The Ecobot II robot is designed to capture the home flies and generate electricity from the skeleton [11]. D. Blibber and colleagues have shown that solar panels used in underwater vehicles can meet their energy needs. In the same way, the SAUVII robot, developed as an underwater vehicle, has come out as a successful work using solar panels. A similar application is an autonomous sailboat with solar panels developed at Australia's Oregon State University. Guerrero-González and his colleagues have developed a system that allows a robot working on observation and inspection to self-charge using solar panels (photovoltaic). In addition to solar batteries, the generation of electricity from the heat energy of the system through the use of thermoelectric power and the production of energy from the wind and motion mechanisms are among the studies carried out [15]. The limited use of energy resources at critical levels in all these studies for adequate power generation makes the saving use of energy in a controlled manner important. For this reason, many methods and strategies have been developed for the effective use of existing energy sources as well as the development of new energy sources. Below, the articles investigated in relation to these methods and strategies are briefly explained.

Wei Zhang and colleagues have presented an approach in mobile robots that shows that the power consumption is minimized by simultaneously controlling the motor speed with the processor frequency. Thus, it is shown that power losses due to different frequencies are prevented and significant power saving is achieved. In previous studies, Jordank suggested that efficient use of the motor in the system would save energy. Ve Brateman and colleagues synchronous operation of the processor frequency and motor speed will

provide a significant amount of energy savings [28]. François Ilichaud and Etienne Kobichaud note that simultaneous operation between motor speed and processor frequency reduces energy losses, Wei Zhang and Jianghai Hu concluded that the simultaneous control of power flows and speeds between motors in the RoboCup project provides significant power savings and Humza Qadir Raja and Oliver Scholz have shown that in parallel with previous work, the motors in the latest mobile robots cause energy losses of up to 66% of frequent stops and improper acceleration [12], [22], [29].

Rohit Kumar and his colleagues conducted a study on the use and analysis of energy resources. The selection of the appropriate energy source in robots and the integration with renewable technologies are key factors in energy management [10].

James and his colleagues presented a new method for power saving in a closed space for a flying robot. To keep the robot in the air longer, it is suggested that the robot be hanged on the ceiling during the media inspection. Since the flying systems do not consume energy when ceiling hanging in the ceiling, power saving is made [30].

Jesús Morales and his colleagues have argued that in real terms energy loss is caused by motor and land conditions. Little use of robot systems means less energy consumption. And that there should be a suitable short-distance route with good land conditions for the solution [8].

Morales and colleagues say that skid-steer tracked robots are spending more energy than wheeled robots. skid-steer tracked robots spend a lot of power due to the terrain conditions and rubbing [31]. Soygüder and his colleagues have shown that the energy saving of the system is significantly reduced by reducing the number of engines in a six-legged robot [32].

In a study conducted at the University of Basque, it has been observed that programming the movements of the robot with the appropriate control device has removed unnecessary wait and delays from the center and saved up to 40% of energy [20].

Dariusz Grzelczyk and his colleagues have focused on the fact that a hexagonal robot developed has caused different power consumption of different walking modes. Appropriate modes of motion have been shown to reduce energy costs [33].

Sun and his colleagues have shown that the availability of floor topography information and associated more convenient ways to save energy will save energy considerably [11].

One important point in power saving is the awareness of the power of the system. Energy saving can be achieved by not using some of the elements according to the planned process priorities. Liu et al., The algorithm for power awareness for the Mars discovery robot is one of the most successful applications on this subject. Parasuramas and colleagues have shown that the knowledge of the energy consumption states of the elements in the mobile robots will allow for an optimized use of energy in subsequent tasks [34].

Apostolos Kottas and colleagues mentioned that robust and realistic prediction of the energy level of the power supply in

robots would provide efficient power management. To this end, a power monitoring platform for the management of big robot teams at the University of Minnesota has been developed. Thus, it is aimed to complete the task according to the set energy condition [35].

Maral Partovibakhsh and Guangjun Liu have presented a study that shows that battery charging status (SoC) information can improve battery usage, battery reliability, and prevent overload and overcharging. In this study, an expanded-thick filter is used. The accuracy of the obtained charge state estimation information will ensure that the energy is planned and operated in the calculated time [36]. Moyra and colleagues have shown that a precise controller algorithm avoids the excessive power consumption by warming up with repeatability and proper positioning operations [37].

In recent years, multiple and herd robots have taken an important place in mobile robots. The energy consumption of these robots together and alone has an important place in the performance of the tasks.

