EVALUATION OF POWER DISSIPATION AND ENERGY IN A ROBOTIC SYSTEM

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Abstract: Robots are widely used in many disciplines like manufacturing, military, and commercial. They are seen as a key to advancements in such fields. A robotic is being used to assure precision and reliability. Some bigger companies like amazon use robotics to achieve stability and speed up their productions. In real-life, robots are mostly used in environments that contain uncertainties events. Additionally, interruptions occur there. Determining several performance quantities such as the execution time, throughput, power dissipation and energy under severe circumstances is crucial in the fields where robotics are used. This paper uses the developed framework earlier on a robotic manipulator to estimate average power dissipation, also known as power consumption, and average energy. Subsequently, a comparison analysis is conducted using several free tools such as Power Gadget, HWMonitor, Sidebar Diagnostics and Open Hardware Monitor. Those free tools are chosen since they are available with no extra hidden charges, and they are easy to download and use. The aim of that analysis is to find the differences between the average estimated value using mathematical equations and the actual ones from those tools. The analysis is performed on a machine running on a Windows-based system. The results that obtained indicate that the estimated/predicted values of the dissipated power and energy are close to the actual values. Likewise, the error between those figures varies between 6% to 11%. This variation happens because the used machine is affected by its specifications, especially the number of cores of its CPU and the clock frequency.

Key words: Robotics, energy, power dissipation, power gadget, open hard monitor.

1. INTRODUCTION

Nowadays, robots have become the main players in several disciplines such as health systems, armed forces, marine, space exploration and mechanization. This happens because of the technological advances [1, 5] and by reason of competitive requirements amid existing competitors in the markets. Using robotics enhances the

Quality of service (QoS), reduces the costs and production time [1]. In addition, they significantly minimize injuries or hazards where human intervention exists.

In industrial and medical applications, robotic arms are the recognized configuration being used and deployed [5]. Those applications require stringent demands and provision for precision, timing, and the quality of delivered services. Robotics provide reliability, accuracy and rapidity in the operations that are being handled and performed by them. Robotics have been deployed in prediction, perception, and educational activities in recent decades [1, 5].

Performance analysis for several metrics is highly needed and crucial in diversified territories such as military systems, manipulators, and sensing ones. The usefulness of that analysis is it shows the evaluation of desired parameters before releasing them to the consumers and users [2, 3, 4]. Reducing the time, costs, dissipated power and produced energy are the motivations for the producers to perform the analysis. This analysis exploits the weaknesses that exist. Thus, it saves time and eliminates the need to wait for final implementation to be performed where the integration of all components is deployed [2, 3].

This research focuses on predicting the power dissipation and produced energy as the performance metrics to be evaluated in the robotic system. Hierarchical Performance Modelling which is also abbreviated as HPM is used along with the analytical approach to derive the Objective Functions (OFs). Those functions represent the required equations to predict the average values of all needed metrics. HPM is composed of 4 layers or levels which are System level, Task level, Module level and Operation level. Those layers can be interpreted as a stack where the operation layer represents the bottom of the stack, and the system level resides at the top. Information about HPM can be obtained from [2, 3, 4].

Herein, estimating the average value of the produced power and energy from the robotic system in [5] is our goal by using the developed approach in [2, 3, 4]. These estimation procedures are applied from bottom to top in the stack layers.

In this paper, the contribution is to dive deep into the analytical method, which is HPM in this case, and use its usefulness to predict the average energy and dissipated power in [5]. HPM along with its Markovian model can be easily integrated and applied on any application such as radars for communications, and medical devices. Several research papers for using HPM have been published and they are publicly available. The remaining paper is arranged as follows: Section II presents the literature review for calculating and estimating performance metrics. Then a discussion on the developed method is presented in Section III. Sections IV demonstrates the simulation and the experiments that were conducted to predict the performance metrics. Finally, the conclusion of this paper is stated in Section V.

