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RESEARCH ARTICLE

Development of an information measuring and control system for a quadrocopter

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Abstract. The article deals with the issues of synthesis and analysis of information-measuring and control systems of quadcopters (QCs). The main sensors and modules used to determine the parameters of the coordinates of QCs are given. The speed-controlled electric drives used for control and the features of their choice are considered. The coordinate systems (fixed and mobile) and the kinematic scheme are given, according to which a system of differential equations is presented. The system describes the dynamics of the QC movement and takes into account the expected smooth movement of the QC with small roll and pitch angles. A functional scheme and a mathematical model of the information-measuring and control system of the QC in the form of a block diagram are developed taking into account the influence of delays in the receipt of information from the sensors of the QC parameters. A special feature of this work is to take into account the specific characteristics of the elements: adjustable electric drives (both direct and alternating current), parameter sensors (barometers, accelerometers, rangefinders, etc.). The paper studies an illustrative algorithm for the operation of the information-measuring and control system of the quadcopter. The type and parameters of the controllers of the QC control systems are determined. Special attention is paid to the settings for the control contours at the corresponding coordinates. The influence of the controllers of the coordinate control systems of the information-measuring and control systems of the QC on the effects of the interaction of coordinates is considered. The simulation results are presented. The optimal number of control loops for the coordinates of the information-measuring and control systems of the QC and the optimal type of settings for obtaining smooth transients (without overshoot) and for excluding the interaction of coordinates on quality indicators are determined.

Keywords: quadrocopter, adjustable electric drive, parameter sensors, optimum modulus

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НАУЧНАЯ СТАТЬЯ

Разработка информационно-измерительной и управляющей системы квадрокоптера

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Резюме. В статье рассмотрены вопросы синтеза и анализа информационно-измерительных и управляющих систем квадрокоптеров. Приведены основные датчики и модули, применяемые для определения параметров координат квадрокоптеров. Рассмотрены регулируемые по скорости электроприводы, применяемые для управления, и особенности их выбора. Приведены системы координат (неподвижная и подвижная) и кинематическая схема, в соответствии с которыми представлена система дифференциальных уравнений, описывающая динамику движения квадрокоптера и учитывающая предполагаемое плавное движение квадрокоптера с малыми углами крена и тангажа. Разработаны функциональная схема и математическая модель информационно-измерительной и управляющей системы квадрокоптера (ИИУС КК) в виде структурной схемы, выполненные с учетом влияния запаздываний поступления информации с датчиков параметров квадрокоптера. Особенностью данной работы является учет конкретных характеристик элементов: регулируемых электроприводов (как постоянного, так и переменного тока), датчиков параметров (барометров, акселерометров, дальномеров и пр.). В работе исследован показательный алгоритм работы информационно-измерительной и управляющей систем квадрокоптера, определены тип и параметры регуляторов систем управления. Особое внимание уделено параметрам настройки для соответствующих контуров управления. Рассмотрено влияние указанных регуляторов информационно-измерительной и управляющей системы квадрокоптера на эффекты взаимовлияния координат. Представлены результаты моделирования. Определено оптимальное количество контуров управления координатами информационно-измерительной и управляющей системы квадрокоптера и оптимальный вид настроек для получения плавных переходных процессов (без перерегулирования) и исключения взаимовлияния координат на показатели качества.

Ключевые слова: квадрокоптер, регулируемый электропривод, датчики параметров, оптимум по модулю

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GLOSSARIUM

Yaw—angular movement of the aircraft around its vertical axis.

Pitch—angular motion in which its longitudinal axis changes its direction relative to the horizontal plane.

Roll—the deviation of the plane of symmetry from the vertical position.

INTRODUCTION

A modern quadcopter (QC) is an unmanned aerial vehicle with four controllable propellers providing movement along a given trajectory, designed for transporting usually light instruments and objects at a limited distance as well as for mineral exploration and other observations [1, 2]. General view of a typical quadcopter is shown in Fig. 1.

Fig. 1. General view of a typical QS

The use of QCs provides certain advantages [3–5]:

- cost-effectiveness;
- responsiveness;
- the capability of reaching high speed, gliding, and hovering over the control point;
- lower cost of manufacturing and operation (with comparable efficiency of fulfilling the assigned tasks);
- possibility of using without pilots. There is no danger of accident at that.

The disadvantages include the outstanding issues of integrating quadcopters into a common airspace as well as the certification, insurance, and registration issues, being already worked on.

