Energy Consumption Analysis Procedure for Robotic Applications in different task motion

Iman Ahmed1, Ishak b. Aris2, Mohammad Hamiruce Marhaban3, Asnor Juraiza Ishak4

1,2,3,4 Electrical and Electronics Engineering, University Putra Malaysia UPM, 43400, Serdang, Malaysia
E-mail: eng.iman79@yahoo.com1

Abstract. This work proposes energy analysis method for humanoid robot, seen from simple motion task to complex one in energy chain. The research developed a procedure suitable for analysis, saving and modelling of energy consumption not only in this type of robot but also in most robots that based on electrical power as an energy source. This method has validated by an accurate integration using Matlab software for the power consumption curve to calculate the energy of individual and multiple servo motors. Therefore, this study can be considered as a procedure for energy analysis by utilizing the laboratory instruments capabilities to measure the energy parameters. We performed a various task motions with different angular speed to find out the speed limits in terms of robot stability and control strategy. A battery capacity investigation have been searched for several types of batteries to extract the power modelling equation and energy density parameter for each battery type, Matlab software have been built to design the algorithm and to evaluate experimental amount of the energy which is represented by area under the curve of the power curves. This will provide a robust estimation for the required energy in different task motions to be considered in energy saving (i.e., motion planning and real time scheduling).

1. Introduction
For the biped robot the energy conservation is one of the important factors that should be taken into account when design or develop any robot movement activity. In general, there are several methods to reduce the energy consumption in robot such as; optimizing the robot path planning, optimizing the robot parameters (speeds, payloads), scheduling the robot operation time, or throughout using integrated control strategy based on data of friction, speed and gravity of robot axes. Finally the on board process frequency. Many potential works have been devoted in order to reduce the consumed energy in robotic application to prolong the operation time. Wigström et al. 2013, Presents a dynamic programming method to achieve a decrease in energy consumption for any given cycle time. By generate new energy optimal trajectories, which follow the same path but in different execution time[1]. Brateman et al. 2006, is introduced an approach for energy saving for mobile robots through controlling both processor’s frequency and motors speed[2]. Chemnitz & Schreck 2011, have showed that the slow motions are not the most energy-efficient and, the best strategy for energy conservation depends on a robot model[3]. Mei et al. 2005, Builds a power model for motion to analysis the energy consumer using two techniques dynamic power management(DPM) and real time scheduling(RTS) which provide greater opportunities to achieve better energy-efficiency[4]. Costa & Moreira n.d. have developed a simulator for humanoid robot which can be used to find the important parameters to optimize energy consumption [5]. Siregar 2005, Presents a technique for numerical optimization for power consumption for five-link planners by taken into account the transients in the circuit of electric motors[6]. Kormushev et al. 2011, Reduces the consumed energy by applying the reinforcement learning algorithm that will affect on the center of mass and the height of the humanoid robot[7].
In all the above mentioned literature related to the energy consumption there is no certain procedure that other researchers can follow to calculate the consumed energy.

The aims of this research are to analyze the energy consumption of the bioloid premium type A robot in different task motion using (single, double and multi servos), also to evaluate the energy consumption for the robot in different speed by utilizing Matlab software integration and bar chart explanation. Finally this integration can be used as a reference for any task motion of robot to calculate the consumed energy. Accordingly we can optimize the parameters that can affect on the reduction of the energy consumption.

To investigate the power consumption analysis practically in robot application, Humanoid Bioloid Robot Type A developed by the Korean company Robotis was used due to its flexibility. The kit with 18 Degrees of freedom (DOF) consists of a CM-530 main Controller, 18 AX-12A DC servo motor. Powered by 11.1v 3S LiPo battery. An overview of the proposed biped robot is shown in figure 1.

2. Experimental procedure measurement for the energy consumption:
The devices used in the experimental measurement to calculate the energy consumption during motion task are shown in figure 2.

![Figure 1. Bioloid premium robot type A](image1)

![Figure 2. Lab. Instruments used for power analysis.](image2)

In this research a measurement instruments have been adopted as an acquisition device to collect and store energy data by utilize the facilities that are available in these smart components. For example, to get the power consumption rate curve, a Fluke current multi-meter, with suitable scale is used as a current sensing element, one oscilloscope channel to measure the drop voltage over that multi-meter terminals to get the instantaneous value of the consumed current as voltage signal, while other channel is used to measure and store the variation in the voltage level. The products of the two channels would generate the power consumption rate curve. Parameters setting up are important to get high resolution and clear data. Finally the data of different task motions were collected using different values of speed or payloads and recorded data transferred for more analysis when USB memory is used to transfer the data points to laptop.

3. Simulation analysis
The Matlab software is utilized to create a program for calculating the area under the power curve which represents the consumed energy, this can be used as a reference for the energy calculation for different robot types. Integration software flow chart is represented in figure 3.
3.1. Power chart
The energy consumption of the biped robot affected directly by power dissipation of the driving and sensors components that accumulated to construct its body, therefore a need of study the power of these components is quite important at project planning aspects and conservation of energy. The estimation of the robot energy of a particular task of motion depends on servo motor power consumption and the number of those servos that participate to implement the task; therefore we studied the power variation range individually for each servo and similarly for multiple servos as well as the limits of stability in each case.

