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ROBUST CONTROL OF REAL EXPERIMENTAL BRIDGE CRANE

Marek Hičár * — **Juraj Ritók** **

The drive control of a bridge crane includes a crane crab, bridge and uplift control. At first, a mathematic and physical analysis of the main crane components was performed and variable system parameters were defined. Robust control by Ackermann ensures crane robustness against the burden weight and rope length variation, which provides sharp positioning and forbidden swinging of the burden in the final position. The real crane will be connected to a distributed control system (DSR). An analysis of the working place is performed with accent on the measurable units of burden swinging, and the results of robust controlling are described.

K e y w o r d s: bridge crane, crane crab, bridge and uplift, robust control, burden swinging

1 INTRODUCTION

The main problem of the crane drive control is to keep almost zero burden deviation in the final crane crab or bridge position. The main variable parameters are the burden weight m_G (detected by a tensometer) and hanging rope length l (measured by an incremental sensor). A robust design by Ackermann's method is preferably used for changeable systems or systems with variable parameters. The range of robustness is checked and areas related to expected variation values are defined. Knowing the values of changing parameters, a robust switch table is configured for their whole range of variance that satisfies the condition of forbidden burden swinging. In the future we will work on eliminating the varying parameters by an observer of the burden weight and burden swinging.

The real crane was completely designed and connected to the distributed control system (DSR). Communication interfaces between the technological, system operator and information levels were created. The bridge crane was identified by ARX model through experimental identification and we obtained the crab, bridge and uplift transfer functions and their transformation to the state description. OE model identified burden swinging in the direction of the crane crab and bridge. The crane position was scanned by incremental sensors. For scanning the burden swinging we first used Hall sensors. Because of interference and output error we eventually measured the swinging by rotary rheostats. The frequency converter NORD is used for the crab, bridge and uplift drive control.

The burden weight, respecting the designed crane construction, ranges from 0 to 100 kg and the rope length from 0 to 2.5 m. When trying to keep zero burden swinging, the worst situation occurs in the case of the shortest rope at the minimum weight because the frequency of periodical vibrations increases.

Fig. 1. Experimental bridge crane.

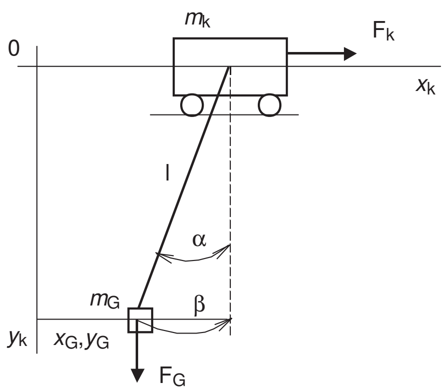

Fig. 2. Model of the crane crab (bridge).

2 ANALYSIS OF CRANE CRAB, BRIDGE AND UPLIFT

The same model of crab and bridge is considered and their motions are perpendicular. For the crab with weight

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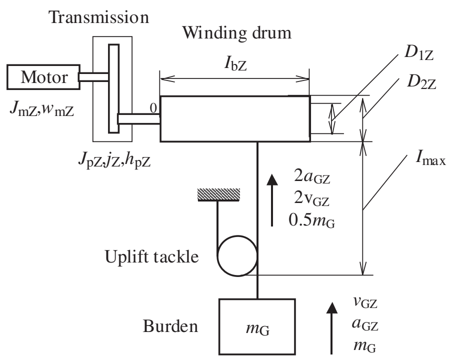

Fig. 3. Detail of the crane crab.