MATERIALS AND METHODS

The QC motion is described in the fixed and moving coordinate systems shown in Fig. 2.

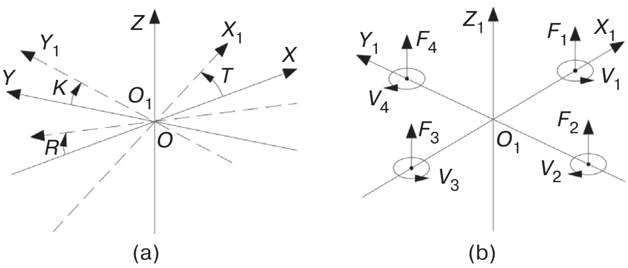


Fig. 2. (a) Fixed and moving coordinate systems, (b) kinematic scheme of a QC

Here, X, Y, and Z is the fixed coordinate system; X_1, Y_1, and Z_1 is the moving coordinate system, F_i are propeller thrust forces; V_i are rotation speeds of actuator motors of electric drives; R is the yaw angle; T is the pitch angle; K is the roll angle; g is the acceleration of gravity; ω_1 is the rotational speed of rotation of the ith propeller ($i = 1, ..., 4$).

The QC dynamics may be described by a system of differential equations in the following form [6]:

$$\ddot{X} = \frac{F_1 + F_2 + F_3 + F_4}{m} \times$$
$$\times \left[\cos R \sin T \cos K + \sin R \sin K\right] - \frac{A_x}{m}\dot{X}, \quad (1)$$

$$\ddot{Y} = \frac{F_1 + F_2 + F_3 + F_4}{m} \times$$
$$\times \left[\sin R \sin T \cos K + \cos R \sin K\right] - \frac{A_y}{m}\dot{Y}, \quad (2)$$

$$\ddot{Z} = \frac{F_1 + F_2 + F_3 + F_4}{m}\cos T \cos K - \frac{A_z}{m}\dot{Z} - g, \quad (3)$$

$$\ddot{T} = \frac{l}{J_{xx}}\left(F_4 - F_2\right), \quad (4)$$

$$\ddot{K} = \frac{l}{J_{yy}}\left(F_3 - F_1\right), \quad (5)$$

$$\ddot{R} = \frac{lb}{J_{zz}K_T}\left(F_1 - F_2 + F_3 - F_4\right), \quad (6)$$

$$F_i = K_T \omega_i^{\,2}. \quad (7)$$

Here, F_i stands for propeller thrust forces; J_{xx}, J_{yy}, J_{zz} are the QC inertia moments about corresponding axes; m is the QC weight; l is the distance from the QC center to the motor mounts; b is the process factor; A_x, A_y, and A_z are drag coefficients, and ω is the motor shaft speed.

The QC specific values are the following: m = 0.5 kg; l = 0.25 m; $K_T = 4 \cdot 10^{-5}$ (H·s^2)/rad^2; $b = 1.2 \cdot 10^{-7}$ (H·m·s^2)/rad^2; $A_x = A_y = A_z = 1$ kg/s; $J_{xx} = J_{yy} = 5 \cdot 10^{-3}$ kg·m^2; $J_{zz} = 9 \cdot 10^{-3}$ kg·m^2; $\omega_{i\max} = 300$ rad/s.

Since smooth motion of the QC with small roll and pitch angles is assumed, $\cos T \approx \cos K \approx \cos R \approx 1$, while $\sin T \approx T$, $\sin K \approx K$, and $\sin(R) \approx 0$. In addition, assuming smooth motion in the XOY plane, i.e., fulfillment of the condition $(F_1 + F_2 + F_3 + F_4) = mg$, equations (1)–(7) may be converted into the following form:

$$\ddot{X} = K_{\mathrm{T}x}\left(T\right) - \frac{A_x}{m}\dot{X}, \quad (8)$$

$$\ddot{Y} = -K_{\mathrm{K}y}\left(K\right) - \frac{A_y}{m}\dot{Y}, \quad (9)$$

$$\ddot{Z} = \frac{F_1 + F_2 + F_3 + F_4}{m} - \frac{A_z}{m}\dot{Z} - g, \quad (10)$$

$$\ddot{T} = \frac{l}{J_{xx}}\left(F_4 - F_2\right), \quad (11)$$

$$\ddot{K} = \frac{l}{J_{yy}}\left(F_3 - F_1\right), \quad (12)$$

$$\ddot{R} = \frac{lb}{J_{zz} \times K_{\mathrm{T}}}\left(F_1 - F_2 + F_3 - F_4\right). \quad (13)$$

Here, $K_{\mathrm{T}x}$ and $K_{\mathrm{K}y}$ are coefficients of mutual influence at corresponding coordinates (*X, Y*) of the QC.

