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CRANES CONTROL IN AUTOMATED MATERIAL HANDLING SYSTEMS – A SURVEY

Abstract: The paper presents a survey of proposed in the scientific works, as well as applications implemented in industrial practice, solutions of anti-sway crane control systems. The example of an adaptive crane control system, based on indirect adaptive pole placement (IAPP) method and neuro-fuzzy crane dynamic model, was also presented, as well as results of experiments carried out on the laboratory object, the overhead traveling crane.
Keywords: anti-sway crane control system

1. INTRODUCTION

The material handling systems are the key part of a manufacturing cycle in which they support technological and storage operations by handle materials within the manufacturing departments and production halls. The Large-Dimensional Rail-Mounted Handling Devices (WSUT) [30, 31] is the class of the material handling devices to which belong the cranes (overhead traveling cranes, gantry, portal, railway and other types of cranes) that are used in many industrial branches, especially in heavy industry, metallurgical, shipbuilding, aircraft, machine-building and armaments industries, etc.

In automated industrial processes the higher and higher requirements are put on time and accuracy of transportation tasks realized by material handling devices. Those requirements can be met by applying automated solutions of material handling systems and control quality improvement. In many manufacturing processes where the transportation operations are realized by cranes the safety and precise transfer of materials is expected with minimizing the load oscillations and the operation time. In the non-automatic systems the resulting performance depends on the human operator experience and capability which can be unreliable.

The problem of positioning a payload shifted by a crane, even though is interesting problem considered frequently in automatics, is not only one to solve when the automation of crane's operations is required in a manufacturing system. Beside transportation cycle time decreasing and precision of a payload positioning the problem of suitable device exploitation quality ensuring is important as well. From safety and reliability point of view it is important as well to reduce overloads that arise during transient states of crane's power transmission systems working which are caused by non-uniform loading. This disadvantageous phenomenon, which leads to the crane's bridge beveling, affects unfavorable on exploitation of a wheel-rail system of the overhead traveling cranes.

The planning, synchronization and optimization of the transportation operations realized by material handling means is the next problem, which can be required to solve in order to increase the productivity and efficiency of the automated manufacturing process. The time-optimization of transportation cycle requires as well to apply in a crane control system algorithms of a payload movement trajectory designing and next its following, taking into consideration a map of a three-dimensional space in which the crane's movement mechanisms shift a payload, as well as the obstructions that can be there found.

To meet those complex requirements the application of automated control system of material handling process should be realized as integrated manufacturing control system, composed of a distributed control system extended by a higher level of control system realized as the HMI/SCADA (Human-Machine Interface/Supervisory Control and Data Acquisition) application used for supervisory control, monitor and manage the whole manufacturing process. More and more compound tasks required contemporary to aid man decision-making process lead to develop and integrate HMI/SCADA tools with higher and higher levels of managing systems like MES (Manufacturing Execution Systems) and ERP (Enterprise Resource Planning).

However the main attention in this paper is fixed on the problem of positioning a payload shifted by an overhead traveling crane. This problem is very interesting from the automatics point of view and widely studied in researches works owing to necessity of solving the problem of anti-sway crane control system adaptation to the changes of controlled object parameters, which are the result of variety values changes of the variables: rope length, on which a payload is suspended, and mass of a payload. This problem becomes also essential in the face of higher and higher requirements that are put on the expected time and precision of realized by cranes handling operations in automated manufacturing processes.

2. THE ANTI-SWAY CRANE CONTROL METHODS

The aim of a crane control system generally is positioning crane's movement mechanisms, which handle a payload suspended on a rope, and reducing the payload swing, which arises in transient states of crane's mechanisms working. From the application side, an anti-sway crane control system can be realized as the open or closed loop control system. The open loop control system simplifies application by lack of trouble with implementing the reliable and effective working in practice a measurement system of the load swing angle. The ASLC (*Anti Sway Load Control*) Module manufactured by HETRONIC is an example of such industrial application, which can be used in overhead traveling and gantry cranes. The solution of open-loop control system, without the load swing feedback considered in control scheme, is designed to aid operator control by preventing load swing, based on information about control signals assigned by operator and measured value of the rope length. The next example of industrial application, which can be used as an open or closed loop control system, is the SmartCrane Anti-sway system, which relies on timing of crane's accelerations to control the sway. Also the DynAPilot sway control system proposed by Konecranes company minimizes the load sway by calculating the optimal acceleration path using load height information and operator commands. The other solution of the load sway preventing system, based on a reaction principle, is proposed by Rima company. The anti-sway system relies on hydraulic unit, which using winches located on the trolley frame dumps oscillations of a payload.

