A MECHATRONIC SLIP ROBOTIC SYSTEM WITH ADAPTIVE CONTROL FOR ERECTING MONOLITH OBJECTS

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Abstract: The paper considers technological features of erecting monolith objects with a variable cross-section, presents the formulated requirements to the mechatronic complex and the principles of its construction and gives the complex structure. Great attention is paid to the problems of the mechatronic complex movements planning taking into account restrictions on control and disturbing influences affecting the structure being erected. In conclusion the paper deals with the problems of forming adaptive laws of for controlling joint coordinates ensuring development of the planned trajectory.

Keywords: monolith construction, slip forms, mechatronic robotic system, planning, control algorithms, visual sensor, mobile robots, planning of the robot’s movement, kinematics.

1. INTRODUCTION

Construction of objects for different purposes requires great labour consumption and a number of regulating operations especially for the structures with varying cross-section and wall width. The carried out analysis of the monolith construction technology has shown that it is possible to make a mechatronic robotic system on the basis of slip forms, which provides mechanization and automation of operations. The mechatronic slip robotic system (MSRS) mainly incorporates a moving platform with slip forms and a concreting robot with a programmable control. Later on it is expected to introduce into the system robots for embedding and anchoring reinforcement, it will make possible to automate the whole cycle of erecting monolith structures. Taking into account complexity of the MSRS as a controlled object, a great number of disturbing and adjusting action and restrictions for control it is of interest to solve the problems of the system operation software, planning its movements and developing adaptive laws of control.

2. THE PRINCIPLES OF CREATING A MECHATRONIC SYSTEM

As base objects of MSRS we took into consideration chimneys television and observation towers having conical and hyperbolic cross-sections. The system development is carried out on the basis of slip forms method, which makes it possible to perform a continuous-cyclic process of concreting. The analysis of technological operations for erecting monolith objects has shown that MSRS is to provide concrete shaping, its consolidation, reinforcement placement and anchoring. Block diagram of the system designed for erecting monolith tower-type objects with variable cross-section is presented in fig.1. Its base is a self-moving platform with the forms equipped with mechanisms for changing panels position. The system comprises a concreting robot, which ensures concrete placement against the forms and its consolidation. To mechanize steels placement the system is provided with two robots one of which is responsible for placing and anchoring vertical reinforcement being fed from the handling-storage device and the second one provides placement of the horizontal reinforcement, which is fed by a special device. The analysis of distinctive features of MSRS control and the study of its properties as a multi-measured object tell us that it is obvious to use a two-stage system of adaptive control. Each robot has its own control system performing tactical and executive problems of control. The robotic system comprises a data-measuring system, which monitors the platform and forms position, concrete and reinforcement placing and its data are used for the purpose of control. Planning of technological operations sequence and synchronization of the equipment operation are carried out by the upper level control system. The mechatronic system provides automatic lifting the robotic system, automatic changing the forms radius during the process of lifting and also correction of the platform position. The robotic system control provides synchronized operation of the platform lifting and adjusting mechanisms taking MSRS is a multimeasuring controlled object the states of which at any period of time can be described by the system of equations