To avoid possible uncertainties in understanding the following material, the concept of an information-measuring and control system (IMCS) of a QC should be introduced.

The QC IMCS implies a combination of hardware and software collecting, storing, and processing data on motion parameters, as well as the development of control actions for the control elements [7].

The following basic sensors are used for determining the QC coordinate parameters [8–11].

A barometer is a pressure measurement device which readings may give an indication of the flight altitude. The combination of a pressure sensor and GPS altitude sensor indicates the least error in determining altitude. The parameters of the commonly used MS5611 barometer (MEAS Switzerland SA) are the following:

- measured pressure ranges from 10 to 1200 hPa;
- accuracy is up to 0.1 m in the most accurate mode;
- measurement time is up to 10 ms.

An ultrasonic sensor is an instrument used for obtaining reliable information on the distance to large targets, even in environments with strong acoustic or electrical noise sources. The parameters of the commonly used I2XL-MaxSonar-EZ4 ultrasonic sensor are the following:

- reading interval is 67 ms (15 Hz);
- maximum distance is 765 cm;
- resolution within the range from 25 to 765 cm is 0.1 m.

A magnetometer is an electronic compass providing flight information relative to the Earth's magnetic field, located on the controller board.

A gyroscope is a device used for measuring the rate of angle change (usually measured along three axes).

An accelerometer is a device used for measuring the QC linear acceleration in the three-axis system. The parameters of the commonly used device combining gyroscope and MPU6050 accelerometer are the following:

- the range of measured angular velocities for gyroscope is ±250, ±500, ±1000, and ±2000 °/s;
- the range of measured accelerations for accelerometer is ±2, ±4, ±8, and ±16g.

A camcorder is a device used for recording the captured image. The parameters of the widely used Stack-X-1080P camcorder are the following:

- focal length is 2.8 mm;
- lens angle is *H*: 130°, *V*: 98°;
- camera sensor is 1/2.5-inch CMOS;
- DVR frame rate is 60 fps;
- NTSC or PAL video format.

GPS/GLONASS navigation module (e.g., H507A-05 Flight control PCBA) allows tracking and measuring distance, speed, and time. In fact, it is also a tracking system allowing identifying the exact location of the vehicle.

A flight controller module allows the QC to track its current location and speed. It also receives signals from the operator's transmitter. The flight controller interacts with the sensors onboard the QC to ensure a smooth flight, in particular with accelerometer, gyroscopes, and all that. In addition, the flight controller calculates the speed of each of the four engines and sends control signals to the electronic speed controllers (ESC).

Adjustable electric drives (***AED***) play a key role in QCs. They consist of an ESC and an electric motor. It is essential that both magnetoelectric and brushless (BL) direct current motors are used currently as electric motors in QCs. However, BL motors have become commonly used recently, which is due to their good performance characteristics [12], such as high specific torque, quick response, and control simplicity.

The parameters of the commonly used AED consisting of the ESC HW30A control unit and Walkera QR X350 motor are the following:

- supply voltage is 12 V;
- maximum current is 30 A;
- nominal rotor speed is 314 rad/s.

The development of the functional scheme and mathematical model for QC IMCS with special attention to its components will now be discussed [13–16]. Here, close attention should be paid to the values of delays in receiving information from corresponding sensors of QC parameters on the position of coordinates and their speeds. In the paper, these delays are considered as time constants for transfer functions of the corresponding sensors.

Taking into account the above equations, the functional and structural diagrams for the QC IMCS shown in Figs. 3 and 4 have been developed.

Here, the following designations are accepted: PC_z, PC_x, PC_y, PC_t, PC_k, and PC_r are position controllers for *Z*, *X*, *Y*, *T*, *K*, and *R* coordinates, respectively; AED1–AED4 are four adjustable electric drives; SC_t, SC_k, and SC_r are speed controllers for *T*, *K*, and *R* coordinates; PS_z, PS_x, PS_y, PS_t, PS_k, and PS_r are position sensors for *Z*, *X*, *Y*, *T*, *K*, and *R* coordinates, respectively; SS_t, SS_k, and SS_r are speed sensors for *T*, *K*, and *R* coordinates; CE1 and CE2 are correcting elements; $U_{\mathrm{SET}z}$, $U_{\mathrm{SET}x}$, $U_{\mathrm{SET}y}$, $U_{\mathrm{SET}t}$, $U_{\mathrm{SET}k}$, and $U_{\mathrm{SET}r}$ are position setting signals for *Z*, *X*, *Y*, *T*, *K*, and *R* coordinates, respectively; $U_{\mathrm{S}z}$, $U_{\mathrm{S}x}$, $U_{\mathrm{S}y}$, $U_{\mathrm{S}t}$, $U_{\mathrm{S}k}$, and $U_{\mathrm{S}r}$ are signals from position sensors for *Z*, *X*, *Y*, *T*, *K*, and *R* coordinates, respectively;

