ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.2478/kones-2019-0008

INTEGRATED SUPERVISION FOR SUPPORTING CONTROL AND PROACTIVE MAINTENANCE OF MATERIAL HANDLING SYSTEM

Paweł Hyla, Agnieszka Kosoń-Schab
Janusz Szpytko, 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: hyla@agh.edu.pl, koson@agh.edu.pl,
szpytko@agh.edu.pl, smoczek@agh.edu.pl

Abstract

Material handling systems, as an important part of different type of manufacturing processes, face the same challenges as manufacturing industries pushed nowadays forward by innovative ideas and technologies to the next level loudly announced as industry 4.0. Development of the next generation of automated manufacturing systems involves advanced approaches to material handling systems design and their close integration with the higher levels of manufacturing and production control and management, e.g. manufacturing execution systems (MES), enterprise resource planning (ERP). In the presence of increasing demands for manufacturing process optimization, the role of supervisory level of material handling systems is much more advanced today, ensuring not only data acquisition, visualization, monitoring, supervisory control, as well as synchronization with the higher control levels (FEM, ERP), but also providing functionality for supporting maintenance and decision-making processes to reduce downtimes, operations and maintenance costs. The article deals with the integration of control and maintenance functions in the hierarchical control system of a crane. The supervisory system for supporting control and proactive maintenance is prototyped at the laboratory overhead travelling crane. The article presents the control-measurement equipment and intelligent software tools implemented in the supervisory control and data acquisition (SCADA) system to aid decision-making process in proactive maintenance. The overview of the main components of the supervisory control and proactive maintenance subsystems is provided, and their respective role in control, supervision, and proactive maintenance is explained. The crane's supervisory control includes the stereovision-based subsystem applied to identify the crane's transportation workspace, determine the safety and time-optimal point-to-point trajectory of a payload. The proactive maintenance module consists of the human machine interface (HMI) supporting decision-making process, intelligent tools for upcoming downtime/ failure prediction, and the crane's girder inspection using the metal magnetic memory technique.

Keywords: *material handling, overhead crane, hierarchical control, proactive maintenance*

1. Introduction

Nowadays, manufacturing industries, driving towards the technological revolution loudly announced as industry 4.0, face challenges to improve productivity and efficiency by using advanced information and manufacturing technologies to be competitive on the market and more attractive for more and more informed, demanding, and aware customers. Development of the next generation of automated manufacturing systems involves advanced approaches to material handling systems design and their integration with the higher levels of manufacturing and production control and management. In the presence of increasing demands for manufacturing process optimization, the role of supervisory level of material handling systems is much more advanced today, ensuring not only data acquisition, visualization, monitoring, supervisory control, as well as synchronization with the higher control levels (MES, ERP), but also providing functionality for supporting maintenance and decision-making processes to reduce downtimes, operations and maintenance costs.

Different types of cranes, such as bridge, gantry, jib, stacker and mobile cranes are extensively used in many industries. The advanced design methods, modern crane control techniques, automation, performances improvement, as well as crane systems integration with modern industrial systems become significant in manufacturing process optimization [1, 4-6, 10, 13]. The article deals with the integration of control and maintenance functions in the hierarchical control system (HCS) [3] of a crane. The HCS was prototyped at the laboratory double-girder overhead travelling crane with hoisting capacity 150 kg. The control-measurement equipment and intelligent software tools developed for supervisory control, proactive maintenance, and decision-making support are described. The overview of main components of the HCS is presented, and their respective role in control, supervision, and proactive maintenance of the laboratory crane system. The attention is focused on the two subsystems, the supervisory control, and proactive maintenance. The crane's supervisory control includes the stereovision-based subsystem applied to identify the crane's transportation workspace, determine the safety and time-optimal trajectory of a payload from point-to-point, and supervise the tracking control process carried out by the industrialized I/O modules applied in the crane's HCS. The proactive maintenance module consists of the HMI supporting decision-making process, intelligent tools for upcoming downtime/ failure prediction, and crane's girder monitoring using the metal magnetic memory non-destructive technique (MMM NDT).