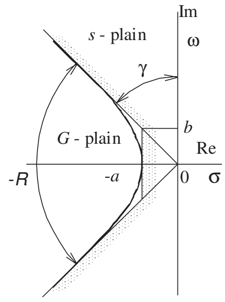

Fig. 5. Definition of Γ-plane

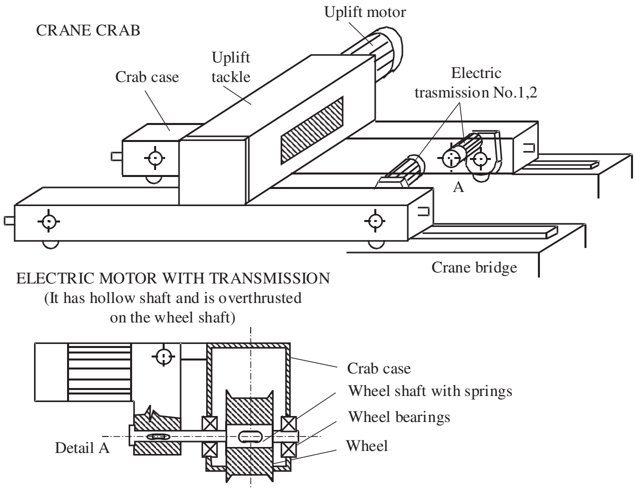

Fig. 4. Model of the crane uplift

m_K (bridge weight m_{K_M}) and for its speed, angular deviation α of the rope with respect to the vertical line occurs (Fig. 2). The angle α changes in dependence on the rope length and can be recalculated to the arc β followed by the burden. The actual position of the crab is x_K (or of the bridge x_{KM}). The crab motion formulas (also for the bridge) are [1, 4]:

$$m_K\ddot{x}_K - m_G\, g\frac{\beta}{d} = F_K\,, \tag{1}$$

$$m_K\ddot{\beta} + (m_K + m_G)\; g\frac{\beta}{d} = -F_K\,. \tag{2}$$

We can modify equations (1, 2) and use the motion equation (3) of the induction motor:

$$\frac{J_c}{p}\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{3p}{2}\frac{L_h}{1+\sigma_2} i_{2m} i_{1y} - m_z\,, \tag{3}$$

$$\ddot{x}_K = a_{31}c_2c_1 i_{2m} i_{1y} + \frac{a_{11}}{n}c_1\beta\,, \tag{4}$$

$$\ddot{\beta} = -a_{31}c_2 i_{2m} i_{1y} + c_3\ddot{x}_K - \frac{a_{12}}{n}\beta\,. \tag{5}$$

In formulas (4, 5) were used the following notation:

$$c_1 = \left(\frac{J_c}{p}\frac{j^2}{r^2}\frac{1}{m_K} + 1\right)^{-1}, \qquad c_2 = \frac{j}{m_K r}\,,$$
$$c_3 = \frac{J_c}{p}\frac{j^2}{r^2 m_K}\,, \qquad a_{11} = \frac{m_G}{m_K}\,, \tag{6}$$

where l is the length of the hanging rope, J_c is the total moment of inertia, p is the number of motor poles, L_h is the main motor inductance, coefficient $\sigma_2 = \frac{L'_{2\sigma}}{L_h}$, m_z is the load moment, r is the radius of the drive wheel and j is the transmission.

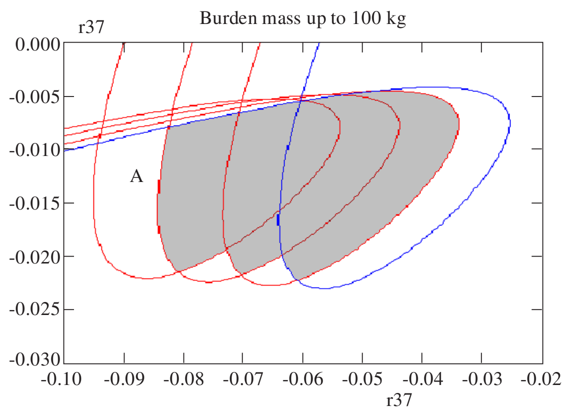

Fig. 6. Three robust areas for the crane crab.

The uplift drive includes the motor, transmission, winding drum and uplift tackle. The torque formula for crane uplift analysis is

$$M_{mZ} - M_{GZ} = J_{CZ}\frac{\mathrm{d}\omega_{mZ}}{\mathrm{d}t}\,, \tag{7}$$

where M_{mZ} is the motor torque, M_{GZ} is the burden torque and J_{CZ} is the total moment of inertia.

Conversion between the shifting burden speed v_{GZ} to the angular motor speed ω_{mZ} is

$$v_{GZ} = \frac{\omega_{mZ}}{j_Z}\frac{D_{2Z}}{4}\,. \tag{8}$$

If $r_{2Z} = \frac{2v_{GZ}}{\omega_{mZ}}$, then the adjusted burden moment of inertia is $J_{CGZ} = \frac{m_G}{2}r_{2Z}^2$. The potential burden torque at uplift when $M_{1Z} = \frac{m_G}{2}gr_{2Z}$ is