2. RELATED WORK

Characterizing the manipulators' performance metrics is conferred by the robotics communities [1]. T. Abukhalil et al in [6] proposed a harmonizing power in a group of robots to reduce individual interference for reviving and restoring the batteries. A power optimization subroutine was used to distribute the power by a Control Unit (CU). Their conducted experiments showed that the robots consumed lower energy and more cost-effective power was gained. In this paper, mathematical equations are used to derive the OFs to predict the average energy. More information is found in [6] for interested readers.

A. Manimuthu et al in [7] proposed a model to characterize the energy based on Newton-Raphson Approach in consolidating and blending with Pulse Width Modulation Bridge. Validation was performed on an 8’ * 8’ square testbed to find an area with the lowest energy. In addition, the authors used the Tabu search and SLEEP approach in their method to estimate the energy cost for every tiling solution. Herein, our approach is different since it predicts the average value for the complete system not just a specific area as happened in [7].

In [8], the authors proposed a new technique for energy modelling to be applied on mobile robots. Each robot can calculate its consumed energy through that approach. This calculation is performed based on three factors which were the sensor system, control system and motion system. Their obtained results showed that the developed method was a good option to determine and estimate energy utilization. However, this technique lacks predicting the energy for all robots’ actions as the conducted experiments were conducted on horizontal roads only. In this paper, HPM along with the analytical are used to predict the energy consumption for any type of action whether it occurs on horizontal roads or other types of roads.

A. Liu et al in [9] proposed software-simulated power data to recognize and distinguish between two forces parameters to estimate the energy utilization in manufacturing robots. The authors analysed the relation between consumed energy and the speed of a robot. ABB IRB 1200 was used to conduct the simulation experiments. The estimated metric was calculated based on 6 links that were available in the considered robot. In addition, 6 Degrees of Freedom (DoFs) was used in ABB IRB 1200. In this paper, our estimation is based on the same DoFs while HPM explores its stack layers to derive the OFs equations in all levels which imply that all parameters are considered. Furthermore, the energy consumption from all arithmetic operations is examined and added to the estimated values. More information can be found in [9].

3. RESEARCH METHODOLOGY

The authors in [2, 3] developed a suitable framework that is applicable to any system. The usefulness of this framework comes from numerous reasons as follows:
It is a generic approach and works for any system despite its complexity. It predicts and evaluates several metrics such as processing time, throughput, and energy consumption. It incorporates diversified components which are related to different levels of hardware and software to estimate needed parameters.

It is utilized and tested on a 6-DoF Independent and self-directed Articulated Robotic Educational Platform (AUTAREP) manipulator which is proposed in [5]. Fig. 1 depicts a similarity between the human arm and a manipulator of the robotic.

The complete detail about the tested robotic manipulator is in [5].

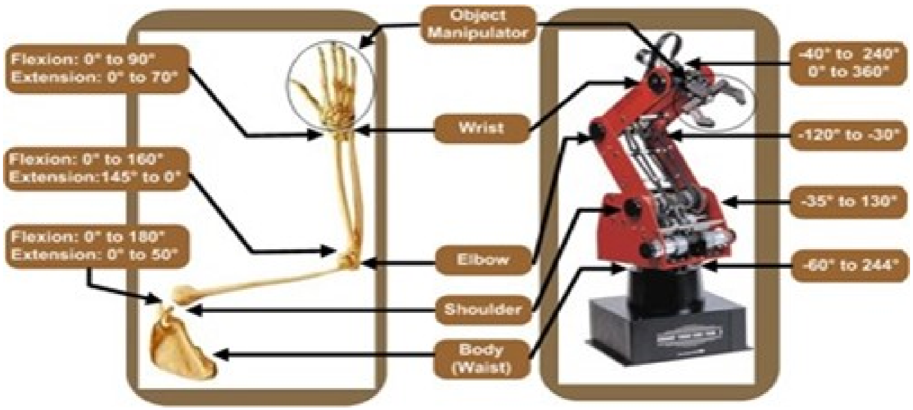

Figure 1. The robotic manipulator and the human arm

Since there are relations between motions and forces to be modelled and developed, thus, system architects and designers shall know these factors and consider them. Herein, both Kinematic and dynamic models have been considered to collect all needed information using the bottom-up methodology to derive the OFs. Those functions are the equations to predict the average values of needed metrics which are the dissipated power and the consumed energy.