The rest of the article is organized as follows. Section two describes the HCS developed on the laboratory stand. Section three focuses attention on supervisory control and stereovision-based subsystem implemented for planning and tracking the point-to-point trajectory of a payload. The proactive maintenance module is discussed in section four. Section five delivers conclusions.

2. Hierarchical control system

Figure 1 illustrates the hierarchical structure of the crane's control system containing the plant level (laboratory crane equipped with sensors), I/O modules realizing the direct control, and the SCADA system ensuring data acquisition, visualization, monitoring, supervisory control, and providing functionality for supporting maintenance and decision-making processes. The HCS has been prototyped on the laboratory stand, the double-girder overhead travelling crane with hoisting capacity 150 kg, span of the girders $L = 2.4$ m, trolley wheelbase $a = 0.3$ m, and the trolley travelling range $D = 2.2$ m (constrained by the limit switches). The crane's bridge, trolley, and hoisting are driven by worm gear three-phase motors supplied from single-phase frequency inverters. The positions of crane and payload suspended on the rope are detected by using incremental encoders attached to the travelling bridge and trolley wheels and the hoisting drum. The encoders with resolutions 400 ppr, 200 ppr and 100 ppr are used to measure positions of the crane's bridge, trolley and rope length, respectively, while incremental encoders with resolution 2000 ppr, which are installed under the trolley and connected with fork-bottomed arms embracing the hoisting rope are used to measure the sway angle of a payload in the two perpendicular planes. The strain gauge, which is supplied by the ADAM-3016 module, is used to measure the strain in the midpoint of the crane's girder. The crane's operating workspace is monitored using the cameras installed under the trolley.

In the level of the direct control, there are used the Programmable Automation Controller (PAC) RX3i series and the Programmable Logic Controller (PLC) FX2N48MR. In this level, the industrialized I/O modules realize the control tasks: positioning of the crane with a payload suspended on the rope in 3D workspace, trajectory tracking, and anti-sway control.

The supervision system was developed using the following software: Wonderware System Platform 3.0/InTouch and MATLAB/Image Processing Toolbox. The SCADA system communicates with the real-time control level, and is responsible for the standard functions, such as data acquisition, visualization, and monitoring of the process, as well as supervisory control. The supervisory control was extended with the subsystem cooperating with the stereovision system employed to identify the crane's workspace and non-collision and time-optimal trajectory planning to ensure the safe and efficient point-to-point transfer of a payload.

The next subsystem, which has been included in the SCADA system, provides the support for proactive maintenance of the material handling device. The conception of this system is based on real-time monitoring the operating conditions and performances of the crane's system and data acquisition utilized in developing and optimizing the fuzzy predictive model for forecasting an upcoming failure, as well as the crane's structure monitoring using the MMM NDT to detect potential defects.