$$M_{1GZ} = \frac{m_G g D_{2Z}}{4 j_Z \eta_{pZ}}\,, \tag{9}$$

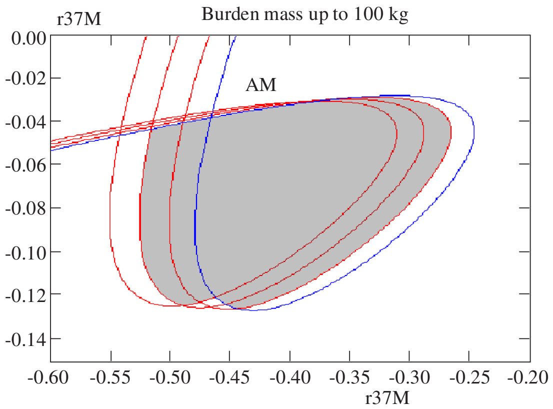

Fig. 7. Two robust areas for the crane bridge.

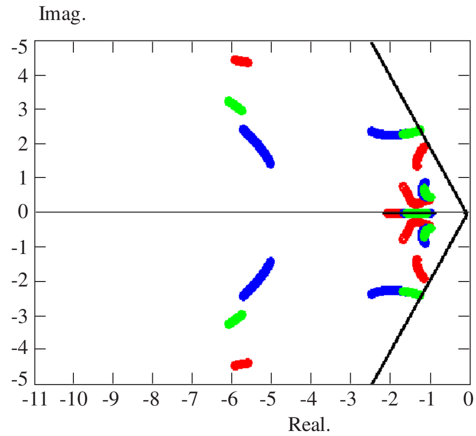

Fig. 8. Verification of robustness by poles motion at burden weight variation.

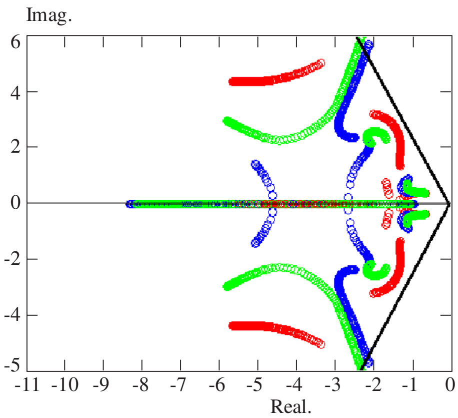

Fig. 9. Verification of robustness by poles motion at rope length variation.

and at burden lowering

$$M_{2Z} = \frac{m_G g D_{2Z}}{4 j_Z} \eta_{pZ} \,. \tag{10}$$

The total moment of inertia for uplift is

$$J_{CZ} = \frac{J_{mZ}}{\eta_{mZ}} + J_{CbZ} + J_{CGZ} \,, \tag{11}$$

where J_{mZ} is the motor moment of inertia, J_{CbZ} is the drum moment of inertia, J_{CGZ} is the burden moment of inertia.

3 ROBUST CONTROL DESIGN

The property of robust control is in system robustness and its correct control against variation of parameters. In formula (12) the polynomial $\mathbf{a}(p)$ includes a variable characteristic polynomial with robust controllers. Solutions are feedback parameters suitable for uncertain parameters and in this meaning required system robustness [1, 2, 3].

$$\begin{bmatrix} d_0(\alpha) & d_1(\alpha) & \dots & d_n(\alpha) \\ 0 & d_0(\alpha) & \dots & d_{n-1}(\alpha) \end{bmatrix} \mathbf{a}(p) = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \text{ where:} \tag{12}$$

$$d_0(\alpha) = 1,\ d_1(\alpha) = 2\sigma(\alpha),\ \alpha \text{ — frequency } (1, \infty),$$
$$d_{i+1} = 2\sigma(\alpha) d_i(\alpha) - \left[\sigma^2(\alpha) + \omega^2(\alpha)\right] d_{i-1}(\alpha)$$
$$\text{for } i = 1, 2, \dots, n-1 \,.$$

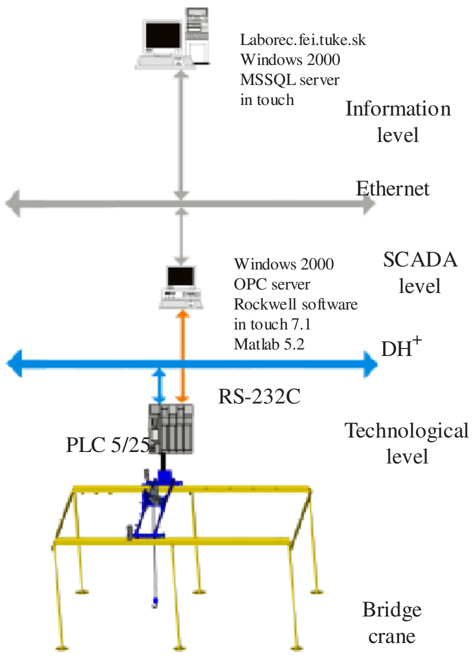

Fig. 10. Distributed crane control system.

