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An analysis of the effect of gravitational load on the energy consumption of industrial robots

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1. Introduction

One of the main goals in the implementation of Industry 4.0 (4th industrial revolution) is to create energy-efficient automation systems. This is due to anticipate that in the near future the energy is mainly generated from renewable energy, such as from wind turbine and solar cells. Such energy producers have a barrier in a number of the capacity and the supply is fluctuated, depending on the season and climate [1]. Therefore, in order to solve this challenge, industry should be able to reduce their energy consumption. Furthermore, an industry needs to reduce their energy consumption to improve their company image and to follow the rule from the governmental policy, such as to fit with ISO 50001 concerning energy management.

In line with industry 4.0 philosophy, the industry in the future is operated fully automated, with more industrial robots and machines. So, the energy consumption of the industry is mainly for operating industrial robots and their systems. For illustration, in the current body shop processes in the automotive industry, industrial robots consume about 40% of the total energy [2]. Therefore, developing methods for reducing the energy consumption of industrial robots is an important issue in the manufacturing industry [3].

There are many methods that were proposed by researchers and industries in order to reduce the energy consumption of industrial robots, some of them were summarized in [3-4].

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From the literature review of the current proposed methods, there is no research that investigates the direct correlation of the gravitational load to the energy consumption of industrial robots. Therefore, in this paper the effect of the gravitational load of the robot's arms to its energy consumption is investigated.

Basically, energy optimization approaches for industrial robots can be divided into two groups: methods trying to optimize trajectories of the robot manipulator regarding to energy efficiency [5-6] and methods optimizing control methods in terms of energy efficiency [7]. Those pieces of research lead to variety of proposed control and path planning algorithms. Most of the proposed controllers, however, are variations of computed torque controllers [8].

The variety of proposed control methods can be seen not least as a consequence of the huge number of factors of influence on both energy consumption and accuracy. Examples of those are elasticity [9], operating velocity, characteristics of actuating drives and control parameters [10-11]. One of the challanges in the development of an energy-efficient control for industrial robots is optimizing the joint torques, which are significantly influenced by gravitational load.

The verification of control methods is done by measurements on real systems as well as simulations on the base of models. Many models developed in former research, however, lack in completeness. Naturally, they concentrate on the ability to reproduce certain effects, which are interesting for the respective research. There are models containing only the mechanical and control system [10] without electrical drives, others containing electrical drives but neglecting mechanical elasticity and damping phenomena [5] as well as the gravitational load.

Measurement, on the one hand, does not allow a deep insight into the system. The main problem is that there is almost no possibility to vary internal electrical and mechanical parameters such as damping and friction in a reasonable way for real systems [12-13].

Simulation, on the other hand, helps out, but the major drawback subject to incomplete models is that interrelations of influencing factors can hardly be taken into account [14].

In this work, a modular and extensible simulation models combining mechanical, electrical and control model is proposed. A Modelica-based simulation tool is used as a multi-domain simulation environment. Capabilities of the model are demonstrated by means of trajectory, mechanical and control properties.

2. Modeling and simulation method

This section presents the description and the methodology for the development of a modular industrial robot model that is used for analyzing the effect of gravitational load to the energy consumption. This includes the description of the industrial robot as a whole mechatronic system along with its main components. The Motoman MH5L and ABB IRB 6620 are used as a case study. This work focuses more on the modeling of the industrial robot's internal components, which in common industrial robot modeling methods are simplified or even neglected.

For the purpose of modeling, the robot is divided into four main components, i.e. mechanical structure, motor drive, control systems and energy & position measurement modules (as pointed out in Fig. 1). The mechanical structure is equipped with 3D CAD for kinematics and work space analysis. The motor drive of the robot is developed based on the permanent magnet synchronous motors (PMSM) structure, since it is commonly used in the industrial robot industry. However, in this research, several other motor models were also developed, both from the modification of the standard library (MSL) and the author's version (as shown in Fig. 2).

