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Application of a mathematical model for the Motoman MH-50 industrial robot's electric drive system

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ABSTRACT

In recent years, there has been a great interest in the transition to digital and automation services for dangerous and menial working processes. Due to its MH50-35 industrial robot, Motoman's properties allow us to improve the control system of an electric drive for industrial robots. The structure of the electric drive for six-axis robot manipulator performance can be superior to conventional Drive Control servos for motor excitation, and a novel automation system can be implemented for its servo performance. To solve these issues, we propose an optimization strategy that allows us to achieve an increase in productivity and labor safety in the industry, reduce the percentage of defects, guarantee product uniformity, and reduce the prime cost of production of items. Ideal conditions were anticipated using a mathematical model. In this study, by using a statistical model, the ideal conditions were synthesized. The optimization of the control system of an electric drive for industrial robot analysis was carried out, and our findings suggest using this model in industrial production to elucidate problems such as high accuracy and speed indicators.

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1. INTRODUCTION

Meeting the demand for better performance and still making profitable robots is in turn a considerable challenge for robot manufacturers. However, stricter requirements increase the cost, and a key factor for success is finding the most profitable balance between quality, performance, and cost. The availability of inexpensive, high-performance digital signal processors with automatics allows the implementation of a novel algorithm for driving applications to execute a wide range of work, such as transferring objects and welding operations [1]. According to the given information by the International Federation of Robotics [2], there are only 4 robots per 10,000 employees in the Russian Federation. For comparison, in Korea, the number of robots reaches 710 units for the same 10 thousand employees [3]. In that way, the issue of robotization of welding processes is relevant for consideration in manufactory conditions in the Russian Federation and gives perspective for integration into production, particularly in metallurgical manufacturing. For the robotization of various production processes, it is most expedient to use axial robot manipulators, which differ from each other by their great versatility and the ability to set virtually any trajectory of movement. To carry out the robotization of various production processes, it is practical to use axial robotic manipulators, which are distinguished by great versatility and the ability to set virtually any movement trajectory [4].

It is not always possible in practice to test the maximum lifts on an industrial robot. Therefore, it is useful to be able to carry out mathematical modeling of the operation for both: a separate robot drive and the entire manipulator. Finally, there is a need to develop a model of an industrial robot to conduct preliminary studies to determine the maximum loads and emergency modes of operation.

The purpose of this work is to explore the elaborate mathematical model of the electric drive of an industrial robot based on a six-axis robot manipulator. Several tasks need to be accomplished to achieve a goal: i) to carry out an analysis of electric drives, which are used in modern industrial electric drives, ii) to perform synthesis of the control system electric drive control system, and iii) to research the modified model of the electric drive of an industrial robot [5].

2. METHOD

The practical significance consists of the research of the automation system having been carried out and the structure of the electric drive having been studied on an industrial robot, which affects the quality of obtaining a welding seam. A six-axis robot manipulator MH50-35 [6], [7] model of the company Yaskawa was chosen as a basic industrial robot, the parameters of which are shown in Table 1. This robot is universal and was designed to execute a wide range of tasks, such as transferring objects and welding operations. There are some restrictions on the rotation axes in this robot, and these ranges are stated in Table 2.

Table 1. Parameters of the robot manipulator

Parameter	Dimension	Value
Controlled axes	-	6
Maximum payload	kg	35
Repeatability	mm	±0,07
Horizontal reach	mm	2,538
Vertical reach	mm	4,448
Weight	kg	570
Power rating	kVA	4.0
Power requirements	-	3-phase 240/480/575 VAC at 50/60mHz
Safe temperature	°C	0…45
Permissible humidity	%	20…80

Table 2. Restrictions of the robot manipulator

Axis	Maximum motion range [°]	Maximum speed [°/sec]	Allowable moment [N·m]	Allowable moment of inertia [kg·m^2]
S	±180	180	-	-
L	+135/-90	140	-	-
U	+251/-160	178	-	-
R	±360	250	147	10
B	±125	250	147	10
T	±360	360	78	4

Restrictions arise due to the mechanical part and cannot be changed, nevertheless. For various purposes, it is also possible to set artificial restrictions. For example, limitations on the working area or reducing the speed of rotation axes due to the requirements of the technological process. The working area with the restrictions given in the table is shown in Figure 1. In addition, this figure shows the dimensions of each of the links.