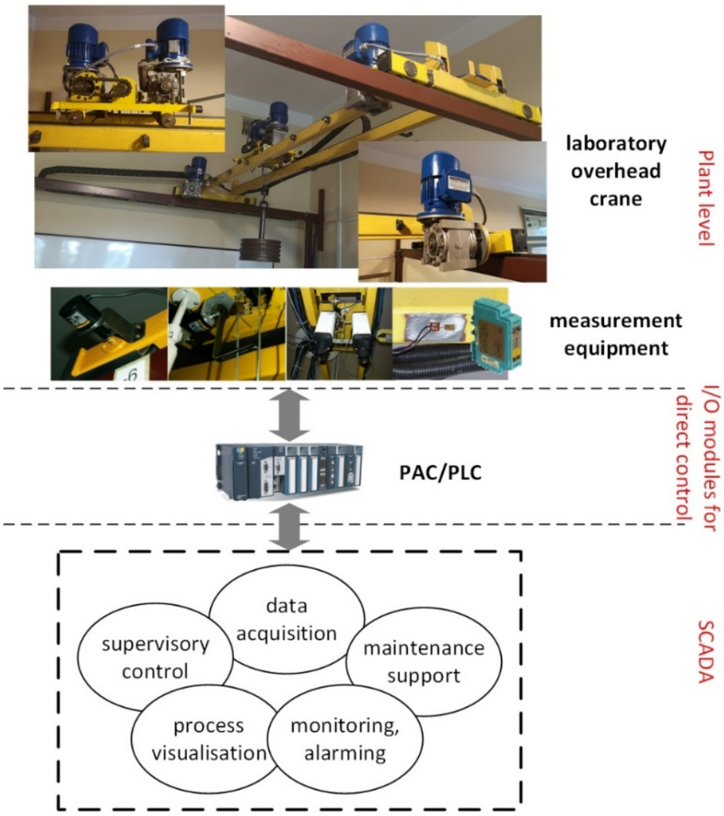

Fig. 1. Schematic structure of the HCS developed on the laboratory stand

3. Supervisory control – stereovision-based trajectory planning

The supervisory control is equipped with the stereovision-based subsystem responsible for determining the non-collision and time-optimal trajectory of a payload transported from a start position to a desired destination. The safety trajectory is passed to the direct control level to realize the trajectory tracking control. The stereovision system consists of the two cameras installed under the trolley for monitoring the transportation workspace (Fig. 2). The stereo pair-images acquired during crane movement are converted to the 3D map of the crane's workspace [12].

A problem of a trajectory planning is solved using the A-star algorithm, which allows to determine the time-optimal trajectory of a payload in three-dimensional graph (rejecting nodes corresponding to the obstacles identified in the crane's workspace), which has been derived from the dense of disparity map. The weights of the graph edges refer to the time-cost of motion in the graph from node to node, which is derived based on the crane's velocities (V_x, V_y, V_z – bridge, trolley, hoist velocities, respectively) in the *XYZ* space

$$w(x, y, z, V_x, V_y, V_z) = \max\left(\frac{x}{V_x}, \frac{y}{V_y}, \frac{z}{V_z}\right). \quad (1)$$

The problem consists in minimizing the following function

$$f(x,y,z,V_x,V_y,V_z) = g(x,y,z,V_x,V_y,V_z) + h(x,y,z,V_x,V_y,V_z), \tag{2}$$

where g is the time-cost of the path from the start node to the current node, and h is the heuristic function that estimates the time-cost of the path from the current node, denoted $o_c(x_c, y_c, z_c)$, to the destination node, denoted $o_d(x_d, y_d, z_d)$:

$$h(x,y,z,V_x,V_y,V_z) = \max\left(\frac{|x_d - x_c|}{V_x}, \frac{|y_d - y_c|}{V_y}, \frac{|z_d - z_c|}{V_z}\right). \tag{3}$$

Figure 3 presents the example of the 3D crane's workspace with arranged location of obstacles and comparison of the designed trajectory and the trajectory executed by the direct control level.

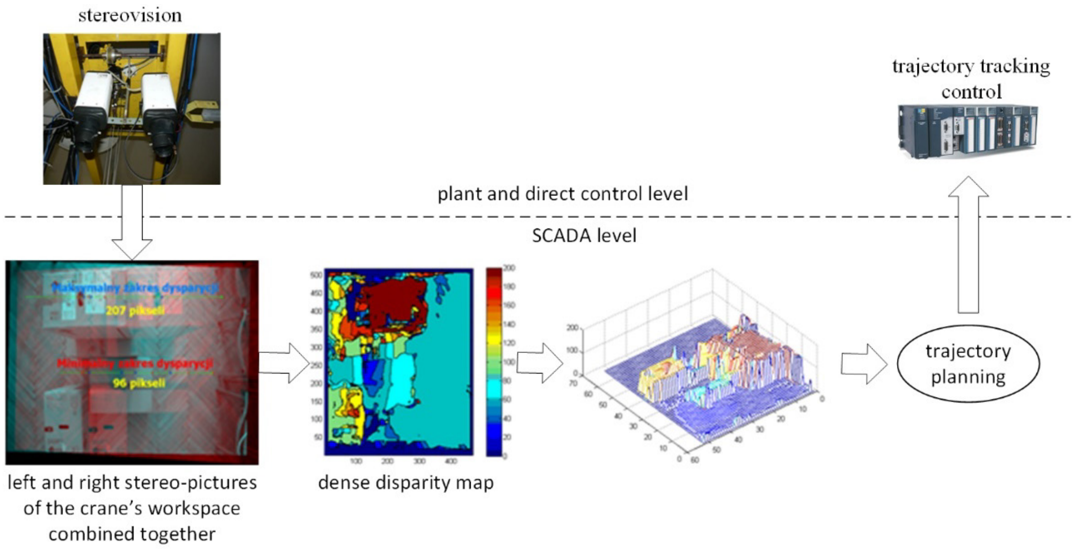

Fig. 2. Stereovision-based subsystem for time-optimal and non-collision trajectory planning

