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A fuzzy decision model in designing an industrial robot's trajectory

***Abstract**. The paper presents a working algorithm and structure of a fuzzy decision model applied in the design of an industrial robot trajectory. Tests were performed on an industrial robot Kawasaki by means of a computer system consisting of measuring transducers, a measuring card and dedicated software. During the tests voltage vs time characteristics and supply current vs time characteristics were recorded for selected motion sequences in dynamic states. Power consumed by the robot's drive system was calculated for specific trajectories. Subsequently, the fuzzy decision model was used for modifying a robot's trajectory on the basis of the values obtained in the measuring tests performed on the robot Kawasaki.*

***Streszczenie.** W artykule przedstawiono algorytm działania oraz strukturę rozmytego modelu decyzyjnego. Przeprowadzono badania robota przemysłowego Kawasaki przy zastosowaniu komputerowego układu złożonego z przetworników pomiarowych, specjalistycznej karty pomiarowej oraz dedykowanego oprogramowania. Podczas badań zarejestrowano charakterystyki czasowe napięcia oraz prądu zasilania dla wybranych sekwencji ruchu w stanach dynamicznych. Przeprowadzono obliczenia mocy pobieranej przez układ napędowy robota przy określonej trajektorii ruchu. Zastosowano rozmyty model decyzyjny do modyfikacji trajektorii ruchu przy uwzględnieniu wyników uzyskanych podczas badań pomiarowych robota Kawasaki. (**Rozmyty model decyzyjny wspomagający planowanie trajektorii ruchu robota przemysłowego**).*

Keywords: industrial robot, fuzzy logic, fuzzy decision model, computer measuring system, non-linear receiver.
Słowa kluczowe: robot przemysłowy, logika rozmyta, rozmyty model decyzyjny, komputerowy system pomiarowy, odbiornik nieliniowy.

Introduction

Nowadays, robots are applied in industrial production processes on a massive scale, since they enable effective use of the machinery park, at the same time shortening the production time and ensuring good quality of the final product. Production companies using robots gain a competitive advantage over those that do not, which contributes to their economic efficiency. Besides, using robots ensures better working conditions for employees, who are spared much tedious and time-consuming work. Despite the fact that introducing robots requires initial investment, it pays off in the long run by reducing other costs and bringing additional benefits [3, 12].

Industrial robots combine precision with high efficiency irrespective of external factors, such as noise, chemical vapors or technological dust, which would impact negatively on work performed by humans. Because of that, robots are widely applied in chemical, pharmaceutical, automotive, shipbuilding, and food industry, as well as in metallurgical and steel plants. Their main applications include putting products into packages, moving elements to and from conveyor belts or gravity roll conveyors, drilling orifices, grinding, spray painting and welding.

When performing its technological routine, an industrial robot repeats the same trajectory a number of times. Optimization of such a trajectory is therefore of key importance from the viewpoint of energy consumption and time needed to carry out a technological sequence, and ultimately, production cost [9, 12].

Anthropomorphic robots typically have 6 axes, although constructions with a smaller number of axes are also attested. A robot consist of a mechanical manipulator, controller, and manual programmer. Alternatively, instead of using a manual programmer, a robot can be programmed by means of a computer with suitable software, connected to the controller. Programming the trajectory of a robot's motion is a task performed by a human operator of a technological process. The trajectory is designed in a three-dimensional space and it is not always possible to take into account all the issues related to the optimization of energy consumption. This justifies the application of fuzzy algorithms for aiding the design of a robot's motion trajectory [1, 2, 4, 8].

A fuzzy decision model

Fuzzy models can be generally divided into two types depending on their structure: Mamdani or Sugeno. In the Mamdani system all inputs and outputs to inference rules are fuzzy sets, whereas in the Sugeno system inputs to inference rules are fuzzy sets but outputs are membership functions [13].

