The Crane Control Systems: A Survey

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Abstract— The paper presents a survey of proposed in the scientific works, as well as applications implemented in industrial practice of anti-sway crane control systems based on the intelligent solution (fuzzy logic, neural network and genetic algorithm and hybrid combine solution. The other part of paper contain review of solution concern crane workspace visualization techniques with obstacle identification for non-collision payload trajectory path planning. Presented solution was base on the image processing techniques, especially base on the stereovision technique.

I. INTRODUCTION

The material handling systems (MHS) are the crucial part of the industrial process supporting the technological operations, handle the goods within the manufacturing departments and production halls. The cranes, which belong to the group of Large Rail-Mounted Handling Devices (LRMHD) [20], play the important role in those transportation operations. In automated manufacturing processes the higher and higher requirements are put on the safety and efficiency of crane operations, that challenge to optimize, organize and synchronize the transportation operations. The automation of crane operations involves implementing in crane control system solutions to satisfy following requirements:

- precise positioning of a payload from starting point to its destination that requires to control the speed of crane motion mechanisms to reduce the sway of a payload while moving it to the desired point as fast as possible,
- reducing the crane skew angle that is caused by non-uniform overloads of crane, e.g. motion mechanisms of a crane's bridge that can affect unfavorable on exploitation of a wheel-rail system of the overhead traveling cranes,
- operating workspace identification with obstacles detection for time-optimal and safe path of a payload planning, and next real-time tracking the designed trajectory, as well as synchronizing the transport operations realizing by devices in the mutual workspace.

The problem of anti-sway crane control has been extensively researched over the past decades. The general taxonomy of proposed solutions can be given by classifying the methods into open and closed-loop control system. The open-loop control usually utilizes the optimal control theory, where the optimal path planning of a payload is determined through minimizing the assumed function, which corresponds to the sway angle and its time derivatives, or to the energy consumption, that ensures transferring the nonlinear system from the initial state to the final state. The closed-loop control system ensures of the robustness against the system uncertainties, parameters variation, system nonlinearities and disturbances affected for example by external phenomena, e.g. wind. The core of the problem in realizing the anti-sway close-loop control system in industrial practice is reliable technique of sway angle measuring. Hence, the feedback control system, which take into consideration the sway angle of a payload suspended on a rope, is proposed in some research works as the software-hardware architecture utilizing the contactless methods of sway angle measuring based on the dynamic system visions. The 3D-image acquisition using cameras, laser scanners, acoustic or radar sensors are also more and more popular to solve the problem of crane workspace mapping, obstacles detection and safe and time-optimal path planning for a transported cargo. Moreover, the anti-sway crane control problem involves to apply the adaptive techniques owing to the nonlinearities of a system, that comes from e.g. stochastic variation of rope length and mass of a shifted load. The proposed approaches are frequently based on the soft computing techniques or their combination with the conventional methods. Especially fuzzy logic, which is the powerful tool that allows to convert the uncertain input information into the crisp output value, has been successfully employed in a lot of the anti-sway crane control applications. The soft computing techniques are also used to solve the problem of scheduling the cranes operations, that can be formulated as the optimal control problem. The scheduling problem of cranes operations is especially the significant in container terminal, as well as automated manufacturing processes. The problem of time-optimization of transportation operations involves to take into consideration the safe synchronization of cranes works, as well as planning the services and fast reaction on the downtime occurring

[18, 43]. The heuristic methods, as well as genetic algorithms motivated by an biological evolutionary processes have found the practical applications in the considered problem.

The paper delivers the survey of selected applications and research studies of crane control problem. The main attention is focused on the so called intelligent anti-sway crane control systems which utilize the soft computing techniques: fuzzy logic, artificial neural network, and evolutionary algorithms. The survey of those control approaches is presented in the section II. The section III is the review of some chosen crane control solutions based on the vision systems. Finally, this paper is concluded in the section IV.

