ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1138640

GENETIC FUZZY APPROACH TO ADAPTIVE CRANE CONTROL SYSTEM

Jarosław Smoczek

AGH University of Science and Technology
Faculty of Mechanical Engineering and Robotics
Mickiewicza Av. 30, 30-059 Krakow, Poland
tel.: +48 12 6173104
e-mail: smoczek@agh.edu.pl

Abstract

In automated manufacturing processes the safety, precise and fast transfer of goods realized by automated material handling devices is required to raise efficiency and productivity of manufacturing process. Hence, in those industrial branches where cranes are extensively used the problem of an anti-sway crane control is especially important to speed-up the time of transportation operations and ensures the safe and effective transportation operations. The precise positioning of a cargo requires controlling the speed of crane motion mechanisms to reduce the sway of a payload. Moreover, the anti-sway crane control scheme involves applying the adaptive techniques owing to the nonlinearities of a system that comes especially from stochastic variation of rope length on which a payload is suspended and mass of this payload. The paper provides the design method of an adaptive control system for a planar model of crane. The control system is based on the gain scheduling control scheme created using fuzzy logic controller with Takagi-Sugeno-Kang-type fuzzy implications. The design process of a gain scheduling control system consists in selecting such a suitable set of operating points at which the linear controllers are determined that interpolation control scheme ensures the expected control quality within the known range of nonlinear system parameters changes, when those parameters vary in relation to the exogenous variables: rope length and mass of a payload. The method that is proposed in this paper to solve the problem of designing the fuzzy gain scheduling crane control system for minimum set of operating points is based on the pole placement method and genetic algorithm.

Keywords: *anti-sway crane control, pole placement, fuzzy logic, genetic algorithm*

1. Introduction

The anti-sway crane control problem is important owing to rising requirements for time-optimization and safety of crane operations. It is especially significant in those industrial branches, where cranes are extensively used, and their automation is indispensable to enhance the efficiency and productivity of manufacturing process. The problem of reduction the deviation of a payload from the equilibrium while a cargo is transferred from point to point by a crane involves implementing the adaptive control scheme of speed of crane's motion mechanisms taking into consideration the variation of parameters: rope length and mass of a cargo suspended on a rope. In the industrial practice, the best-known solutions of anti-sway crane control systems are mostly based on the open-loop method, without feedback from sway angle of a transferred cargo. The ASLC (Anti Swing Load Control) manufactured by HETRONIC [13] is an example of industrial application of an open loop crane control system, which can be used in overhead travelling or gantry cranes. The solution of anti-sway crane control system is designed to aid operator control by preventing the load swing, based on information about control signals assigned by operator and measured value of the rope length. The other example, SmartCrane Anti-sway system [16], relies on timing of crane's accelerations to control the sway. The DynAPilot sway control system proposed by Konecranes company [14] minimizes the load sway by calculating the optimal acceleration path using the load height information and operator commands. The Rima company [15] proposes the anti-sway system in which hydraulic unit and winches located on the trolley frame are used to reduce oscillations of a payload based on the reaction principle.

The solutions of anti-sway crane control problem based on the soft computing techniques, fuzzy logic, artificial neural network and evolutionary algorithms are frequently proposed in the scientific works. In [7] the Mamdani-type fuzzy controller was applied to solve the problem of time optimal crane control. In [1] the combination of proportional-derivative (PD) controller of crane position and speed, and the fuzzy controller of the load swing was considered for three-dimensional overhead crane. In [3] the camera detector-based sway angle of a payload measurement system and fuzzy controller are used to shape the acceleration and deceleration of crane's motion mechanism. The fuzzy gain scheduling approach is presented e.g. in [4, 12, 10]. The gain scheduling system design technique based on the clustering method is delivered in [9] for the anti-sway tower crane control system. The iteration method based on the interval mathematic employed to design the fuzzy gain scheduling system of planar crane is provided in [11].The time-optimal control with using genetic algorithm (GA) was proposed for unconstrained optimal crane control in [5]. The real-coded GA was used to find the desired initial co-states of the system with no-constrains. The objective function was formulated as the minimum cost co-states calculated based on the ability to move the system to the desired state after a given amount of time. In [6] the GA was used to determine the coefficients of an optimal feed forward control law used to suppress the load sway of a shipboard crane due to the ship rolling. In [8] the anti-sway crane control problem was solved by using the neural controller trained by GA. The unconventional method of chromosomes tree encoding in GA applied in crane control system was presented in [2]. The control algorithm was presented in form rules separately for swing increasing and dumping, based on heuristic knowledge about the crane laboratory model. The parameters of controller were modified by GA during experiments carried out on the laboratory stand.