Spherical wrists are a key component of almost all modern arm-type robots. They feature three orthogonal rotational axes that meet at a single location. This is a gimbal-like mechanism. At the wrist's median point, the pose, location, and orientation of the robot end-effector are established. The wrist axes produce no translation since they meet at the same location. Therefore, only the first three joints can affect where the end-effector is located. An arbitrary end-effector orientation is achieved independently of the three wrist joints [8], [9].

For electric drives, which are applied in the operation of robotic devices, requirements are i) high precision in positioning; ii) positional error is kept to a minimum; iii) speedy operation; iv) no over-regulation in the position channel, a wide range of regulatory coordinates, lightweight to reduce the load on the axis of rotation of the robot; and v) engine compliance overload capacity, mechanical rigidity at its highest. According to the requirements, the most appropriate types for application in the servo drives of an industrial robot are synchronous engines, with permanent magnets, valve engines, and brushless DC motors [10], [11].

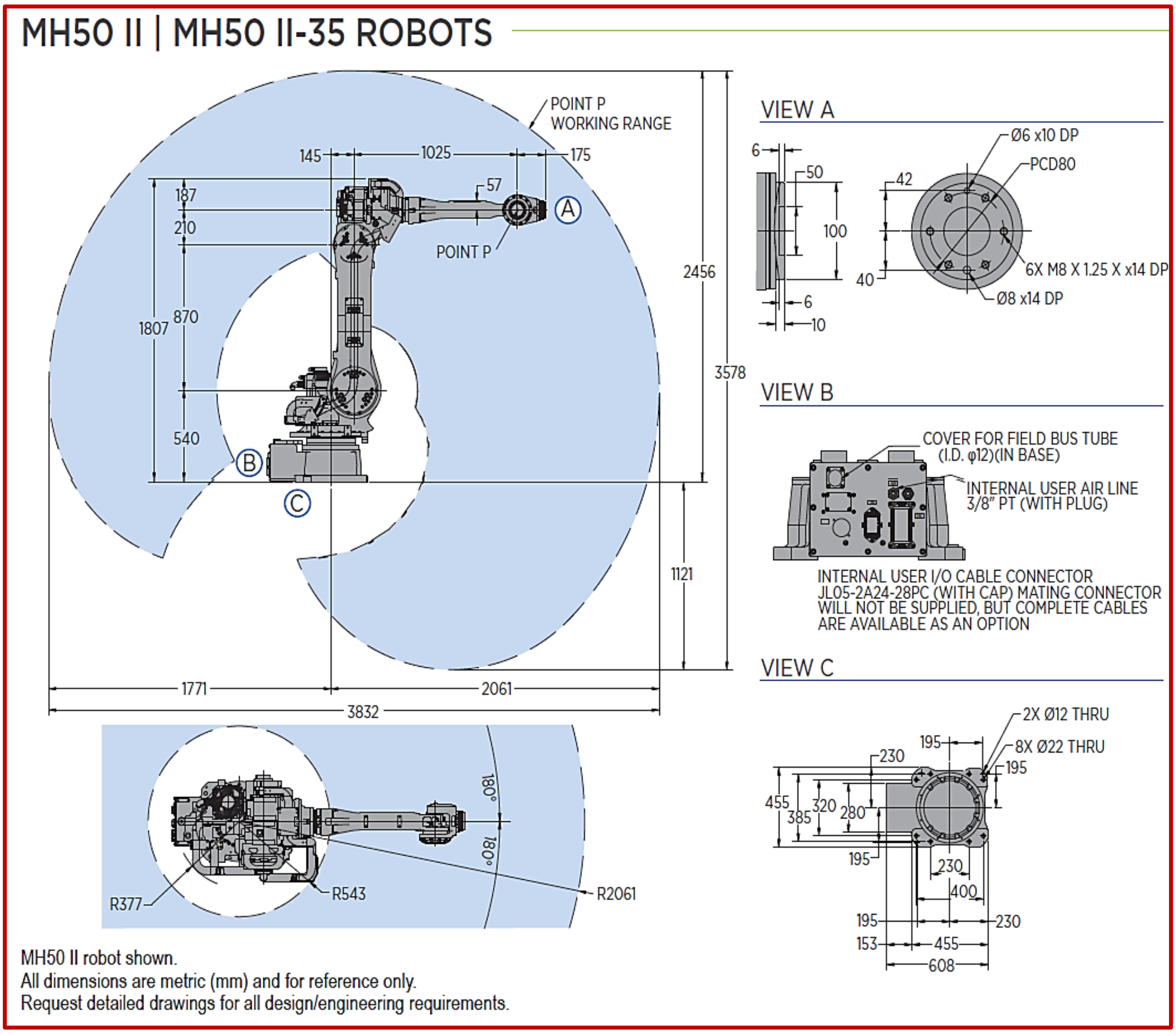

Figure 1. Six-axis robot manipulator

A system of equations in *dq*-coordinates was chosen as a base system of (1) to model the operation of an electric drive of an industrial robot [12].

$$\begin{cases} U_d = R_S \cdot I_d + L_S \cdot \frac{dI_d}{dt} - \omega \cdot Z_p \cdot L_S \cdot I_q \\ U_q = R_S \cdot I_q + L_S \cdot \frac{dI_q}{dt} + \omega \cdot Z_p \cdot L_S \cdot I_d + \omega \cdot Z_p \cdot \Psi_f \\ M_e = \frac{3}{2} \cdot Z_p \cdot (I_q \cdot \Psi_d - I_d \cdot \Psi_q) \\ \frac{d\omega}{dt} = \frac{1}{J} \cdot (M_e - M_f) \end{cases} \tag{1}$$

