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Battery Management for Rescue Robot Operation

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Abstract— **In a real-time rescue robot operation, the operator must avoid any mistakes during a mission. Effective robot operation requires the robot is supplied with the sufficient power for the entire duration of a mission. This study addresses battery management for rescue robot operation. Our experience and knowledge on battery management for rescue robots is summarized in this paper as a guideline for new developers. This paper covers the topics of power consumption, battery selection, battery charging/ discharging and battery maintenance.**

I. INTRODUCTION

Rescue Robots are designed to rescue people and/or provide environmental data to the rescue team in order to facilitate a rescue mission. The robots are mainly employed in extreme situations such as natural disasters, chemical/structural accidents, explosive detection, etc. Rescue robots therefore require sufficient energy to operate in harsh environments throughout a mission. The power supply of a robot affects its performance and may cause the robot to stop during the mission. This failure may result in the deficiency of the assigned task and/or mission; however, it is possible to minimize this risk by considering battery management system.

In practice, a set of batteries is supplied to a rescue robot to operate several electrical components (sensors, actuators, etc.). The robot's operational time therefore relies on the service life of the battery. Rechargeable and high-current output capacity batteries are preferable to provide effective power and longer operational times. However the drawback is the charging time of these batteries. The higher the current output capacity, the longer the charging time. In addition, the power consumption of the robot is relative to the difficulty of the task and obstacles. For example, the robot will draw more power on rough terrain than on smooth terrain, which can reduce the service life of the batteries faster than the normal usage. This issue will become an obstruction when there is a limitation of time in a real-life situation.

The trend of miniaturization is ever-increasing, that is to make the robot lighter and smaller for the benefits in mobility and transportation. In this case, a smaller-size battery is attractive, which is in direct contrast to the high-current output capacity that the robot requires. Most rescue robots use DC motors, sensors, microcontrollers and embedded computer. These motors convert electrical energy to mechanical energy to drive the robot. Sensors usually consist of laser ranger, odometer and inertial measurement unit, which can provide environmental data to the robot. While microcontrollers are used for low-level control in order to directly control motors, sensors and transmit data to an embedded computer. This embedded computer is used for high-level computations: motion planning, image processing and navigation. These components consume a large amount of power.

By studying this power consumption the appropriate power source can be chosen; this is the basic concept of battery charging and management. The user can modify this method corresponding to each robot design. The present study shows that battery management has an important role for the optimum use of energy in practical rescue robot applications. As the battery is costly, proper management and maintenance should be applied to enhance the battery life [1,2].

II. RELATED WORKS

Since Bergveld et al. introduced the battery management by modelling, they combined electrical and electrochemical modelling results in a method for modelling batteries that can be readily applied to all kinds of batteries. In that case, the charging algorithm could be simulated to provide the charging efficiency [3]. Notten et al. [4] implemented the electronic network models for Nickel Metal Hydride (NiMH), and Li-ion batteries to describe the behavior of batteries during normal operation and over (dis)charging to visualize the various reaction pathways. Their studies are focused on internal reactions inside a battery. Some researchers are interested in the battery's discharging performance under various load conditions to find the energy efficiency. Barili et al. [5], Sun et al. [6], Y. Mei et al. [7] and Yamasiki et al. [8] considered only the motion power. Liu et al. [9] and Michaud et al. [10] considered energy consumption of different components on the robot. In this paper, we focus on the power consumption of multiple components combing together. The power models are obtained to evaluate each significant component [11].

Therefore, four key steps for battery management are listed and discussed in following sections: power requirement, battery selection, battery charging/discharging, and battery maintenance. These steps are critical to the performance of a robot since any errors in these steps may cause the robot to be nonfunctional or fail during the

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practical application. And some tips: battery health and transportation are discussed to enhance the battery's life and accommodate the users respectively.

