DESIGN AND SIMULATION OF BIOTECHNICAL MULTIDIMENSIONAL MOTION CONTROL SYSTEMS OF A ROBOT MANIPULATOR

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KEYWORDS

Biotechnical Systems, Human Operator, Robot-Manipulator, Motion Control, Design of Control Algorithms, Robot Velocity Control, Robot Position Control, Robot Force Control, Computer Simulation.

ABSTRACT

The design of multidimensional velocity, position and force control algorithms for a semi-automatic motion control system of a robot-manipulator has been performed. Mathematical and computer models of a motion control system with reconfigurable structure have been developed for a 3-link robot performing standard operations set by a human operator with a 3-degree-of-freedom handle.

Simulation of dynamic processes in a system with different control algorithms has been performed and their precision characteristics have been evaluated. The achieved results may be of interest for designers who develop training simulators for human supervisors of robot motion control systems.

INTRODUCTION

A human operator of biotechnical semi-automatic control systems performs remote motion control of a robot using handles in the form of joysticks with multi-degree of freedom and special calculator units. Control systems of this kind, in which an operator is considered to be a part of a control system, are widely used in high-risk work environments - in underwater vehicles, at space stations, etc. (Golovin 2011; Petukhov 2012; Soares 2008). These systems can be applied for real-time robot motion control and installed in training simulators for human operators (for example, astronauts, surgeons, etc.). The development of effective training simulators for human operators is an important practical issue (Strakhnov et al. 2016; Denisov 2016; Alferov et al. 2006).

In semi-automatic systems different algorithms of motion control are implemented depending on a type of technological operations performed by robots (Filaretov 2011, 2013). For transportation operations that do not require high accuracy, the gripper velocity control is usually used, while for precise point-to-point and continuous-path control it is necessary to use the gripper position control. When contact operations are performed (e.g. assembling) the control of force and torque in a robot gripper is required (Arkhipov et al. 2017).

In this paper we consider a semi-automatic motion control system for a robot-manipulator in which different control algorithms are combined. The actuators of robot links are local servosystems with digital PID regulators of motor speeds, positions and torques, which depends on an operation mode.

The purpose of the work is the structural design of motion control systems with different types of algorithms and the investigation of its dynamics in typical operation modes of a robot. The main problems of the research are the following:

1. The structural design of algorithms for open-loop and closed-loop velocity, position and force control.
2. Building computer models for the analysis of dynamic processes in control systems under consideration in standard operation modes.
3. Simulation of the control systems for a robot performing the following standard operations:

(1) - Transportation of the gripper to a specified area in the velocity control mode;

(2) - Point-to-point positioning of the gripper into a given point of a trajectory;

(3) - Precise movement of the gripper along a trajectory in continuous-path control mode;

(4) - Applying specified force to a fixed contact point.

4. The evaluation of dynamic errors that occur when a robot performs transportation, positioning, continuous-path motion and force operation.
It is believed to be acceptable to use simplified computer models of a robot and joint actuators for the comparison of motion control systems with different open-loop and closed-loop structures. So, for the solution of the problems stated above only kinematic models of a robot were used, without the consideration of its nonlinear dynamics. The drives were simulated by linear dynamic models of the 2nd and 3rd order. The animations of links of the handle and the robot were created with the use of functions from MATLAB Robotics Toolbox (Corke 2012, 2017)).

ALGORITHMS OF OPEN-LOOP ROBOT MOTION CONTROL

Human-handle interface of semi-automatic motion control systems of a robot-manipulator includes the solution of the following problems:
1) The forward kinematics problem related to the handle position:

$$S_h = F_h(q_h) = (X_h, Y_h, Z_h)^{\mathrm{T}} \tag{1}$$

where q_h – the vector of the handle joint positions, $F_h(q_h)$ – the vector-function corresponding to the handle kinematics scheme. The calculated coordinates X_h, Y_h, Z_h are interpreted as the vector of velocity, position or force coordinates set by a human operator.
2) In corresponding control mode the programmed velocities, positions and forces of the robot gripper are scaled as follows:

$$V_p = (V_{xp}, V_{yp}, V_{zp})^{\mathrm{T}} = (M_{vx}X_h, M_{vy}Y_h, M_{vz}Z_h)^{\mathrm{T}} \tag{2}$$

$$S_p = (X_p, Y_p, Z_p)^{\mathrm{T}} = (M_x X_h, M_y Y_h, M_z Z_h)^{\mathrm{T}} \tag{3}$$

$$F_p = (F_{xp}, F_{yp}, F_{zp})^{\mathrm{T}} = (M_{fx}X_h, M_{fy}Y_h, M_{fz}Z_h)^{\mathrm{T}} \tag{4}$$

where M_* - scale gains.
The algorithm of open-loop robot velocity control is based on the solution of the inverse kinematics problem related to the programmed robot joint velocities:

$$\dot{q_p} = J_M^{-1}(q)V_p \tag{5}$$

where $\dot{q_p}$ – the vector of the robot joint velocities, q – the vector of the robot joint positions, $J_M^{-1}(q)$ – the matrix inversed to the Jacobian matrix of the robot-manipulator.
The algorithm of open-loop robot position control is based on the solution of the inverse kinematics problem related to the programmed joint positions:

$$q_p = F_M^{-1}(S_p) \tag{6}$$

where $F_M^{-1}(S_p)$ – the vector-function inversed to the vector-function $F_M(q_p)$ of the robot.
And the algorithm of open-loop robot force control is based on the solution of the inverse kinematics problem related to the programmed joint torques:

$$Q_p = J_M^{\mathrm{T}}(q)F_p \tag{7}$$

where Q_p – the vector of the robot joint torques, q – the vector of the robot joint positions, $J_M^{\mathrm{T}}(q)$ – the matrix transposed to the Jacobian matrix of the robot.

ALGORITHMS OF CLOSED-LOOP ROBOT MOTION CONTROL

Closed-loop velocity control of a robot gripper

The algorithm of closed-loop velocity control includes the sequential solution of the following problems:
1) The forward kinematics problem related to the robot gripper velocity, which is solved in the real time mode:

$$V_r = J_M(q) \cdot \dot{q} = (V_x, V_y, V_z)^{\mathrm{T}} \tag{8}$$

where $\dot{q}$- the vector of the robot joint velocities; $J_M(q)$ - the Jacobian matrix of the robot.
2) Calculation of the error vector for gripper velocity:

$$\mathrm{dV} = V_p - V_r \tag{9}$$

3) The inverse kinematics problem related to the joint velocities:

$$G = J_M^{-1}(q) \cdot U_V \tag{10}$$

where $J_M^{-1}(q)$ – the matrix inversed to the Jacobian matrix of the manipulator, $U_V = (u_{vx}, u_{vy}, u_{vz})^{\mathrm{T}}$ – the output vector of multivariable PID velocity controller, $G = (g_1, g_2, g_3)^{\mathrm{T}}$ - the input vector of velocity drives.

Closed-loop position control of a robot gripper

The algorithm of closed-loop position control includes solution of the following problems:
1) The forward kinematics problem related to the robot gripper position, which is solved in the real time mode:

$$S_r = F_M(q_r) = (X_r, Y_r, Z_r)^{\mathrm{T}} \tag{11}$$

where q_r – the vector of the robot joint positions, $F_M(q_r)$ – the vector-function corresponding to the robot kinematics scheme.
2) The error vector calculation for gripper position:

$$dS = S_p - S_r \tag{12}$$

3) The inverse kinematics problem related to the programmed robot joint velocities:

$$\dot{q_p} = J_M^{-1}(q)U_s \tag{13}$$

where $\dot{q_p}$ – the programmed vector of the robot joint velocities, $J_M^{-1}(q)$ – the matrix inversed to the Jacobian matrix of the manipulator, $U_s = (u_x, u_y, u_z)^{\mathrm{T}}$ – the output vector of multivariable PID position controller outputs.

Closed-loop force control of a robot gripper

The algorithm of closed-loop force control includes the sequential solution of the following problems:
1) The forward kinematics problem related to the robot gripper force:

$$F_r = \left({J_M}^T(q)\right)^{-1} Q \tag{14}$$

where q – the vector of the robot joint positions, $J_M^{\mathrm{T}}(q)$ – the matrix transposed to the Jacobian matrix of the robot, Q – the vector of the robot joint torques.

2) Calculation of the error vector for gripper force:

$$dF = F_p - F_r \tag{15}$$

3) The inverse kinematics problem related to the programmed robot joint torques:

$$Q_p = J_M^{\mathrm{T}}(q) U_f \tag{16}$$

where $J_M^{\mathrm{T}}(q)$ – the matrix transposed to the Jacobian matrix of the robot, $U_f = \left(u_{fx}, u_{fy}, u_{fz}\right)^{\mathrm{T}}$ – the output vector of multivariable PID force controller.

COMPUTER MODELS OF CLOSED-LOOP ROBOT MOTION CONTROL SYSTEMS

Figure 1 shows the Simulink model of the closed-loop velocity control system with the vectorial feedback. The model includes the following blocks:
Block *Human-Handle Interface* calculates expression (1) and expression (2);
Block *fkine_V* in the feedback solves the forward kinematics problem related to the gripper velocity using expression (8);
Block *PID-V* is the multivariable PID controller of the gripper velocity coordinates.
Block *ikine_V* calculates the input actions for the robot joint velocity drives using expression (10).
Block *Velocity Drives* contains the models of velocity drives of the robot links.
Block *fkine_P* solves the forward kinematics problem related to the gripper position using expression (11).