U_d and U_q are the components of the stator voltage vector (V); I_d and I_q are the components of the stator current vector (A); Ψ_d and Ψ_q are the components of the stator flux linkage vector (Wb); Ψ_f is the flux linkage of the permanent magnets of the rotor (Wb); Z_p is the number of motor pole pairs; M_e is the electromagnetic torque of the motor (N·m); M_f is the static moment of resistance (N·m); J is the moment of inertia of the engine (kg·m^2); R_S is stator phase resistance (Ohm); L_S is stator phase inductance (H); and ω is the rotor speed (rad/s).

Theoretical studies are based on the basic provisions of the theory of electric drive and the theory of automatic control. The studies of block diagrams were carried out using the apparatus of transfer functions and methods of structural modeling. Mathematical models are developed in the MATLAB package (Simulink application). Experimental studies were carried out on the developed laboratory setup, and the method of direct oscillography of coordinates was used, followed by mathematical processing of the results.

3. RESULTS AND DISCUSSION

We designed the model of an electric drive control system for an industrial robot to analyze the possibility of its use as an automated system for performing the welding process. The main requirements when performing welding operations are high accuracy and speed indicators. Therefore, a vector control system using an absolute encoder [13], [14]. In this case, the control system will comply with the vector control system used in high-precision drives, as presented in Figure 2.