A. Power consumption

The power consumption is an important factor that quantifies how much power is required by the robot during the mission; it will influence to battery selection and details on battery management strategies for rescue robots. The measurement of power consumption can be directly obtained from the robot, but it provides the approximate result which is the power consumption of the entire robot. This method is not economic and it is possible to choose an overrated battery type and size, this result in an excessive robot size, this is not desirable when trying to optimize the design of a robot. As each electrical component has its particular voltage requirement, so it specifically draws the current from the power source. It is possible to consider the power consumption for each electrical component and analyze the total power consumption of the robot. This approach is more useful and accurate. Additionally, the power consumption of each electrical component is commonly given on the product's specification, and is assumed to be reliable. Therefore, the main electrical components of each robot can be listed and analyzed for the power consumption.

As mentioned above, the rescue robot mainly operates in high-level and low-level control. Its major energy consumers are motors, sensors, microcontroller and embedded computer as shown in Fig. 1. The power consumption of these components could be evaluated by using the power models from [11] for each particular part as follows:

For motion power (p_m), the power consumption is the summation of the output mechanical power and the transforming loss (p_l) in motors as shown in (1):

$$p_m\,(m,v,a) = p_l + m(a+g\mu)v \tag{1}$$

where m is the mass of robot, a is the acceleration and v is the speed. The gravity (g) and ground friction (μ) are constant. The transforming loss is decreasing when the speed is increasing in DC motors. So, this model shows the linear relationship when the transforming loss and acceleration are ignored.

For sensing power (p_s), the power consumption can be modeled as a function of the sensing frequency (f_s) from sensing components such as video camera, laser ranger and etc. combing with other sensors as shown in (2)

$$p_s\,(f_s) = c_{s0} + c_{s1}(f_s) \tag{2}$$

where c_{s0} and c_{s1} are the positive constant coefficients of sensors. The power model of microcontroller is constant because of its fixed tasks. On the contrary, the embedded computer's power consumption varies across different running programs. Their study shows that motion consumes almost 50 % of the power consumption. The total power consumption can be approximately obtained to accommodate the selection and optimize the numbers of the battery. However, the power consumption can vary in different environment and variable loads. Hence, considering the power consumption can provide the optimum charging time for the robot.

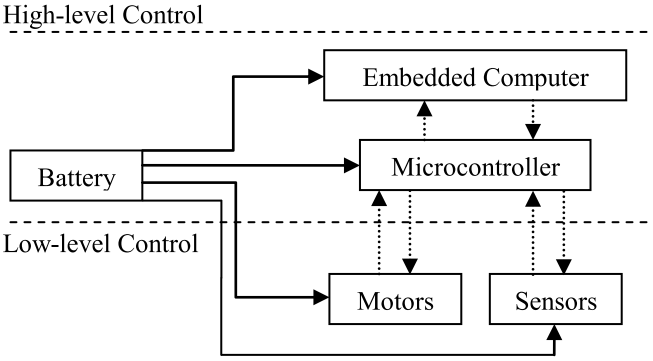


Figure 1. Overview of major energy consumers on a rescue robot.

B. Battery selection

More than 60 years, battery technology has been growing in commercial use; the development started from Nickel cadmium (NiCD), Lead-Acid Sealed, Nickel-Metal Hydride (NiMH) and Lithium-Polymer (Li-Po) batteries. The battery's variation can be the cell chemistry and the technologies used. Table. 1 is listed the characteristics of rechargeable batteries that are widely used in rescue robots [12].

TABLE I. MAIN BATTERIES USED IN RESCUE ROBOTS.

Parameters	**Lead-Acid**	**NiMH**	**Li-Po**
Average Voltage/ cell (V)	12	1.2	4.1
Specific Energy (Wh/kg)	30-50	60-120	150-190
Self-Discharge /month at 25°C	5%	30%	<10%
Load Current	0.2C-5C	<0.5C	<3C
Internal Resistance (mΩ)	<100 (12V Pack)	200-300 (6V Pack)	100-130 per cell
Operating Temperature	-20-60 °C	-20-60 °C	-20-60 °C
Quick Charge Time (hr)	8-16	2-4	1.5-3
Over Charge Tolerance	High	Low	Low
Cycle Life	200-250	300-500	1000
Maintenance Requirement	3-6 months	60-90 days	Not Required
Toxicity	Very High	Low	Low
Weight (approx.12 V Pack)	Very High	Moderate	Low
Cost	Low	Moderate	High

