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Physical Modelling of Energy Consumption of Industrial Articulated Robots

Akeel Othman[1], Květoslav Belda[2] and Pavel Burget[1*]

[1] Department of Control Engineering, Faculty of Electrical Engineering, Czech Technical University in Prague
Karlovo nám. 13, 121 35 Prague 2, Czech Republic (pavel.burget@fel.cvut.cz) * Corresponding author
[2] Department of Adaptive Systems, Institute of Information Theory and Automation of the CAS
Pod Vodárenskou věží 4, 182 08 Prague 8, Czech Republic (belda@utia.cas.cz)

Abstract: The paper deals with a modelling of the energy consumption of industrial articulated robots. The proposed modelling way is based on graphically-oriented computer-aided concept that exploits CAD software Solidworks and simulation environment MATLAB/Simulink with SimMechanics and SimPowerSystems libraries. These software tools are used for the composition of a dynamical simulation model that represents both mechanical robot structure and robot drives during robot motions. The paper addresses mathematical analysis and interpretation of the considered simulation model. Here, equations of the motion for the mechanical robot structure and appropriate dynamical equations of the robot drives are introduced. Using these equations, the energy consumption equation is defined. The proposed way is demonstrated by simulation experiments for several different velocities of the robot motion along a selected trajectory. For the experiments, industrial articulated robot KUKA KR 5 arc driven by PMSM drives is considered.

Keywords: Industrial articulated robots, energy consumption, mathematical analysis, computer-aided modelling.

1. INTRODUCTION

The robots are utilized widely in industrial applications due to their flexibility, accuracy and high performance. They comprise the essential parts of modern production lines and belong to the parts with the substantial energy consumption. Nowadays, the energy cost continually rises with correspondence to increasing energy demands. In this respect, new methods for measuring, prediction and optimization of a robot energy consumption are required to be developed. There exist several methods that determine energy consumption. They are based either on mathematical analysis, or on direct measurement on real robot. Mathematical approach, e.g. in [1] and [2], follows from a specific expression of an energy consumption equation in dependence on given robot trajectory [3]. On the other hand, the approach based on real measurements focuses on processing and analysing real data such as in [4], [5] and [6]. It combines specific direct measurements of the energy consumption with its computer evaluation.

This paper deals with a description of the fully graphically-oriented computer-aided modelling and its mathematical analysis that is used for the determination of the robot energy consumption. It represents specific mathematical approach. The computer-aided modelling follows from a pure geometrical 3D CAD model. This model is split by the CAD software Solidworks into particular robot components that are supplemented with appropriate physical parameters as volumes, masses and moments of inertia. It is shown that such component model, which represents physically a mechanical robot structure, can be converted into a simulation model operated in the Matlab/Simulink environment. This model is completed by blocks representing the robot drives.

The significant contribution of the paper consists in a mathematical analysis and interpretation of composed graphically-oriented simulation model of the robot. On the basis of the mathematical analysis, the robot energy consumption function is expressed, which allows finding the amount of energy needed for a robot motion along a given trajectory for an admissible range of velocities. Then, the energy consumption function can illustrate the optimal speed for the given trajectory. The evaluation of the robot consumption is shown for selected point-to-point motion task applied to the robot KUKA KR 5 arc as an example of an industrial articulated robot. The energy function can be used e.g. in a global optimisation of the energy consumption for a robotic cell that contains several robots. Such an approach has been presented in [7] and is subject to further research.

The proposed design demonstrates a full exploitation of the advantages of the software tools Solidworks and MATLAB/Simulink with SimMechanics and SimPowerSystems libraries, as single environments for multiple physical domains with customisation of physical components and extensive range of tools for various analyses and 3D visualisations. Such a design enables user to create efficient models very close to kinematic and dynamic behaviour of real robots.