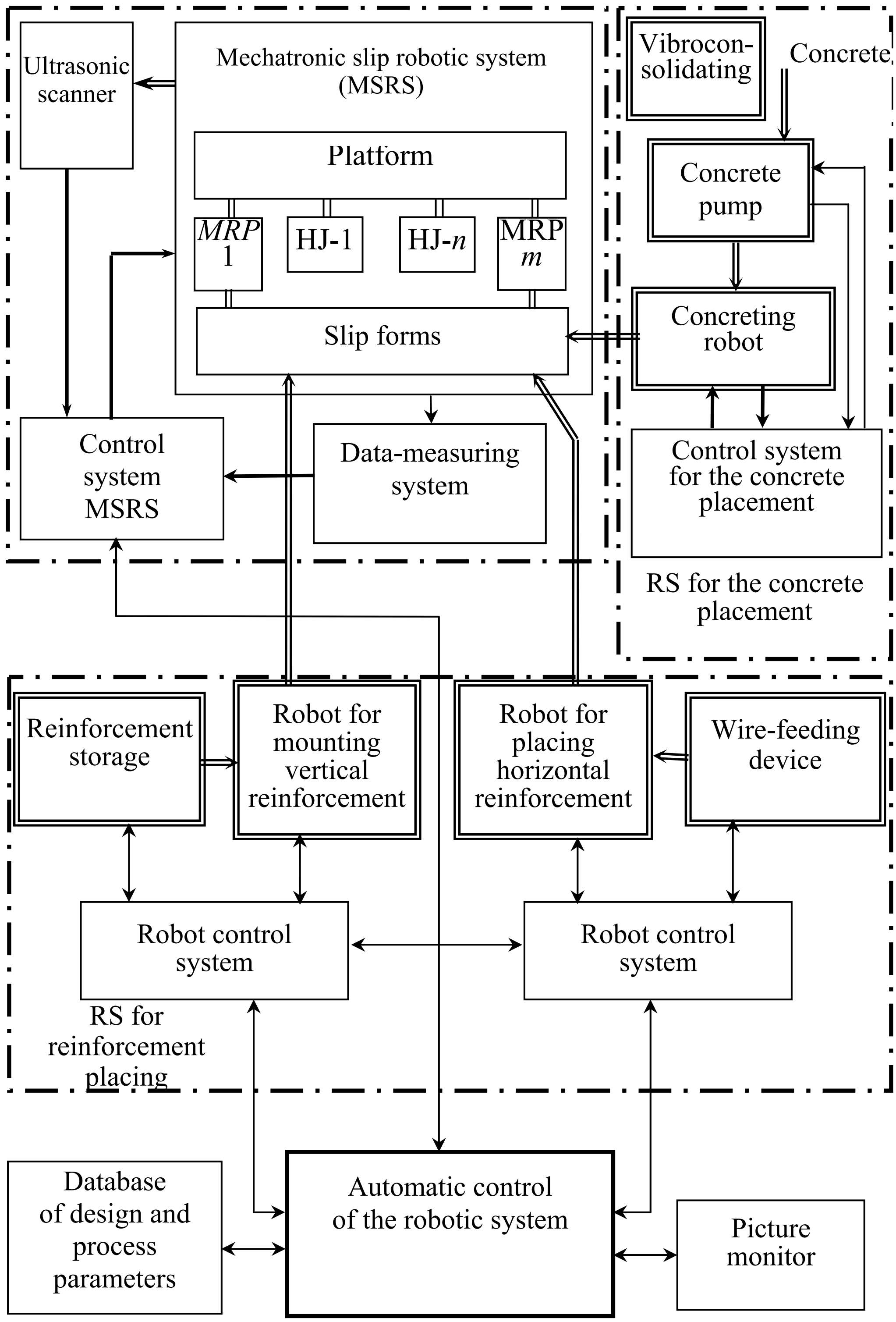

Fig. 1

$$\begin{cases} \overline{U}_{hj} = \left[U_{hj}^{(1)}, U_{hj}^{(2)}, \ldots U_{hj}^{(m)}\right]; \\ \overline{U}_{rm} = \left[U_{rm}^{(1)}, U_{rm}^{(2)}, \ldots U_{rm}^{(n)}\right]; \\ \overline{Y}_{ms} = \left[x_n, y_n, z_n, R_o, б_n, \beta_n, и_n\right]; \\ \overline{F}_1 = \left[F_w, F_s\right],\ \overline{F}_2 = \left[Q_{н}, F_{тр}, F_{сц}, F_{тм}, F_y\right], \end{cases}$$

where $\overline{U}_{hj}$, $\overline{U}_{rm}$ are the vectors of control actions directed to the hoisting jacks and the mechanisms of radial displacement (MRP); $\overline{Y}_{ms}$ is the vector of the output parameters of the MSRS state; $\overline{F}_1$ and

$\overline{F}_2$ are the vectors of disturbing influences acting on the erected construction and the mechatronic system.

The system state at any moment is determined by the coordinates x_p , y_p , z_p of the center position in the system of coordinates of the erected object $X_oY_oZ_o$, by the forms radius R_o, by the angle of the platform inclination α_p, by the direction of the inclination vector β_p and by the platform turning (twisting) angle ψ_p round the vertical axis. For the structures of conical shape the relation between radius R_o and the object height has the form of

$$R_o = R_o^* - (h \cdot \mathrm{tg}\varphi_o)$$

where R_o^* is the radius of the structures at zero mark.

Two groups of quantities are considered in MSRS as control actions. One of them is intended to control hoisting jacks ($U_{hj}^{(i)}$) and the other one – mechanisms of radial displacement ($U_{rm}^{(j)}$). Between these control actions there is a relationship ensuring synchronization of the both groups of mechanism operation.