On the other hand the open loop crane control system does not ensure compensation of load swing for external disturbances such as wind. The load swing feedback enables to realize the adaptive control system, taking into consideration the uncertainty of control object parameters, and real time identification of a crane dynamic model based on input and output signals of a controlled object.

The anti-sway crane control system presented in the scientific works frequently concern the crane dynamic models simplified to a two-mass model consists of a payload mass suspended on a rope connected to the crane mass moving along an axis of the assumed coordinate system. The crane control system is a nonlinear system which can be simplified by presenting a crane dynamic system as a linear model with varying parameters. For this reason a crane control system requires to apply the adaptive techniques.

In many of science works the problem of a load swing dumping is considered using optimal control theory [2, 3, 12, 25]. The problem of an optimal path planning of a payload moved by crane is generally solved by minimizing the assumed function, which corresponds to the swing angle and its derivative or to the energy consumption, that leads to obtain the values of control variables which transfer the nonlinear dynamic system from the initial state to the final state.

In [4, 6, 7, 10] the problem of moving a suspended load using a crane was addressed and solved using the feedback linearization. In [4] the robust crane control system is presented based on a sliding mode control technique. In both [4] and [7] was assumed that the actual system parameters are uncertain but belonging to a known compact domain. In [6] the indirect adaptive crane control system is based on the feedback linearization method and estimator of crane model parameters.

In some scientific works a crane dynamic system is considered as a linear model with varying parameters, which allows to solve the crane control problem using conventional controllers type of proportional-integrate-derivative (PID) [29], and using adaptive control algorithms that were determined based on poles assignment [17, 19, 20, 27, 28], Linear Quadratic Regulator (LQR) [5, 17], gain scheduling [9], Lyapunov-equivalence-based observer [11], and Ackermann's method [13].

The most popular unconventional methods used in crane control problem are based on so called artificial intelligence, mostly fuzzy logic and 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, in which the antecedent and consequent of fuzzy rule are both expressed in form of fuzzy sets, that allows to take into consideration the uncertainty of controlled system parameters. The examples of fuzzy crane control systems based on Mamdani fuzzy model are presented in [5, 8, 15, 18, 22, 24].

In [22] the Mamdani fuzzy controller was applied to solve the problem of time optimal crane control. The robust fuzzy controller was compared in [5] with conventional LQR method, and quality of both control algorithm were analyzed considering the dry friction varying in crane system, proving that the better results were obtain with Mamdani controller which ensured compensation of disturbances. In [8] the combination of proportional-derivative (PD) controller of crane mechanisms position and speed, and the fuzzy controller of the load swing was considered for three-dimensional overhead crane. In [15] the measuring method of the load swing based on a camera detector is presented together with fuzzy controller of the load swing, which was used to modify the assumed pattern of acceleration and deceleration of crane's movement mechanism.

The other type of inference system, based on Takagi-Sugeno-Kang (TSK) implication, or similar structure of fuzzy rule used in crane control system, was presented in [16, 26, 28, 32, 33]. In [16] a robust switching control scheme was proposed for a gantry crane. The control scheme was based on fuzzy TSK system which switches several controllers, each designated for a different fixed-length of a rope nominal model. In [32, 33] the 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 other approach to crane control system, based on artificial neural network is presented in [1, 21, 23], 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 control parameters are adjusted using the neural network trained on-line to minimize a quadratic cost function. The learning of the neural network is realized following the backpropagation algorithm. The combination of neural network and fuzzy logic was used to solve the crane control problem for example in [14, 27, 28]. In [14] a fuzzy neural network was trained using backpropagation method to control an overhead traveling crane.