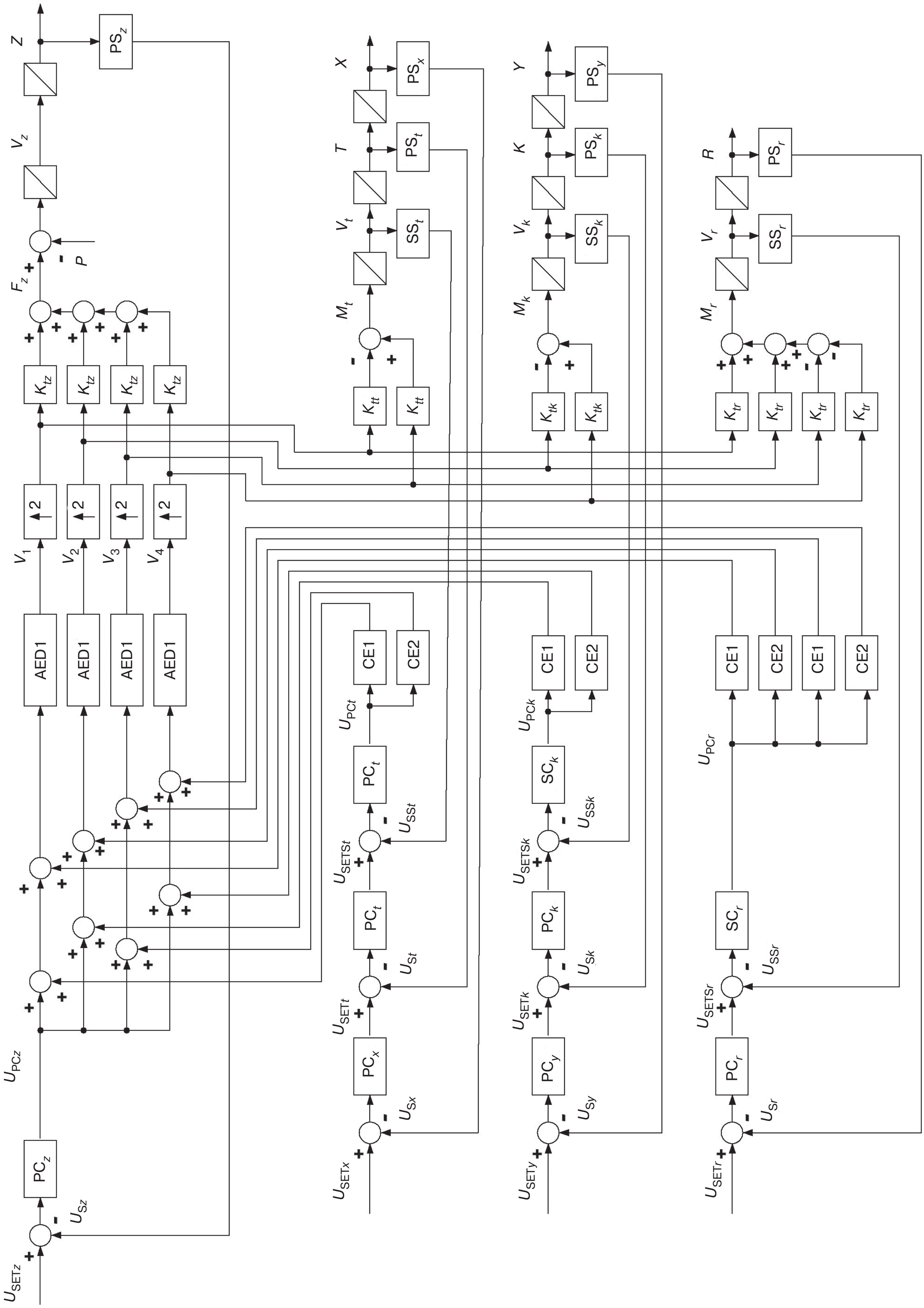


Fig. 3. A functional diagram for QC IMCS

U_{PCz}, U_{PCr} are output signals from Z and R coordinate position controllers, respectively; U_{SETt}, U_{SETk} are signals of setting T and K coordinates; U_{SETSt}, U_{SETSk}, and U_{SETSr} are signals of setting T, K, and R coordinate speeds, respectively; U_{SCt}, U_{SCk}, U_{SCr} are signals from controllers of T, K, and R coordinate speeds; F_z is the thrust force at Z coordinate; P is QC weight; V_z is the displacement velocity at Z coordinate; M_k, V_k are the torque and speed at T coordinate; M_k, V_k are the torque and speed at K coordinate; M_r, V_r are the torque and speed at R coordinate; K_{tz}, K_{tt}, K_{tk}, and K_{tr} are physical factors; $W_{PCz}(S)$, $W_{PCx}(S)$, $W_{PCy}(S)$, $W_{PCt}(S)$, $W_{PCk}(S)$, and $W_{PCr}(S)$ are transfer functions of position controllers for Z, X, Y, T, K, and R coordinates, respectively; $W_{SCt}(S)$ and $W_{SCk}(S)$ are transfer functions of speed controllers for T and K coordinates, respectively; S is the Laplace operator; K_{AED} and T_{AED} are the transfer factor and time constant for AED, respectively; K_{PSz} and T_{PSz} are the transfer factor and time constant for position sensor at Z coordinate, respectively; K_{PSx} and T_{PSx} are the transfer factor and time constant for position sensor at X coordinate, respectively; K_{PSy} and T_{PSy} are the transfer factor and time constant for position sensor at Y coordinate, respectively; K_{PSt} and T_{PSt} are the transfer factor and time constant for position sensor at T coordinate, respectively; K_{PSk} and T_{PSk} are the transfer factor and time constant for position sensor at K coordinate, respectively; K_{PSr} and T_{PSr} are the transfer factor and time constant for position sensor at R coordinate, respectively; K_{SSt} and T_{SSt} are the transfer factor and time constant for speed sensor at T coordinate, respectively; K_{SSk} and T_{SSk} are the transfer factor and time constant for speed sensor at K