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Overview of Battery Monitoring and Recharging of Autonomous Mobile Robot

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Abstract : Mobile robots should be capable of operating with a great degree of autonomy to operate in real social environments. Mobile robotic systems draw power from batteries which have a limited power life. This poses a greater challenge for an autonomous robot. Monitoring the status of the battery power in the robot is therefore important for autonomous robotic systems. Docking and recharging are crucial abilities of autonomous mobile robot to ensure its performance. In this paper, the focus of attention is on the significance of power monitoring for long-term operation of autonomous robots and power estimation and auto-recharging. This paper attempts to brief about a literature review of complete solution for docking methods and recharging the battery of a mobile robot. Major progress is being done on both technology and exploitation of docking mechanism and recharging without any human intervention. This review paper gives the overview of related work in terms of immediate challenges for true energy autonomy in mobile robots with respect to battery technology, power estimation and auto recharging.

Keywords*-Battery recharging, Docking mechanism, Autonomous mobile robot, Power monitoring.*

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I. INTRODUCTION

Electric power is a basic necessity for any electronic device to operate. In order for robots to be fully autonomous with no human intervention, power management issues are critical and require special attention. Power management is thereby an important feature possessed by the robot . Many devices like mobile phones and laptops used in today's life operate on batteries. Research on power management has been a topic of interest in the automotive field and the electric home appliance field. The same applies to autonomous robotic systems. Currently most autonomous mobile robotic systems draw power from batteries carried on the robot in order to operate various sensors and actuators in order to perform tasks. Batteries have a limited power life which leads to constrains on the operational time of the robot [1]. An autonomous robot planning tasks must be aware of power resources available, tasks on hand and the time required to recharge its batteries.With robots being more autonomous these days, it becomes necessary to check their power needs while performing other operations. Most mobile robots of today use rechargeable batteries to provide power both for motion and computation. Batteries can only store finite amount of energy [2]. Modern robots have increase in complexity as new applications like cameras or a navigation module gets added to the basic system with increased power requirement. If the battery gets depleted, the robot needs to locate the charging station and dock to it. The robot at the charging station will be docked to the docking station till the battery gets completely charged. Then it will get detached from charging station and will carry on with the existing task. Therefore, the management of the energy supply for the robot is a crucial requirement for long term operations [3]. This paper reviews current advances related to the need of power management for long-term operation of mobile robots, focusing on power estimation and auto-recharging methods. This review paper is organized as follows: Section II will discuss about the motivation of research in context of autonomy. Section III gives an overview of previous research work carried out in the field of battery technology, power estimation and auto recharging of mobile robot. Section IV gives an overview about conclusion and further improvements.

II.MOTIVATION

Autonomy

The term "autonomy" has been ascribed to robotic systems to demonstrate their ability to perform tasks without human supervision. For robots autonomous, they have to manage resources, and they should be able to sustain themselves over extended periods of time [4]. Autonomy in robots has been often linked to searching behavior found in animals and insects, where robots are capable of searching for recharging station to get the battery charged to its max value. H¨olldobler and Wilson explain a more comprehensive taxonomy of insect foraging as a combination of strategies for (1) hunting, (2) retrieval and (3) defense. Many actual or potential real world applications for robotics are examples of foraging robots, for instance cleaning, harvesting, search and rescue, land- mine clearance or planetary exploration [5]. Since robots are machines which requires energy to perform tasks, power management is important. At the same time the robot is equipped with current and voltage measurement circuitry which can be used to estimate the amount of charge remaining in the batteries and hence the amount of time available for the robot to dock and recharge. However, the term autonomy can be somewhat flexible. For example, consider the case of a robot whose batteries are connected to charging by a human and then released to carry out its task without further external intervention [6]. This can raise the question of true autonomy as it will keep the human operator in the loop and also demand maintenance on the part of the human. For robots to be fully autonomous, they should be able to monitor its battery level, dock and recharge itself without any human intervention.

III. Related Work

This section gives an overview of the related work in terms of immediate challenges for true energy autonomy in mobile robots with respect to battery technology, power estimation and auto recharging.