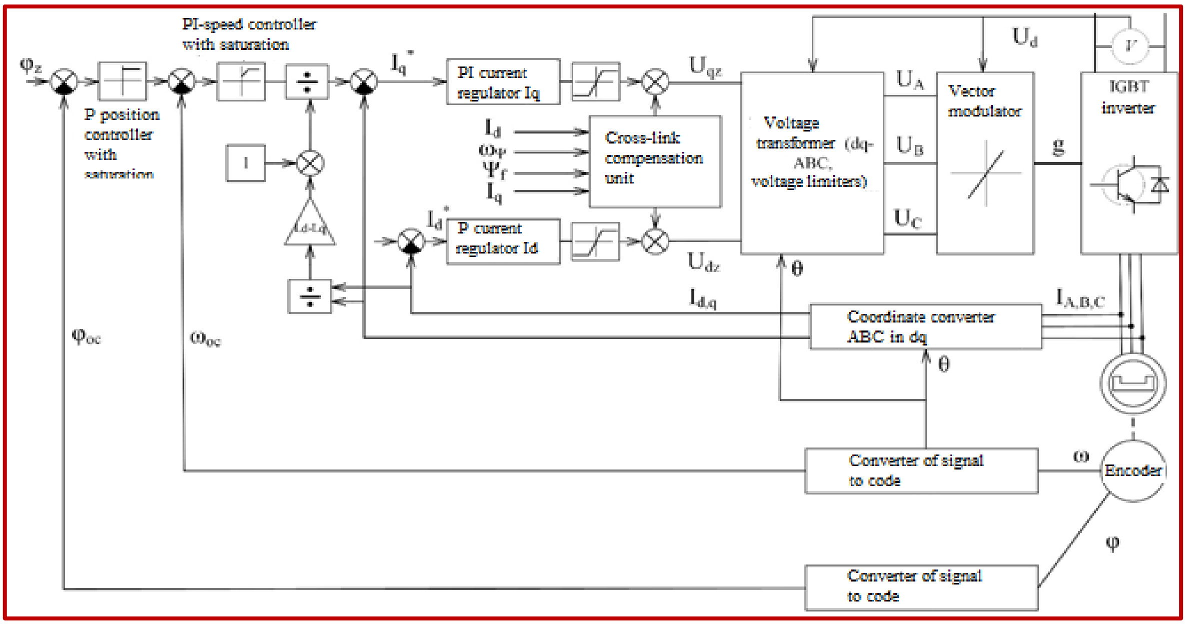

Figure 2. The servo-drive control system of the industrial robot

A robot servo-drive comprises an actuator or motor and transmission to connect it to the link. Consideration of each joint or axis as a separate control system that tries to precisely follow its joint angle trajectory is a popular strategy for controlling robot joints [15], [16]. However, as we expected this is complicated by various disturbance torques due to gravity, velocity, and acceleration coupling, as well as friction that acts on the joint. Nesting control loops are a widely popular type of control structure. The scheme of the servo-drive control system of the industrial robot includes a frequency converter, engine, absolute encoder, signal converters from a three-axis fixed coordinate system to a two-axis rotating one, current transducer, current, speed, and position regulators, and cross-link compensation unit [17]–[19]. To obtain dynamic characteristics of the electric drive of an industrial robot, it is necessary to synthesize a virtual model of the engine. The model developed in the MATLAB Simulink software is shown in Figure 3.

The system was made digitally and added an extra regulator, which performs the calculation of the derivative of the assignment channel by position, adding the resulting value to the speed contour [20]. It allows us to significantly increase the performance of this system. Besides that, the ramp generator has been added instead of a filter circuit at the input of the speed setting for the possibility of changing the acceleration. To take into account the dependence of the torque on the angle of rotation of the axis, blocks were added to calculate the cosine of the perturbation angle.

Both the torque and speed of electric motors are constrained. The maximal current that the drive electronics can deliver determines the maximum torque [21], [22]. A motor also has a maximum rated current at which it risks overheating or demagnetizing its permanent magnets, reducing its torque constant permanently. The mechanical output power has a maximum value and is calculated as the product of motor torque and speed. Motors can withstand certain overloading, peak power, and peak torque for brief periods, but the sustained rating is much lower than the peak. Signals of the driving and disturbing influences, as well as the transient characteristics of the system, are shown in Figure 4.