Ammar Amory and colleagues present an approach to V-shaped restructuring of underwater robotic suites relative to their energy capacities. These robots are localized by GPS. The goal is to have the proper swarm behavior for efficient use of energy [38].

Patil et al. have emphasized the need to be aware of the lifetimes of their power sources for the efficient use of the total energy of the herd. It is emphasized that the energy distribution and management of the herd will provide economical use of energy depending on this information [18].

Taranovich et al. presented a control algorithm that allows the selection of the number of robots required for a task and the components that these robots should use according to their task. Thus, the number of robots needed in the herd robots and the sufficient use of their components prevent excessive power consumption [27].

### III. CONTRIBUTION

In this study, the selection of appropriate power sources for the efficient use of energy resources by mobile robots, self-charging strategies, robot management algorithms, use of renewable and hybrid energy sources, robot motion patterns, robot designs, sharing strategies of workloads in multiple robots, road and mission planning algorithms Have been studied.

In this way, more successful studies on the correct selection and management of the power systems that are anticipated as an important constraint on mobile robots will be presented.

### IV. ENERGY STRUCTURES USED IN MOBILE ROBOTS

Today, many power supply technologies are designed in different types for different systems. In the world of robotics, these technologies have been adapted to their systems and used in various forms. Some energy sources are designed solely to meet the power demand in this area. In autonomous systems outside the industrial field, the batteries were first used to provide power even in the short term. Later more

advanced species emerged. However, the disadvantages of their replacement and manual recharging have led to the development of rechargeable batteries. At the same time, solar cells are integrated into the system as renewable energy in these robots. They are also used in hybrid systems [11]. Other potential energy sources for robotic systems are flywheel energy storage, hydraulic, pressurized gases, batteries, renewable batteries, photovoltaic cells - solar cells, super capacitors, ultra capacitors, thermoelectric, generators, hybrid structures [9], [10], [39].



Fig. 4 Lithium polymer batteries [40]

#### A. Batteries

The most widely used technology as a mobile energy source in robots is the pillars. They are available in two forms as Non-rechargeable and rechargeable batteries. Non-rechargeable batteries are used in some cases especially for systems with high energy requirements. Charging times for non-rechargeable batteries vary depending on the elements and size of the charge. This causes weights in systems that require too much power. Rechargeable batteries have a wide range of applications in terms of more practical and cost effective. There are battery types such as alkaline, zinc, lithium, lead acid, nickel cadmium (NiCd), lithium polymer (LiPoly), Li-ion battery, Li-Fe batteries, nickel metal hydride, silver zinc, silver cadmium, sodium sulphide [39].

Alkaline, zinc and lithium batteries are non-rechargeable batteries. Alkaline batteries are non-rechargeable batteries with alkaline electrodes consisting of zinc and manganese. These batteries are the most widely used battery that provides safe and sufficient power. They will empty if not used for a certain period of time [10], [35]. Zinc batteries are used in devices that require lower current than alkaline batteries. They are used in devices such as TV controls, clocks, lanterns. Lithium batteries are the preferred long-life batteries for larger machines operating at low currents, providing a voltage of 3V-3.6V.

When we look at the rechargeable batteries, there are variations depending on their size, chemistry, currents they produce.

Lead acid batteries are the first developed rechargeable batteries. However, low power provides extra weight. This provides a limited use area due to its use in projects requiring low energy. They are not environmentally friendly. They are used in cars, on motorcycles, in medical devices [10], [14], [21], [39].

Nickel Cadmium (NiCd) batteries have the same structure as lead acid batteries. Differently, it is used in systems



requiring higher currents. The cost is low. Constant discharge voltage is available. Charging time is more successful than lead acid battery. The battery must be charged before it is fully discharged [39], [41].

Nickel Metal Hydride (Ni-MH) batteries are another rechargeable technology. Memory effect such as nickel cadmium batteries is available. They provide higher power. But if they are not used, they will discharge faster. They consist of chemicals that make them long lasting. At the same time, it is nature friendly because it does not contain heavy metals such as lead and mercury [39], [42].

Li-ion batteries are small power sources. They are widely used in small devices such as mobile phones, mp3 players, laptops, mini robots. The power they provide is directly proportional to their size. Power loss is low when not used because there are no memory problems. The chemicals are lighter, but the charging densities are higher. There is a risk of explosion at high temperatures. Over time they lose their capacities [35], [39], [43].

Lithium Polymer (Li-Poly) is high energy batteries in small dimensions. They provide less power than lithium-ion batteries. Easy mounting to systems and fast charging features have caused widespread use. It has the ability to protect itself from sudden power changes in the system in which it is used [14], [16], [26], [42].

