THE APPLICATION OF A NEURO-FUZZY ADAPTIVE CRANE CONTROL SYSTEM

BADANIA APLIKACYJNE NEURO-ROZMYTEGO ADAPTACYJNEGO REGULATORA W UKŁADZIE STEROWANIA SUWNICĄ POMOSTOWĄ

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Abstract: The unconventional methods, mostly based on fuzzy logic, are often addressed to a problem of anti-sway crane control. The problem of practical application of those solutions is important owing to come the growing expectations for time and precision of transportation operations and exploitation quality of material handling devices. The paper presents the designing methods of an adaptive anti-sway crane control system based on the neuro-fuzzy controller, as well as the software and hardware equipments used to aid the programming realization the fuzzy control algorithm on a programmable logic controller (PLC). The proposed application of control system was tested on the laboratory model of an overhead traveling crane.

Keywords: overhead traveling crane, fuzzy logic, neural network

Streszczenie: Sztuczna inteligencja, w szczególności logika rozmyta, znalazła skuteczne zastosowanie w systemach sterowania mechanizmami ruchu suwnic. Problem aplikacyjności tych rozwiązań jest istotny z uwagi na rosnące wymagania odnośnie poprawy czasu i precyzji realizowanych zadań transportowych, jak i jakości eksploatacji i niezawodności środków transportu technologicznego. W artykule przedstawiona została metodyka procesu prototypowania systemu sterowania mechanizmami ruchu suwnicy pomostowej z zastosowaniem neuro-rozmytego adaptacyjnego regulatora, oraz sprzętowo-programowe narzędzia umożliwiające realizację on-line rozmytego algorytmu sterowania na sterownikach PLC. Badania aplikacyjne wykonane zostały na laboratoryjnym obiekcie.

Słowa kluczowe: suwnica pomostowa, logika rozmyta, sieci neuronowe
1. Introduction

Automation of the material handling systems and devices has increasing significance in automated manufacturing processes where productivity and efficiency are more and more required. The time and precision of transportation tasks, as well as exploitation quality improvement of material handling devices are the subject of greater and greater attention. The problem of crane control system, to which the paper is addressed, is popular in automatics and frequently solved in scientific works using different methods. However, the application of adaptive crane control systems, especially presented in scientific literature unconventional methods based on so-called artificial intelligence, are still hardly ever proposed and implemented. For this reason the application of adaptive crane control system, based on the neuro-fuzzy controller implemented on programmable logic controller (PLC) is shown in the paper with experimental results obtained during tests carried out on a laboratory object, the double-girder overhead traveling crane with hoisting capacity $Q=150$ [kg]. The aim of this paper is to show, that the intelligent control methods, based on fuzzy logic can be applied to a crane control problem, as well as implemented on the control devices which are frequently used in industrial practice.

The unconventional methods applied to a crane control problem are mostly based on fuzzy logic, also on artificial neural network, as well as their hybrids. Especially fuzzy logic approach has found practicable applications in a nonlinear crane control system owing to possibility of control algorithm expressing as the heuristic control strategy formulated by using the fuzzy implications if-then. The most frequently used in the fuzzy approach to a crane control system, and presented in the scientific works, is the fuzzy inference system based on Mamdani’s implication (Benhidjeb, and Gissinger, 1995; Cho, and Lee, 2002; Itoh, et al., 1993; Mahfouf, et al., 2000; Nalley, and Trabia, 2000).

In (Kang, et al., 1999) a robust switching control scheme was proposed for a gantry crane. The control scheme was based on fuzzy Takagi-Sugeno-Kang (TSK) system which switches several controllers, each designated for a different fixed rope length nominal model. In (Yi, et al., 2003) the TSK fuzzy controller of a crane position and the load swing was based on fuzzy implications with singleton fuzzy functions used in consequents of fuzzy rules.

The approach to a crane control system, based on artificial neural network is presented in (Acosta, et al., 1999), where Authors carried out with success simulations using the neurocontroller which is a self-tuning system consisting of a conventional controller combined with a neural network to calculate the coefficients of the controller. The combination of neural network and fuzzy logic was used to solve the crane control problem for example in (Ishide, et al., 1993; Smoczek, and Szpytko, 2009).