The paper is organized in the following way. Section II deals with graphically-oriented computer-aided modelling used for the design of physical simulation model. Section III outlines mathematical analysis of the physical model including the model of the robot structure and the model of the robot drives. Section IV is dedicated to the equations of electric input power and robot energy consumption. The illustrative evaluation of the robot energy consumption is presented and demonstrated in Section V by a set of simulation experiments.

2. PHYSICAL SIMULATION MODEL

This section deals with a design of the physical model. The design arises from a pure geometrical model and its modifications within software Solidworks (Subsection 2.1). A conversion of the modified Solidworks model into a Simulink model is considered (Subsection 2.2), where the Simulink is taken into account as the target environment for the simulation. The obtained physical model represents the robot structure (part 2.2.1) to which a suitable model of the robot drives (part 2.2.2) is connected. In this way, the complete simulation model is composed.

2.1 Physical 3D CAD Model in Solidworks

Let pure geometrical model be considered, see e.g. [8]. Such models usually represent the overall robot surface only, i.e. the model does not consist of individual physical robot elements with appropriate physical parameters. Thus, for physical parameter inclusion, the initial model has to be split into individual robot elements. This operation is realized by Solidworks software. By specification of the robot element density, as only one necessary parameter, other physical parameters (masses, moments of inertia and centers of gravity) are computed automatically by Solidworks. To prepare proper kinematic relation for a simulation model, the individual elements of the physical model are connected to particular coordinate systems for articulated robots to Denavit and Hartenberg frames (DH-frames) [9] as it is shown in Fig. 1.

The physical robot model is synthesized using the kinematic constraints among individual robot elements. The kinematic constraints define the motion between two neighbourhood elements in correspondence to the appropriate admissible number of degrees of freedom (DOF). In case of articulated robots, there is always one DOF for rotation in each robot joint. The individual robot elements are assembled in Solidworks by definitions of their constraints via mates as it is described in [10]. Each mate applies a geometric relationship between mate entities on each robot element (robot joint, link, flange etc.).

One DOF in rotation is obtained by applying Solidworks-mates as follows. First, one concentric mate between the cylindrical joint hinge of the two robot elements is applied. Then, the joint DOF are reduced from six to two DOF – translation and rotation along the rotation axis. Second, an appropriate coincident mate between two planes normal to the cylindrical axis is used. Thus, the joint DOF are finally reduced to only one DOF – rotation around the hinge axis of the joint [10].

Applying this procedure for all robot elements, the final physical model, consisted of just all individual robot elements, is ready for a conversion into the target simulation model under MATLAB/Simulink environment.

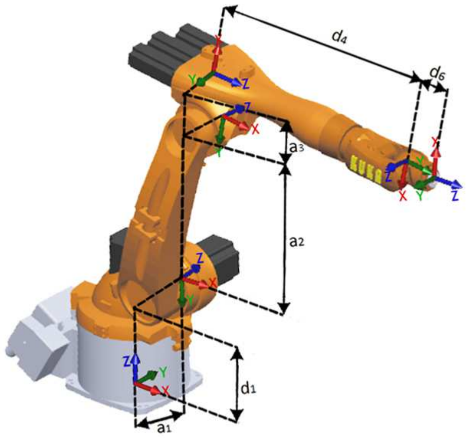

Fig. 1 CAD model of articulated robot in Solidworks.

2.2 Simulation Model in MATLAB/Simulink

The simulation model consists of a model of the robot structure and robot drives. The former component is generated automatically from Solidworks [11] and later component (drives) is constructed directly in Simulink environment [12]. The following two subsection parts show the arrangement of these two components. The complete model will be shown in third part.

2.2.1 Modelling of Robot Structure

The initial Simulink model of the robot structure is generated from Solidworks according to procedure described in [10]. The obtained model Fig. 2 consists of standard blocks of SimMechanics library [11].