All poles of the characteristic polynomial have to be located in the left part of Γ-area (Fig. 5) and to distance $-a$ from the imaginary axis and inside the sector assigned by the damping value $d = \sin\gamma$. Then stability and desired damping are ensured (Fig. 5). $n-2$ back-feed parameters have to be known for the design to be robust. A graphical computing method can locate the values of the rest two controllers r_1, r_2 which are included in $\mathbf{a}(p)$. Then curves A for the minimum and maximum values of variable parameters plot the possible selection of robust controllers [5].

We solved the system robustness against the burden weight and the rope length. The created robust areas are

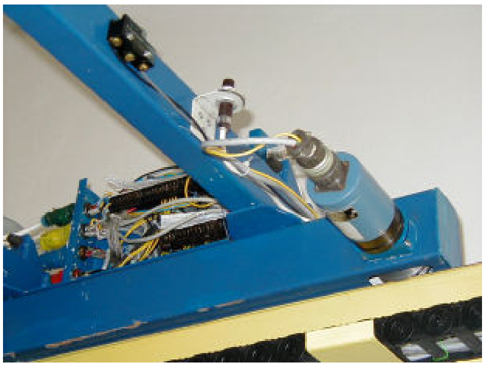

Fig. 11. Incremental sensor for measuring the bridge position.

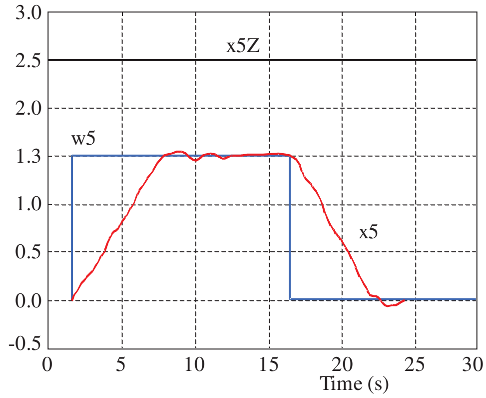

Fig. 12. Sensor of swinging in direction of crane crab and bridge.