The paper provides the method of designing the adaptive anti-sway crane control system using the fuzzy logic, GA and pole placement method (PPM). The adaptive control system is proposed as a gain scheduling control scheme created using the fuzzy rule-based controller (FRBC) with fuzzy implications type of Takagi-Sugeno-Kang (TSK) corresponding to the linear controllers designed at specified operating points represented by fixed values of rope length and mass of a payload. The design process consists in selecting such a suitable set of operating points at which the linear controllers are determined using PPM that fuzzy interpolation control scheme ensures the expected control quality within the assumed range of nonlinear system parameters changes, when those parameters vary in relation to the exogenous variables, called scheduling variables: rope length and mass of a payload.

2. The fuzzy gain scheduling anti-sway crane control scheme

The problem under consideration is simplified to the planar crane transferring a payload with mass m suspended on a rope with length l. The motion equations of dynamic system can be derived from Lagrange's second law type equation (1) converted next to the form of two continuous transmittances presenting, respectively, the relationships between sway angle of a payload and input function (2), and the crane position and sway angle (3).

$$\begin{cases} \ddot{x} = \dfrac{m \cdot g}{M}\alpha + \dfrac{1}{M}F, \\ \ddot{\alpha} = -(1+\dfrac{m}{M})\dfrac{g}{l}\alpha - \dfrac{1}{m \cdot l}F, \end{cases} \tag{1}$$

$$G_1(s) = \frac{\alpha(s)}{U(s)} = \frac{-\dfrac{1}{Ml}}{s^2 + (1+\dfrac{m}{M})\dfrac{g}{l}}, \tag{2}$$

$$G_2(s) = \frac{X(s)}{\alpha(s)} = \frac{-ls^2 - g}{s^2}, \tag{3}$$

where:

$g = 9.81[m/s^2]$ – acceleration of gravity,

$\omega_n = \sqrt{\left(1+\frac{m}{M}\right)\frac{g}{l}}$ – natural pulsation of the payload sway.

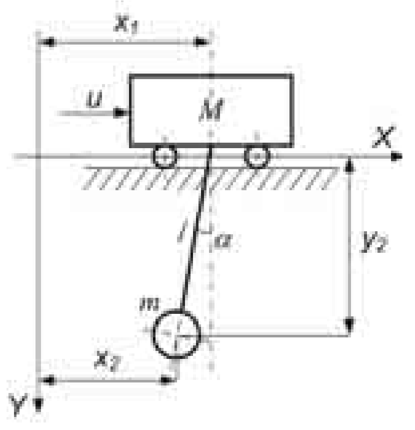

Fig. 1. The model of planar crane

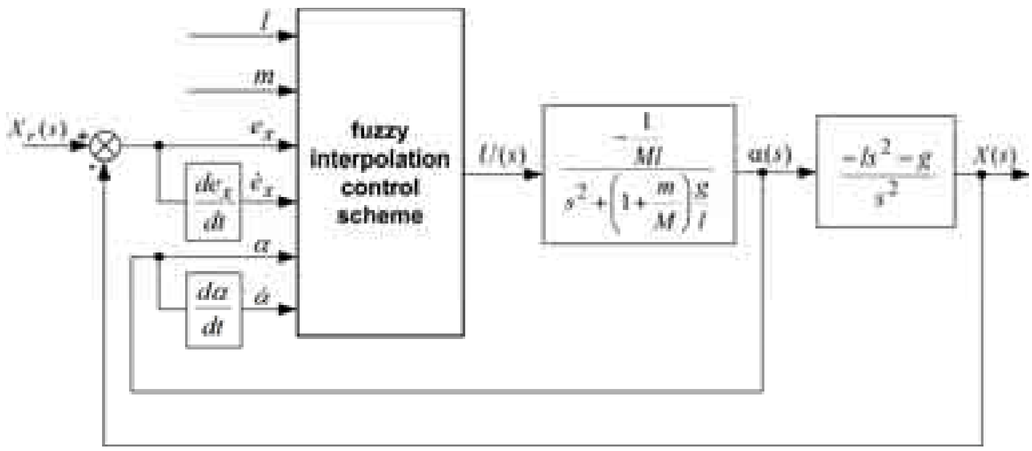

Fig. 2. The model of a planar crane

The fuzzy-based control scheme is presented in the Fig. 2. The fuzzy controller consists of a set of TSK-type if-then implications:

$$\text{IF } l \text{ is } MF_i(l) \text{ and } m \text{ is } MF_j(m) \text{ THEN } u_k = \begin{bmatrix} e_x \\ \dot{e}_x \\ \alpha \\ \dot{\alpha} \end{bmatrix}^T \cdot \begin{bmatrix} K_{k1} \\ K_{k2} \\ K_{k3} \\ K_{k4} \end{bmatrix}, \tag{4}$$

where:

l, m – the scheduling variables,

$MF(l)$, $MF(m)$ – the membership functions (MFs) distributed within the domains of scheduling variables,

$K_{k1}, K_{k2}, K_{k3}, K_{k4}$ – the gains of linear controller specified for a given fuzzy region of operating points,

$k = 1, 2, ..., N$ – the number of fuzzy rule in FRBC.

The scheduling variables l and m are fuzzified using triangular MFs distributed within the specified intervals $l=[l_l, l_n]$m and $m=[m_l, m_r]$kg (Fig. 3).

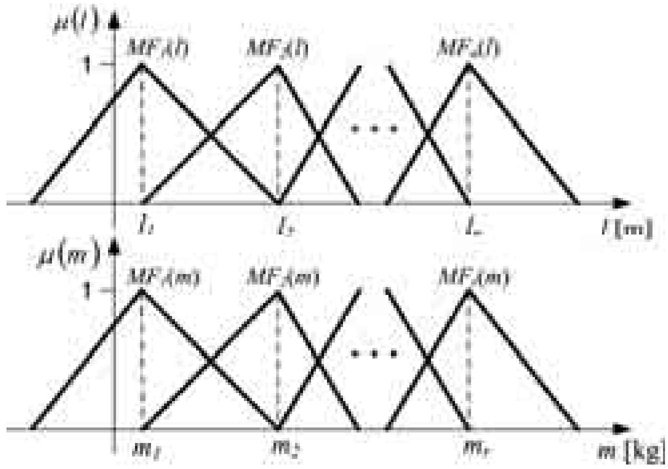

Fig. 3. The triangular MFs distributed within the intervals of rope length (l) and mass of a payload (m)

The neighbouring MFs overlap uniformly, thus the crossover points always correspond to the fuzzy grade equal to $\mu = 0.5$. Hence, the control scheme is based on the FRBC with N rules (4) corresponding to the linear proportional-derivative controllers used in the crane position and sway angle of a payload feedbacks. The controller's gains $\{K_{k1}, K_{k2}, K_{k3}, K_{k4}\}$ are determined at operating points represented by $N = n \cdot r$ combinations of MFs centre points $\{l_i, m_j\}$. The control signal u of the FRBC is calculated at a current operating point in specified interval $l=[l_1, l_n]$m and $m=[m_1, m_r]$kg as a weighted average of all rules outputs:

$$u = \sum_{k=1}^{N} w_k \cdot u_k \,, \tag{5}$$

where w_k is a weight of k^{th} rule determined as a product of fuzzy grades of crisp input values to the MFs:

$$w_k = \mu_{MF_i}(l) \cdot \mu_{MF_j}(m) \,. \tag{6}$$

3. The GA and poles assignment-based approach to design the FRBC

The linear closed-loop control system (Fig. 2), represented by a single rule of FRBC, is described by the four-order continuous transmittance (7). Assigning the four poles of control system at the same point equal natural pulsation $s_1 = s_2 = s_3 = s_4 = -\omega_n$ of a system, the gains of linear closed-loop control system, which are derived from the Diophantine equation (8), will ensure at the k^{th} operating point aperiodic reaching the reference value x_r (without overshoot).