The neuro-fuzzy controller proposed in this paper was created using Takagi-Sugeno-Kang (TSK) fuzzy inference system. The TSK fuzzy controller is
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created in the off-line process of neural network learning based on data obtained by simulating the conventional proportional and derivative (PD) controllers of crane position and the load swing. The set of those controllers are achieved using pole placement method for identified models of a crane dynamic system for fixed values of rope length and mass of a load. The application of crane control system was built based on a programmable logic controller (PLC) on which proposed fuzzy control algorithm was implemented using instructions untreatable for employed in experiments the PLC’s unit, FX2N series manufactured by Mitsubishi Electric.

The next problem, which is also considered and solved in this paper, concerns the method of prototyping and programming realization of fuzzy control algorithms on a PLC. This problem was solved by creating the higher level of control system, which aim is to supervise the lower level of control system, in which PLCs realize data gathering from measurement circuits and control tasks according to an algorithm written in a central processor unit (CPU) of a PLC. The HMI/SCADA system (Human Machine Interface/Supervisory Control And Data Acquisition) was equipped in tools, which besides the controlling, supervising, monitoring and visualization tasks, allows to create and modify on-line a fuzzy controller implemented on a PLC. The fuzzy system modeling on a PLC is realized using the fuzzy interface, created on the model of Fuzzy Logic Toolbox in Matlab program, using Wonderware System Platform and InTouch software.

Using proposed and presented in the paper methods of adaptive crane control system designing, the solution, which can be applicable in industrial practice, was built and tested on the laboratory object. The results of experiments are shown and analyzed in the paper.

2. The neuro-fuzzy approach to an adaptive crane control system

The Takagi-Sugeno-Kang (TSK) fuzzy controller presented in the figure 1 consists of the sixth input signals: rope length $l$, mass of the load $m_2$, error of crane position $e_x = x_d - x$ (where $x_d$ is expected crane position), crane velocity $\dot{x}$, deviation of a load from vertical symmetry axis of the rope drum $l \cdot \alpha$ (calculated as a product of rope length $l$ and load swing angle $\alpha$) and velocity of this deviation $l \cdot \dot{\alpha}$ (calculated as a product of rope length $l$ and velocity of swing angle $\dot{\alpha}$).

The fuzzy system, used in the proposed approach, is to choose suitable vector of controller gains, based on the key scheduling variables, rope length $l$ and mass of a load $m_2$. The base of knowledge is composed of $N = n \cdot m$ fuzzy implications, which single $k$-rule can be formulated as:
IF \( l \) is \( LM_i(l) \) and \( m_2 \) is \( LM_j(m_2) \) THEN \( u_k = f_k(l,m_2,e_x,\dot{x},l \cdot \alpha, l \cdot \dot{\alpha}) \) \( \text{(1)} \)

where:

\[
\begin{align*}
  k & = 1, 2, ..., N \\

\end{align*}
\]

The diagram illustrates the crane control system with a TSK adaptive neuro-fuzzy controller.

The function defined in each of \( k \) fuzzy rule consequence takes form:

\[
 u_k = X^T \cdot K_k = \begin{bmatrix} l \\ m_2 \\ e_x \\ \dot{x} \\ l \cdot \alpha \\ l \cdot \dot{\alpha} \\ 1 \end{bmatrix}^T \begin{bmatrix} k_{6k} \\ k_{5k} \\ k_{4k} \\ k_{3k} \\ k_{2k} \\ k_{1k} \\ k_{0k} \end{bmatrix} \quad \text{(2)}
\]

The vector \( K \) consists of controller’s gains specified for each \( k \) nominal operating point which corresponds to the fixed value of rope length and mass of a load \( \{k_{fi}, m_2, j\} \). The crisp output signal of the TSK controller (Fig. 1) is the weighted average of all rules outputs, computed as:

\[
 u = \frac{\sum_{k=1}^{N} w_k \cdot u_k}{\sum_{k=1}^{N} w_k} \quad \text{(3)}
\]
The weight of a \( k \) fuzzy rule \( w_k \) is calculated as a product of membership coefficients for \( l \) and \( m_2 \) input values to the triangular membership functions \( LM_i(l) \) and \( LM_j(m_2) \) shown in the figure 2.