3.1. Kinetic Model

It characterizes and describes the time-based parameters such as acceleration, orientation, velocity, and position [1, 5]. It contains the derivation of the forwarding and inversing kinematics. Fig. 2 illustrates the frame assignment for the joints in the considered robot.

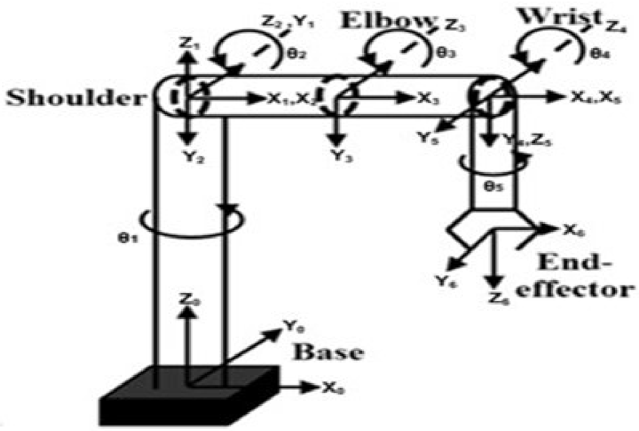

Figure 2. Robot frame assignment

Some information such as the weight in (KG), the payload in (KG) and maximum reaching distance in (m) have been omitted herein because of the space limitation. Eq. 1 describes the overall rotation and translation of end-effector w.r.t. its base [5]:

$$y = \begin{bmatrix} c_1c_5s_{234} + s_1s_5 & -c_1s_5c_{234} + s_1c_5 & -c_1s_{234} & c_1A \\ s_1c_5c_{234} - c_1s_5 & -s_1s_5c_{234} - c_1s_5 & -s_1s_{234} & s_1A \\ -c_5s_{234} & s_5s_{234} & -c_{234} & B \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where $c_1 = \cos\theta_1$, $c_{12} = \cos(\theta_1 + \theta_2)$, $A = l_2c_2 + l_2c_{23} - l_4s_{234}$ and $B = l_1 - l_2s_2 - l_2s_{23} - l_4c_{234}$.

The articulation connections which represent the angles of the robotic handler, which is also called the arm, are derived as follows:

$$\theta_1 = Atan2(p_y, p_x) \quad (2)$$

$$c_3 = \frac{1}{2l_2l_3}\left((c_1p_x + s_1p_y + l_4s_{234})^2 + (p_z - l_1 + l_4c_{234})^2 - {l_2}^2 - {l_3}^2\right) \quad (3)$$

$$s_3 = \pm\sqrt{1 - {c_3}^2} \quad (4)$$

$$\theta_3 = Atan2(s_3, c_3) \quad (5)$$

$$c_2 = \frac{1}{(c_3l_3 + l_2)^2 + {s_3}^2{l_3}^2}\begin{pmatrix} (c_1p_x + s_1p_y + l_4s_{234})(c_3l_3 + l_2) - \\ (p_z - l_1 + l_4c_{234})s_3l_3 \end{pmatrix} \quad (6)$$

$$s_2 = -\frac{1}{(c_3l_3 + l_2)^2 + {s_3}^2{l_3}^2}\begin{pmatrix} (c_1p_x + s_1p_y + l_4s_{234})s_3l_3 + \\ (p_z - l_1 + l_4c_{234})(c_3l_3 + l_2) \end{pmatrix} \quad (7)$$

$$\theta_2 = Atan2(s_2, c_2) \quad (8)$$

$$\theta_4 = \theta_{234} - (\theta_2 + \theta_3) \quad (9)$$

where p_x, p_y and p_z refer to the target distance from the center of the base in all dimensions respectively.