A. Battery Technology

Batteries are devices that convert chemical energy into electrical energy [7]. This allows for both energy storage as well as producing of direct current (DC) electricity. The electrical energy is created as a result of electrochemical oxidation reduction (redox) reaction within the battery[8]. When connected to a load, batteries will supply electrical energy until the reactants are depleted. There are many types of batteries. This section will focus only on secondary or rechargeable batteries since these are of interest in robotics both for environmental reasons and for ease of repowering the system. Lithium ion, nickel-metal hydride, lead acidic, alkaline manganese etc. are the main types of batteries used in mobile robots. These types of batteries vary in several important aspects according to the cell chemistry and the technologies used [9]. Selection of a battery technology involves a trade-off based on characteristics such as cost, charge-discharge properties, weight, charge retention, energy density etc. However, the maximum power available from a battery depends on its internal construction. A Honda humanoid robot can barely walk for 30 minutes with a battery pack on the back [10]; battery life is the most important

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challenge for mobile robots. Rybski et al. show that power consumption is one of the major issues in their robot design. Furthermore, the recharging of batteries also takes significant time. For example, a Pioneer P3AT robot by ActivMedia with an onboard computer takes about 3-4 hours to recharge and delivers about 3-4 hours of operational time. Roomba [11] takes about 3 hours to recharge and gives about 2 hours of operational time on single recharge. As we see from these examples, if a mobile robot has to perform over a long period then it would spend about the same amount of time recharging itself as performing tasks. The recharging issue highlights the need for some kind of power aware scheduling of tasks in the design of robotic systems, especially where tasks take more time than the battery can last on a single recharge. A good estimate of the remaining battery power will be useful for task scheduling.

Lead-Acid Batteries

Lead-acid batteries are either flooded type or valve-regulated type [12]. Flooded lead-acid batteries are composed of lead plates serving as electrodes that are immersed in water and sulphuric acid. These batteries require maintenance due to the loss of hydrogen over time. On the other hand, Valve-regulated lead-acid batteries are sealed and have a pressure-regulating valve to keep air from getting into the cells. However, sealed lead-acid batteries are more expensive and have a shorter life than flooded batteries [13]. These batteries contain either a liquid or gel electrolyte. Low internal resistance allows discharge currents of up to ten times the rated capacity of the batteryThis makes them ideal for applications where a large amount of power is suddenly needed – this is the reason for their use in electrically starting internal combustion engines of most vehicles. The cost of lead-acid batteries is the lowest of all rechargeable battery types for the amount of power delivered [14]. Problems with these batteries include sensitivities to temperature that affect both the life of the battery and cycle life.

- **Alkaline Batteries**

Rechargeable alkaline batteries available in several types. The first type has a nickel oxide cation electrode and an iron anode and is commonly referred to as nickel-iron batteries [15]. The second type also has a nickel oxide cation electrode but the anode is composed of cadmium so that these batteries are commonly called nickel-cadmium (NiCd or NiCad) batteries. Nickel-hydrogen and nickel-metal hydride (NiMH) batteries are used in many applications. Nickel-iron batteries have twice the specific energy of lead-acid cells, are rugged, have a long life cycle at deep discharges (80% depth of discharge) and can handle fairly high discharge rates[16]. However, they do not perform as well as lead-acid batteries at low temperatures and they can be damaged by high temperatures.

Lithium Batteries

Lithium is attractive because it is the lightest metal, and thus produces lighter batteries. It also has a high specific power and specific energy [17]. Lithium is not used with an aqueous electrolyte to avoid undesired chemical reactions. Lithium in metal form is not used in rechargeable batteries because it forms dendrites that tear through the separator and cause the electrodes to short. Instead, rechargeable lithium batteries use lithium ions spread within a carbon anode (when charged) or oxide cathode (when discharged) [18]. This technology holds a lot of promise, but does not completely replace alkaline batteries due to its higher cost. Due to cost and safety considerations, lithium-ion technology is used primarily for small consumer electronics and slowly now being used in vehicles and other high-power applications.

Table1: Comparison of Battery Properties

Parameter	Lead-Acid Battery	NiMH Battery	NiCd Battery	Li-Ion Battery
Specific energy	35-50Wh/kg	60-80Wh/kg	30-60Wh/kg	80-180Wh/kg
Specific power	150-400W/kg	200-300W/kg	80-150W/kg	200-1000W/kg
Cell voltage	2.1V	1.2V	1.2V	3.05V; 4.2V
Cycles	250-1,000;	300-600	1,000to 50,000	3,000
Life	5years	2-5years	10-15years	5+years

Efficiency	75-85%	60-70 %	60-70%	80-85%
Max depth of discharge	20-80%	60-80%	60-80%	100%
Self discharge rate	20-30% /month	15-25% / month	5-15% / month	2-10% / month

B. Power Estimation

An accurate estimate of the remaining battery power that the robot is carrying is needed in order to schedule recharging [19]. There are a number of methods for making such estimates. The accuracy of these approaches varies depending upon the battery chemistry and methods by which the monitoring is conducted. Such an estimation requires knowledge of battery structure, chemical composition, temperature, capacity, etc. [20]. One empirical model computes the efficiency of multi- battery systems through the usage of interleaved power supply and load splitting. Other models use Weibull fitting in addition to simple empirical measurements [21]. Electrical circuit models are in terms of passive circuit elements, these methods result in the largest observed estimation error [22]. Current challenges with battery technology urge the requirement of power management systems for power efficiency.