3. PROTOTYPING OF ANTI-SWAY INTELLIGENT CRANE CONTROL SYSTEMS

The problem of anti-sway crane control is the subject of researches realized in Laboratory of Automated Transportation Systems and Devices at the AGH University of Science and Technology. The attention is focused on control methods based on conventional as well as intelligent systems (fuzzy logic, artificial neural network) tested on laboratory object, the overhead traveling crane with hoisting capacity Q=150 [kg], The example of indirect adaptive pole placement (IAPP) crane control system, tested on the laboratory object, is shown in the figure 2. The proposed system is based on conventional discrete crane position and the load swing controller which gains are adjusted using pole placement method (PPM) according to real-time estimated parameters of the crane dynamic model. The model of controlled object is composed of two time-discrete transmittances $G_{\dot{x}}(z)$ and $G_{\alpha}(z)$.

$$G_{\dot{x}}(z) = \frac{\dot{X}(z)}{U(z)} = \frac{d_0}{z + c_0} \tag{1}$$

$$G_{\alpha}(z) = \frac{\alpha(z)}{\dot{X}(z)} = \frac{b_1 z + b_0}{z^2 + a_1 z + a_0} \tag{2}$$

where: $\dot{x}$ - crane speed, α - the load swing, u - control signal

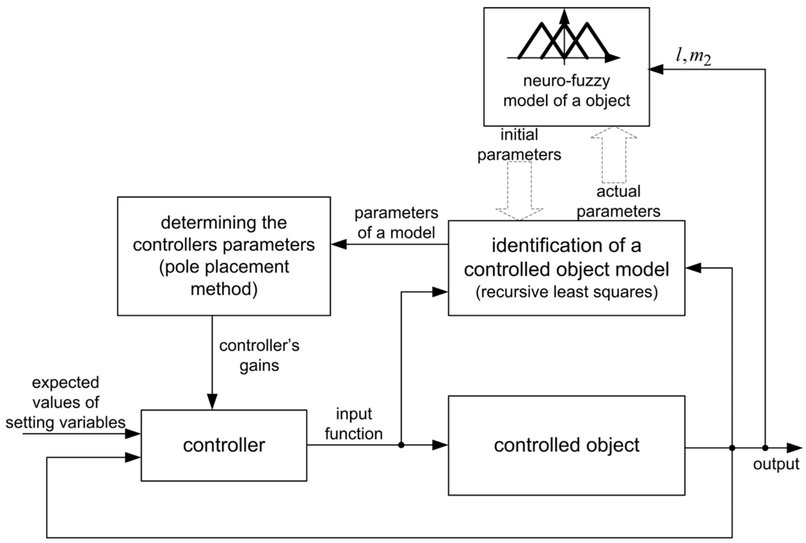

Fig. 2. The general example of the IAPP crane control system
with neuro-fuzzy estimator of a crane dynamic model parameters

The parameters of the crane dynamic model are real-time identified using Recursive Least Squares (RLS) algorithm, of which working is speeded-up by neuro-fuzzy crane dynamic model, derived in off-line neural network learning, and next improved on-line by RLS algorithm. The neuro-fuzzy crane dynamic model is based on Takagi-Sugeno-Kang (TSK) fuzzy inference system consisting of the set of N models corresponded to the fuzzy implications, in which parameters of considered in actual sample time k model, are estimated based on scheduling variables, rope length l and mass of a load m_2, and assumed for input signals membership functions $LM_i(l)$, $LM_j(m_2)$:

$$\text{IF } l \text{ is } LM_i(l) \text{ and } m_2 \text{ is } LM_j(m_2) \text{ THEN } \mathbf{Y_k} = [d_{0k}, c_{0k}, b_{1k}, b_{0k}, a_{1k}, a_{0k}]^T$$

where: $k = 1, 2, ..., N$, and $i = 1,2,..., n$, $j = 1,2,..., m$.

The control assumptions and aims were formulated as expected positioning accuracy for crane's mechanism and shifted a payload, and acceptable tolerance of oscillations and overshoots of output signals equal 0,02 [m], as well as the setting time about 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 [kg], and expected position of crane and payload $x_d = 1[m]$, are presented in the figures 3 and 4.