The meaning of the blocks in Fig. 2 is the following. (A) is a World frame block. It represents the global reference frame (basic frame), therefore other frames are defined with respect to this frame. (B) is a Mechanism configuration block of general parameters used in the simulation e.g. gravity acceleration and sampling. (C) is a Solver configuration block defining simulation property information. (D) is a Rigid transform block representing a transformation matrix that allows a follower (following mechanical robot element) to rotate or to shift (or both motions together) with respect to the basic frame. (E) is a Link block, which represents the rigid body with its DH frame and appropriate information about body mass, moment of inertia in respect to its center of gravity. (F) is the Revolute joint block with one DOF. The information about its angle, angular velocity, angular acceleration and actuating torque are obtained from a built-in joint sensor. (G) is the next Link connected to the next revolute robot joint. (H) is a Path generator. It feeds the trajectory coordinates to each joint through block (I) called Simulink-PS Converter that converts the unit-less signal inputs into physical signals with appropriate physical units. On the contrary block (J), called PS-Simulink Converter, converts physical signals into Simulink value signals. (K) is a Scope block that serves for drawing the signals of kinematical quantities.

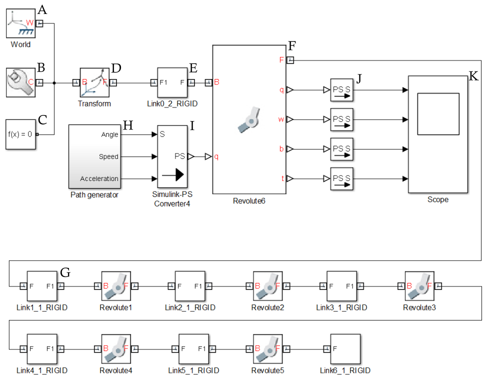

Fig. 2 Block diagram of robot structure in Simulink.

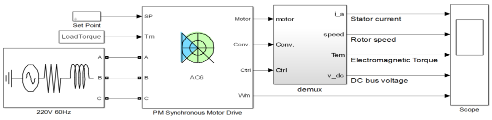

Fig. 3 Block diagram of robot drives in Simulink.

The simulation model in Fig. 2 is done generally. However, it requires to specify proper physical parameters of a robot motion. They are inserted to blocks B, F and H. While blocks B and F need only modification of parameters (gravity vector etc.), block H requires a detailed user specification defining the robot motion, which can be done in different ways that depend on the order of the acceleration polynomial. In our case we choose the acceleration polynomial of zero order i.e. constant acceleration and deceleration leading to the fastest motion [13], which is suitable for the purpose of this paper.

2.2.2 Modelling of Robot Drives

Let the Permanent Magnet Synchronous Motor (PMSM) drives be considered as widely used robot actuators. An appropriate PMSM model block from SimPowerSystems library of MATLAB/Simulink is shown in Fig. 3, whereas the PMSM block consists of six main blocks as shown in Fig. 4. These blocks form together one PMSM drive system, which has three inputs (one three-ABC-phase power source, load torque and speed set-point) and four outputs (stator current, rotor speed, electromagnetic torque and DC Bus voltage). For a determination of the energy consumption of PMSM motor, the electromagnetic torque is crucial. It is in the proportion with the input energy needed for the robot motion along a desired trajectory.

2.2.3 Complete Simulation Model

As mentioned, the complete simulation model of the robot consists of the model of a robot structure and the model of the appropriate robot drives. It determines necessary torques for the required robot motion. The model can be used for the determination of the energy consumption. The consumption is computed by additional Simulink block as indicated in Fig. 5.

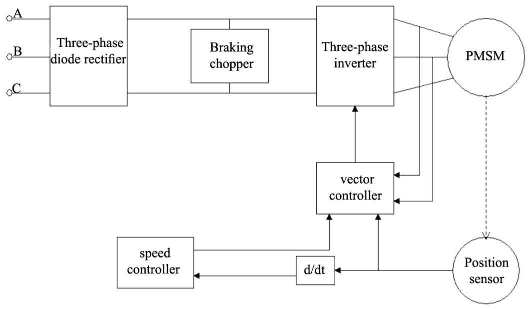

Fig. 4 Conceptual control diagram of PMSM drive.