Based on the obtained graphs, it can be concluded that i) the current does not exceed the maximum values; ii) the moment varies according to the cosine law, at the beginning of the work, there is a starting moment of 10 Nm; iii) the speed reached a steady value in 0.45 seconds, which corresponds to an acceleration of 6.5 rad/s^2; and iv) the transition time in the position contour was 1.3 s, which corresponds to the theoretical calculation.

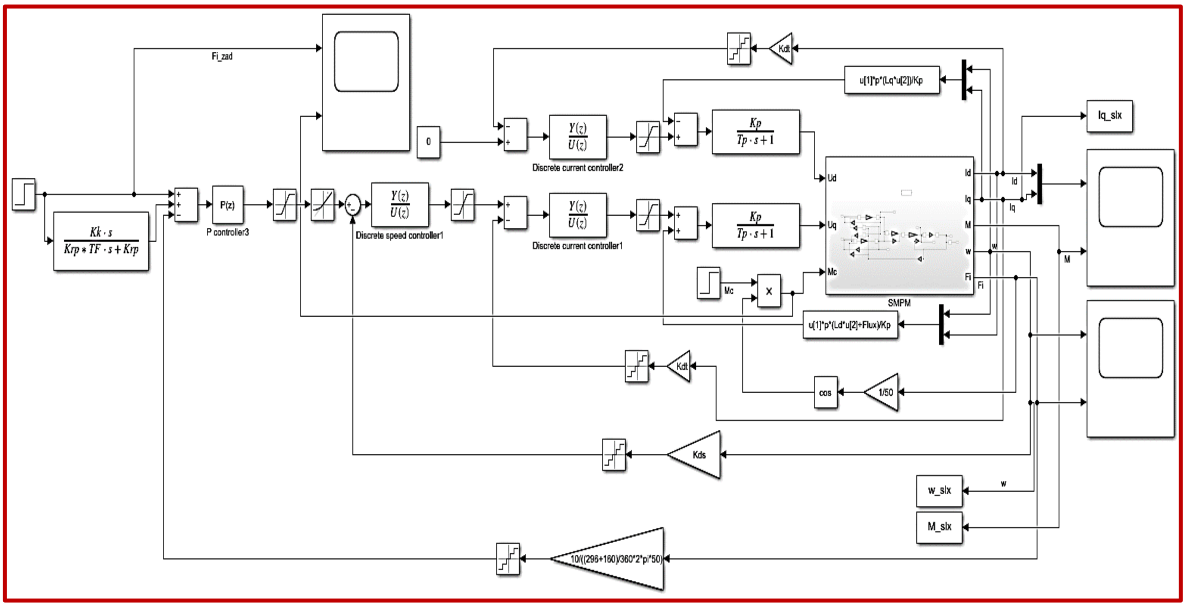

Figure 3. Control system of the synchronous motor with permanent magnets

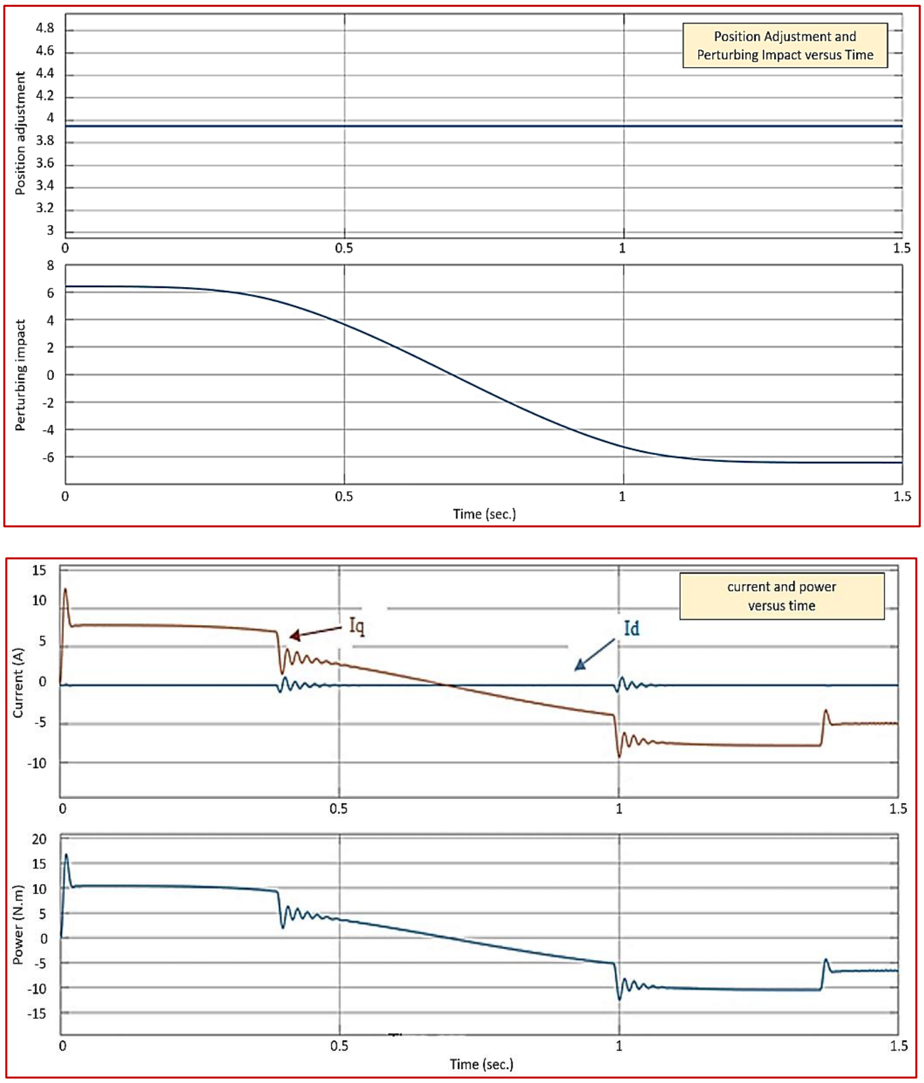

Figure 4. Transient characteristics of the system

A spinning motor acts like a generator and produces a voltage called the back electromotive force (EMF) which opposes the current flowing into the motor. Back EMF is proportional to motor speed, where the motor torque is constant, whose units can also be interpreted. When this voltage equals the maximum possible voltage from the drive electronics, then no more current can flow into the motor and torque falls to zero. This provides a practical upper bound on motor speed and torque at high speeds [23]–[25]. Accordingly, the developed model of the electric drive can be used to perform welding operations. It is necessary to select the equipment for the implementation of the welding process, as well as to research the developed algorithm on real equipment.

Based on the technical characteristics of the Yaskawa Motoman MH50 robotic arm, its mathematical model was developed. The developed mathematical model even taking into account the accepted simplifications in the mechanical part of the robot, can be used as a digital twin of an industrial robot, allowing preliminary tests to determine the maximum loads.

4. CONCLUSION

This research work offers a novel scheme for the industrial robot servo control system. The steady-state performance of the permanent magnet synchronous motor (PMSM) driven by the control system can be improved to a certain level based on the appropriate dividing criterion of active factors discrete values. The results of the experiments show unequivocally that the torque and flux linkage of the PMSM powered by the control system scheme are well controlled, with smaller steady-state ripples and faster transient response performance.

Investigated concept of a system in industrial robots was applied to welding operations. From an industrial standpoint, the result is the reduction of costs while simultaneously managing the trade-off between lifetime and performance. It needs some practical experiments by using a developed control system model on a real industrial robot to study the effects of all the factors, and the optimum combination of all the variables can be revealed, which requires some time and effort. With all these advantages, it will be used not only in welding processes but also in other areas in the future.

In comparison to manual manufacturing, robots enable higher production quality at lower operating costs. They support the production of more components with fewer flaws while utilizing less machinery and keeping their adaptability for future developments.

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