$$G_k(s) = \frac{X(s)}{X_r(s)} = \frac{\frac{1}{Ml}\left(K_{k2} l s^3 + K_{k1} l s^2 + K_{k2} g s + K_{k1} g\right)}{s^4 + \frac{1}{Ml}\left(K_{k2} l + K_{k4}\right) s^3 + \left[\left(1 + \frac{m}{M}\right)\frac{g}{l} + \frac{1}{Ml}\left(K_{k1} l + K_{k3}\right)\right] s^2 + \frac{1}{Ml} K_{k2} g s + \frac{1}{Ml} K_{k1} g}, \tag{7}$$

$$\begin{bmatrix} 0 & 0 & \frac{1}{M} & 0 & \frac{1}{Ml} \\ \left(1+\frac{m}{M}\right)\frac{g}{l} & \frac{1}{M} & 0 & \frac{1}{Ml} & 0 \\ 0 & 0 & \frac{g}{Ml} & 0 & 0 \\ \left(1+\frac{m}{M}\right)\frac{g}{l} & \frac{g}{Ml} & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ K_{k1} \\ K_{k2} \\ K_{k3} \\ K_{k4} \end{bmatrix} = \begin{bmatrix} 4\omega_n \\ 6\omega_n^2 \\ 4\omega_n^3 \\ \omega_n^4 \end{bmatrix}. \tag{8}$$

The problem of FRBC designing relies on selecting minimal set of linear controllers (fuzzy rules) to satisfy the conditions specified for control performances in all range of scheduling variables changes. It can be obtained by finding the minimal set of MFs for scheduling variables (Fig. 3). Hence, the optimal solution of this problem is a maximal value of a sum of distances between midpoints of neighbouring MFs, which simultaneously guarantees at the most hazardous operating points corresponding to the crossover points of neighbouring MFs that a system's performances satisfy the control quality demands. Simultaneously, the maximal acceptable distance between two neighbouring operating points corresponds with minimal difference between acceptable and real value of indicator assumed to evaluate the control system performances obtained at the midpoint between those operating points. Hence, assuming that the performances of a closed-loop control system are evaluated based on the acceptable value of overshoot χ_a the objective function can be formulated as the sum of absolute differences between the assumed value χ_a and the maximal overshoot χ measured at each hazardous operating point:

$$f(\chi) = \sum_{h=1}^{H} |\chi_a - \chi|, \tag{9}$$

where $H = (n-2)(r-2)$ - the number of crossover points of MFs (Fig. 3).

The Pittsburgh-based genetic searching strategy can be used to find the optimal solution of FRBC encoded using real-valued chromosome represented by the vector of MFs centre points:

$$\lfloor l_1, l_2, ..., l_i, ..., l_n, m_1, m_2, ..., m_j, ..., m_r, n, r \rfloor, \tag{10}$$

where the n and r are the numbers of centre points of MFs distributed, respectively, within the assumed intervals of rope length and mass of a payload.

The proposed evolutionary searching strategy consists in exploring the space of possible solutions, which differ in the size of rules (the number of linear controllers). Hence, in reproduction process, before crossover and mutation, the small number of individuals is selected to produce the new individuals by removing or merging the neighbouring MFs. This operation leads to enrich the genetic material in existing population and prevents of premature convergence (domination of fuzzy controllers with the same or similar number of rules in population). The number of MFs of considered individual is decreased or increased based on, respectively, p_D and p_I probabilities, which are calculated based on $\bar{n}$ average, $n_{\min}$ minimal, and $n_{\max}$ maximal number of MFs for a given input variable in a population:

$$p_D = \frac{\bar{n} - n_{\min}}{n_{\max} - n_{\min}}, \; p_I = 1 - p_D, \tag{11}$$

The genetic operations are based on the arithmetical crossover and max-min non-uniform mutation.

4. The simulation results

The proposed method of fuzzy logic-based anti-sway crane control system design was applied to create the gain scheduling control scheme for scheduling variables varying in the intervals l=[1, 10]m and m=[10, 1000]kg. The GA was implemented using Matlab software in which the own algorithm was written in form of M-functions. The fitness of the individuals, evaluated using the equation (9), was calculated based on the assumed overshoot χ_a=0.02, expected at each MFs crossover point. The termination condition of GA was assumed as, either the maximal number of iterations set to 200 is exceed, or the overshoot of object response at each MFs crossover point is in interval $\chi = \chi_a \pm 0.005$. The population size was 16 individuals, while crossover and mutation probability were, respectively, set to p_c=0.875 and p_m=0.125. The Fig. 4 presents the MFs tuned by

GA, with centre points distributed within the intervals l=[1, 10]m and m=[10, 1000]kg. The solution of FRBC was obtained at 170 iteration, when the best individual in population satisfied the termination condition: the overshoot in the desired interval χ=[0.015, 0.025] at each from 9 operating points corresponding to the all combinations of crossover points of MFs tuned for rope length and mass of a payload.