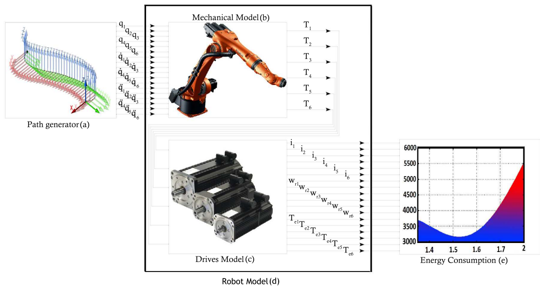

Fig. 5 Complete simulation model of the robot.

3. MATHEMATICAL ANALYSIS OF SIMULATION MODEL

In this section, the mathematical analysis of the simulation model Fig. 5 is described with considering 6-DOF robot structure in Fig. 1. Since it consists of both mechanical robot structure and drives, the mathematical description has to address pure mechanical equations of motion and also dynamical electro-mechanic equations.

3.1 Mathematical Model of Robot Structure

To obtain mathematical model of the mechanical structure, the kinematic and dynamic relations of given robot have to be considered. The following subsection parts make appropriate overview and show specific key-points of the mathematical description leading to the equations of motion.

3.1.1 Description of the Robot Kinematics

Let two main descriptive coordinate systems be considered. One, usually Cartesian coordinate system, describes the motion of robot end-effector in natural Cartesian coordinates. The second system is connected with the description of the robot motion from the drive point of view. It uses joint coordinates. In our case, for purpose of the evaluation of energy consumption, the initial coordinates are the joint coordinates that are also the coordinates of equations of motion. The transformations among individual joint coordinates system (DH frames as in Fig. 1) are necessary for construction of these equations. The transformations describing kinematic relations are defined as a specific matrix according to DH approach as follows

$$T_{i-1}^{i}=\begin{bmatrix} cos\vartheta_i & -cos\alpha_i\, sin\vartheta_i & sin\alpha_i\, sin\vartheta_i & a_i\, cos\vartheta_i \\ sin\vartheta_i & cos\alpha_i\, cos\vartheta_i & -sin\alpha_i\, cos\vartheta_i & a_i\, sin\vartheta_i \\ 0 & sin\alpha_i & cos\alpha_i & b_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where a_i, d_i, α_i and ϑ_i are DH parameters and this transformation matrix represents transformation between two neighborhood DH frames (between two separate rigid bodies). For the whole coordinate transformation from basic frame ($i = 0$) to end-effector ($i = n$, where n is a number of rigid bodies), the individual coordinates are connected by the following chain equation

$$T_f = T_0^n = T_0^1\, T_1^2\, \cdots\, T_{n-1}^n = \prod_{i=1}^{n} T_{i-1}^{i} \quad (2)$$

Individual transformations in Eq. (2) and their meaningful combinations are involved in the composition of equations of motion. This DH approach represents a suitable way, which allows simple and systematic composition of the mentioned equation.

3.1.2 Description of the Robot Dynamics

Since the articulated type of robots is considered, a suitable way for the composition of equations of motion is the Lagrange approach based on Lagrange equations of second type, defined as

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\partial \mathcal{L}}{\partial \dot{q}}\right)^T - \left(\frac{\partial \mathcal{L}}{\partial q}\right)^T = \xi \quad (3)$$

where $\mathcal{L}$ is Lagrangian, q is generalized coordinates and ξ is generalised force effects. Lagrangian represents difference of kinematic E_k and potential energy E_p as follows

$$\mathcal{L}(q, \dot{q}) = E_k(q, \dot{q}) - E_p(q) \quad (4)$$

Considering Eq. (4), Lagrange equations can be expressed in the following modified form