A fuzzy decision Mamdani system applied in the design of a robot's trajectory can be defined by means of the following rule base:

$$
\begin{aligned}
&R^{(1)}: IF\ (x_1\ is\ LX_1^{(1)})\ AND\ (x_2\ is\ LX_2^{(1)})\ ...\\
&\qquad AND\ (x_n\ is\ LX_n^{(1)})\ THEN\ (u\ is\ LU^{(1)})\\
&R^{(2)}: IF\ (x_1\ is\ LX_1^{(2)})\ AND\ (x_2\ is\ LX_2^{(2)})\ ...\\
&\qquad AND\ (x_n\ is\ LX_n^{(2)})\ THEN\ (u\ is\ LU^{(2)})\\
&\qquad \dots\dots\dots\dots\dots\dots\\
&R^{(k)}: IF\ (x_1\ is\ LX_1^{(k)})\ AND\ (x_2\ is\ LX_2^{(k)})...\\
&\qquad AND\ (x_n\ is\ LX_n^{(k)})\ THEN\ (u\ is\ LU^{(k)})
\end{aligned}
\tag{1}
$$

where: $x_1, x_2,...,x_n$ – input linguistic variables, $LX_1^{(1)}, LX_2^{(1)},..., LX_n^{(1)}$; $LX_1^{(2)}, LX_2^{(2)},..., LX_n^{(2)}$; $LX_1^{(k)}, LX_2^{(k)},..., LX_n^{(k)}$ – linguistic values of input variables, u - output linguistic variable, $LU^{(1)}, LU^{(2)},..., LU^{(k)}$ - linguistic values of output variable, k - number of rules.

Defuzzification of the fuzzy model was carried out by means of the center of area method. On this method, the output characteristic is continuous and all activated membership functions are included. The fuzzy decision model was constructed by means of the software Matlab/Simulink and the package Fuzzy Logic Toolbox. As rule inputs triangular membership functions were used, which can be represented as follows:

$$
\mu_{TMF}(x) = \left\{ \begin{matrix} 0 \ for\ x \le a \\ \dfrac{x-a}{m-a}\ for\ a < x \le m \\ \dfrac{b-x}{b-m}\ for\ m \le x < b \\ 0\ for\ x \ge b \end{matrix} \right\}
\tag{2}
$$

where: a - lower limit, b - upper limit b, m - central value.

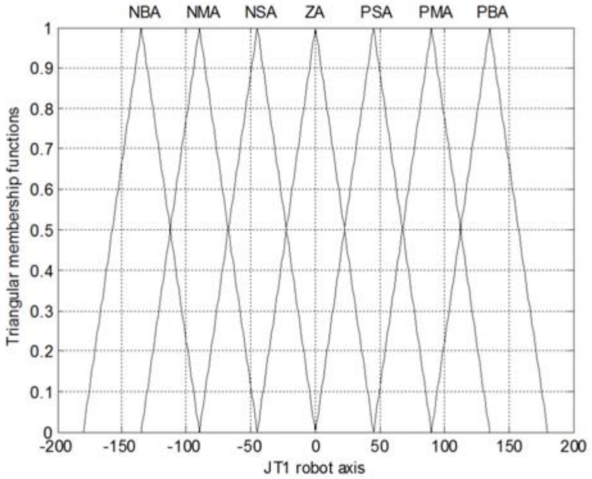

Fig. 1. The input triangular membership functions

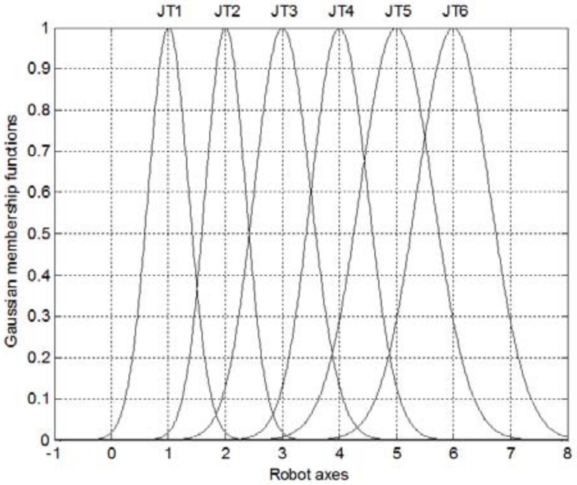

Fig. 2. The output Gaussian membership functions

The linguistic input data include the triangular membership functions. The functions are labelled as follows: NBA – negative big angle, NMA – negative medium angle, NSA – negative small angle, ZA – zero angle, PSA – positive small angle, PMA – positive medium angle, PBA – positive big angle. The functions are presented in Fig. 1.