3.1.1. Single Servo Motor Power chart
Three cases study of power measurements have been taken in this research as shown in figure 4. There is a similarity at the minimum value limits for both Servo 1, and Servo 5, this result is reasonable because that, each of them has consumed power due to controller torque-on magnitude, which is essential to maintain position control of the servo and the slight difference results from the servo location in the structure of humanoid body.

The power can be given by the equation:

\[ P_{k,\text{servo}}(\omega) = P_{\text{Tor}} + P_k(\omega) \]  \hspace{1cm} (1)

\[ P_{\text{Tor}} \] = torque-on consumed power which is essential to maintain the stability, it is constant whenever the humanoid and the servo were settled on (no-motion state).

\[ P_k(\omega) \] = consumed power at a specific angular speed \( \omega \).

3.1.2. Double Servo Motor Power chart
The minimum and maximum limits of the 2 servo column chart in figure 4, represents another study of power consumption limits.

referring to equation (1), it’s obviously that the minimum bar represents the consumed power of the two servos with torque-on power results from not only their own consumption but also from all other 16th servos that constitute this type of humanoid, so equation (1) is still valid in this case but with attention to construction, or the type of the motion task, and the number of servos.

The suitable expression to this type of power can be as follow:

\[ P_{\text{nservo}}(\omega) = P_{\text{Tor}} + \sum_{k=1}^{n} P_k(\omega) \]  \hspace{1cm} (2)
3.1.3. Multi servo Motion Power Chart

For motion planning design the energy consumption and the stability are the most essential parameters that should be taken to maintain the task specifications. Figure 5, shows two types of task motion, they are: 14 servo (Bravo motion), and 8servo (Bow motion), the main objectives of these experimental measurements are to specify the consumed power and variation range at different angular speed values, and assign the angular speed value at which the critical stability could be affected for each task. As seen in figure 5, both blue colour bars are relatively equal in values, the reasonable interpolation based on the torque-on power of all servos, similarly to the previous case, the slight difference between these two bars results from (due to) robot orientation(position) or the mass distribution of humanoid position. The peaks values of the bars in each motion indicate the critical angular speed on which the robot tends to be unstable, it is 1.5 rad/sec at 29.24 watt consumed power in (bravo motion), while it is 2.5 rad/sec at 32.46 watt power(in bow motion).

3.2. Energy Chart

3.2.1. Single Servo Motor Energy Chart

Servo1, end location servomotor in the robot hand, with lower load and less power consumption servo as shown in figure 6. This figure shows the photo, power rate curve, and the energy difference in both angular speed rate (1 and 3) rad/sec.

Servo5, shoulder location servomotor, more power consumption within the same hand, which means more payload than previous servomotor. Figure 7, shows the difference in the power consumption rate through the two value of speed (1 and 3) rad/sec.
3.2.2. **Double Servo Motor Energy chart (2 servos up moving)**

![Figure 8. Power consumption rate & energy of 2 servos](image1)

3.2.3. **Multi servo Motion Energy Chart**

As depicted in the above figures (6-10), for all task motions the energy rate is larger in slow speed than in high speed rate for example in (2servo up) motion task the amount of the consumed energy at (1rad/sec) equal to 0.0078 Wh which is more than at (3rad/sec) 0.0049 Wh. And this is due to two reasons; first, the longer execution time for the slow motion and second, is the fast task motion has high power consumption for short pin as shown in the above figure. Put this is not common for all application since in certain task motion the slow motion consume energy for less than higher motion.

Several batteries have been selected based on market availability to evaluate the most important parameter in mobile robot battery which is the energy density as shown in table(1), a model equation have been conducted for each type of battery or hybrid battery.

3.3. **Total Battery Capacity**

Energy consumption of the battery is tested under high power consumption motion task which includes 8 servomotors.

We have used the general energy equation, Eq.(3) to find out the experimental energy capacity in specific type of task motion which is shown in figure 11, this represents the energy consumption of 8 servos motion task which is elapsed 10 times and finished within 200sec.

![Figure 9. power consumption rate & energy of 8 servos. Bow motion (8 servos)](image2)

![Figure 10. power consumption rate & energy of 12 servos Bravo motion (12 Servos)](image3)

![Figure 11. Energy consumption of 8 servos motion task](image4)
\[ W_{\text{robot}} = \int_{0}^{t} P_{\text{robot}} \, dt \]  

(3)

The above case study has been used as a base to find out the modelling power equations for different power sources.

The difference between the manufacturer and experimental energy capacity can be shown in table 1, for several battery types, the differences are due to some battery parameters such as; the state of charge (SOC), discharge rate, and the battery life cycle.