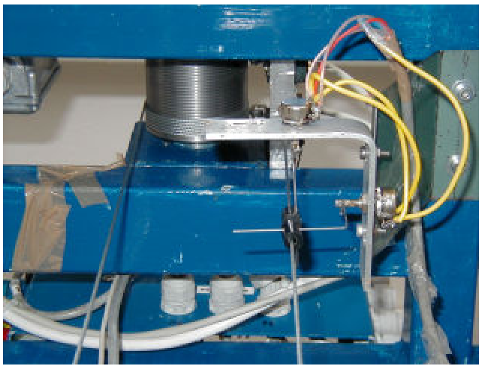

Fig. 13. Crab trajectory

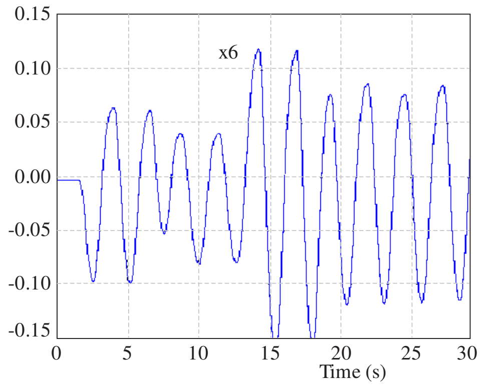

Fig. 14. Crab swinging without robust control

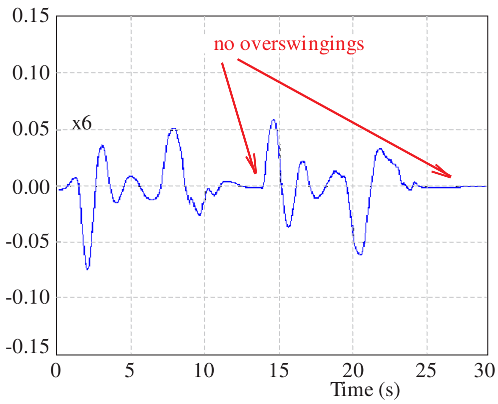

Fig. 15. Crab swinging with robust control

divided by these variable parameters. In fact we received two robust areas in the case of a long rope ($l = 2.5$ to 1.5 m) and three areas for a short rope ($l = 2.5$ to 1.5 m). For robust control of the crane bridge, three areas are found at all weights and rope lengths. We have chosen just one robust pair of speed controllers r_{36}, r_{37} type PI (for bridge r_{36M}, r_{37M}) from each robust area A for varying weight and rope length (Figs. 6 and 7). Verification of the correct choice of the robust controllers is performed by displaying the poles motion of the characteristic polynomial at burden weight and rope length variations. The requirement is to keep the poles in the labelled area, which provides stability and desired system damping. Based on our experience and consultation with the crane producer KPK Martin spol. s r.o. we allowed the maximum burden swingings at the final position to be 0.5 cm, this value having no effect upon the quality of control. The poles located at the edge of the sector cause overswinging by 0.5 cm at small rope lengths ($l = 2.5$ to 0.5 m).

4 DISTRIBUTED CONTROL SYSTEM (DSR)

Technological control level — here belongs the model of technological equipment (crane bridge), technological nets, control systems and programmable logical automatons. Data from this level include process data, information about the equipment state, its configuration parameters and so on. Process data continue to a higher level with system state information. Backwards go the control data.

SCADA/HMI level — parts of this level are the devices of SCADA/HMI systems and process database, in our cause MS SQL. This level is intended for primary collection of process data, monitoring, controlling and pro-

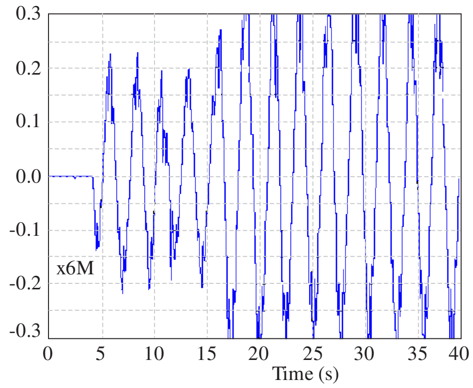

Fig. 16. Incremental sensor for measuring the bridge position.

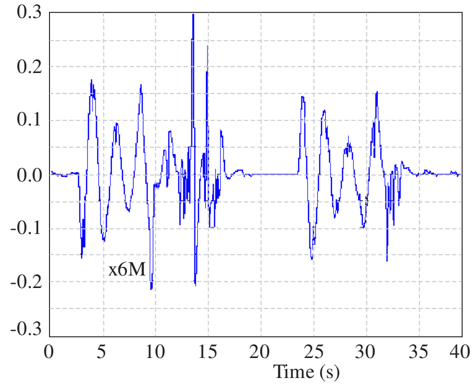

Fig. 17. Sensor of swinging in direction of crane crab and bridge.

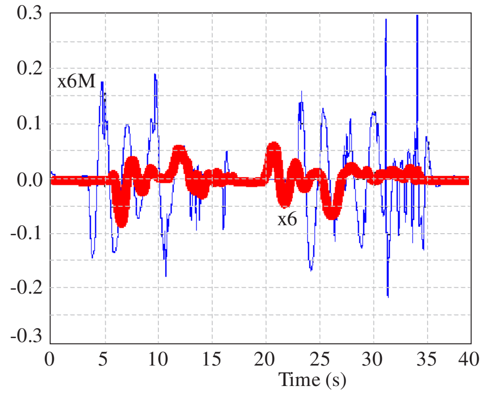

Fig. 18. Crab and bridge swinging

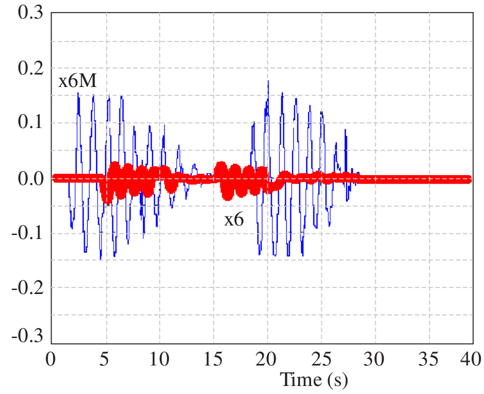

Fig. 19. Crab and bridge swinging

cess evaluating and visualizing. The data gained can be next used in the information control level.