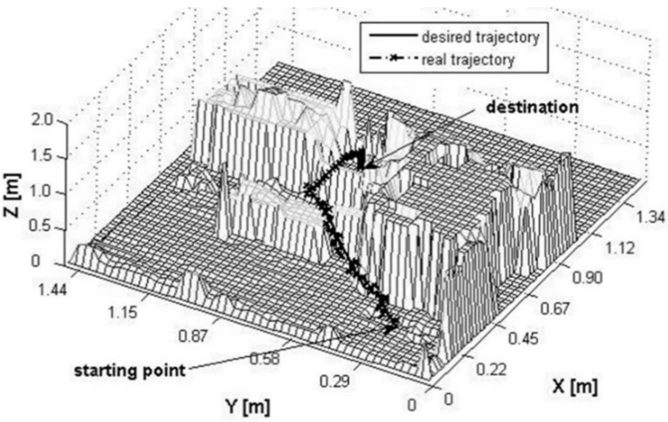

Fig. 3. The non-collision trajectory tracking by crane control system

4. Subsystem for proactive maintenance support

This section provides overview of the proactive maintenance subsystem implemented in the supervision system of the laboratory crane. The two main components of this subsystem are reported: i) the HMI to aid the decision-making process, monitoring system performances and operating condition, as well as predict the upcoming failure; ii) the MMM NDT applied to identify the stress concentration zones in the crane's structure.

4.1. Fuzzy predictive model of TBF

The objective of the proposed approach to proactive (predictive) maintenance is to support decision-making process by forecasting the upcoming failure and delivering the maintenance heuristic strategy based on the knowledge base created by experienced user/operator, and a predictive model of time between failure (TBF), both evolved during system operating and monitoring the operational states between failures. The conception of maintenance-aided decision-making tool is based on the monitoring the operating conditions and performances of a system. The operational parameters measured between failures are collected in database of the SCADA system. The application delivers the tools developed in the form of the HMI for experienced user/operator of a system to create the heuristic database including the hierarchical structure of a system decomposed for subsystems, their elements, and components (Fig. 4). The integration of those databases enables to create the knowledge base consisting of historical data about occurrences in a system, including the downtime and uptime (TTR – time to repair, TBF) of system equipment, and heuristic maintenance strategy (history of reactive and proactive actions, potential consequences and reasons of occurred events). The application delivers tools for runtime creating and updating distributed alarming system. The user can analyse the real-time and historical data (input/output variables of a system) for defining the alarms and their conditions validated next during system operation. The early stage of monitoring process leads to select for each registered failure a group of operating conditions that will be used as the initial input arguments of a fuzzy predictive model of TBF.