II. The Anti-Sway Crane Control System

An anti-sway crane control problem is generally solved in the scientific works using open-loop or closed-loop control approach. The open-loop control usually utilizes the optimal control theory, where the optimal path planning of a payload is determined through minimizing the assumed function, which corresponds to the sway angle and its time derivatives, or to the energy consumption, that ensures transferring the nonlinear system from the initial state to the final state. The most applications dedicated for industrial systems are based on the open-loop control technique. For example the ASLC (*Anti Sway Load Control*) module manufactured by HETRONIC 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 SmartCrane Anti-sway system consists in timing of crane acceleration to control the sway. The DynAPilot sway control system, proposed by Konecranes company, minimizes the load sway by calculating the optimal acceleration path using the load height information and operator commands, while the anti-sway crane system proposed by Rima company relies on hydraulic unit, which based on the winches located on the trolley frame reduces oscillations of a payload.

The optimal control theory is applied to the problem of anti-sway crane control system in e.g. [7, 21, 25, 40]. In [2] the crane control system is solved using Lyapunov-equivalence-based observer. The feedback linearization is addressed to the crane control in [9], where the sliding control technique is proposed, as well as in [8], where indirect adaptive technique is based on the estimator of crane model parameters. Some other applications are based on the LQR method [22], poles assignment [3, 29], as well as the classic PID controllers [37].

The unconventional methods based on soft computing techniques are frequently applied to the problem of adaptive crane control. The fuzzy logic, artificial neural network, evolutionary algorithms, their hybrids, as well as combination with the conventional methods allows to take into consideration the uncertainty of controlled system parameters, express the heuristic strategy in form of implications, and apply the machine learning techniques and evolutionary algorithms to design and optimize the control scheme. Especially the fuzzy logic is often addressed to the crane control owing to the possibility of expressing the nonlinear control system strategy in form of implications if-then. In [1, 30, 31, 32, 35, 37] the fuzzy crane control scheme are delivered using the Madani-tipe implications. In [32] the Mamdani fuzzy controller is applied to solve the problem of time optimal crane control. The robust fuzzy controller was compared in [1] 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 [37] 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.

The method of gain scheduling designing based on the fuzzy interpolation scheme is proposed for the crane control problem in [42], where a robust switching control scheme was described for a gantry crane. The control scheme is based on fuzzy Takagi-Sugeno-Kang (TSK) system which switches several linear controllers designated for a different fixed-length of a rope nominal model. The similar approach based on the TSK-type fuzzy inference system is proposed in [12, 15, 23, 24, 42]. In [23, 24] 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. In [13] the iterative techniques of designing the fuzzy gain scheduling anti-sway crane control system is delivered. The pole placement methods and interval mathematics is used to select a minimum set of operating points at which the linear controller are designed that lead to obtain the fuzzy scheduling scheme ensuring the expected control quality in all range of scheduling variables changes. The fuzzy gain scheduling system design technique based on the clustering method is proposed in [34] for the anti-sway tower crane control system.

The artificial neural network approach to crane control problem is presented in [11, 27, 28], where the control parameters are adjusted using the neural network trained on-line using back propagation method to minimize a quadratic cost function. The combination of neural network and fuzzy logic is used in [12, 15, 39]. In [39] a fuzzy neural network was trained using backpropagation method to control. In [12] the indirect adaptive control system consists of neuro-fuzzy model of crane dynamic.

The genetic algorithm-based crane control system are proposed in e.g. [5, 6, 14, 26]. In [5, 6] the time-optimal control with using genetic algorithm was proposed for unconstrained optimal crane control. The unfitness function was formulated as the minimum cost of co-states quantified based on the ability to move the system to the desired state. In [14] the genetic algorithm is utilized to on-line identify the crane model parameters in indirect crane control scheme. The parameters of a crane dynamic model are used to calculate the gains of linear controllers for desired poles at a operating point currently identified by genetic algorithm. In [26] the anti-sway crane control problem was solved by using the neural controller trained by genetic algorithm. The tree-encoding-based genetic algorithm is used in [4] to search the control laws presented in form of rules, formulated separately for swing increasing and dumping. The initial control strategy is created based on the heuristic knowledge acquired from the laboratory model of a crane. The parameters of controller were modified by genetic algorithm during experiments carried out on the laboratory stand.