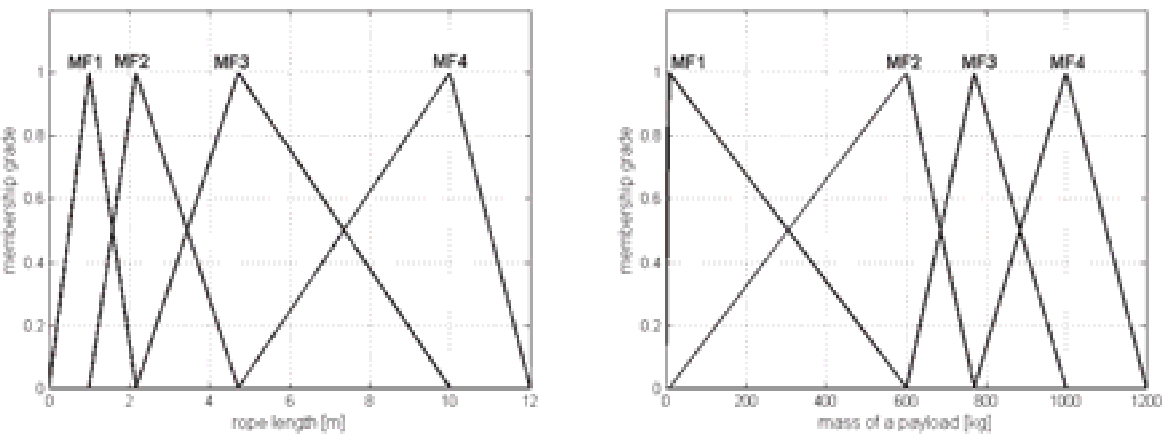

Fig. 4. The MFs tuned using GA for scheduling variables of FRBC

The GA has led to design the fuzzy gain scheduling system consisting of 16 TSK-type implications (4) created as the combination of 4 MFs tuned for rope length and mass of a payload input variables of FRBC. The gains of linear controllers, specified in conclusions of those rules, were determined at the midpoints of MFs formulated in rule's antecedent based on Diophantine equation (8). The Fig. 5 presents the performances of the anti-sway crane control system for different operating points.

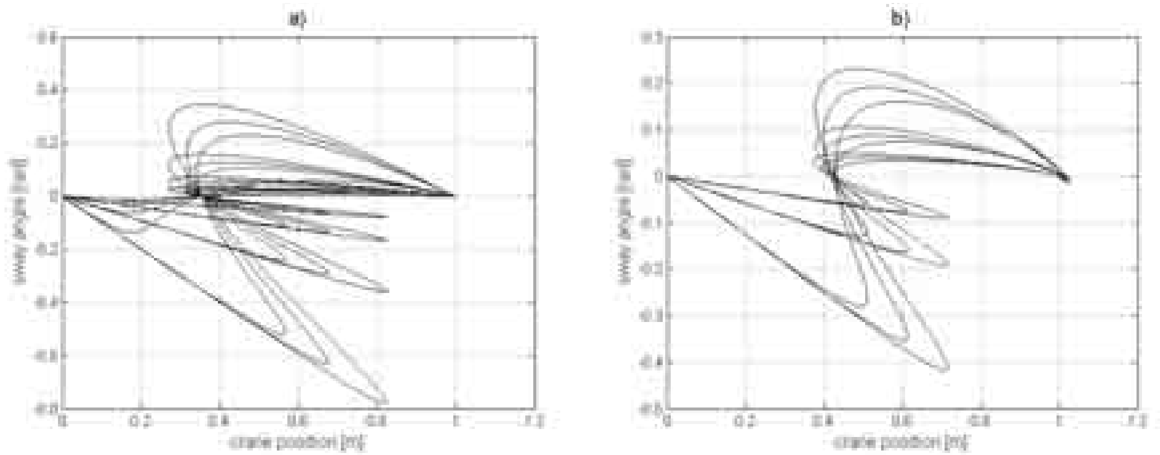

Fig. 5. The control system performances in form of phase portraits presenting the relation between crane position and sway angle of a payload: a) for 16 operating points corresponded to the midpoints of fuzzy regions represented by antecedents of 16 if-then rules of FRBC, b) for 9 operating points corresponded to the crossover points of MFs

The simulation results are depicted in form of the phase portraits presenting the relations between crane position and sway angle of a payload. The Fig. 5a presents the simulation results for 16 operating points corresponded to the combination of centre points of 4 MFs specified for rope length and 4 MFs distributed within the interval of mass of a payload. The performances at those operating points characterize lack of overshoot: the expected position x_r=1m is obtained with suppressing the sway of a payload. The Fig. 5b presents the control system performances for 9 operating points corresponded to the crossover points of MFs. The crane is obtaining the expected position with overshoot exactly in the interval χ=[0.015, 0.025], that means that the adaptive crane control system satisfies the condition: the overshoot at the most hazardous operating points is less than 0.025.