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\partial E_k}{\partial \dot{q}}\right)^T - \left(\frac{\partial E_k}{\partial q}\right)^T + \left(\frac{\partial E_p}{\partial q}\right)^T = \xi \quad (5)$$

By application of Eq. (5) and appropriate physical parameters of given articulated robot, equations of motion can be composed. For given articulated robots, generalized coordinates are identical with joint coordinates $q = \vartheta$ and generalized force effects correspond to input torques of appropriate joints $\xi = \tau$, then the equations of motion are

$$B(\vartheta)\, \ddot{\vartheta} + C(\vartheta, \dot{\vartheta})\, \dot{\vartheta} + g(\vartheta) = \tau \quad (6)$$

where $B(\vartheta)$ is an inertia matrix, $C(\vartheta, \dot{\vartheta})$ is a coefficient matrix of Coriolis and centrifugal force effects, $g(\vartheta)$ is a vector of gravitational effects, $\vartheta = [\,\vartheta_1\ \vartheta_2\ \cdots\ \vartheta_n\,]^T$ is a vector of joint angles and $\tau = [\,\tau_1\ \tau_2\ \cdots\ \tau_n\,]^T$ is a vector of torques acting on appropriate joints [9].

3.2 Mathematical Model of Robot Drives

In this paper, the PMSM drives are considered in respect to given robot used for energy consumption evaluation. The description of *i*-th motor arises from the voltage distribution in the individual phases of three AC phase system and from equilibrium equation. Considering Clarke and Park transformation, the initial set of equations of voltage distribution defined in d-q rotating field coordinate system (rotating reference frame) can be expressed as follows

$$u_{Sd_i} = R_{S_i} i_{Sd_i} + L_{d_i}\frac{d}{dt}\, i_{Sd_i} - L_{q_i}\omega_{e_i} i_{Sq_i} \quad (7)$$

$$u_{Sq_i} = R_{S_i} i_{Sq_i} + L_{q_i}\frac{d}{dt}\, i_{Sq_i} + L_{d_i}\omega_{e_i} i_{Sd_i} + \psi_{M_i}\omega_{e_i} \quad (8)$$

where R_{S_i}, L_{d_i}, L_{q_i} and ψ_{M_i} are motor parameters, u_{Sd_i}, u_{Sq_i} are d-q voltages (system inputs), i_{Sd_i}, i_{Sq_i} are d-q currents, ω_{e_i} is the electrical rotor speed.

Then, the equilibrium equation among electromagnetic torque and (mechanical) load torques is defined as

$$\tau_{e_i} = \tau_i + B_i\, \omega_{m_i} + J_i\, \frac{d}{dt}\, \omega_{m_i} \quad (9)$$

where J_i and B_i are other motor parameters; ω_{m_i} is mechanical rotor speed related to electrical speed as $\omega_{m_i} = \omega_{e_i}/p$ considering p for a number of pole pairs; τ_i is a one load torque component of the torque vector τ from Eq. (6); and τ_{e_i} is electromagnetic torque defined as follows

$$\tau_{e_i} = \frac{3}{2}\, p\, (\psi_{M_i}\, i_{Sq_i} + (L_{d_i} - L_{q_i})\, i_{Sd_i}\, i_{Sq_i}) \quad (10)$$

A dynamic model of *i*-th PMSM, representing appropriate simulation block, can be formulated by the following first-order differential equations:

$$\frac{d}{dt}\, i_{Sd_i} = \frac{1}{L_{d_i}}(u_{Sd_i} - R_{S_i}\, i_{Sd_i} + L_{q_i}\, p\, \omega_{m_i}\, i_{Sq_i}) \quad (11)$$

$$\frac{d}{dt}\, i_{Sq_i} = \frac{1}{L_{q_i}}(u_{Sq_i} - R_{S_i}\, i_{Sq_i} - L_{d_i}\, p\, \omega_{m_i}\, i_{Sd_i} - \psi_{M_i}\, p\, \omega_{m_i}) \quad (12)$$

$$\frac{d}{dt}\, \omega_{m_i} = \frac{1}{J_i}(\tau_{e_i} - \tau_i - B\, \omega_{m_i}) \quad (13)$$