\[
w_k = \mu_i(l) \cdot \mu_j(m_2)
\]

where:
\( i = 1, 2, ..., n \), \( j = 1, 2, ..., m \) - where \( n \) and \( m \) are respectively numbers of fuzzy sets defined for rope length and mass of a load input variables, as well as numbers of constant values of those variables for which the coefficients of membership functions equal one.

\[
\mu_m(l) = \mu_n(m_2) = \sum_{i=1}^{n} \mu_i(l) \cdot \mu_j(m_2)
\]

\( l_1, m_{21} \)
\( l_2, m_{22} \)
\( l_{n-1}, m_{2(n-1)} \)
\( l_n, m_{2n} \)
\( l, m_2 \)

**Fig. 2. The triangular membership functions defined for \( l \) and \( m_2 \) input variables of the TSK fuzzy controller**

The TSK controller was converted to the structure of neural network by using in Matlab program the *Adaptive Neuro-Fuzzy Inference System* (ANFIS) toolbox (Fig. 3).

**Fig. 3 The structure of the TSK fuzzy controller presented as neural network**
The parameters of TSK controller (vectors of controller gains $K$) are obtained in the neural network learning process using the Least Mean Squares (LMS) algorithm applied to learn the consequences of fuzzy implications. The training data, used in the neuro-fuzzy TSK controller learning, is obtained based on the parametric models of a crane dynamic identified using output error method based on data measured during experiments carried out on controlled object for fixed rope length and mass of a load. The crane dynamic model is expressed by two time-discrete transmittances, which express dynamic behavior of oscillating object formulated as a second-order system denoted as $G_{\alpha}(z)$ (5), and dynamic behavior of a crane power transmission simplified to a first-order system, denoted as the transfer function $G_{\dot{x}}(z)$ (6).

$$G_{\alpha}(z) = \frac{\alpha(z)}{\dot{X}(z)} = \frac{B(z)}{A(z)} = \frac{b_1z + b_0}{z^2 + a_1z + a_0}$$

$$G_{\dot{x}}(z) = \frac{\dot{X}(z)}{U(z)} = \frac{D(z)}{C(z)} = \frac{d_0}{z + c_0}$$

The set of $N$ models of controlled object leads to obtain the matrix consisting of $N$ rows vectors of parameters (7), based on which the $N$ non-adaptive time-discrete controllers of crane position and speed, and load swing can be obtained using pole placement method (8).

$$\begin{bmatrix}
da_{01} & d_{02} & \cdots & d_{0N} 
c_{01} & c_{02} & \cdots & c_{0N} 
b_{11} & b_{12} & \cdots & b_{1N} 
b_{01} & b_{02} & \cdots & b_{0N} 
a_{11} & a_{12} & \cdots & a_{1N} 
a_{01} & a_{02} & \cdots & a_{0N}
\end{bmatrix}$$

$$\begin{bmatrix}
K_{px1} & K_{px2} & \cdots & K_{pxN} 
K_{ps1} & K_{ps2} & \cdots & K_{psN} 
q_{11} & q_{12} & \cdots & q_{1N} 
q_{01} & q_{02} & \cdots & q_{0N} 
s_{01} & s_{02} & \cdots & s_{0N}
\end{bmatrix}$$

where:

$K_{px}$, $K_{ps}$ - the proportional gains of crane position and speed controllers, respectively,
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\[ q_1, q_0, s_0 \] - the gains of anti-sway controller, assumed as follows:

\[ R_\alpha(z) = \frac{Q(z)}{S(z)} = \frac{q_1 z + q_0}{z + s_0} \] (9)

The unknown gains (8) of closed loop control systems can be derived for known parameters (6) of controlled object’s models from Diophantine equation formulated based on the characteristic equation of considered closed loop control system transmittance, and expected characteristic equation denoted as \( P(z) \), determined for desired poles. In the expression (10) the Diophantine equation was formulated based on the \( A, B, C, D \) matrixes consisting of parameters of crane dynamic model, and \( P \) vector of desired characteristic equation coefficients.