coordinate, respectively; K_{SSr} and T_{SSr} are the transfer factor and time constant for speed sensor at R coordinate, respectively; K_{vz} and T_{vz} are the transfer factor and time constant for velocity node at Z coordinate, respectively; K_{vx} and T_{vx} are the transfer factor and time constant for velocity node at X coordinate, respectively; K_{vy} and T_{vy} are the transfer factor and time constant for velocity node at Y coordinate, respectively; K_{vt} is the transfer factor for velocity node at T coordinate; K_{vk} is the transfer factor for velocity node at K coordinate; K_{vr} is the transfer factor for velocity node at R coordinate; F_{PCz}, F_{PCx}, F_{PCy}, F_{PCt}, F_{PCk}, F_{PCr}, and F_{PCz} are nonlinearities of position controllers at Z, X, Y, T, K, and R coordinates, respectively; $F1$, $F2$ are nonlinearities of correcting devices; F_{SCt} and F_{SCk} are nonlinearities of speed controllers at T and K coordinates.

The QC coordinate control loops are adjusted to technical and symmetrical optimums [17]. Specific values for the QC IMCS are given below.

For the control loop at Z coordinate:

$K_{tz} = 4\cdot10^{-5}$ (H·s^2)/rad^2; $K_{vz} = 5$ (1/s); $T_{vz} = 2$ s; $K_{AED} = 2.5$ rad/(discrete·s); $T_{AED} = 0.001$ s; $K_{PSz} = 1$; $T_{PSz} = 0.01$ s. The loop is adjusted to the technical optimum; in this case,

$$W_{PCz}(S) = 5000(1 + 0.5S)/(1 + 0.05S).$$

For the control loop at X coordinate:

$K_{tt} = 4\cdot10^{-5}$ (H·s^2)/rad^2; $K_{vt} = 50$ 1/(kg·m^2); $K_{vx} = 50$ (1/s); $T_{vx} = 2$ s; $K_{SSt} = 1$; $T_{SSt} = 0.01$ s; $K_{PSt} = 1$; $T_{PSt} = 0.05$ s; $K_{PSx} = 1$; $T_{PSx} = 0.05$ s. The speed loop at T coordinate is adjusted to the technical optimum; in this case,

$$W_{SCt}(S) = 500.$$

The position loop at T coordinate is adjusted to the technical optimum; in this case,

$$W_{PCt}(S) = 500.$$

The position loop at X coordinate is adjusted to the technical optimum; in this case,

$$W_{PCx}(S) = 0.1(1 + 0.5S)/(1 + 0.05S).$$

For the control loop at Y coordinate:

$K_{tk} = 4\cdot10^{-5}$ (H·s^2)/rad^2; $K_{vk} = 50$ 1/(kg·m^2); $K_{vy} = 50$ (1/s); $T_{vy} = 2$ s; $K_{SSk} = 1$; $T_{SSk} = 0.01$ s; $K_{PSk} = 1$; $T_{PSk} = 0.05$ s; $K_{PSy} = 1$; $T_{PSy} = 0.05$ s.

The speed loop at K coordinate is adjusted to the technical optimum; in this case, $W_{SCk}(S) = 500$.

The position loop at K coordinate is adjusted to the technical optimum; in this case, $W_{PCk}(S) = 500$.

The position loop at Y coordinate is adjusted to the technical optimum; in this case,

$$W_{PCy}(S) = 0.1(1 + 0.5S)/(1 + 0.05S).$$

For the control loop at R coordinate:

$K_{tr} = 4\cdot10^{-5}$ (H·s^2)/rad^2; $K_{vr} = 50$ 1/(kg·m^2); $K_{SSr} = 1$; $T_{SSk} = 0.01$ s; $K_{PSr} = 1$; $T_{PSr} = 0.01$ s.

The speed loop at R coordinate is adjusted to the technical optimum; in this case, $W_{SCr}(S) = 500$.

The position loop at R coordinate is adjusted to the technical optimum; in this case, $W_{PCr}(S) = 500$.

Since all coordinate control systems of QC perform their functions through 4 actuating motors, there is a strong mutual influence between them to be considered in using.

In the paper, rather the simple but illustrative operation algorithm for the QC IMCS has been investigated: the QC gains a height of 1 m; after 1 s, the QC moves to the right by 1 m; then the QC moves to the left by 1 m. In this case, the control systems for Z coordinate, X coordinate, and T coordinate (as intermediate one) are activated in the QC. When the control system is in operation, it is essential to observe the influence of a single coordinate (e.g., X) on the control system operating at another coordinate (e.g., Z), one after one. This influence should be minimal with the controllers selected properly.