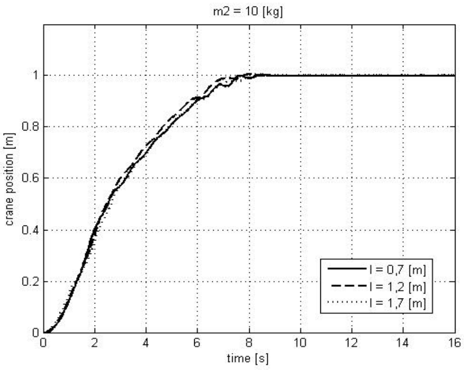

Fig. 3. The crane position for $l = \{0,7;1,2;1,7\}$ $[m]$ and $m_2 = 10[kg]$

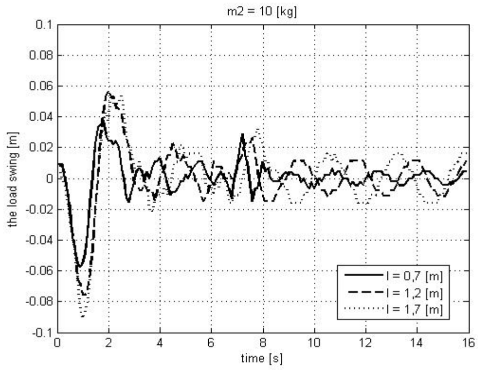

Fig. 4. The load swing for $l = \{0,7;1,2;1,7\}$ $[m]$ and $m_2 = 10[kg]$

The results obtained using the IAPP control system (Fig. 4) with TSK fuzzy estimator are satisfied for the assumed control conditions. The oscillations of a payload are reduced about expected tolerance (0,02 [m]) just between 3-4 seconds, and next dumped in expected setting time, about 7-8 seconds to the assumed acceptable tolerance 0,02 [m]. The results of experiments confirm effectiveness of the proposed adaptive control system.

4. CONCLUSIONS

The problem under consideration, the time and positioning accuracy of transportation tasks realized by cranes, is important according the rising demands put on automated material handling systems (AMHS). The fast and safety transfer of materials is required to increase productivity and efficiency of manufacturing processes. One of the main problem in crane control system is to minimize the load swing, which extend the transportation operation time and is dangerous to workers and devices found in the crane workspace, as well as to a handled materials. The proposed industrial application are mostly solutions of open-loop control systems are not robustness on disturbances and uncertainty of system actual parameters. The problem of closed-loop anti-sway control system is frequently considered in automatics. Generally the approach to the considered problem is based on a crane dynamic model formulated as nonlinear system or linear system with time varying parameters. The solutions presented in science works are mainly based on optimal control theory, adaptive systems with real-time estimated parameters of controlled object, as well as robust controllers with programming scheduled gains, as well as intelligent systems based on fuzzy logic and artificial neural network.

The presented in the paper example of adaptive anti-sway crane control system with neuro-fuzzy model of a crane dynamic was tested on the laboratory model of an overhead traveling crane. The results of experiments confirm effectiveness of the proposed control system.

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PRZEGLĄD ROZWIĄZAŃ SYSTEMÓW STEROWANIA SUWNICAMI W ZAUTOMATYZOWANYCH SYSTEMACH TRANSPORTU BLISKIEGO

Streszczenie: W artykule przeprowadzony został przegląd rozwiązań systemów sterowania mechanizmami ruchu suwnic, których celem jest pozycjonowanie ładunku oraz tłumienie jego wychyleń w stanach nieustalonych pracy tych urządzeń. Przedstawiono zarówno wybrane znane aplikacje stosowane w praktyce przemysłowej, jak również przeprowadzono przegląd rozwiązań adaptacyjnych systemów regulacji prezentowanych w literaturze naukowej. Podany został także przykład adaptacyjnego systemu sterowania z zastosowaniem lokowania biegunów oraz neuro-rozmytego modelu dynamiki suwnicy, oraz wyniki eksperymentów przeprowadzonych na obiekcie laboratoryjnym.

Słowa kluczowe: suwnica, sterowanie adaptacyjne