3.2. Dynamic Model

This part characterizes and expresses the relationship amid numerous factors that cause the changes [1, 5]. The Euler-Lagrange scheme has modeled the dynamic approach for the considered robotic. The dynamic model is illustrated as follows [5]:

$$\tau = M(q)\ddot{q} + V(q, \dot{q}) + G(q) \quad (10)$$

$$\ddot{q} = M(q)^{-1}\left(\tau - V(q, \dot{q}) - G(q)\right) \quad (11)$$

q¨denotes the acceleration of the robotics' links where τ represents the torque that is fed, q denotes the link's angular position, $M(q), V(q, \dot{q})$ and $G(q)$ express matrices corresponding to inertia, forces which are Corollis, Centrifugal and gravity respectively.

The Linear Quadratic Regulators, abbreviated as LQR, is expressed as follows:

$$J = \int_0^\infty [x^T(t)Q(t)x(t) + u^T(t)R(t)u(t)]dt \quad (12)$$

where $u(t)$ and $x(t)$ denote the corresponding input matrices and the present state respectively. $R(t)$ represents a genuine proportional affirmative distinct matrix while

$Q(t)$ denotes a clear, certain and real semi-definite matrix. The matrices $R(t)$ and $Q(t)$ are selected and picked to distinctively interpret the roles and involvements of the states and to control inputs [5]. Scholars can get extra information from [5].

To evaluate the average power and energy in the considered robotic system, the components have been allocated to every layer in the HPM approach. This allocation is performed using the proposed method in [2]. Furthermore, HPM is applied after converting that FSM into a Markovian representation [2]. Readers can have more information from [2, 3].

obtaining a relationship to estimate the Average dissipated power and the consumed energy is derived after incorporating and encapsulating all previous equations from (1) to (12), so the needed equation is as follows:

$$DP = (1 * C_{initial}) + [(1 + e_4) * (C_{check} + C_{test})] + [(e_9 - e_8) * (C_{wait} + C_{test})] + [(e_{11} + 1) * C_{decision}] + [e_{11} * (C_{exe} + C_{test})] \quad (13)$$

where DP stands for dissipated power. Thus, the consumed energy is calculated as:

$$\text{Energy} = \text{DP} * \text{T} \quad (14)$$

T denotes the time in second and it is set to 60s = 1 min.

In (13), every variable C is affiliated and linked with its parameter e which denotes a cost in a certain route when going from a starting point to an end point. This route exists in a graph known as a Control Flow Graph (CFG) which is found in [2, 3, 4]. In [2, 3, 4], all needed information about which activities take place in every state and their analysis is found there.

4. EXPERIMENTS AND RESULTS

MATLAB R2017b is used as a simulation tool to perform several experiments. In addition, 4 free tools are used, and those tools have been named earlier. All experiments were conducted on a 64-bit machine that has Windows 10 Professional Operating System and runs using 2.4Ghz I7-8700T/8th Gen. and its memory is 16GB RAM.

So, to estimate DP, the assumption of an even chance of performing an if-else statement is considered, thus p and q in the possibility point of view hold the same value. In each state in Fig. 5, several actions, and procedures along with their computations occur which are detailed in [2, 3, 4]. All movements from the considered robot are divided and fitted into HGFSM so OFs are easily obtained. Furthermore, all equations from (1) to (12) are encapsulated into eq. (13) according to their movements. Thus, every movement is associated with its equations and their computations so every parameter in eq. (13) can be found. The Suspend state is not integrated into eq. (13) since the robot has successfully executed all tasks, hence, no task was sent to this state. The decision and the execution procedures are encapsulated in the processing state.