Li-Fe batteries, lithium-ion type batteries Provides longer charging times than other types. They are safe and durable. Because they have low peak power, they are not much preferred in systems of high power required. On the contrary, they are used extensively in systems that require low power and light weight. They have a fixed discharge voltage [39], [41], [44].

Silver Zinc (AgZn) and Silver Cadmium (AgCd) batteries are used in sudden and high power required applications. The prices are high. Usage times are short. They have fixed discharge voltage ensures trouble-free operation in critical applications [10], [41].

Both Sodium Sulfide (NaS) and Lithium Chloride batteries offer high power but have high operating temperatures. Sodium Sulfur starts to work at about  $300^{\circ}\text{C}$  and Lithium Chloride at about  $350^{\circ}\text{C}$ . Sodium Sulphide batteries are designed for automobiles in the 1960s. They lead to 4-5 times more energy than lead acid batteries.

### B. Solar Batteries

Photovoltaic (PV) or solar cells are devices that generate electricity from sunlight. It has an important place because it gives self-charging ability in terms of autonomy in robotic applications. They can work even for a few hours without the sun when they are integrated with capacitors. The charging state is performed up to the voltage level set by the capacitors [10], [15], [39], [45].

### C. Fuel Cells

Fuel cells are devices that convert the chemical energy of a fuel into electricity and heat energy. Although it was developed in 1838, it was not used until the 1960s space

exploration. Today it is also used in space vehicles, cars and buses. It is a system that provides energy conversion in high efficiency up to 75%. The opposite of electrolysis works logically. The efficiency of fuel cells can be increased to about 80% using waste heat [10], [14], [16], [19].



Fig. 5 Solar powered robot [15]

### D. Thermoelectric

They are devices that work on generating electric energy from temperature differences known as Seebeck effect. Electric current and voltage are generated from the temperature difference between the terminals of these devices made up of different conductors. Generally used in hybrid power systems in mobile robots. It offers an important contribution in terms of renewable energy [10], [39].

### E. Super/Ultra Capacitors

Super or ultracapacitors are the most popular new rechargeable power supply in recent years, enabling the storage of energy on plates separated by a dielectric material that carries electrical charge, unlike other batteries with chemical construction. Very fast charging and forwarding capabilities increase the power performance of the systems. However, they have limited usage due to their low capacity. Hybrid uses are common to increase the power performance of systems. The fact that the capacitors are light and recently the increase of power capacities caused more use in mobile robots [10], [25], [44].

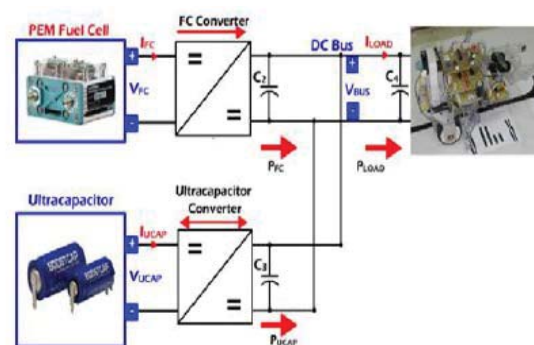


Fig. 6 Ultra capacitors in hybrid systems [16]

### F. Hybrid Power Supplies

As is known, different power requirements of systems have made it necessary to use more than one power source in some

cases. This has led to the formation of hybrid structures. Hybrid systems consist of different power sources or mechanisms, re-powering technologies, support power structures, power supply protection and monitoring systems. Batteries and capacitors are available as hybrid systems of different types, such as batteries and fuel cells, motion power systems and batteries, solar panels. With these systems, proper use of power and prevention of power losses can be made to a considerable extent [10], [13], [16], [17], [39], [44].

#### V. ENERGY MANAGEMENT PROBLEMS IN MOBILE ROBOTS

There are many problems with the proper use and management of energy in mobile robots. Detection of these problems and knowing their solutions means that there is a decrease in time, money and performance losses in later work. Based on the literature review, problems related to energy management in mobile robots are listed below

- Incorrect power supply selection that is not suitable for the system [39],
- Unknown charging and discharging status of power supplies, reliability problems [27], [36],
- Failure to take into account deformations of power supplies [37],
- No consideration of charging times [21]
- Use of unnecessary or more hardware units [8], [32]
- Units not synchronized, uncontrolled motor and system usage [45], [47]
- Instant acceleration and deceleration increase power consumption [8], [48]
- Random movement of the system and its maneuvers [48],
- Not calculation of the power consumption of each element of the system [28], [47],
- Incorrect task planning in multi robots [11], [30], [49],
- The randomization of the motion model of the system.