5. Conclusions

The paper provides the method of adaptive anti-sway crane control system designing. The control system that has been presented in the paper is based on the fuzzy interpolation control scheme that relies on switching the linear controllers, represented by TSK-type implications, for the varying rope length and mass of payload variables. The contribution of this paper is the novel approach to design the fuzzy control scheme, which has been based on the PPM and GA. The design method is based on selecting the minimal set of operating points at which the linear controllers are determined using PPM. The selection of those points is realized using GA-based searching process. The presented approach contributes to the genetic fuzzy systems through providing the evolutionary algorithm that ensures wide exploration of searching space by optimizing the size of fuzzy system's rule base together with fine-tuning the MFs. The proposed method to fuzzy gain scheduling anti-sway control system designing has been successfully tested for simplified model of planar crane. The simulation results encourage implementing this method in automated crane control applications.

Acknowledgement

The project is financed by the Polish National Science Centre.

References

[1] Cho, S. K., Lee, H. H., *A fuzzy-logic antiswing controller for three-dimensional overhead cranes*, ISA Transactions 41, pp. 235-243, 2002.

[2] Filipic, B., Urbancic, T., Krizman, V., *A combined machine learning and genetic algorithm approach to controller design*, Engineering Applications of Artificial Intelligence, Vol. 12, pp. 401-409, 1999.

[3] Itoh, O., Migita, H., Itoh, J., Irie, Y., *Application of fuzzy control to automatic crane operation*, In Proceedings of IECON 1, pp. 161-164, 1993.

[4] Kang, Z., Fujii, S., Zhou, C., Ogata, K., *Adaptive control of a planar gantry crane by the switching of controllers*, Transactions of Society of Instrument and Control Engineers, Vol. 35, No. 2, pp. 253-261, 1999.

[5] Kimiaghalam, B., Homaifar, A., Bikdash, M., Dozier, G., *Genetic algorithms solution for unconstrained optimal crane control*, IEEE Congress on Evolutionary Computation, July 6-9, Washington DC 1999.

[6] Kimiaghalan, B., Homaifar, A., Bikdash, M., Sayyarrodsari, B., *Genetic algorithm based gain scheduling*, In Proceedings of the Congress on Evolutionary Computation, pp. 540-545, 2002.

[7] Moon, M. S., VanLandingham, H. F., Beliveau Y.J., *Fuzzy time optimal control of crane load*, Proceedings of the 35th Conference on Decision and Control, pp. 1127-1132, Kobe, Japan 1996.

[8] Nakazono, K., Ohnisihit, K., Kinjot, H., *Load swing suppression in jib crane systems using a genetic algorithm-trained neuro-controller*, In Proceedings of International Conference on Mechatronics, Kumamoto Japan 2007.

[9] Sadati, N., Hooshmand, A., *Design of a gain-scheduling anti-sway controller for tower cranes using fuzzy clustering techniques*, In Proceedings of Int. Conference on Computational Intelligence for Modeling, Control and Automation, Sydney, Australia 2006.

[10] Smoczek, J., Szpytko, J., *A mechatronics approach in intelligent control systems of the overhead travelling cranes prototyping*, Information Technology and Control, Vol. 37, No. 2, pp. 154-158, 2008.

[11] Smoczek, J., Szpytko, J., *Fuzzy logic approach to the gain scheduling crane control system*, In Proceedings of 15th Int. Conference on Methods and Models in Automation and Robotics*,* *MMAR 2010*, 23-26 August, pp. 261-266, Miedzyzdroje, Poland 2010.
[12] Yi, J., Yubazaki, N., Hirota, K., *Anti-swing and positioning control of overhead travelling crane*, Information Sciences 155, pp. 19-42, 2003.
[13] http://www.hetronic.co.uk.
[14] http://www.konecranesamericas.com.
[15] http://www.rimagroup.com.
[16] http://www.smartcrane.com.