To compute and identify the values of all e parameters, considering a type of probability distribution being used is taken [2, 3]. Obtaining the overall aggregate entries of visits matrix [V] in every phase/state is vital to verify and compute the Estimated Average Dissipated Power (EADP), which is calculated as:

$$EADP = \sum (V_i * C_i) \quad (15)$$

where i indicates the number of phases in the HGFSM, in this case i starts from 1 and ends with 6. $[V]$ is determined as follows:

$$[V] = [I - P]^{-1} \quad (16)$$

I refers to the identity matrix and P denotes the changing probability matrix. The entries of this matrix represent all probabilities for all phases which are discussed in [2] and is computed as follows:

$$P_{ij} = K_{ij} / N \quad (17)$$

towards a destination state (j), N indicates the total number of activities that exist in the source state.

Now, Actual Average Dissipated Power (AADP) is important to be evaluated to calculate the percentage of error between AADP and EADP which is computed as:

$$E\% = ABS[(AADP - EADP) / AADP] * 100 \quad (18)$$

The execution time for the if-else condition is noticed and observed to have almost no effect on the calculation, hence, it can be ignored and disregarded. Thus, C_{test} is 0. In addition, all activities were executed and delivered successfully and sent into the final state without visiting the Waiting state which implies that C_{wait} = 0. Table 1 lists the values for all parameters C and e in the eq. (13).

Table 1. Parameters values

Parameters	***Value***
$C_{initial}$	*4.98*
C_{check}	*3.04*
C_{test}	*0*
C_{wait}	*0*
$C_{decision}$	*2.14*
C_{exe}	*5.78*
e_4	*0.5*
e_8	*0.5*
e_9	*1*
e_{11}	*1*

The entries of matrix [V] is 1. Now, applying eq. (15) on eq. (13) is performed so the EADP = 4.98 + (3.04 * 1.5) + 0 + (1.5 * 2.14) + 5.78 = 18.53W.

The actual average DP varies between 15.9W which is the minimum obtained reading and 19.82W which refers to the maximum reading from the tools. Those values are being estimated after running all tools more than 100 times and taking the average. Hence, the average value for the actual dissipated power is nearly 17.36W for 1 minute.

The following figures display the values of the actual dissipated power by using the free tools.