### 3.4. Energy Density

The energy density is a measure of the amount of energy per unit weight or per unit volume which can be stored in a battery. Thus for a given weight or volume a higher energy density cell chemistry will store more energy or alternatively for a given storage capacity a higher energy density cell will be smaller and lighter. The table below shows some typical examples.

For example; for Lithium ion Polymer battery, Energy Density is 211 Wh/Kg.

However, there is a significant different between the experimental and the manufacturer value of the battery energy capacity, whereas the manufacturer value of energy can be calculated directly from the following Eqs.(4,5):

\[ E_{\text{th}} = \frac{P \cdot t}{v} \]  

(4)

\[ P_{\text{th}} = \frac{I \cdot v}{y} \]  

(5)

\[ E_{\text{th}} = \text{Theoretical energy; ; } P_{\text{th}} = \text{Theoretical Power.} \]

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**Table 1. The energy parameters for different power sources**

| Battery Type          | Weight (gm) | Voltage (Volt) | Specific energy (Wh/g) theoretical | Modelling Equation | time (min.) | Practical Energy (W.h) | Practical Specific energy (Wh/g) | Capacity (mA.h) |
|-----------------------|-------------|----------------|-----------------------------------|-------------------|-------------|-------------------------|----------------------------------|----------------|
| Robot on-board Li-Polymer | 79          | 11.1           | (1*11.1)/79=0.14                  | \( y = 0.0488x + 12.168 \) | 41          | 7.631                   | 0.0966                           | 1000            |
| Li-Polymer            | 84          | 11.1           | (1.6*11.1)/84=0.211               | \( y = 0.0348x + 10.918 \) | 34          | 5.851                   | 0.0696                           | 800             |
| Li                    | 134         | 11.1           | (3.6*11.1)/134=0.298              | \( y = 0.059x + 11.028 \) | 27          | 4.604                   | 0.0343                           | 3600            |
| SuperCap +LiP        | 116         | 11.1           | 0.211+2.1=2.311                   | \( y = 0.055x + 11.475 \) | 25          | 4.492                   | 0.0387                           | 60.5            |
| SuperCap             | 7*4=28      | 11.1           | 60.5/28=2.1                       |                    |             |                        |                                  |                 |

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**Figure 12.** Power Modelling Equations for different power sources.
3.5. Energy Modeling Equations for different power sources

It is obviously that the power tends to be linearly reduces down with a constant slope which is easily found by the equation:

\[ P = 0.0488 \times t + 12.168 \]  

(6)

\[ P = \text{the instantaneous power given by (Watt)}; \quad T = \text{is the time in (minutes) in this measurements}. \]

The Total Energy can be found by integrating the power line over the time (0-39) mints.

From Eq.(6), The energy consumption which is the area under the curve is given by

\[ E = \int_{0}^{39} (0.0488 \times t + 12.168) \, dt = -0.0488/2 \times (39)^2 + 12.168 \times 39 = 7.29066 \text{ Watt.h} \]

\[ E = \text{the experimental energy}. \]

On the same concept of Eq.(6), we have found out the modelling equation and calculated the total capacity of each energy source, as described in figure 12, for the energy equivalent sources; the existence robot battery, lithium ion polymer battery, Lithium ion polymer+ super capacitor, and lithium ion respectively.

However, there is a significant different between the experimental and the manufacturer value of the battery energy capacity, whereas the manufacturer value of energy can be calculated directly from the following Eqs.(7,8):

\[ E = P \times t \]  

(7)

\[ , \quad \text{Where} \quad P = I \times v \]  

(8)

4. CONCLUSION.

Energy consumption in robot application is one of the most important issue in research area, this paper focuses on best, reliable, and simple method as well as an algorithm to be utilized in energy analysis and conservation, it is found that the main two energy parameters (current, voltage) can be measured based on the capabilities of the laboratory instruments that are considered as trusted and more reliable devices, thus an accurate measurements are obtained and recorded, this procedure can be considered as a reference simple method to any researcher in this field.

The percentage of power consumption rate is some times more less than the total power rate which is consumed thought task execution and consequently, we need to take into account this value which is called (on-torque energy) of the robot. The (on-torque) is the energy required to maintain the stability of the robot orientation and its servos position angles, this amount of energy can be reduced by energy saving motion planning design tasks.

It is found that the consumed energy is not always inversely proportional with the task execution speed, but it may have a direct proportional according to the task type.

The power source type and brand of the humanoid robot is most effective parameters on the performance. Practically, it is found that the capacity of the on-board battery is about 65.7% with respect to that value mentioned in its datasheet, while this percentage is not the same with other types and even the brand over the same type as described in figure 12, and table 1.

Thanks of Matlab software facilities; it’s easy to integrate the area under the power rate curves of all types of batteries that subjected to energy measurements test.

This analysis can open a horizon to search a more effective, long life and motion duration with high energy density especially with mobile robot. In the future work, the researcher should tackle firefly in more various types of problem such as find optimum method that will effect on the energy saving, or try to find alternative power source.
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