The battery selection is dependent on these factors listed in Table I. The selection must be appropriate for the design of the robot, i.e. its size and weight. The weight of the batteries is an important variable since it influences the robot's center of gravity, this is especially important for autonomous operation. The number of batteries must adhere to mission runtime. The capacity in watthour (Wh) provides the robot the estimated runtime corresponding to the discharging condition. The study indicates that the capacity of the battery (Wh) is invariant, regardless of the discharge load. Increasing discharge rate can increase the loss of capacity. However, Li-Po battery shows that it is superior to other batteries in term of maintaining its capacity even higher discharge rate. Li-Po battery is possibly the better choice in the market [12,13].

C. Battery charging and discharging

Battery charging and discharging control is necessary to ensure the reliability of a robot. For example, the voltage of a battery directly influences the RPM of the robot's motors. Lack of sufficient control can suddenly stop the robot functioning. Sometimes, the capacity of these batteries can be partially used and charged for each runtime resulting in capacity reduction and higher internal resistance. Higher setting on chargers and over discharging batteries can cause overvoltage and reverse voltage. Such NiMH battery, lower than 0.5C charging rate can cause overcharge as the lack of voltage and temperature profiles can trigger full charge detection on an advanced charger. This overcharging causes the memory effect, which is the reduction of voltage with the full capacity of batteries and the battery life. The proper protocol should be implemented to maximize the performance of the batteries throughout the mission.

In this case, there are two significantly interesting parameters of a battery; capacity and voltage. Fig. 2 shows the rate capacity effect for ideal and practical batteries. Ideally, rising in the discharging rate does not affect to the capacity. And the battery's voltage remains constant throughout the discharging and instantaneously drops to zero when the battery is fully discharged. The voltage is the rated voltage of battery. While the capacity is given in C rating, that is used to normalize the load current to the battery's capacity. For example, a load current of 0.1C for a battery with the C rating of 5000 mAh is 500 mA. Practically, the capacity drops at higher discharging rate. Besides, the rated voltage slowly drops during the discharging as shown in Fig. 2(a) and (b) respectively. An interesting parameter is discharging time (t_d); the approximated time when the battery supplies charge to a device under the valid discharge rate before the voltage of battery will be lower than the End-of Discharge voltage. Hence, the discharging time (t_d) can be estimated from (3) and (4), depending on a constant power and current loads respectively:

$$t_d = C.V/P_{avg} \quad (3)$$

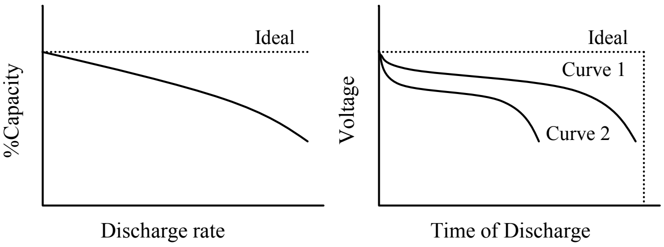
$$t_d = C/I \quad (4)$$

where C is the capacity of the battery (Ah), V is the rated voltage of battery, P_{avg} is the average power of load and I is the load current [14].

Each type of battery requires specific charging and discharging methods and their compatible chargers. An advanced charger will provide specific charging function for individual type of battery. The setup of the charger can indicate the overcharging or over discharging limit to prevent damage to the battery. In this case, the overcharge function on an advanced charger can be activated to detect the voltage. The charger provides a method called negative delta V (NDV). NDV responds to the voltage drop of 5mV per cell or less. Moreover, the advanced charger is programmed to be able to detect one of these parameters; NDV, voltage plateau, delta temperature, temperature threshold and time-out timer whichever comes first. The number of chargers should be sufficiently provided to charge each set of battery following the safety charging rate. The time taken to charge is calculated approximately by (5):

$$t_c = C/I_c \quad (5)$$

where t_c is the total charging time (hr), C is the battery's capacity (Ah) and I_c is the charging rate (A).



(a) (b)

Figure 2. The capacity as the function of discharge rate (left) and the voltage over time for a low and high current, curve 1 and 2 respectively (right). The dotted lines represent the ideal battery's properties.