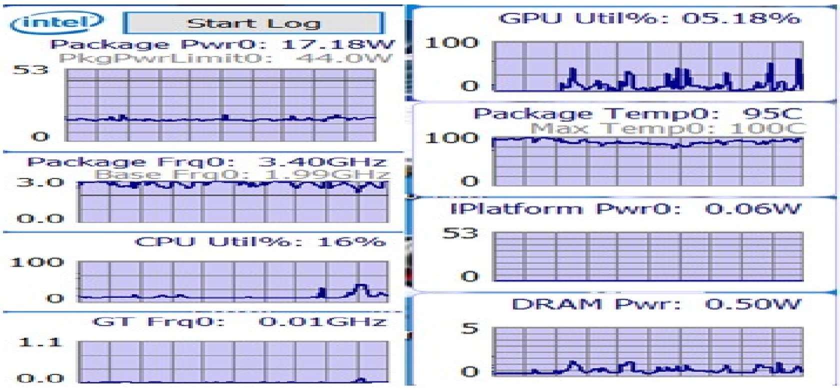

Figure 3. Power consumption from Sidebar Diagnostics

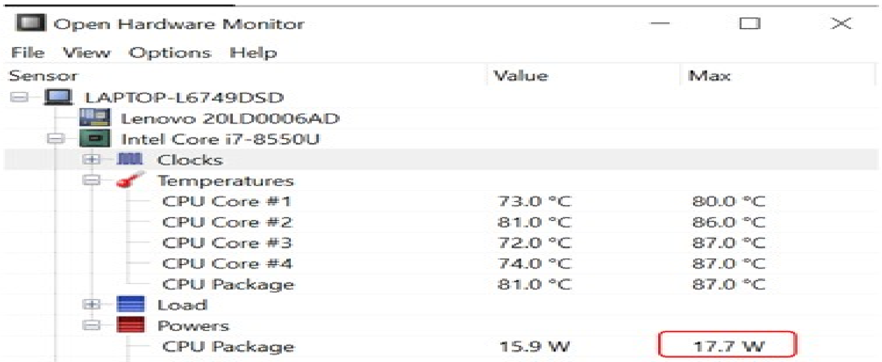

Figure 4. Power consumption from Open Hardware Monitor

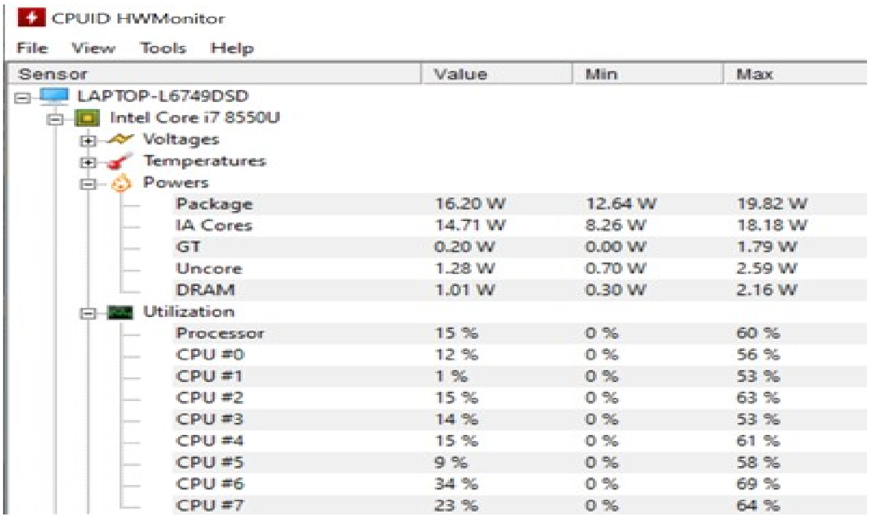

Figure 5. Power consumption from HWMonitor tool

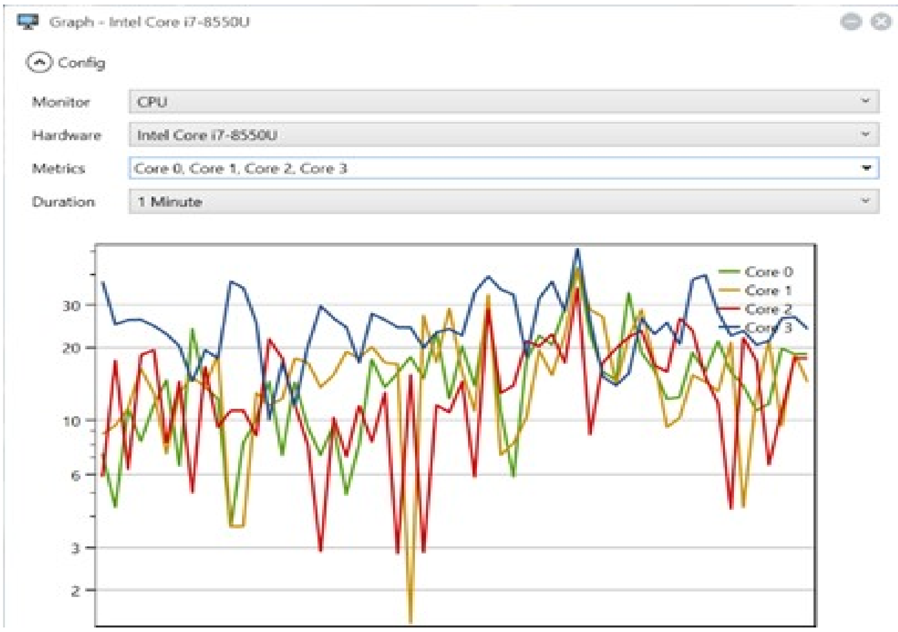

Figure 6. CPU resources utilization

Fig. 7 illustrates the average values of actual and predicted power dissipation in mw while fig. 8 depicts the same for the produced energy for 60s during the simulation experiments.