#### VI. TECHNIQUES USED FOR EFFECTIVE ENERGY MANAGEMENT

In previous chapters, the importance of correct use and saving of energy resources in mobile robots was mentioned and the necessity of energy management techniques was emphasized. In this section, information is given about what the efficient management techniques are and what solutions they bring.

Proper power supply selection is the most important factor in the design and operation of mobile robots. Not select of proper source appropriately significantly affects the system's continuity, performance and energy management. The selected power supply has to be capable of meeting the power demand in accordance with the current and voltage limits of the system being designed. Otherwise the system will not work or will be damaged [25]. For example, using a source that provides high power in a system that requires low power will cause unnecessary power consumption and, in some cases, damage the system [13], [42]. Besides, in systems with high power requirements, the use of low power sources will not meet the requirements [16]. In some cases, it should be able to meet

sudden power demands [13], [44]. The power supply must be at the capacity to complete the targeted tasks. The chargeable or non-chargeable choice must be determined according to the intended use, duration of use, and the environment in which it is being used. In terms of autonomy and practicality, the use life should not be short, and frequent charging or replacement should not be necessary [31]. Reliability must be high [19], [27]. Thus, there will be no interruption in the operation of the elements and the robot in the system. The size of the power source must be large enough to fit the size of the mobile robot and not restrict its movement. It should not aggravate the system. Otherwise the system will cause excessive energy consumption for movement. Large power sources should not be selected for longer use. Instead, light but longer energy sources should be used [9], [10], [42], [48]. No hazardous power source should be selected for the environment in which it is used. For example, a robot used in reactors operating at low temperatures can cause significant damage due to heat of power supply. May be exploded by environmental conditions or may damage system units [14], [35], [43]. Compatible power supplies should be selected in hybrid systems. Selected power sources should not harm each other. The power supply must be capable of integrating with systems that produce its own energy. The cost should not constitute a large part of the total cost. Generally, more than 20% of the system cost is undesirable [39].

Power supplies are deformed over time. Deformation also causes the weakening of the power source and the shortening of its life. However, some power sources are deforming faster than the system, and the power situation information can be misleading. For this reason, it is important to know how fast and what the deformation is. Thus, the suitability and usability of the system can be measured [27], [37].

The attenuation with deformation negatively affects the charging and discharging situations. Incorrect charge status information causes incorrect planning to occur. For this reason, the relative and absolute charging conditions must be known. The relative charge is the rate of charge seen in measurements. Absolute charge is the real charge state by adding losses to the account. Absolute charge information also reveals the states of the cells of the batteries. Depending on the correct charge status information, the extent to which tasks can be performed, that is, reliability, can be understood. The working priorities of the elements can be adjusted. Various power aware algorithms can be developed for this [27], [35], [36], [43].

Self-charging of mobile robots is desirable in terms of autonomy. To achieve this, wired and wireless charging strategies have been developed. As charging station, fixed or mobile charging units are used. The first thought is that the mobile robot is integrating itself into a unit. But reaching and integrating the charging unit is a tough application. At the same time, it requires more power [13], [24]. Some robots can be designated as charging units based on task sharing in multiple robots. So other robots can recharge with less energy. There are many methods for exchanging of batteries. However, their implementation is both in hardware and in

algorithmically very difficult. Similar to these, there are available also work on the the charging of power supply of by taking electricity of the environment where the robots are located. However, these are only suitable for large systems and reaching the charging unit is problematic [11], [22], [49].

When mobile robots are required to be charged during duty, the use of long charge batteries slows operation. It can even lead to negativity and failures. For this reason, batteries should be selected according to charging times and tasks should be planned accordingly. Working with batteries that can be charged quickly and with low energies will lead to more successful results [11], [21], [24].

Integration and transportation problems have increased wireless charging efforts But, wireless charging units only provide energy at low levels. Charging times are very long. The fact that mobile robots are becoming less costly and less energy-consuming structures has made wireless charging feasible. In recent years, wireless charging units have been used in capsule robot work in medicine. The aim was to avoid false measurements due to the depletion of charge and sudden energy loss. It is expected to be used effectively also in micro robot work [24], [25], [50].

Hybrid structures, as is known, offer successful solutions for power. Correct and controlled a hybrid system provides high performance. Providing sufficient energy to each element allows the system to use long-term power. For example, batteries used with ultracapacitors are both faster charging and longer life. The energy demand of the hydraulic systems can also be provided with hydraulic power. Thus, the life of the other power source is longer. The most important point in these generated hybrid systems is the planning of power flow. For this reason, control units should be created, or software solutions should be introduced [10], [12], [26].