D Battery maintenance

Careful battery management provides the maximum efficiency to the robots, moreover, it is possible to increase the battery life. Another significant factor is internal resistance (IR), this rating affects the energy delivered to the motors, speed controller and other electrical components. The voltage of the battery will drop as the result of the continuous current draws of the load. In this case, a loss in motor speed can occur. This relationship can be approximated as per (6) and (7):

$$V = IR \quad (6)$$

$$RPM = VK_v \quad (7)$$

where V is the voltage drop at battery (V), I is the continuous current (A), R is the internal resistance (Ω). The voltage can be substituted into equation (7) to estimate the changing in motor speed (RPM) by using the motor velocity constant (K_v).

The value of internal resistance is sometimes shown on the datasheet while some batteries require the IR to be measured using an advanced charger. This type of charger is able to measure the internal resistance on individual cells and whole packs. The results indicate the battery's health which corresponds to the performance of the robot. The higher the rating, the more difficult it becomes for energy to transfer to the destination. The reasons behind this problem are different for several types of batteries. For example, NiMH the electrodes can grow large crystals on the surface and reduce in capacity. An increasing internal resistance can damage the separator that keeps the positive and negative plates from touching. For Lithium polymer batteries, a build-up in Li_2O forms on either terminal of the battery. The cause of this problem stems from the use of batteries under extreme conditions such as overcharging, repeated partial charging and so on.

III. Implementation of Battery Management on Rescue Robots

The implementation is performed on our tele-operative rescue robot (Tele-Op IV) to determine the most possibly efficient techniques for battery management as shown in Fig. 3. The above approaches are analyzed and presented in this section. The approximate power required for electrical components determines the capacity of the batteries. Variable loading conditions are found throughout the test, this affects the choice of battery. The load factor is considered in continuous or transient full load due to the capability of devices. And the battery management strategies are concluded in this section for rescue robots. Furthermore, many factors could impact the final draw on batteries such as the terrain, the size of the robot's tracks and weight, so the final draw could be higher than the rated motor draw. The capacity of the batteries is then estimated to sustain the full load in short periods. The robot's description and specification are briefly listed to provide the general concepts. A list of electrical components in this robot and their power consumption is shown in Table II. to be a case study for other robots' design.

Tele-operative robot (TeleOp IV) has superior driving components. It is highly mobile robots with tracking locomotion systems, making the robots more mobile in various terrains. A brief specification is listed as following:

- Size: 540 x 570 x 400 mm.
- Weight: 70 kg.
- 4 independently controlled flippers (two flippers at the front end and two more at the rear end)
- Inverse-kinematics controlled manipulator with various life-signal detecting sensor on the end-effector (ex. heat sensors, real-time motion image detector, carbon dioxide sensor, and a two-way voice communication system)
- Manipulator with multiple degrees of freedom with both rotational and prismatic joints
- 2-D mapping by using SLAM system

Figure 3. Extended manipulator of Tele-Op IV reaching the victim at red zone in World RoboCup 2014, Brazil.

TABLE II. Components and power consumption for Tele-op IV.

Components	Qty	Voltage (V)	Full Load Current (A)	Max. Power (W)	Total Power (W)
Driving System					
Flipper Motors	4	24	2.5	60	240
Drive Motors	2	24	6.25	150	300
Manipulator Motors	2	24	0.25	6	12
Manipulator Motor	2	12	1.5	17	34
RC-Servo Motors	2	12	1.5	18	36
Controllers					
Drive Controllers	11	12	0.25	3	33
Microcontroller (Arduino Mega 2560)	1	5	0.5	2.5	2.5
Sensing System					
Cameras	4	5	0.5	2.5	10
Heat Sensor	1	5	0.005	0.025	0.025
Co$_2$ Sensor	1	3.3	0.033	0.109	0.109
Laser Scanner	1	12	1	12	12
Computer Components					
Computer	1	12	5	60	60
USB Hub	1	5	2.5	12.5	12.5
Communication System					
Ethernet I/O	1	5	0.5	2.5	2.5
Wireless Router	1	24	0.5	8	8
Video Server	1	12	2	24	24
LAN Hub	1	9	0.6	5.4	5.4
General Component					
LED arrays	1	12	0.083	1	1
			Total = approx. **780W**		