\[ (z - 1) \cdot (A \cdot C \cdot S + K_{P_\alpha} \cdot A \cdot D \cdot S - B \cdot Q \cdot D) - K_{P_\alpha} \cdot K_{P_\alpha} \cdot z A \cdot D \cdot S = P \] (10)

The training data, used to TSK neuro-fuzzy controller learning, consisting of the input and output signals of the TSK controller (Fig. 1) is obtained from simulations carried out using the non-adaptive crane control systems. The training data can be formulated as a matrix denoted as \( TD \):

\[
\begin{bmatrix}
  l_1 & m_{21} & e_{x1} & \dot{x}_1 & l_1 \cdot \alpha_1 & l_1 \cdot \dot{\alpha}_1 & u_1 \\
  l_1 & m_{22} & e_{x2} & \dot{x}_2 & l_1 \cdot \alpha_2 & l_1 \cdot \dot{\alpha}_2 & u_2 \\
  \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
  l_1 & m_{2m} & e_{xm} & \dot{x}_m & l_1 \cdot \alpha_m & l_1 \cdot \dot{\alpha}_m & u_m \\
  l_2 & m_{21} & e_{x(m+1)} & \dot{x}_{m+1} & l_1 \cdot \alpha_{m+1} & l_1 \cdot \dot{\alpha}_{m+1} & u_{m+1} \\
  \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
  l_n & m_{2m} & e_{x(m-n)} & \dot{x}_{m-n} & l_n \cdot \alpha_{m-n} & l_n \cdot \dot{\alpha}_{m-n} & u_{m-n}
\end{bmatrix}
\] (11)

3. The application of neuro-fuzzy crane control system

The presented in the previous stage method of neuro-fuzzy controller designing is realized using the hardware-software platform, based on PC with I/O board (PCI-1710HG control-measurement card manufactured by Advantech) and Matlab software environment, which allows to identify models of controlled object, elaborate the control algorithm, simulate and testing it on the researches object. The PC platform with interface cards and MS Windows operating system is rather not designed for industrial practice. Simultaneously the programmable logic controllers (PLC), frequently used in industrial control applications, are hardly ever supported with software tools, that enable to realize fuzzy control algorithm on a PLC. It causes that user have to realize programming implementation of the designed fuzzy controller
on a PLC using the standard instructions understood by a PLC unit (e.g. using structural text, ladder format), and logical devices (data registers, timers, counters etc.). It is time consuming process of programming the PLC and reprogramming, in case of necessary changes which could appear in the result of testing control algorithm on a controlled object, because those changes are realized in off-line process. For this reason the application for supervisory control and monitoring the transportation process realized by laboratory overhead traveling crane was created using the Wonderware System Platform and InTouch software, and equipped in fuzzy interfaces for Mamdani and Takagi-Sugeno-Kang (TSK) controllers (Fig. 4).

![Diagram of crane control system](image)

**Fig. 4** The prototyping process of fuzzy crane control system using PC platform with Matlab software tools and the HMI/SCADA application used for on-line fuzzy algorithm implementation on a PLC

The tools allow to built or rebuilt in on-line process the fuzzy algorithm written in a PLC. The tests were carried out using the FX2N programmable logic controller manufactured by Mitsubishi at which the fuzzy control algorithms, Mamdani and TSK were implemented. The fuzzy interface is similarly to the Fuzzy Logic Toolbox - fuzzy interface realized in Matlab.
program. Owing to the PLC’s hardware restrictions the fuzzy interface realized for the PLC has some limitations in the number and shapes of membership functions (triangular or trapezoidal functions), the number of fuzzy implications, as well as methods of fuzzy implications executing, aggregation and defuzzification. The proposed HMI/SCADA tools enable to quick and easy pass from the process of controlled object identification, control algorithm designing and verification made using the PC platform with control-measurement card, to create application of fuzzy control system based on a PLC (Fig. 4).

The HMI/SCADA application created with using Wonderware System Platform and InTouch program exchanges data in real time with PLC’s physical and logical devices, which enables to change the control algorithm in on-line process (the parameters and gains of a fuzzy controller). The higher level of control system realized as the HMI/SCADA application delivers for user many integrated tools that allow to create and real-time change the fuzzy control algorithm and monitor the transportation process realized by an overhead traveling crane.