The process of the system operation is accompanied by influencing on it several kinds of disturbing influences. The first group comprises influences leading to deformation of the erected structure and displacement of the platform with the forms. They cover influence F_s connected with the structure sun-heating and influence F_w caused by the wind load. Due to the temperature difference $\Delta\tau = \tau_s - \tau_c$ of the sunny and shady sides there occurs deformation of the structure and its deviation from the designed axis. The deviation quantity δ_s is the function of the height h, the object diameter D, the walls width b, and the period of heating t_s: $\delta_s = f_s(\Delta\tau, h, D, b, t_s)$. In order to evaluate the influence of the object temperature gradient on the MSRS operation we have introduced the coefficient of deformation, which is calculated by the formula: $k_d^{(s)} = h \cdot \varepsilon_s /(16\pi \cdot R_o)$. The platform deviations connected with temperature heating will be

$$\Delta x_s = 0{,}5 k_s^{(h)} \cdot h \cdot \Delta ф \cdot \cos и_s ;$$

$$\Delta y_т = 0{,}5 k_s^{(h)} h \cdot Дф \, \sin и_m ;$$

$$\Delta z_s = k_s^{(h)} \cdot R_o \cdot \Delta\tau ; \; \Delta\alpha_s = k_s^{(\varphi)} \cdot \Delta\tau .$$

As a result of the wind load there occurs inclination of the structure by the angle of α_w and deviation of the MSRS platform center from the vertical. The deviation parameters can be evaluated by the formulae:

$$\Delta x_w = k_w^{(h)} \cdot F_w \cdot \cos\theta_w ;$$

$$\Delta y_w = k_w^{(h)} \cdot F_w \cdot \sin\theta_w ,$$

where $k_w^{(h)}$ and $k_w^{(\varphi)}$ are the coefficients determined by the structure shape and its rigidity; F_w and α_w are the quantity and direction of the wind load.

The second groups of the disturbing influences constitute those applied to hoisting jacks and mechanisms of radial displacement. During the system operation hoisting jacks are under action of static and dynamic loads created by the weight of the platform, forms, equipment and materials: $Q_\Sigma = \sum Q_i$ and also under the influence of friction forces F_{fr} and cohesive forces F_c of panels with concrete.

The movement of the system being under control actions ($\overline{U}_{hj}, \overline{U}_{rm}$) and disturbing influences ($\overline{F}_1, \overline{F}_2$) is described by the equation:

$$\overline{Y}(t) = A(s) \cdot U_{hj}(t) + B(s) \cdot \overline{U}_{rm}(t) +$$
$$H_1(s) \cdot \overline{F}_1(t) + H_2(s) \cdot \overline{F}_2(t),$$

where $A(s), B(s)$ is a matrix of particular transfer functions which characterize the dynamics of hoisting and adjusting units; $H_1(s)$ and $H_2(s)$ are matrices of transfer functions in terms of disturbing influences.

3. FORMATION-CONTROL SYSTEM

The solution of the problems of MSRS control is connected with control of the parameters related with the system state and the environment conditions. To control the system lifting it is necessary to obtain data about the platform with forms position, levels of hoisting jacks and radial position of the forms panels. Implementation of the adaptive control laws is connected with forces control in hoisting jacks, wind and temperature loads on the object.

Checking the vertical position of the erected object and the platform position is carried out with laser devices equipped with photomeasuring panels. The laser device consists of two laser set-point devices for the vertical axis and two photoreceiving panels with modules for reading-out and processing data. Location of the laser beam center on the photoreceiving matrix is determined by the way of photopanels scanning. And the coordinates of the beam center are calculated from the formulae:

$$x_{pr} = 0{,}5\begin{bmatrix} \left(8\left(d_i^{(x)} - 1\right) + b_i^{(x)}\right) + \\ \left(8\left(d_l^{(x)} - 1\right) + b_l^{(x)}\right) - N_{pr} \end{bmatrix};$$

$$y_{pr} = 0{,}5\begin{bmatrix} \left(8\left(d_i^{(y)} - 1\right) + b_i^{(y)}\right) + \\ \left(8\left(d_l^{(y)} - 1\right) + b_l^{(y)}\right) - N_{pr} \end{bmatrix},$$

where $d_i^{(xx}, d_i^{(yy}, d_l^{(xx}, d_l^{(yy}$ are initial and last active bytes when scanning along the axes X and Y; $b_i^{(xx}, b_i^{(yy}, b_l^{(xx}, b_l^{(yy}$ are initial and last bytes corresponding; d_i , d_l ; N_{pr} is the number of digits)in bits) on the photopanel.