Our selection of the type of batteries corresponds to the power consumption results in delivering sufficient current for driving robots without inducing risk of damage. In addition, the ground isolation is considerable to avoid any electrical failure. Even though the full load current would occur in a short period of time, but the battery's capability should satisfy the requirement. So, the electrical power consumption can be determined from the multiplication of the full load current and nominal voltage. As the study obtained from [11], we grouped the electrical components into 3 main sections: motion, electronics and computers. The motion section composes of all driving system. Drive motor and flipper motors are DC motors; they contribute the major roles in the motion section. As seen in our experience, the drive motor practically consumes more power than flipper motors due to the movement over different terrains. This motion power will be discussed in our further study to specify the particular power consumption for the rescue robot under different terrains. From our design, the robot's weight is distributed to the base which also has limit space. In this case, NiMH batteries are used for flipper motors and drive motors respectively. For the electronics section, it consists of controllers, sensing system, communication and general electrical components. Their power consumption is unsteady due to the sensing and communication system. When the robot's speed is higher, the sensing frequency increases to satisfy the speed's need. And the remotely operative robot requires sending data through wireless communication, which consumes more power in further distance. For computer section, it consumes a large amount of power during navigating, data processing and etc. So, two types of battery; Li-Po and NiMH are used in our approach. Table III shows these batteries' specifications and compares their benefits. For example, Li-Po batteries are light and are provided in various shapes and sizes, which help when designing the robot. Li-Po batteries also have high capacities allowing them to store more power, whilst high discharge rates allow highly sustained loads. On the other hand, NiMH batteries are easy to use and require less maintenance.

Considering the robot's need, the maximum voltage used in each section corresponds to the selection of batteries. As shown in Table IV, the driving system and electronics need 24V voltage. Then, six packs of 12V NiMH batteries are used in parallel and series connection to gain more capacity for the motion section. The total capacity and voltage are about 13.5Ah and 24V. Two Li-Po batteries are used for electronics and computers sections.

TABLE III. SPECIFICATIONS OF NIMH AND LI-PO BATTERIES.

Parameters	**NiMH**	**Li-Po**
Cell Counts (approx. 24 V)	20	6
Capacity (mAh)	4500	5500
Energy (Wh)	108	122.1
Discharge Rating (C)	1C	45C
Dimension / pack (mm)	90x7.5x36	145x43x60
Weight (approx. g)	1180	850
Cost (USD)	152	70

TABLE IV. SELECTION OF BATTERIES TYPE USED FOR THREE SECTIONS.

Sections	**Voltage (V)**	**Max. Power (W)**	**Type**	**Numbers of Pack**
Driving System	24	600	NiMH 24V, 4.5Ah	6
Electronics	24	100	Li-Po 24V, 5.5Ah	1
Computers	12	80	Li-Po 24V, 5.5Ah	1

NiMH and Li-Po batteries require specific charging and discharging methods and their compatible chargers. The charging rate of NiMH is 0.5C or higher to achieve a reliable voltage signature in the overcharge function. Step-differential charging method is suitable for NiMH batteries as fast charging with a high current occurs at the beginning of the charging process. When it reaches the voltage threshold, the battery is cooled down for few minutes and then continuously charged with lower and lower current throughout the process. This method provides approximately 6% of capacity gain over basic charging methods but it has a disadvantage in shortening battery life. Moreover, NiMH batteries should not be discharged lower than 0.9 V/cell during usage.

Li-Po charging and discharging methods are obviously different to NiMH. Li-Po batteries require constant current/constant voltage charging; the charging rate is constant until the voltage reaches to 4.2 V peak voltages per cell. After that, the voltage is maintained while the current is reduced. Another important aspect is balancing, which equalizes the voltage of each cell in a pack for acquiring the same amount of cell discharges. A safe charging rate is 0.5C-1C. During a run, these batteries should not be discharged lower than 3 V per cell. In this case, a low voltage cutoff on the speed control is helpful to detect the voltage and divide it by the cell count of battery.