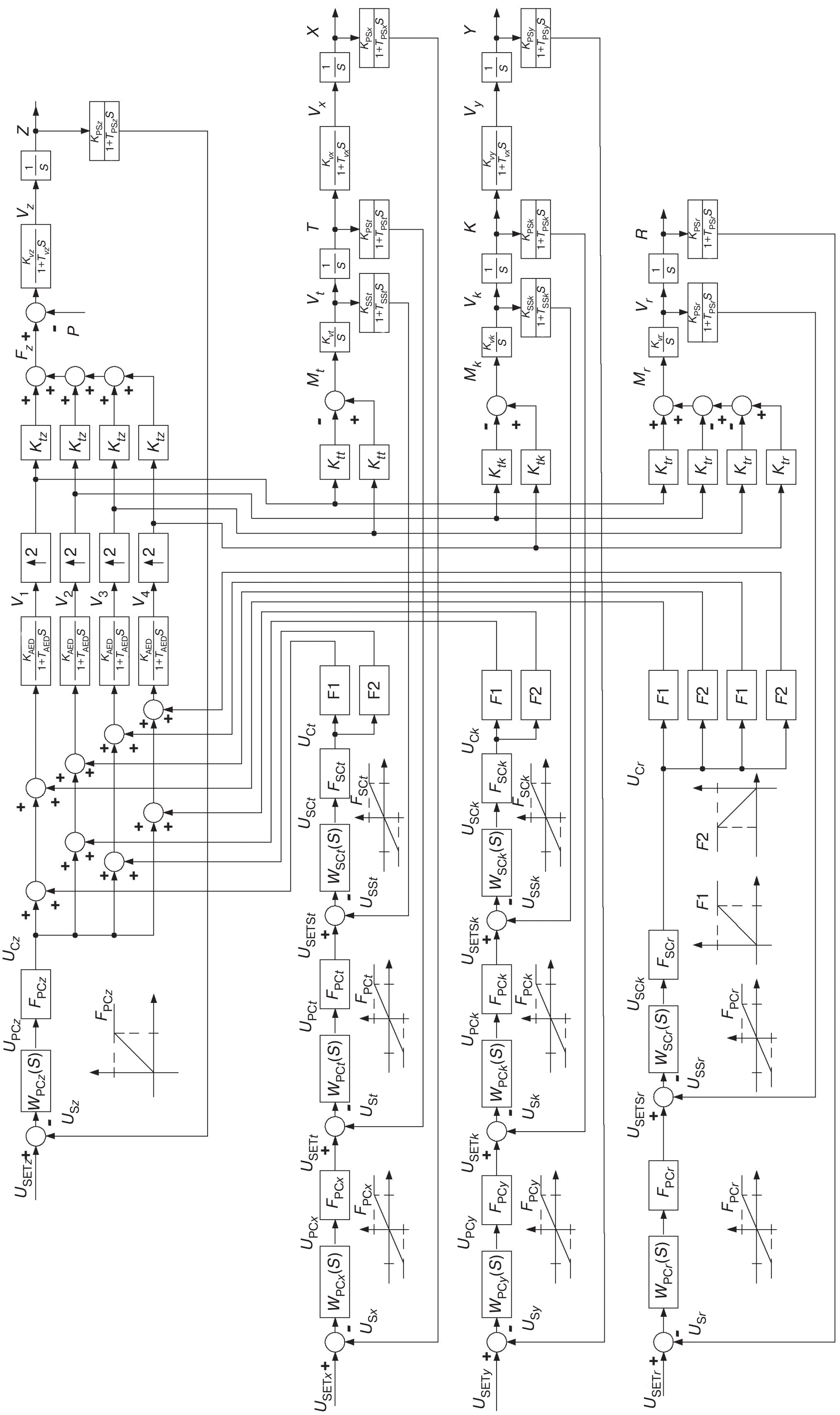


Fig. 4. A structural diagram for the QC IMCS

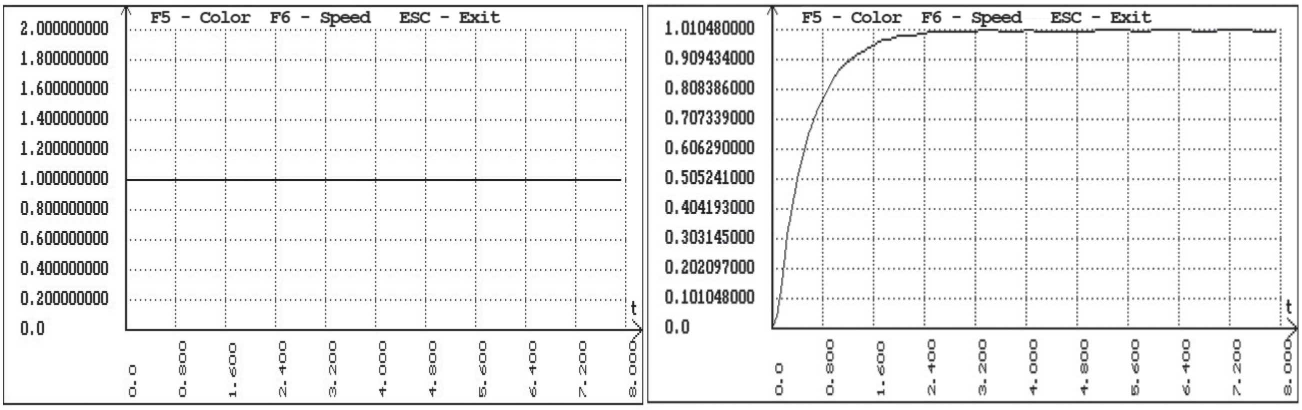
SIMULATION RESULTS

The behavior of the synthesized QC IMCS is simulated by applying the step signal having amplitude of 1 m to the input of the Z coordinate control system as well as the meander-type signal having amplitude of 1 m and frequency of 0.125 Hz to the input of the X coordinate control system after a time equal to 1 s. The simulation results are shown in Figs. 5–7.

The analysis of Figs. 5–7 shows that the synthesized IMCS as a part of the QC has the good control characteristics that are the absence of the overcontrol and the low static error (less than 10 mm). It should be noted that such good results have been obtained with the errors of the QC coordinate parameter sensors neglected. When they are taken into account, static errors increase significantly.