For rule outputs a Gaussian membership function was applied as in the formula:

$$\mu_{GMF}(x) = e^{-\frac{(x-m)^2}{2d^2}} \tag{3}$$

where: m - central value, d - standard deviation.

The linguistic output data include the Gaussian membership functions. The functions are labelled as follows: JT1 – first axis, JT2 – second axis, JT3 – third axis, JT4 – fourth axis, JT5 – fifth axis, JT6 – sixth axis. The functions are presented in Fig. 2.

Measuring system of the Kawasaki robot

The measuring system for registration and visualization of the time curves was constructed with the use of a computer equipped with the measuring card Adlink 9118L. The card has a 12-bit A/D transducer enabling the read-out and registration of time curves on up to eight bipolar channels. The maximal sampling frequency of the measuring card is 100 kHz. The galvanic isolation between the high-current circuit and the measuring circuit was provided by means of measuring transducers manufactured by LEM, with the transducer LV25-P connected in the voltage circuit, and the transducer LA55-P connected in the current circuit. The low-voltage outputs of the measuring transducers were connected to the external module of the measuring card Adlink 9118L. A block diagram of the computer measuring system is presented in Fig. 3.

On the basis of the supply parameters, the robot can be considered as a nonlinear receiver. When constructing the measuring system it is therefore necessary to take into account issues related to measurements in converter drives and nonlinear circuits as well as general problems concerning measurements of electrical and non-electrical quantities [4, 5, 10, 11].

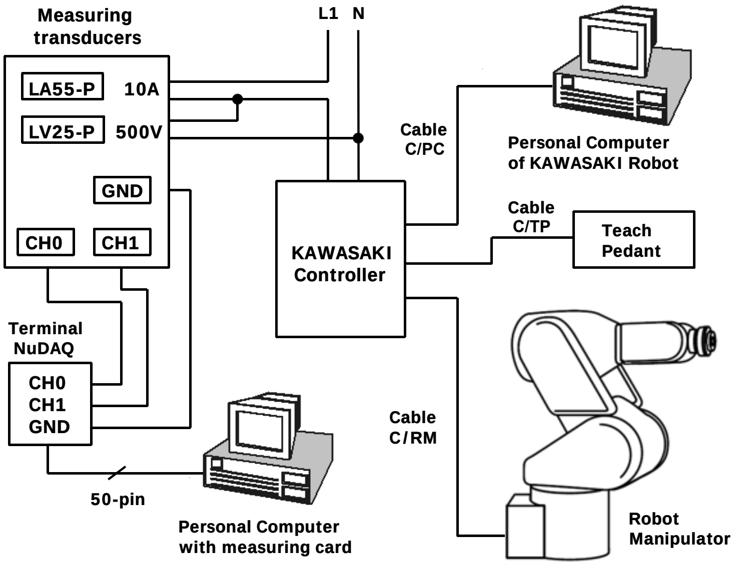

Fig. 3. The block diagram of the computer measuring system of the Kawasaki FS03N robot

For recording and visualization of the supply voltage and supply current vs time curves the software DASYLab was used. Measuring signals from the voltage transducer and current transducer are read by two channels of the card Adlink 9118L and subsequently processed by the program DASYLab. The processing of the measuring signals includes the following stages: calibrating voltage and current, calculating selected parameters, read-out by the digital meter module and graphic presentation of the time curves. It is also possible to record the measurement results in files, which can be subsequently analyzed off-line. A block diagram of the measurement signal processing system is presented in Fig. 4

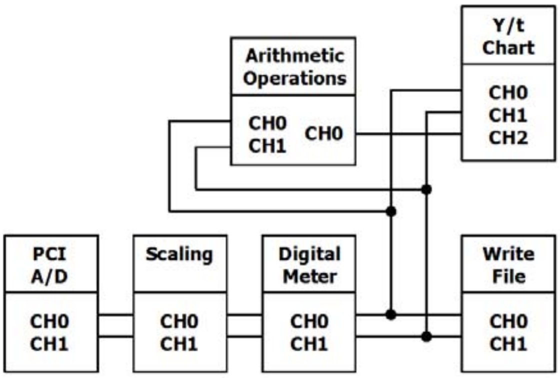

Fig. 4. The block diagram of measurement signal processing system of the Kawasaki robot

Selected parameters of the measuring card and measuring transducers are specified in Table 1.