On the basis of the beam location coordinates on the photoreceiving panels we determine the position of the platform center:

$$x_{pl} = x_p^{(oo} = 0{,}5\left(x_{pr}^{(1)} + x_{pr}^{(2)}\right)\cdot \cos\psi_p ,$$
$$y_{pl} = y_p^{(oo} = 0{,}5\left(y_{pr}^{(1)} + y_{pr}^{(2)}\right)\cdot \sin\psi_p ,$$

where ψ_p is the twist angle of the platform relative to Z_o axis.

On the basis of the obtained average values of the platform deviation from the designed axis we calculate modulus and the direction of displacement:

$$\delta_{pl} = \left[\left(x_{pl}\right)^2 + \left(y_{pl}\right)^2\right]^{1/2};$$

$$\beta_d = \arccos\left(\frac{x_{pl}}{Д_{pl}}\right) = \mathrm{arctg}\frac{y_{pr}^{(1)} + y_{pr}^{(2)}}{x_{pr}^{(1)} + x_{pr}^{(2)}} .$$

The data received from the photopanels make it also possible to determine the twist angle of the platform with the forms

$$\psi_p = \mathrm{arctg}\left[\left(y_{pr}^{(1)} - y_{pr}^{(2)}\right)/\, l_{pr}\right],$$

where l_{pr} is the distance between photoreceiving matrices.

The platform deviation is closely connected with disturbance of its horizontal position therefore a hydrostatic leveling device has been introduced into the system. It permits checking the platform deformations and the swivel angle and also deviations of some jacks relative to others. Using level detector readings $\Delta z_{ld}^{(i)}$ we determine upper and lower marks of the platform hoisting jacks position

$$\Delta z_{hj}^{(\max)} = \max\left(\Delta z_{ld}^{(i)}\right); \Delta z_{hj}^{(\min)} = \min\left(\Delta z_{ld}^{(i)}\right) \rightarrow$$
$$i = 1, 2, ..., n$$

and calculate the platform swivel angle and the direction of the swivel angle vector:

$$\alpha_p = \mathrm{arctg}\left(\frac{\Delta z_{ld}^{(\max)} - \Delta z_{ld}^{(\min)}}{4R_{hj}}\right),$$

$$\beta_p = \frac{2\pi}{n}\left[i\left[\max\left(\Delta z_{ld}^{(i)}\right)\right] - 1\right].$$

The data about the jacks' deviation $\Delta z_{hj}^{(i)}$ from the horizontal plane are used to synchronize movements of the hoisting jacks. To provide the platform correcting inclination hoisting jacks' speeds are set according to the required swivel angle α_p^* :

$$v_{hj}^{(i)} = v_p\left[1 + R_{hj}\cdot \sin\alpha_p^* \cdot \cos\left(\frac{2\pi}{n}(i-1) - \beta_p\right)\right],$$

where v_p is the average speed of the platform hoisting.

4. PLANNING OF THE MECHATRONIC SYSTEM MOVEMENT

Planning of the MSRS movement may be considered one of the main control problems, which includes building of the motion path and formation on its basis the control laws for hoisting and adjusting mechanisms. When the platform is in the design position the system displacement is carried out without any correction and described by the algebraic equation

$$z_{pl}^{(w/c)}(t) = \sum_{i=1}^{k-1} h_{pl}^{(i)} + \int_0^t v_{pl}^{(k)}dt,$$

where $h_{pl}^{(i)}$ is the quantity of lifting on the i-th step; $v_{pl}^{(k)}$ is the speed of hoisting on the k-th step; k is the current step of hoisting of the trajectory section under consideration. MRP movement is carried out proportionally to the system lifting and the radius of arrangement of the forms panels changes according to the equation $r_{rm}^{(k)}(t) = \sum_{i=1}^{k-1} r_{rm}^{(i)} + K_\varphi \int_0^t v_{rm}^{(k)}dt$,

$r_{rm}^{(j)}(t) = r_{rm}^{(w/c)}(t)$, $(j = 1,2,...,m)$,

where $r_{rm}^{(i)}$ is the radius change for the i-th step; $r_{rm}^{(j)}(t)$ is the forms' panels displacement by the j-

th MRP; $K_{\varphi} = \left(\mathrm{tg}\varphi_{o}\right)^{-1}$ is the coefficient of proportionality determined by the object taper.