4. The experimental results

The subject of experiments carried out using PLC and HMI/SCADA platform was testing the crane control system with TSK neuro-fuzzy controller presented in the figure 1. The control system under consideration was realized for the laboratory overhead traveling crane, with hoisting capacity $Q=150$ [kg], localized in the Laboratory of Automated Transportation Systems and Devices at the AGH University of Science and Technology in Krakow. The TSK neuro-fuzzy controller presented in the stage 2 was designed based on data measured during experiments conducted on the laboratory object for chosen constant values of rope length and mass of a load, $l = \{0.7; 1.2; 1.7\}$[m] and $m = \{10; 30; 50; 70\}$[kg]. The experimental researches were focused on the crane’s bridge movement mechanism. The triangular membership functions with coefficients equaled one for assumed constant values were defined for key scheduling variables. The assumed linguistic terms of membership functions were formulated as follows: $LM_i(l) = \{$Small, Medium, Large$\}$ and $LM_j(m) = \{$Small, Medium, Large, Very Large$\}$. The knowledge base was expressed by twelve fuzzy rules type of:

\[
\text{IF } l \text{ is } LM_i(l) = \{$Small, Medium, Large$\} \text{ and } \text{m}_2 \text{ is } LM_j(m) = \{$Small, Medium, Large, Very Large$\}
\text{THEN } u_k = f_k(l, m_2, e, \dot{x}, l, \cdot \alpha, l \cdot \dot{\alpha})
\]
The control system was tested with satisfactory results using the PC platform with control-measurement card PCI-1710HG and Matlab program. In the next step, the control algorithm was implemented on the PLC (FX2N series) by using the fuzzy interface created in the HMI/SCADA system installed on PC exchanging data with PLC by using DASMTFX server. The crane control system was designed for control assumptions and aims formulated as the expected positioning accuracy of crane’s mechanism and a payload, and acceptable tolerance of oscillations and overshoots of output signals equal 0.02 [m], as well as the expected setting time about 7–8 seconds. The examples of experimental results for chosen values of rope length $l = \{0.7; 1.2; 1.7\}$ [m] and mass of a load $m_2 = \{10; 50\}$ [kg], and expected position of crane and a payload $x_d = l$ [m], are presented in the figures 5–8 in the form of time characteristics of crane position $x$ [m] and the load deviation assumed as $l \cdot \alpha$ [m].

The results obtained using the TSK fuzzy robust crane control algorithm realized on the PLC (FX2N series) are satisfied in comparison with results obtained using PC platform with I/O board (the same positioning accuracy and setting time which was about 7 seconds). The oscillations of a payload are reduced about expected tolerance just between 3–4 seconds, and next dumped in expected setting time 7–8 seconds to the assumed acceptable tolerance 0.02 [m]. The results of experiments confirm that the robust fuzzy crane control system can be realized successfully with using PLC.
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5. Conclusions

In the proposed crane control system the expected control quality is obtained by adjusting the controller gains by fuzzy inference system to the controlled object parameters changes. The parameters of a crane dynamic system varies in stochastic way according to scheduling variables, rope length and mass of a load, which change among the known ranges $l = \{l_{\min}, l_{\max}\}$ and $m_2 = \{m_{\min}, m_{\max}\}$. On the basis of this fact, the adaptive crane control system can be created as robust in the expected range of parameters changes. The presented control system is created in the process of off-line neural network learning, based on a set of conventional time-discrete controllers obtained for chosen operating points.

The aim of researches was to elaborate the application of a crane control system based on frequently used in industrial practice control devices. The proposed method of fuzzy control algorithm programming realization on a PLC was based on the fuzzy interface built on the model of Fuzzy Logic Toolbox in Matlab program. The fuzzy interface, created as a HMI/SCADA application, allows to on-line built and modify a fuzzy controller implemented on a PLC. The presented experimental results confirm effectiveness the methods of proposed adaptive crane control system designing, addressed to a problem of practical application, which is
significant regarding to come higher and higher expectations for time and accuracy of transportation operations, as well as device exploitation quality.

References


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