Information level — here are computer servers (Topla, Laborec, Ondava, Alf, Poprad), database equipment (Oracle, MsSQL) for a higher control level and Internet [6].

Fig. 10 Distributed crane control system.

5 CRANE PARAMETERS MEASUREMENT

The crane position and its recalculated speed are measured by two kinds of incremental sensors (Fig. 11). Two sensors of IRC 120 type are assigned for measuring the bridge position, next two Hengstler type were used for crab and uplift measuring. Their function is to transform the rotary motion to electrical signals proportional to the passed trajectory. The cables from sensors have to be shielded otherwise interference and self-graduation of incremental sensors will be observed [7, 8]. The experimental crane was assembled with position switches that protect the crab, bridge and uplift from moving outside the allowed area.

Swinging was scanned by four Hall probes (two for the crab and two for bridge direction). Because of a strong interference signal at the start of *ac* motors this sensor was replaced by rotary rheostats. All rheostats are located upright, one corresponds to swinging in crab direction and other one in bridge direction. Burden swinging is transmitted through the hanging rope so that chromo bars are installed on the rope and connected with the corresponding rheostat. For correct robust control it is necessary to know the burden weight and rope length. The load weight is gained from the strain-gauge sensor that corresponds to the resistance value at burden variation.

6 RESULTS OF CRANE MEASUREMENTS

The control program consists of these main parts: calibration and crab, bridge and uplift drive control, calculation block, setup parameters, identification. We deal firstly with crab and bridge motion but to reduce the time of transport it is very efficient to test simultaneously the motion of both components.

1. Crab motion: $m_G = 50$ kg; $l = 2.5$ m (Figs. 13, 14).

Figure 13 displays the actual rope length x_{5Z} (m), reference w_5 (m) and real x_5 (m) crab position. Simulation of burden deviation x_6 (m) is in Fig. 14 without robust control and shows forbidden periodical oscillation in the terminal position ($x_5 = 1.5$ m and back to 0 m).

Simulation in Fig. 15 presents robust control of burden swinging to the zero value with allowance of 0.5 cm overswinging. The burden is damped by the control system to zero oscillation. Simulations of the bridge motion are in

Figs. 16 (switch off control) and 17 with robust control. We observe again damping of burden deviation x_{6M} (m) in the direction of the bridge to the zero value.

2. Bridge motion: $m_G = 50$ kg; $l = 2.5$ m (Figs. 16, 17).
3. Simultaneous crane crab and bridge motion: $m_G = 50$ kg; $l = 2.5$ and 0.5 m (Figs. 18, 19).

Control system simultaneously adjusts burden deviation in the direction of the crane crab and also of the bridge. The reference position of both components is $w_5 = w_{5M} = 1.5$ m and backwards.

Figure 18 shows the burden deviation x_6, x_{6M} (m) with robust control. In the final position of motion the burden will be damped with the allowed tolerance 0.5 cm. The worst situation of control is met at the minimum rope length (Fig. 19) where correct designed controllers were employed to damp burden swinging.

7 CONCLUSIONS

The aim of the control design of the experimental crane was to ensure crane robustness against the burden weight and rope length variations. The designed drive control of the crane crab, bridge and uplift warrants sharp burden positioning and avoids burden swinging in the final position. These conditions improve precision and transport speed of the load. We have verified a correct selection of robust controllers by poles movement at changing variable parameters, which demonstrated stability and system damping. The distributed control system gives transparent information on the control of separate components. The technological level is intended for elaboration of process data and full information about the system state. The second level is used for monitoring and controlling the lower level. Project crane is integrated into the information level by computer nets, which allows to control the object from a further station. Measuring of necessary parameters is realized mostly by incremental sensors and for measuring of swinging a rotary rheostat was effectively used.

Simulation results obtained suggest profitable using of the robust crane control with guaranteed forbidden swinging. Stability and correct damping were kept at different burden weight and rope length. Simultaneous crab and bridge motion has increased the effectiveness of transport, where individual control systems controlled burden swinging in specific directions.

The next trend in upgrading the experimental crane control will be made by a weight and deviation observer, which eliminates sensor measuring of parameters.

Acknowledgements

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