Considering appropriate components of torques τ_i from the equations of motion in Eq. (6) the model in Eqs. (11) $\sim$ (13), formally identical for all robot drives but different appropriate physical parameters, represents complete dynamical description of the robot i.e. mathematical interpretation of the complete simulation model in Simulink environment shown in Fig. 5.

4. ROBOT ENERGY CONSUMPTION

The energy consumption is an important parameter for each electrical appliance like robots, because it shows their efficiency in respect to all energy inputs. For robots, its determination arises from the input power of the individual drives that are loaded by the mechanical robot structure and possibly other further outside loads. In this paper, the unloaded case is considered so the drive load is represented only by mechanical robot structure.

4.1 Equation of Electric Input Power

The electric input power for a set of n 3-phase PMSM drives as a balanced system in considered d-q rotating reference frame is defined as

$$P = \frac{3}{2}\sum_{i=1}^{n}(u_{Sd_i}\, i_{Sd_i} + u_{Sq_i}\, i_{Sq_i}) \tag{14}$$

Considering Eqs. (7), (8) and (10), the electric input power is expressed as

$$P = \frac{3}{2}\sum_{i=1}^{n}[R_S\,(i_{d_i}^2 + i_{q_i}^2) + i_{d_i}\, L_d \frac{d}{dt}\, i_{d_i} + i_{q_i}\, L_q \frac{d}{dt}\, i_{q_i}] + \sum_{i=1}^{n}\omega_{r_i}\,\tau_{e_i} \tag{15}$$

The equation of input power can be simplified by the assumption $i_{Sd} = 0$ due to no need of field-weakening option and by omitting negligible term $d/dt(i_{Sq})$

$$P = \frac{3}{2}\sum_{i=1}^{n} R i_{q_i}^2 + \sum_{i=1}^{n}\omega_{m_i}\,\tau_{e_i} \tag{16}$$

Considering Eq. (9), the complete equation for the input power is

$$P = \frac{3}{2}\sum_{i=1}^{n} R i_{q_i}^2 + \sum_{i=1}^{n}\omega_{m_i}(\tau_i + B_i\omega_{m_i} + J_i\frac{d}{dt}\,\omega_{m_i}) \tag{17}$$

Now it is possible to specify energy consumption.

4.2 Equation of Robot Energy Consumption

The equation of the robot energy consumption is computed as a time integration of total input power along the considered motion trajectory within corresponding time interval as it is indicated by the following equation:

$$E = \int_0^{\Gamma}\left[\frac{3}{2}\sum_{i=1}^{n} R i_{q_i}^2 + \sum_{i=1}^{n}\omega_{m_i}\,(\tau_i + B_i\,\omega_{m_i} + J_i\,\frac{d}{dt}\,\omega_{m_i})\right] dt \tag{18}$$

By evaluating energy consumption according to Eq. (18) for different admissible kinematic parameters but along only one motion trajectory, it is possible to construct energy consumption curve that can be use for the selection of the optimal kinematic parameters for the considered trajectory. It will be shown in the next section.

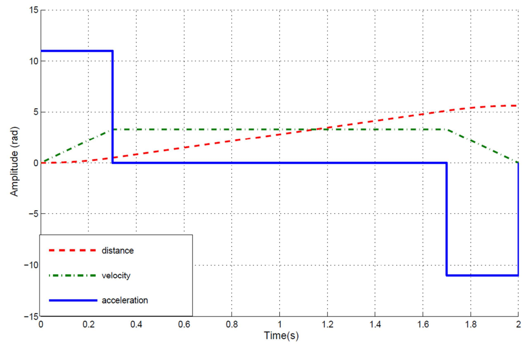

Fig. 6 Typical kinematical profiles of the robot motion.