Table 1. The selected parameters of the measuring card and transducers [7]

Designation	Selected parameters
Measuring card Adlink 9118L	channels 16 single-ended or 8 differential resolution 12-Bit conversion time 3 μs maximum sampling rate 100 kS/s overvoltage protection continuous ±35 V input impedance 1 GΩ trigger modes software, external trigger
LEM voltage transducer LV25-P	measurement range 100V, 500V measurement accuracy ± 0,8 % linearity ± 0,2 % response time 40 μs
LEM current transducer LA55-P	measurement range 10A measurement accuracy ± 0,65 % linearity ± 0,15 % response time 40 μs

Table 2. The range of admissible positions of the Kawasaki FS03N robot axes [6]

Robot axes	Range of admissible positions
JT1 - Arm rotation	from -160° to 160°
JT2 - Arm out-in	from -60 to 150°
JT3 - Arm up-down	from -150° to 120°
JT4 - Wrist swivel	from -360° to 360°
JT5 - Wrist bend	from -135° to 135°
JT6 - Wrist twist	from -360° to 360°

The industrial robot Kawasaki FS03N has six axes with electric drives and a separate system of a pneumatic end effector, connected to a compressor with an air container. The controller consists of a rectifier system, a DC circuit, converters for the drives of the axes, the control module and communication module. The mechanical manipulator, the controller and manual programmer are interconnected by dedicated cables. The robot's controller is supplied by standard alternating single-phase voltage [6].

The compressor of the end effector is supplied from a separate circuit independent of the circuits supplying the drives for the six axes. The manipulator's arm takes a position depending on the parameters prescribed for the individual axes. The range of admissible positions of the Kawasaki robot axes is presented in Table 2.

Results of the measuring tests

The measurements carried out in the study included time curves for supply voltage and supply current in dynamic states. The robot was programmed to work in the variable angular position mode for the individual axes. For a given dynamic state, an angular movement was performed for a selected axis, with the other axes being immobilized. In this configuration it was possible to measure voltage, current and power during the sequential operation of the robot's individual axes. Selected time curves recorded for dynamic states are presented in Fig. 5-6.

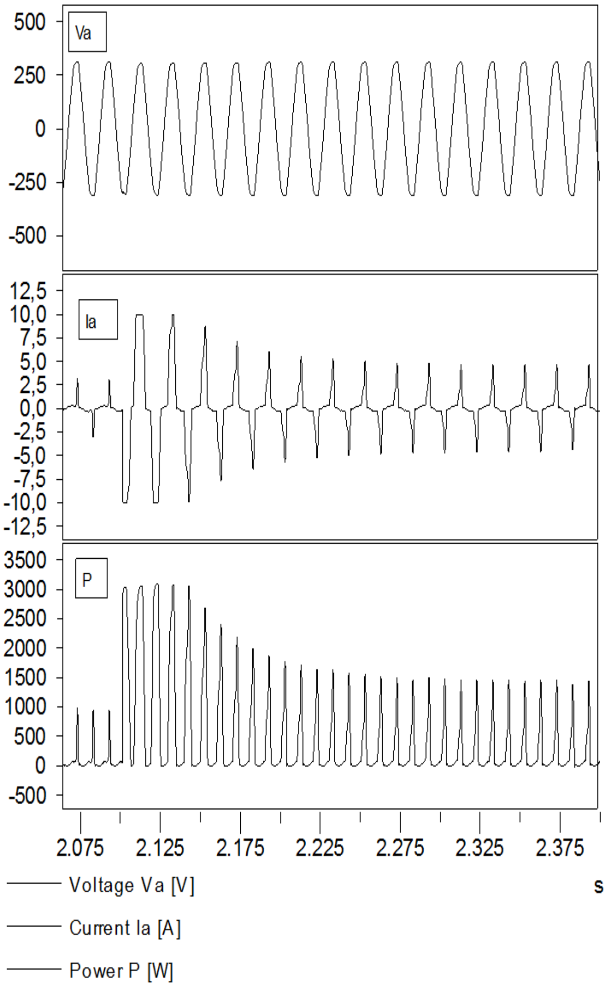

Fig. 5. The time characteristics of the supply voltage, the supply current and the active power of the Kawasaki robot at angular moving the JT3 axis