Autonomous systems are expected to produce their own energy in long-term missions. For this, power generation systems such as solar panels, heat and wind energy systems, hydraulic systems can be created. Thus, systems that can be operate longer can be developed.

In power systems, only power supply does not cause problems. Equipping the designed system with many elements other than the duty purpose or using heavy materials will cause excessive energy consumption. For example, selecting too many motors, integrating unused components, using energy demanding units that are not suitable for the power supply. Designing the system with simpler, lighter and sufficient hardware will save energy [28], [32].

Knowing the level of energy consumed by the elements in the generated systems also enables successful energy management. It can be planned which elements will be used during the tasks. In order to accomplish the task according to the power expenditure during the tasks, re-system use plan can be made. In this way, unnecessary energy use is prevented, and the performance of the task is increased.

Passiveization of the mobile robot or certain units relative to the surrounding area and relative to the applied tasks provides more extended use. For example, a robot that only perceives sounds in the environment is going to sleep mode in

silent conditions [8], [24], [42].

The fact that the elements in the system are not synchronized also causes excessive energy consumption. For example, when the operating frequencies of the robot engine and the processor are different, too much energy is used. The difference in communication speed between the other units also leads to incorrect energy expenditure. However, power loss can be avoided by power flow control when units operate synchronous. Power management algorithms can be used for this purpose [16], [18], [25], [27], [47].

In systems, the engine is seen as the most energy-consuming unit. Efficient use of the engine also provides great energy savings. For this reason, strategies should be developed to prevent the engine from running unnecessarily. A way to make the engine run less is to find the shortest path for the movement. For this reason, road planning plays an important role in robots. Finding the shortest, most efficient and unobstructed path will ensure that energy consumption is minimal. Many algorithms such as genetic algorithm, ant colony, particle swarm algorithm, levy flight are used for this purpose. Each algorithm has different characteristics and successes according to the medium they use [31], [46], [47], [51].

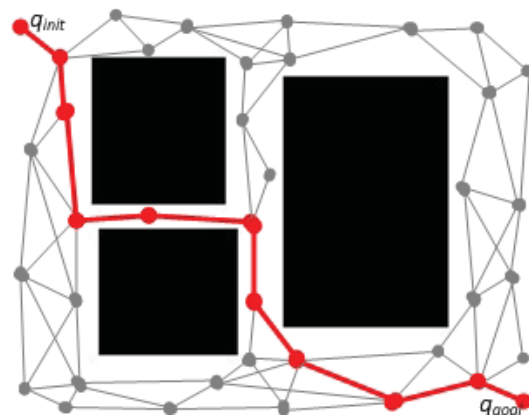


Fig. 7 Probabilistic road maps [52]

In addition, knowing the terrain conditions provides proper motion planning and engine speed regulation. Because working in the same motor level in any environment will make movement difficult and cause uncontrolled power usage [48]. Torque distribution algorithms can also be used, depending on the motor force [33]. Uncontrolled operation of the engine also causes sudden acceleration and deceleration. This causes system wear and excessive energy consumption [48].

Robot walking and driving strategies also affect power consumption. The selection of the walking frequencies and the determination of the movement patterns in humanoid robots provide great energy savings. For this reason, it is necessary to determine proper maneuver manners and shapes [12], [33], [43], [48], [53]. Some systems make similar movements. Energy losses are avoided if the robots do these movements accurately and at the proper timing. Various controllers are



designed for this purpose. In this way up to 40% energy savings can be achieved [20].

Compared to single robot systems, energy management is more difficult for multiple robots. For this reason, planning should be done correctly in multiple robots. For example, incorrect placement of herd robots causes unnecessary movement and excessive energy consumption. Strategies such as the excessive selection of robots used in missions and the distribution of missions negatively affect power expenditure [18], [24], [38], [42]. Communication in robotics requires significant energy. Not selecting appropriate communication technology for the environment and robots, and not setting the distance of the communication station correctly will cause the robots to expend too much power. By moving the communication station to the appropriate position, communication distances can be shortened, and energy saving can be achieved. Otherwise, maximum energy may be required. Each robot acts like a communication station, causing too much energy loss. Instead, it is only possible to assign a robot that is suitable for its position as an energy station during the task [31], [38], [42].

## VII. CONCLUSION

When studies on mobile robots are examined, the power system is seen as an important constraint. Establishing the correct and systematic power system increases the performance of the robots. At the same time, it has been seen how important the efficient use of limited power technologies is. For this purpose, we aimed to shed light on later works by examining the efficient power structures and methods in our article.

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