5. RATE OF ENERGY CONSUMPTION

In this section, the evaluation of the energy consumption is demonstrated on the KUKA KR 5 arc robot (see [14] and Fig. 1). The energy consumption for this robot is evaluated for point-to-point motion task, i.e. only initial and final robot position has to be kept. The trajectory for this task is simply prepared by considering usual kinematic relations between individual quantities, i.e. angular position, speed and acceleration – see Fig. 6. According to this figure, the used representative trajectory is based on zero order profile of acceleration.

Shown profiles represent pattern for all six joint angles of the considered robot for the selected trajectory time duration. Individual joints have modified profiles according to selected time duration to be synchronized to each other. The details on trajectory planing are in [13].

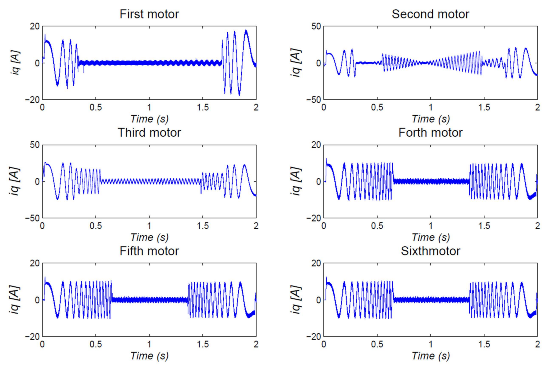

Fig. 7 Example of time behaviours of currents i_{Sq_i}.

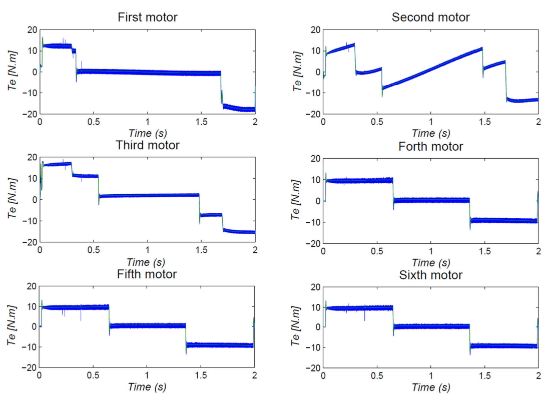

Fig. 8 Example of time behaviours of torques τ_{e_i}.

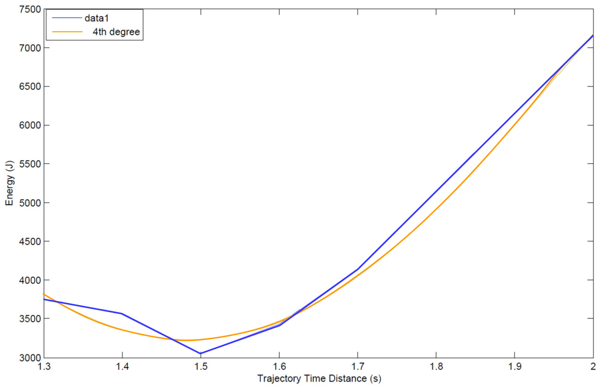

Fig. 9 Energy consumption relative to motion duration.

For the specified trajectory, individual time behaviour of current i_{Sq_i} and electromagnetic torques τ_{e_i} are demonstrated in figures 7 and 8, respectively. These figures show examples of specified quantities of one testing trajectory realization for time duration equal to 2 s. This duration is selected from considered set of reasonable durations = [1.3s, 1.4s, 1.5s, 1.6s, 1.7s, 2s]. Considering these parameters for all duration realizations, the resulting individual energy consumptions of the robot motion are shown in Fig. 9.