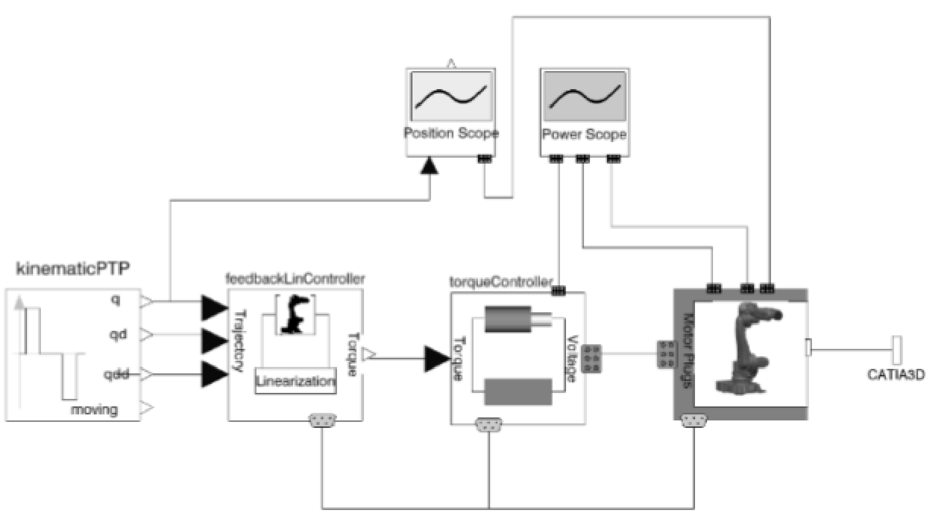

Fig. 1. Model of the complete system including mechanics, electrics, control and path-planning.

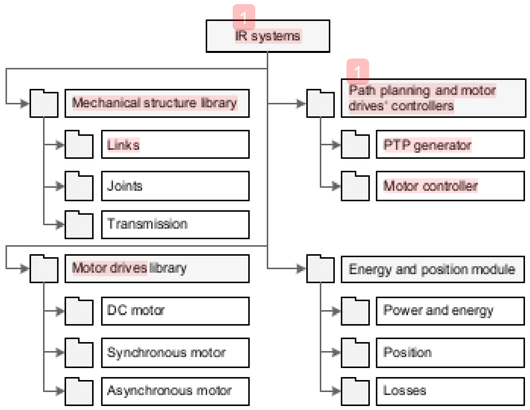

Fig. 2. The main components of the industrial robots (IR) and their sub-components.

The control system of the industrial robot is modeled using single axis position controllers, while to create the robot movement, a PTP (point-to-point) planner is used. Besides these main components, the energy evaluation module is created for visualizing the energy consumption and the power losses of the robot, and the position evaluation module is used to monitor the position of the robot arm.

To cope with the modularity requirement, other several robot models are also developed and examined. This modularity was possible by developing the standard component models of industrial robots. Thus, it can be used for other industrial robot models by changing the robot parameters, such as the dimensions, the 3D model and motor specifications. However, the modular model also has a limitation in its model accuracy, due to the limited data that can be obtained from the industrial robots' manufacturers.

Thus, a verification and validation of the simulation models and their results is suggested in almost every engineering simulation work to ensure that the digital models are an accurate representation of the real system under study [14]. As shown in Fig. 3, a verification and validation method for analyzing and improving the simulation model of the industrial robots is used.

The verification activity focuses on the internal components of the simulation process, e.g. the integrity of the mathematical and simulation code and their accuracy; while the validation activity is done by using experimental investigation to define the accuracy of the developed model.

The verification and validation of the industrial robot model is performed based on the standard procedure that was developed by SCS (the society for modeling & simulation international), as shown in Fig. 3. However, due to limited experiment time and for efficiency purpose, a verification and validation process is designed for a specific operation condition of the industrial robots, which is also commonly employed in the verification and validation process. This means that the collected data for validation is only based on these specific conditions. Therefore, the simulation model cannot prove its accuracy for all possible operation conditions. However, it can provide the evidence that the models are accurate for the purpose of the study, especially for energy examination.

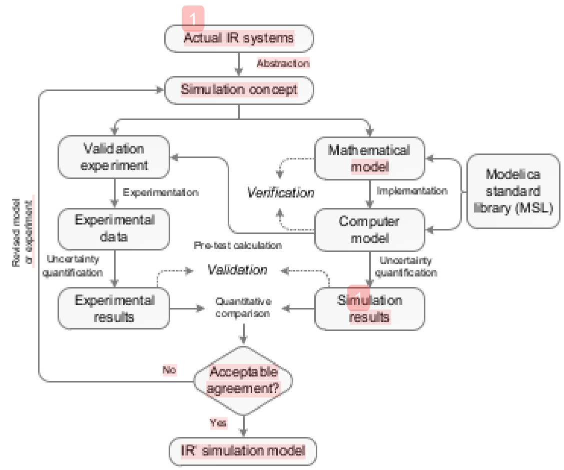

Fig. 3. The model development, verification and validation process of the industrial robot model.

The deviation between the simulated and experimental results is between 2-5%, this value is relatively low and within the defined acceptance criteria, which is set at a maximum of 7%. Based on the analysis, the deviation is caused by several factors, such as the limitation of the software tool for modeling the robot's operating conditions [1].