Battery Monitoring

Battery monitoring deals with the remaining capacity estimation and communication with the host through interface [23]. The battery State-of-Charge (SOC) is calculated basically taking into account the difference between the charging and discharging currents (Coulomb-Counter method). Measurements of voltage, temperature, charging and discharging currents are made in a continuous loop by a multi-channel Analog-to- Digital Converter (ADC). The battery monitoring software collects data from the ADC and battery models from the EEPROM. Voltage measurements are a good parameter to determine the SOC when no load is applied, since Open-Circuit-Voltage (OCV) and SOC are correlated [24]. The impedance of the battery distorts the voltage measurements during power consumption and this is why SOC calculations should not rely on those only. Nevertheless, voltage can be an indicator to know if we are close to the threshold value, and the open circuit voltage should be employed in combination with Coulomb-Counter methods to perform accurate remaining capacity estimations [25]. A continuous monitoring of the battery and the position in the robot is monitored from the control room. The transmission of this data between the robot and the control room are accomplished by the Radio Frequency transmission [15].

C. Methods of SOC Determination

Accurate SOC (State-of-Charge) estimation has been an important part for all applications including energy storage systems. The accurate SOC estimation protects a battery to be deeply discharged and over-charged. Many studies on SOC estimation methods have been developed for evaluating more accurate SOC value [26]. The battery SOC can be influenced by the battery temperature, the type of battery and the external conditions [27]. Most methods for state-of-charge (SoC) estimation in lead acid and lithium-ion cells are based on ampere-hour counting, estimation of the open-circuit-voltage (OCV), impedance measurement, in particular the ohmic and the DC internal resistance of the cell [28].In this paper, common methods of SoC determination and relate them for application to LFP/LTO cells. The battery is one of the most attractive energy storage systems because of its high efficiency and low pollution [29]. The battery has the advantages of high working cell voltage, low pollution, low self- discharge rate, and high power density. SOC estimation is a fundamental challenge for battery use. The SOC of a battery which is used to describe its remaining capacity is an important parameter for the control strategy [30]. As the SOC is an important parameter which reflects the battery performance, accurate estimation of the SOC not only protect battery, prevent over discharge, and improve the battery life but also allow the application to make rational control strategies to save energy [31].However, battery is a chemical energy storage source, and this chemical energy cannot be directly accessed. This issue makes the estimation of the SOC of a battery difficult. Accurate estimation of the SOC remains very complex and is difficult to implement because battery models are limited and there are parametric uncertainties [32]. Many examples of poor accuracy and reliability of the estimation of the SOC are found in practice.

An ampere hour counting method is the most common technique for estimating a battery SOC by integrating the current from a battery. This estimation method is a better method for tracking the rapid changes of SOC. If an initial value of SOC at time t1 is already known, the battery SOC at the specific time t2 can be obtained. An Open Circuit Voltage (OCV) SOC estimation especially works for a lead-acid battery [20]. This type of battery SOC estimation technique with an open circuit voltage is the easiest method gives approximate value. The open circuit voltage of a battery depends on the ambient temperature of cells. A battery SOC estimation method with a Kalman filter is based on an algorithm which uses in accurate measured state variables due to time-varying noises [21]. The Kalman filter estimates the SOC value by modeling the battery system including the unspecific parameters required for the SOC measurement. An advantage of the Kalman filter estimation method is that, it can automatically provide an estimation value in the dynamic state. An Electrochemical Impedance Spectroscopy (EIS) SOC estimation method uses the impedance spectra of the measurement object. This method can estimate State-of-Health (SOH) as well as SOC in all energy storage systems because SOC and SOH affect battery impedance. This EIS method is suitable for a lead-acid battery and SOH estimation is more accurate than SOC estimation [22]. A Neural Network uses a

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mathematical algorithm model for Complex Neural Network characteristics or parallel process. The Neural Network can achieve processing data and solve relations between various initial complex factors. A back propagation Neural Network is one of Neural Network algorithms which solves a non-linear system and has a simple topology structure compared with the typical Neural Network methods. A Locally Linear Model Tree SOC estimation method uses a Nero- fuzzy network system [44]. This method estimates the SOC of a non-linear battery system with a local linear model which is based on an assumed non-linear function and polynomial linear models. The Locally Linear Model Tree is based on the normalized Gaussian weighting functions.