The curve in this figure is an approximation of the values of energy consumptions corresponding to the mentioned set of reasonable duration times. The appropriate values are listed in Table 1. The curve illustrates the energy consumption profile that can serve for the selection of optimal time for the given trajectory. In the case of our example, the optimal time duration is 1.5s. More details are provided in [7].

The result shows that the shortest time requires for the robot acceleration and braking extra energy for coping with inertia force effects and on the opposite side for long time durations, the energy consumption increases due to demands on more or less static support of the mechanical robot structure during the motion. Between these two cases, there is short interval, which represents balanced optimum. The optimum is characterized by suitable acceleration and deceleration profiles not to excite increase of inertia effects too much and at the same time, the duration time is not too long to require support force inputs of robot structure.

Table 1 Energy Consumption for Trajectory Realizations

Point No.	Trajectory duration [s]	Robot velocity $[\mathrm{m\,s^{-1}}]$	Consumption [J]
1	1.3	0.11430	3751
2	1.4	0.09648	3564
3	1.5	0.09434	3052
4	1.6	0.09045	3429
5	1.7	0.08890	4143
6	2.0	0.06300	7167

6. CONCLUSION

The paper presents the application of specific graphically-oriented computer-aided modelling approach to model the energy consumption of industrial articulated robots. The construction of the complete simulation model has been described. Simultaneously, the composition of the corresponding mathematical equations describing the simulation model has been introduced. On their basis, the equation of the energy consumption has been derived. The proposed approach of the determination of the energy consumption has been illustrated by the set of simulation experiments that demonstrate evaluation of the energy consumption for one selected motion trajectory for several different time durations. The experiments have been realized with real physical parameters of industrial robot KUKA KR 5 arc as the representative of industrial articulated robots.

REFERENCES

[1] R. Saravanan, S. Ramabalan, and C. Balamurugan, “Evolutionary optimal trajectory planning for industrial robot with payload constraints,” *The Int. J. of Advanced Manufacturing Technology*, vol. 38, no. 11-12, pp. 1213–1226, 2008.

[2] S. Bjorkenstam, D. Gleeson, R. Bohlin, J. Carlson, and B. Lennartson, “Energy efficient and collision free motion of industrial robots using optimal control,” in *IEEE Int. Conf. on Automation Science and Engineering*, 2013, pp. 510–515.

[3] G. Sharma, “Optimization of energy in robotic arm using genetic algorithm,” *Int. J. of Comp. Sci. and Technology*, vol. 2, no. 2, pp. 315–317, 2011.

[4] A. Smetanová, “Optimization of energy by robot movement,” *Modern Machinery Science Journal*, vol. 3, no. 1, pp. 172–176, 2010.

[5] M. Chemnitz, G. Schreck, and J. Kruger, “Analyzing energy consumption of industrial robots,” in *Proc. of IEEE Conf. on Emerging Technologies & Factory Automation*, 2011, pp. 1–4.

[6] C. Bryan, M. Grenwalt, and A. Stienecker, “Energy consumption reduction in industrial robots,” in *Proc. of ASEE North Conf.*, 2010, pp. 1–4.

[7] L. Bukata and P. Šůcha, “High-level optimisation of robotic lines with respect to power consumption and given production cycle time,” in *27th Conf. on Combinatorial Optimization*. TU Munchen, 2014.

[8] *KUKA 3D CAD Model in step format*, KUKA Roboter CEE GmbH, 2015.

[9] B. Siciliano and L. Sciavicco et al., *Robotics - Modelling, Planning and Control*. Springer, 2009.

[10] *Matlab Documentation*, MathWorks, Inc., 2015.

[11] *SimMechanics, User’s Guide R2015a*, MathWorks.

[12] *SimPowerSystems & Simulink*, MathWorks, 2013.

[13] *Armtutorial1*, KUKA Roboter CEE GmbH, 2015.

[14] *Arc Welding and Magnetic Blow*, KUKA, 2015.