Having obtained the results of the dynamic state measurements, the next step was to design the trajectory of the angular movement for selected axes, using the fuzzy inferencing model. The fuzzy algorithm enabled a modification of the trajectory such that the minimization of energy consumption was taken into account. The results obtained were verified in the next round of measuring tests, as presented in Fig. 7.

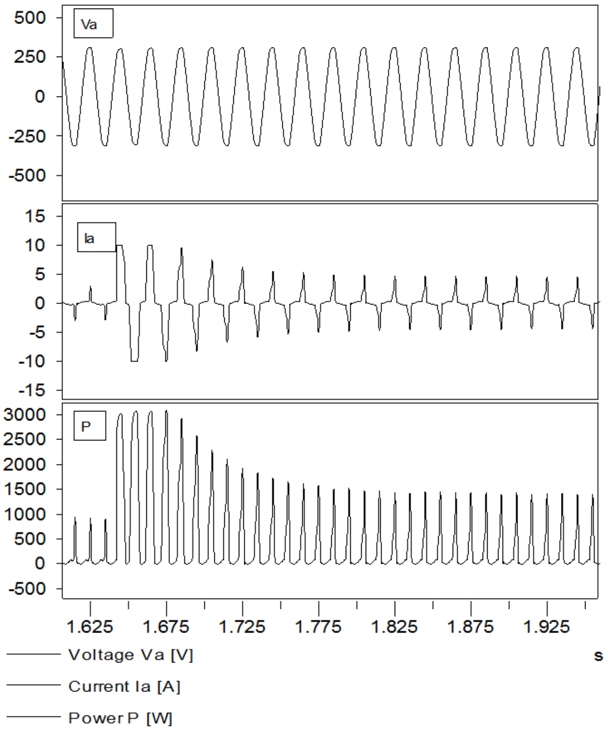

Fig. 6. The time characteristics of the supply voltage, the supply current and the active power of the Kawasaki robot at angular moving the JT4 axis

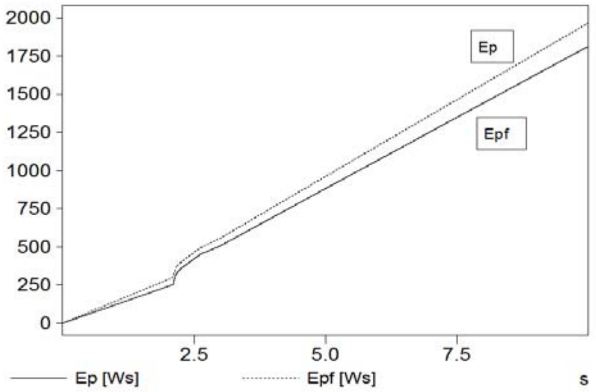

Fig. 7. The time characteristics of active energy of the Kawasaki robot at moving the JT3 axis for the standard trajectory and the modified trajectory

Conclusions

Application of a fuzzy decision system is instrumental in modifying the robot manipulator trajectory oriented towards minimizing energy consumption. The modification involves minimization of the range of angular movement for an axis at which energy consumption is high, possibly accompanied by increase in the range of angular movement for an axis at which less energy is consumed. This kind of strategy helps to lower energy consumption for a prescribed trajectory. For this strategy to be applicable, it is however necessary to perform measurements for selected dynamic states of the robot and subsequently to verify the results after trajectories have been modified.

A fuzzy decision model has significant advantages over a conventional method of planning the positions of the manipulator in the Cartesian coordinate system by the operator of the technological process. This results mainly from the fact that the decision system makes use of the operator's knowledge transcribed in the form of rules and additionally has access to measuring data on energy consumed by the robot given the angular movement at its particular axes.

The study presented here should be continued in order to investigate the operation of the fuzzy decision system for complex dynamic states involving angular movement at the robot's axes combined sequentially with the movement of the end effector in the Cartesian coordinate system.

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