3. Results and analysis

In the normal installation position (vertical position), a six-axis industrial robot has to bear the gravitational load on axis 2, 3 and 5, while the gravitational load for axis 1, 4 and 6 is relatively small and therefore can be treated as negligible. Thus, the investigation of the influence of the gravity load on the energy consumption is performed here by analyzing the energy consumption behavior of axis 1 and 2, since in axis 1 the gravitational load is relatively small compared with axis 2.

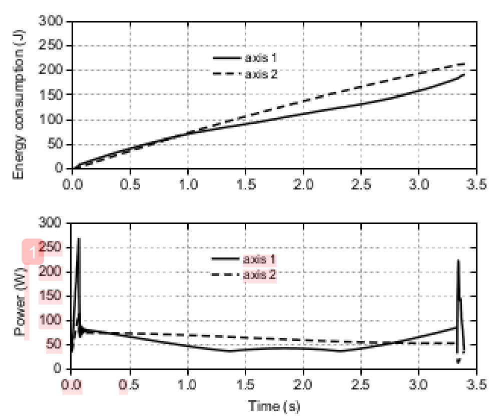

Fig. 4. Effect of the gravitational load on robot power and energy consumption (Motoman MH5L, at 20% of maximum speed and a 3 kg payload).

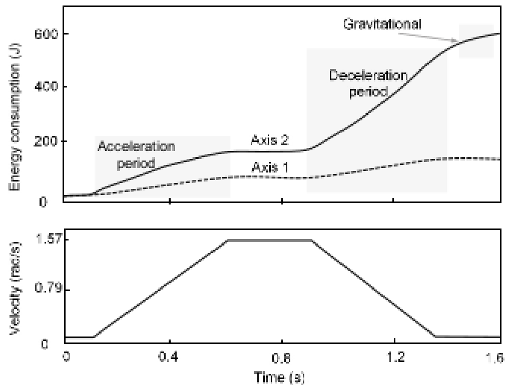

Fig. 5. The effect of the gravitation load on robot energy consumption for ABB IRB 6620.

In relation to the gravitational effect, the simulation results are shown in Fig. 4. The curves indicate that axis 1 has only to bear the torque effect but axis 2 needs to compensate not only for the torque but also the gravitational load as well. The figure also indicates that the gravitational load for a small robot like MH5L is not significant. However, in the heavier robot system, which has a greater mass, the gravitational load is significant (as shown in Fig. 5). In Fig. 5, the experiment is conducted on the ABB IRB 6620, which is 900 kg in weight with a maximum handling capacity of up to 150 kg.

Since the result shows that the gravitational load has a major influence on the robot energy consumption in the high-mass indutrial robot. Thus, the position of the installation of the robot also has a big influence on the energy consumption. Consequently, finding suitable positions for robot installation can also be used to reduce the energy consumption, which in many cases means the vertical position is more energy efficient than the horizontal position. After considering process layout constraints, installing the robot on the vertical position is suggested, whenever possible.

These investigation results also indicate that during the standstill position, the robot needs a big amount of energy to maintain the position of the axis and to resist the gravitational load. Thus, it is suggested to choose a standstill arms position which requires small gravitational loads, when not in operation. Another solution, proposed in [15], for reducing the energy during standstill-mode, is by using a mechanical brake system for one or more robot axes. However, the amount of the energy reduced depends on the standstill duration. This means that when an industrial robot is often in operation at the standstill-mode and for a long duration, it is suggested to implement this energy reduction method. Furthermore, since the brake mechanisms in many industrial robots used to maintain the standstill position do so by using a permanent magnet or a spring-set brake system, early brake release is suggested to reduce the energy that is used for both holding the brake and counteracting the gravitational load [6].

However, on industrial robots, the gravitational load can be used to reduce the load of the motor drive when the robot arms are performing a downward motion. Therefore, this motion recuperates some energy. Since many motor drives employed in industrial robots have two different modes, this can be performed by setting the motor drives in a generator mode instead of a motor mode. Future investigations, on the control strategy to optimize energy recuperation, should offer interesting insights.

4. Conclusion

This paper investigates the effect of the gravitational load to the industrial robot's energy consumption. Mechatronic modeling method using a Modelica-based simulation tool was used. The entire electromechanical model of the industrial robot Motoman MH5L and ABB IRB 6620 are successfully developed. The models were built in a modular way, easing extension and variation, for example in terms of adaption to other industrial robots or investigation of different control principles. The applied model based computed torque controller is supposed to cover a wide range of proposed control setups, since many of them are derivatives of the computed torque approach.

However, because of the fact that detailed mechanical, electrical and control parameters are unknown and withheld, the real systems can only be approximated as far as the made assumptions admit. Nevertheless, the model itself is coherent. One the one hand, its behavior with regard to energy consumption could be explained by investigation of internal quantities, such as joint torques. Their accessibility is a major advantage of simulation.

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