Table 2 : Summary of SOC estimation methods

Method	Application	advantage	Disadvantage
Ampere Hour Counting	All energy storage	Online, easy, simple, accurate	Sensitive to parasitic reaction, cost for accurate current estimation
Open circuit voltage	Lead Acid, Li-ion, Zn/Br	Online, simple	Low dynamic, need long rest time, sensitive to temperature
Kalman filter	Dynamic application, HEV, EV	Online, dynamic	Need a suitable battery model, initial parameter problem
EIS	All energy storage	SOH estimation, Online	Sensitive to temperature, sensitive to frequency (High frequency required)
Neural network	All energy storage	Online, simple	Need many training data for accuracy
Linear model	Lead acid, HEV	Online, simple	Need reference data for fitting parameters

Table 2 compares the battery SOC estimation methods [43]. Based on the comparison of these estimation methods, it can be concluded that the ampere hour counting method is the most suitable technique for all energy storage systems because it can directly and easily transfer SOC information from a battery to a system. If the battery currents are accurately measured, this method can also estimate the accurate SOC of the target battery.

D. Autonomous charging and docking

Estimations of the remaining power on the robot can be used to decide when to recharge. A second challenge for long-term operation of mobile robots is autonomous recharging [33]. The mobile robot should be able to dock and recharge itself without any human intervention. There has been several approaches in developing auto- docking mechanisms [34]. In late 1940's, Grey Walter developed the first autonomous recharging for mobile robots, named Tortoises. These robots used a light following behavior to find their way into a hut containing a light beacon and a battery charger that made electronic contact when the robot entered. In the late 1990's, Hada and Yuta, proposed a battery charging system for long- term operation of mobile robots using infrared sensors and a reflective tape on the floor to reach the docking station [35] Oh. Zelinsky and Taylor proposed a docking system similar to an aircraft landing. The robot will approach the docking station using a long-range infrared beacon and a sonar. when the robot was in proximity to the station, a Sick laser range finder will be used to align the robot to a grid with a pattern designed to distinguish it from the surrounding environment. Silvermann et al. [36] developed a docking system which allowed a high angular and displacement error during the docking process [42]. A combination of vision and laser beacons was then deployed to perform the autonomous recharging of pairs are seen. Some researchers have also investigated continual charging from electrified floor in robot arena to provide power to the robots[37]. Some commercially available auto-docking mechanisms specified by the manufacturers of robots [38] are also available in Pioneer 2DX robot. They further enhanced their approach by adding circuitry that shuts down all systems upon identification of a successful dock [39]. This results in a faster and more efficient recharging cycle time, and allows for a full recharge. Cassinis, R et al [40] proposed a robot docking algorithm, inspired by an ancient navigation aid Bowditch proposed the use of range lights, the light pairs indicate a specific line of position when they are in line [40]. The higher rear light is placed behind the front light which aids the navigation depending on the position from where the light pairs are seen. Some commercially available auto-docking mechanisms provided by the manufacturers of robots are also available [41].Docking solution in passive charging docks for autonomous mobile robots use the QR codes as landmarks and Infrared distance sensors [42]. Infrared distance sensors are used to perform different approaching strategies depending on the distance.

IV. CONCLUSION

This survey paper provides a literature review of docking and the significance of power management for long-term operation of mobile robots. The immediate challenge for true energy autonomy in mobile robots is the battery technology, power estimation and auto recharging. It also discussed on some approaches related to power estimation for mobile robots. Based on the comparison of these estimation methods, it can be concluded that the ampere hour counting method is the most suitable technique for all energy storage systems because it can directly and easily transfer SOC information from a battery to a system. A docking method based on the self- localization of the robot and the infrared detectors of the docking station is proposed. The robot can navigate back to the docking station for recharging operations when the on-board battery is low. The future work can address the challenge of power prediction algorithm. This information is used to direct the robot for navigation towards docking station for recharging. A new beacon based charging system employing a suitable algorithm to allow the robot to perform a successful charging operation. In the future works, beacons can be detected using combined information from both ultrasonic range sensor and the infrared sensors. The algorithm consists of two modes of operations namely seek source mode and beacon recognition mode. The development of a charging station and robot autonomous recharging mechanism facilitates the mobile robot to align and attach to the power source for recharging. Design of hardware interface and development of algorithms will facilitate to monitor the charging status of the battery in the mobile robot while residing at the charging station.

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