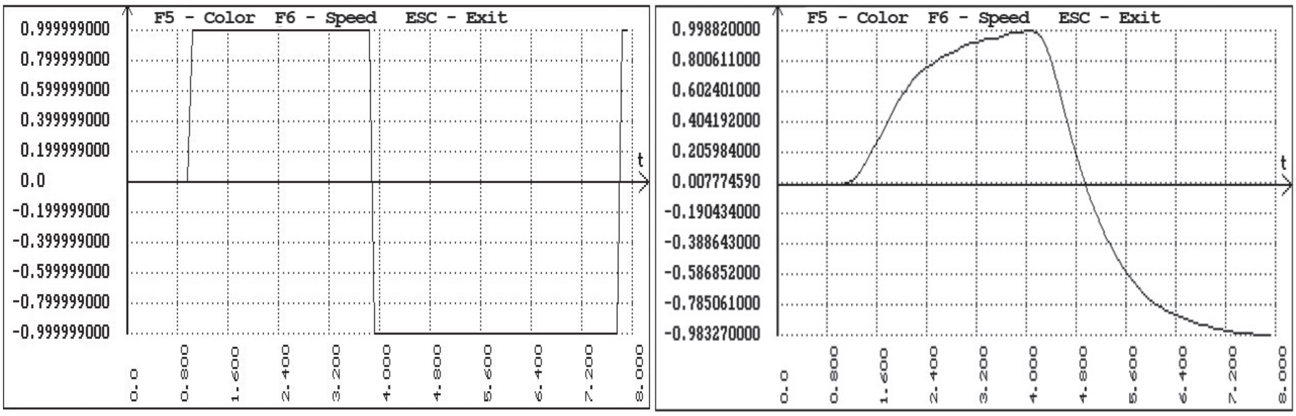
In addition, the regulators of the QC IMCS coordinate control system neutralize the mutual influence of coordinates.

With the parameters of coordinate controllers changing towards performance degradation of control



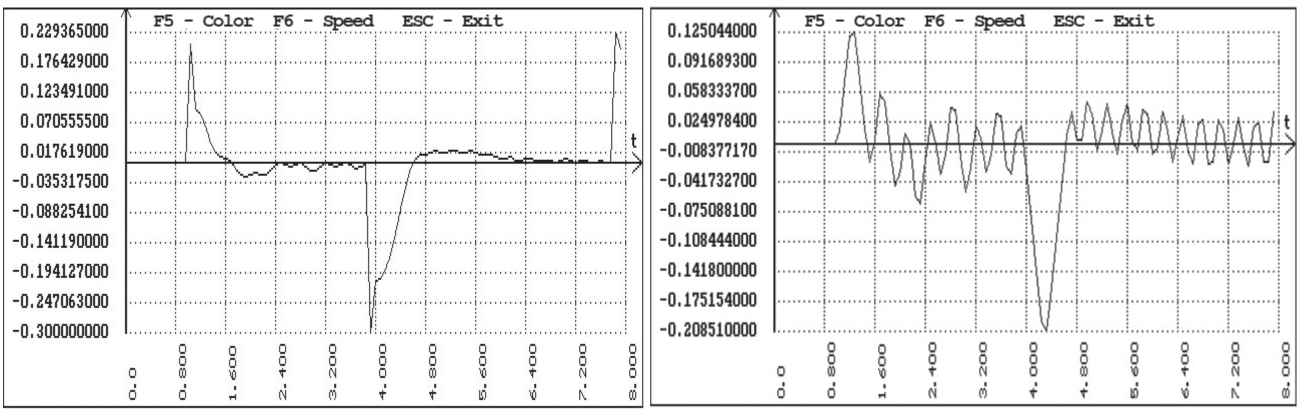
(a) (b)

Fig. 5. Position setting signals for Z coordinate (a) and actual position signals (b)



(a) (b)

Fig. 6. Position setting signals for X coordinate (a) and actual position signals (b)



(a) (b)

Fig. 7. Position setting signals for T (a) coordinate (a) and actual position signals (b)

loops, the effects of mutual influence of coordinates manifesting in shifts of some coordinates during operation of other coordinates, etc., are evidenced.

CONCLUSIONS

Based on the above, the following conclusions can be drawn:

- it would be advisable to implement the QC IMCS in the form of four control loops for the *X*, *Y*, *Z*, and *R* coordinates;
- control loops for the *T* and *K* coordinates should be subordinated to the position controllers of control loops for the *X* and *Y* coordinates;
- control loops for coordinates should be adjusted to the optimum modulus, thus obtaining smooth transients (without overcontrolling) and practically excluding the mutual influence of coordinates.

Authors' contribution. All authors equally contributed to the research work.

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