Measurements conducted after the several charging and discharging stages of batteries show that the internal resistance of both Li-Po and NiMH batteries is higher than the beginning. For the Li-Po batteries, the internal resistance varies considerably from cell-to-cell: some cells have internal resistances 4 times higher than others, resulting in the inequality of cells. For the NiMH is approximately 50% higher than the original value. To solve this problem, the batteries should be discharged to approximately 0.9V/cell to break up the lower-voltage compound and convert it back to normal stage.

To enhance NiMH battery life, the battery should first be conditioned. This initial conditioning, called forming, is done at the manufacturing stage and maintains this condition for months. Before using them another conditioning should be done to bring no load capacity and voltage back to their rated properties. Each pack of batteries must be charged and discharged at 0.1C and 1C rates respectively. This process should be performed 2-3 cycles. The batteries must not be overcharged or trickle charged over 24 hours so as to prevent large crystal growth. As mentioned above, regularly discharging batteries to 0.9V/cell helps breaking up these crystals. High internal temperatures are found in shrink-wrapped packages, the use of low discharging current should be performed to prevent overheating.

To store NiMH longer than a month, they should be discharged to 0.9 V/cell and partially charged about 10% of their capacity. During the storage, the battery conditioning should be done 1-2 cycles for every 3-4 weeks. After storage, the same conditioning should be done 3-4 cycles to regain the rated capacity. But if there is no conditioning during the storage, it is required to charge at 0.05C-0.1C rate and discharge at 1C or less for 1-2 cycles before using and normal charging. NiMH lifetime is approximately 500-100 charge/discharge depends on the quality of batteries.

As Li-Po is flammable and more delicate than NiMH, proper care should be taken to prolong their life. As Li-Po composes of several chemicals, the reactions could provide problems as previously mentioned. This higher internal resistance results in higher operating temperatures during use. The package will swell, at which point the battery should be disposed of. Continuous use will induce more heat and cause a thermal runaway process that is a self-sustaining reaction. The seals of the battery will eventually burst which may lead to a fire.

Thus, after using Li-Po batteries they should be stored at room temperature at 3.8V/cell. An advanced charger will provide the storage function to either put the voltage down or up to the storage value. Li-Po batteries should not be fully charged for storage, as it is vital to their life. Self-discharging constantly occurs and the charger will not be able to charge through Li-Po function. Many recommendations offer the use of NiMH charging function on the charger. This function can manually apply very low current to put the voltage up to 4.2 V/cell, but it is an unreliable method. The fully attention is necessary during activating this method as the overheating can occur. By the way, this function cannot recognize and equalize each cell voltage. However, this study offers the future approach for our new robot, we plan to extend the use of Li-Po for every section and propose the new management strategies.

Battery transportations for personal use followed the IATA Dangerous Goods Regulations (DGA) of 57th edition is up to date. Both NiMH and Li-polymer batteries are required to be wrapped and sealed in safety package. NiMH batteries are allowed to be in checked and/or carry-on baggage. However, the permission is different according to the airline and the departure / arrival country. This complication would cause the prohibition during the transportation, such that these batteries would be taken away without the warning at the airport. For Li-Po batteries, the Watt-hour rating of each battery is strictly considerable as its high rating is more than 100Wh but not exceeding to 160 Wh, so the maximum of two spare batteries are carried in each passenger's carry-on baggage [15].

IV. CONCLUSION

Sometimes battery issues are neglected, but it can be a primary cause of robot failure. Regular maintenance will sustain the battery capability and life. This paper has provided details on battery management strategies for rescue robots. The implementation was performed on our tele-operative robot as a case study for other robots' design. Comprehensive battery management will yield effective performance of robots throughout the usage, the proposed approaches were tested in competition environments and mitigated battery failure. The selection of batteries is flexible and dependent to the power consumption and each robot's design. Our future approach has been planned to use Li-po batteries for all sections. As the new rescue robot has been developed to operate in remote and autonomous functions, we plan to conduct the experiment to measure the power consumption of all electrical components for this new system.

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