III. VISION SYSTEMS-BASED CRANE CONTROL

The overhead travelling crane workspace modeling could minimize delays associated with set correct payload trajectory points successfully by-pass identified obstacles. The problem of ensuring the safe and efficient cranes operations in automated manufacturing processes involves the needs of the operating workspace identification. One of the primary areas in three-dimensional imaging is a recovery the 3D information about the shape of objects (obstacles), using known vision analysis methods.

An scientific literature an information about the first described an application for poses an information about additional object shape (3D) was publish in 1930 [33]. Main concept based on a mirror. The mirror gave a second view of the object during recording process. Information about additional second view of the object was saved together with mother image.

In another year scientist and engineers try find techniques more useful and universal to extract 3D information from 2D image. Today a number of different methods for obtaining a 3D geometry with use images analysis is very rich. One of the most popular technique to poses full three-dimensional information about the observed scene is stereovision. Stereovision base on the binocular technique where information about the viewed scene depth is extracted from slightly different images.

The overhead travelling crane can be described like a large workspace robot [36] . If we interpret the crane hook as robot effector, then is possible to equip cranes mechanisms into cameras for acquire pair of images for poses information about workspace and potential obstacles in stereovision mode [16].

In the papers [10, 38, 41], authors use stereovision technique to enable automatic recognition crane proper position or storage recognition. In paper [10] authors described a real-time auto-landing system for container position estimation to mount automatically the container to spreader using stereo vision. In the [41] article was described a method for physical observing the crane effector with the movable stereo head system. With this tools help was possible to measure the sway angle of the payload and hook trajectory tracking. In [38], authors presented a method for automatic recognition geometric feature when the crane transport always the same type of the payload. This functionality make possible unsupported by the men payload lifting of the same type.

In article [19] was presented method of adaptation a 3D laser scanner for acquire a three-dimensional OTC workspace model. On the fig. 1 is present a part of 3D rendered model, generated on the cloud of points base recorded with the help laser scanner - Imager 5006.

Figure 1. The 3D model of overhead travelling crane workspace

Another type of application are complex vision system solution. In the paper [16, 17], authors propose vision system for the gather information about unknown obstacles, their dimension and localization in the crane workspace. The crane control system was built on the laboratory stand with physical model of an overhead travelling crane (fig. 2). The architecture of the control system is based on the FX2N 48MR PLC series (programmable logic controller) and measurement systems consisting of the incremental encoders used to measure the positions and speeds of crane's motion mechanisms, the high resolution camera with IP (Internet Protocol) communication interface installed under the trolley of a crane to capture the stereo pairs of images of a crane workspace, and sway measurement circuit consisting of contact and contactless method of sway angle measuring based on, respectively, high resolution incremental encoder and the intelligent camera type of Sony XCI V3 applied to detect the sway of a rope caused by crane. The intelligent camera is installed under the trolley, and the vision software (Vision Builder for Automated Inspection) integrated with the embedded system allows to extract the specified region of snapshot with full width resolution and part of height resolution to reduce the number of processing pixels in each recorded frame. The sway angle of a rope is determined based on the plot of rectangular region with isolated rope edge and the parallel line of image height. The communication system between the controller and vision system is realized based on the OPC server/client architecture. The stereovision system is based on the single camera that guarantees identical focal length for each snapshot, and additionally parallel orientation of the images baseline to the image plane. The stereo pair of images is acquired as the sequence of snapshots of operating workspace during the crane/trolley movement, while the current location of the camera is identified through measuring the crane or trolley position using incremental encoders. The images are captured and used to determine the disparity map by Image Processing Toolbox of the Matlab software. The coordinates of collision-free trajectory of a payload are calculated using graph search algorithm, which has been based on the A-star method, and send to the HMI/SCADA (Human Machine Interface/ Supervisory Control and Data

Acquisition), which is implemented as the higher level of control system.