During the process of the system lifting there may be deviations from its design position and their compensation requires building correcting trajectories. Taking into account the requirement of monotonicity and smooth transitional trajectory and also limitations on its curvature, which can be defined by the forms' panels taper, we suggest to divide the correcting trajectory into two sections (fig. 2).

The first change (*AD*) deals with gradual change of the forms' swivel angle in order to reduce deviations. In the first part of the section (*AB*) there is an increase of the platform deviation from the design axis and it reaches its maximal value $\delta_p^{(\max)}$ in point *B*. While approaching the design axis it goes to the second section (*ED*) and it is during this part that the platform is gradually leveled. After the correction has been completed (*E*) the platform center is to take the design position and the platform itself – horizontal position.

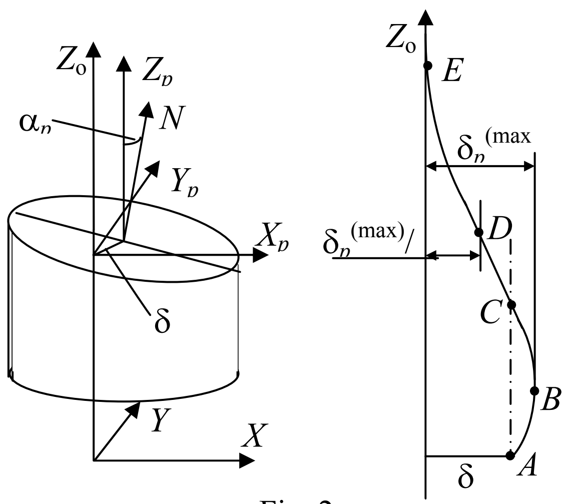

Fig. 2

Applying the results of the investigations we suggest to approximate the first part of the trajectory by the parabolic function

$$\delta_1(l) = a_2 l^2 + a_1 l + a_0$$

the coefficients of which are determined from the initial conditions:

$$\delta_1(0) = a_0 = \delta_p; \;\; \dot{\delta}_1(0) = a_1 = \alpha_p^*;$$

$$\ddot{\delta}_1(0) = a_2 = -\gamma/2$$

The second trajectory section (*DE*) is to provide smooth approach to the design axis with simultaneous platform leveling in point *E*.

These requirement are satisfied by exponential dependency

$$\delta_2(l) = C_{21}e^{\lambda_{21}(l-l_s)} + C_{22}e^{\lambda_{22}(l-l_s)},$$

where l_s is the path of conjugation of two trajectory sections (point *D*).

Applying approximating dependencies we present the MSRS movement trajectory while correcting the platform position in the form of

$$\delta(l) = \begin{cases} a_{12}l^2 + a_{11}l + a_0 & \rightarrow \; l < l_s \\ C_{21}e^{\lambda_{21}(l-l_s)} + C_{22}e^{\lambda_{22}(l-l_s)} & \rightarrow \; l \geq l_s \end{cases}$$

The trajectory points coordinates at the end of the next lifting step *k* are connected with the equation $\delta(l)$ by the relationships:
$x_p^{(k)} = \delta(l_k)\cos\beta_p$; $y_p^{(k)} = \delta(l_k)\sin\beta_p$,
$z_p^{(k)} = z_p^{(A)} + l_k$,

where $l_k = k \cdot h_s$ is the travel from the initial correction; h_s is the lifting step.

The control influences formation is carried out on the basis of planning algorithms subject to adaptation to heat and wind influences on the erected object. The points coordinates of the planned trajectory at each lifting step are corrected by the amount of existing thermal and wind deviations. Control influences for hoisting mechanisms are generated with account of the platform slope compensation because of thermal and wind deformations. The direction of the slope is determined by the direction of external influences on the object.

5. CONCLUSION

The presented paper has been prepared on the basis of the authors' research work, which was carried out during the development of the problems dealing with automation and robotization of monolith construction. The presented principles of the mechatronic slip robotic system creation can be used while developing the projects for robotization of construction of chimneys, television and observation towers, water-cooling towers and other objects of monolith concrete. Data-measuring information described in the given article is put into the basis of the developed by the automatic system for collecting and processing measuring data for MSRS which contains interface supplying all necessary data about the system condition and graphical display of its position. Computer simulation of MSRS lifting has demonstrated efficiency of the suggested procedure of movements planning and control influences development and the described approaches can serve as the foundation for developing the system control algorithms.