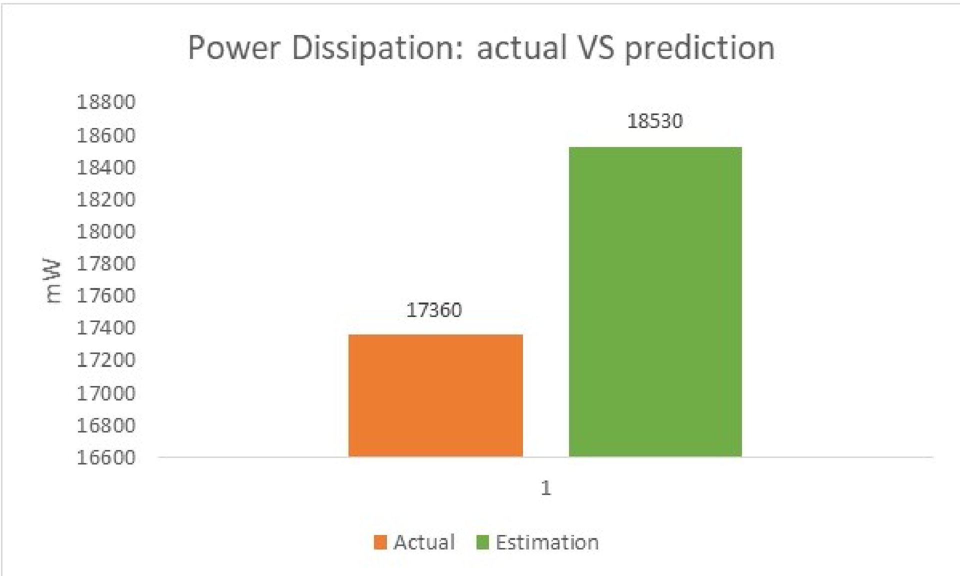

Figure 7. Actual and predicted power dissipation

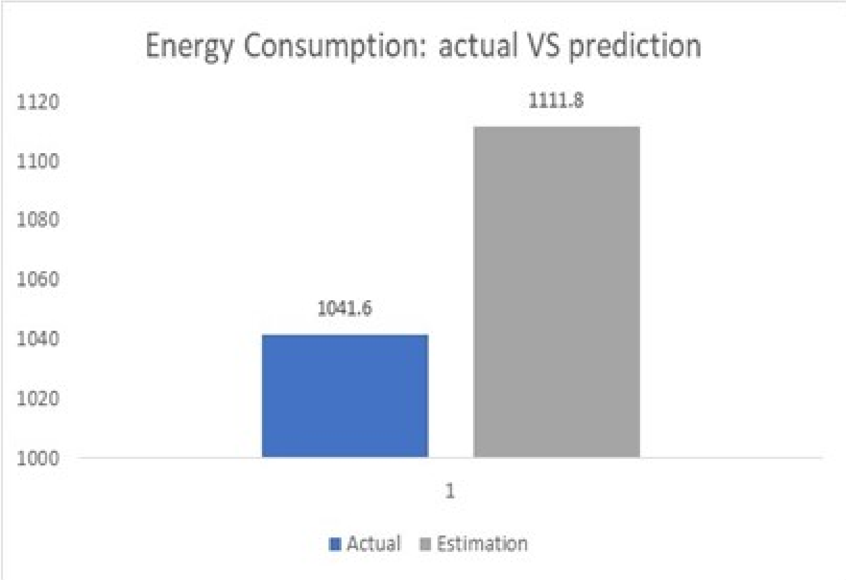

Figure 8. Actual and estimated energy consumption

5. CONCLUSIONS

This research focuses on calculating the estimated average dissipated power and the energy produced from the robot. The obtained results from the analytical analysis, simulation experiments and the free tools show that the calculated values are close to the actual figures. The percentage of error between the actual and the estimated DP and energy has been found to be in acceptable range without using any specific hardware or an expensive software/tool. It doesn't exceed 11% and the minimum value was found around 6.63%. All the obtained results have been estimated after performing profiling on MATLAB for the considered system.

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