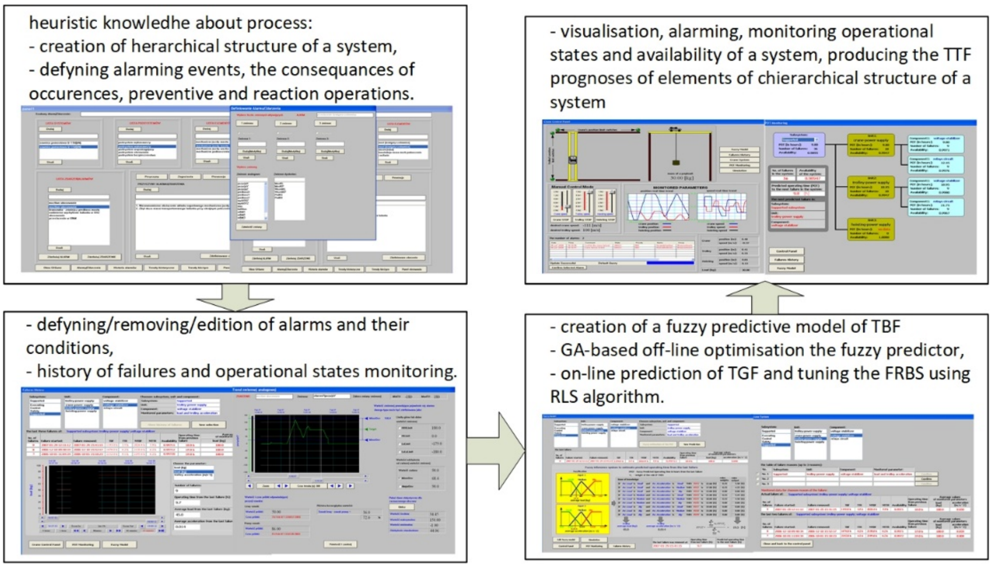

Fig. 4. The HMI for proactive maintenance support

The intelligent data-driven approach to predict the upcoming failure is based on the real-time monitoring of system performances and operating conditions $X = [x_1, x_2, \ldots, x_n]^T$. Assuming that the failure process is depended on variation of operational state of a system, the estimator of operating time between failures $T\hat{B}F$ is a function of temporal variations of monitored variables – the mean values of $X\,(\bar{x}_1, \bar{x}_2, \ldots, \bar{x}_n)$ measured within operating time period between the last failure t_f and the current instant t_c. This relationship can be expressed in the form of k fuzzy rule

$$\text{If } \bar{x}_1 \text{ is } MF(\bar{x}_1) \text{ and } \bar{x}_2 \text{ is } MF(\bar{x}_2) \text{ and } \ldots\ \bar{x}_n \text{ is } MF(\bar{x}_n), \text{then } y_k \text{ is } T\hat{B}F_k, \quad (4)$$

where $MF(\bar{x}_i)$ compactly denotes the fuzzy set in x_i characterized by the membership function (MF) and y_k is the k-rule output, while the fuzzy model output is weighted average of all rules outputs:

$$T\hat{B}F = \sum_{k=1}^{N} w_k \cdot T\hat{B}F_k \cdot \left(\sum_{k=1}^{N} w_k \right)^{-1}, \tag{5}$$

where w_k is the weight of a fuzzy rule.

The HMI/SCADA application with the fuzzy predictive model of TBF is used to real-time monitoring the mean values of operating conditions in operating time Δt between the time of last failure and the current time $[t_f, t_c]$. Thus, the online prognosis of remaining useful life (RUL) is determined based on the TBF estimated by a fuzzy predictive model according to the formula:

$$R\hat{U}L = T\hat{B}F - \Delta t. \tag{6}$$

The two techniques were adapted to identify the fuzzy prediction model. The fuzzy model is derived off-line from historical data using the real-coded evolutionary algorithm (EA) proposed in [11], while the real-time estimation of fuzzy model parameters is carried out using recursive least square (RLS) algorithm. Detailed description of the intelligent approach to predict the upcoming failure, and results of experiments are reported in [11].

4.2. Crane structure monitoring

The proactive maintenance component, which is steel developed part of the considered supervision system, is the monitoring of the crane's structure using the MMM NDT, which relies on the measurement of self-magnetic flux leakage (SMFL) arising in ferromagnetic and paramagnetic materials as a result of stress concentration zones under the influence of operational or residual stresses. The MMM NDT consists in registration and analysis of the normal H_y and tangential H_x components of the magnetic field and local magnetic anomalies. Their abnormal changes are observed on local stress concentration zones where a significant deformation is present due to an unsuitable combination of component features, structural heterogeneity, and workloads [2]. As the advanced non-destructive technique, which does not require the use of a special magnetizing device, this method can be reliable alternative to classic methods used for crane's inspection [7-9]. The MMM NDT can be employed for inspection of crane structure during operation (continuous monitoring), that can lead to reduce downtimes and increase the safety confidence in the monitoring process. Thus, the MMM NDT was employed for inspection the laboratory crane's girder, as the part of supervision system. The experimental results are presented in Fig. 5. The tangential H_{Px} and normal H_{Py} components of the SMLF signal, as well as the gradients dH_{Px}/dx and dH_{Py}/dx were measured along the girder length L = 2.4 m. The inspection results in identifying the stress concentration zone located between x = 0.93 m and x = 0.94 m (location of the potential defect). At this point, the H_{Px} riches the extreme value (above - 4000 A/m), and the H_{Py} changes its polarity. More details and analysis of the experimental results is delivered in [9].