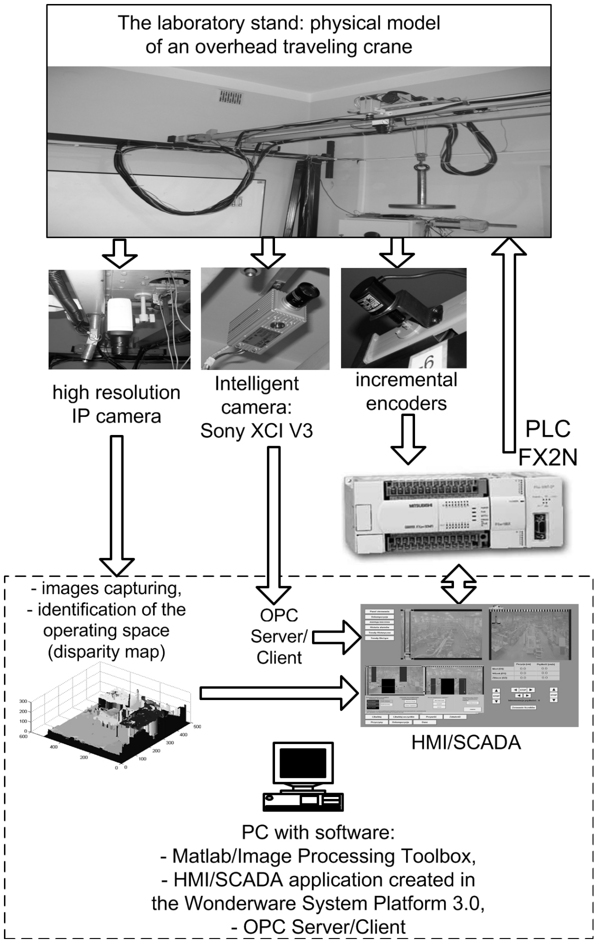

Figure 2. Architecture of the crane control system

Additionally in the paper [35] was presented measuring method of the load swing based on a camera detector. The complete solution was described 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.

IV. CONCLUSUION

The paper describes the most important elements of the application of contemporary automated crane control system. The identified problem are: crane workspace visualization, potential obstacles detection for non-collision path planning, non-collision and time-optimal path of a payload designing, designing a robust anti-sway crane control system realized both in closed-loop and open-loop control system.

The all presented solution described in this paper are crucial in the time and positioning accuracy of transportation tasks realized by the AMHS (Automated Material Handling Systems), especially by the cranes. The main author attention was focused off the shelf application as well as individual of other authors solution discovered in the world scientific literature. On the base described solution and presented scientific works content is possible to draw the following final conclusions:

- The real-time precision path following by a payload, involves a need the sway counteract. For many authors problem formulated as follows: *a moving a suspended load with using a crane without a sway* (so-called crane anti-sway problem) are crucial.
- Is impossible precisely moved a suspended load from start point to goal point according with desgin optimal trajectory, when the payload sway freely, especially problem occurring in a heavy and large-dimensional loads,
- With use an intelligent crane control techniques is possible a simplified a nonlinear crane dynamic model to linear system with varying parameters, like a rope length and payload mass, which can be used as key variables useful in anti-sway system designing,
- The problem of assurance the efficient cranes operations generate needs of gather information about crane workspace and existing obstacles. In a lot of scientific publications, authors solve a problem of identification a obstacles with the same type or shape. For full automatic system it is not enough and techniques ensure obstacles detection of unknown types must be continuously and still improve,
- Vision systems are perfect not only in acquiring an information about crane workspace and potential obstacles dimension, but also useful as a standalone measurements system of chosen and important crane parameters e.g. angle of swinging rope [17],

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