The results of experiments carried out on the laboratory stand proved that the MMM technique can be successfully utilized in periodically made inspections, as well as continuous monitoring of a crane structure to improve effectiveness of material handling system proactive maintenance. However, it should be also mentioned, that the MMM technique is effective to identify location of a possible defect, but the influence of the defect characteristics on the magnetic field intensity is not clear.

5. Conclusions

Development of the next generation of automated manufacturing systems involves advanced approaches to material handling systems design and their integration with the higher levels of manufacturing and production control and management. In the presence of increasing demands for manufacturing process optimization, the role of supervisory level of material handling systems is much more advanced today, ensuring not only data acquisition, visualization, monitoring, supervisory control, as well as synchronization with the higher control levels (MES, ERP), but also providing functionality for supporting maintenance and decision-making processes to reduce downtimes, operations and maintenance costs.

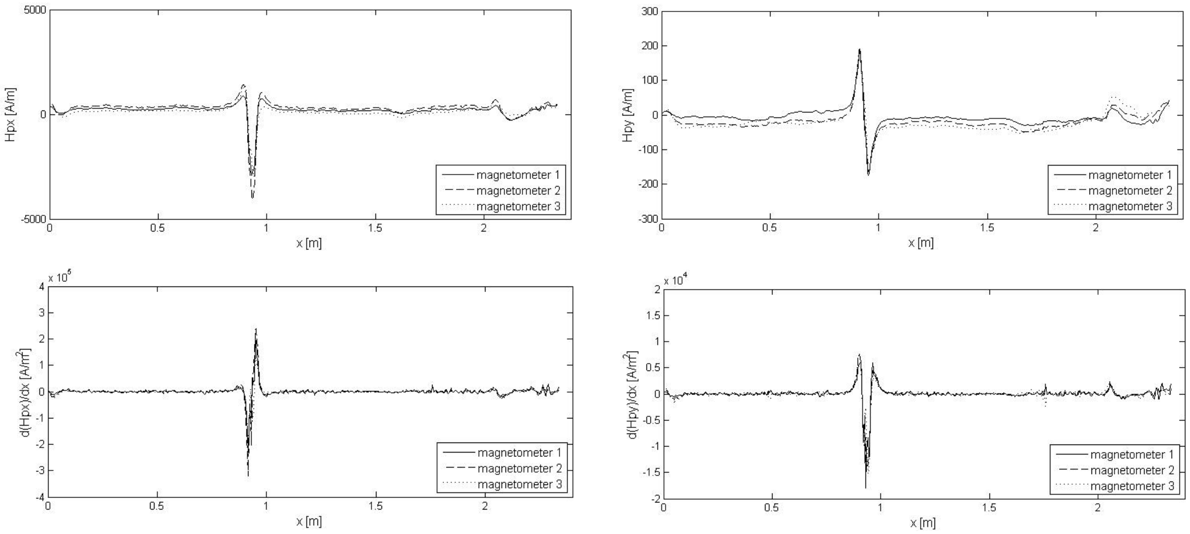

Fig. 5. Changes of H_{Px} and H_{Py} and their gradients dH_{Px}/dx and dH_{Py}/dx along the surface of inspected crane's girder

The article presents the hierarchical control system developed on the laboratory stand, overhead travelling crane. The overview of main components of the HCS is presented, and their respective role in control, supervision and proactive maintenance of the laboratory crane system. The crane's supervisory control includes the stereovision-based subsystem applied to identify the crane's transportation workspace, determine the safety and time-optimal trajectory of a payload from point-to-point, and supervise the tracking control process carried out by the industrialized I/O modules. The proactive maintenance module consists of the HMI supporting decision-making process, intelligent tools for upcoming downtime/failure prediction, and the MMM NDT-based crane's structure early defects detection.

Acknowledgement

The work has been supported by the Polish Ministry of Science and Higher Education from funds for year 2019.

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Manuscript received 15 January 2019; approved for printing 26 March 2019