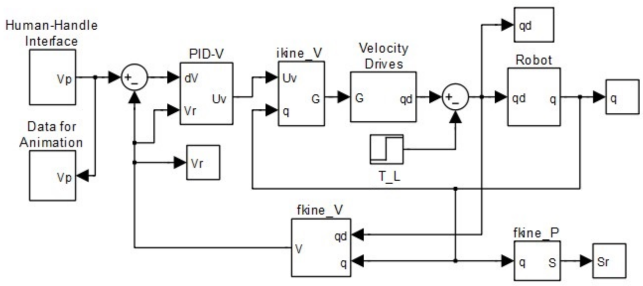

Figure 1: The model of closed-loop velocity control system

Figure 2 shows the Simulink model of the closed-loop position control system with the vectorial feedback. The model includes the following blocks:
Block *Human-Handle Interface* calculates expression (1) and expression (3).
Block *fkine_P* in the feedback solves the forward kinematics problem related to the gripper position using expression (11);
Block *PID-S* is the multivariable PID position controller.
In the closed loop block *ikine_V* calculates the input actions for the robot joint velocity drives.
The second block *ikine_V* calculates programmed gripper velocities using expression (6) in order to compensate for velocity errors when the robot operates in continuous-path control mode.
Block *Kk* is the vector of parameters of velocity error compensators.

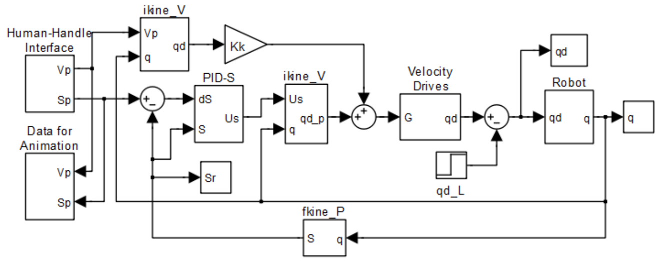

Figure 2: The model of closed-loop position control system with velocity drives

Figure 3 shows the Simulink model of the closed-loop force control system with the vectorial feedback. The model contains the following blocks:
Block *Human-Handle Interface* calculates expression (1) and expression (4).
Block *fkine_F* in the feedback solves the forward kinematics problem related to the gripper force using expression (14).
Block *PID-F* is the multivariable PID controller of the gripper force coordinates.
Block *ikine_F* calculates the input actions for the torque drives of the robot links using expression (16).
Block *Torque Drives* contains the models of the robot link torque drives.
The switch block in the model in Figure 3 allows to analyse the dynamic processes in the system for two operations: (1) – for the contact force operation and (2) – for the motion force operation.

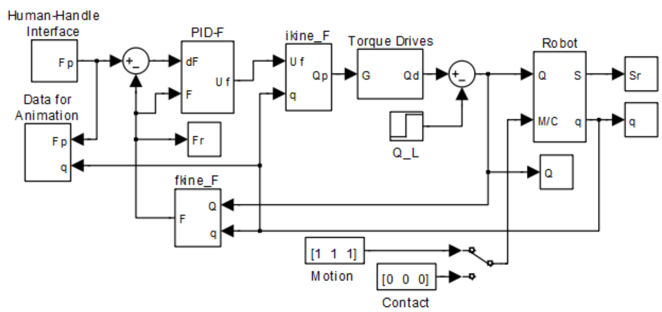

Figure 3: The model of closed-loop force control system with torque drives

Blocks T_L, qd_L and Q_L in the models above represent external loads (disturbances).

ANALYSIS OF DYNAMIC PROCESSES IN ROBOT MOTION CONTROL SYSTEMS

The results of simulation and dynamic analysis of open-loop position and velocity control systems for a robot which performs a transportation operation, point-to-point positioning and continuous-path motion were presented in (Rostova et al. 2018). And the results of investigation of closed-loop velocity, position and force control systems are represented below.

The processes in a control system when the robot performs a transportation operation

When the robot performs some transportation in the velocity control mode a human operator quickly turns the handle keeping it in this position and then quickly returns it to the initial position. In this mode the trajectories of handle links have trapezoidal shape.
Figure 4 represents the animations of the gripper and the robot when the gripper is moving in a required direction.

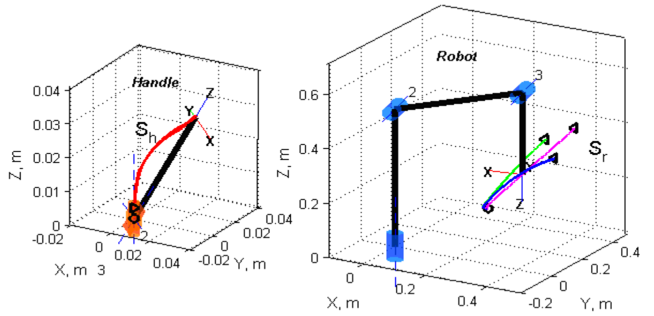

Figure 4: The handle and the robot animations for velocity control mode

The blue and green curves correspond to the open-loop velocity control when the Jacobian matrix in (5) is calculated using the programmed or real robot joint positions, correspondently. Both curves significantly differ from the required straight-line motion of the gripper and show a rather big contour error.
The pink curve that corresponds to the closed-loop velocity control is straight-line and depicts a small contour error. Figure 5 shows the gripper velocities for this case where the programmed coordinates are represented by a dash line (p) and the real coordinates - by a solid line (r).

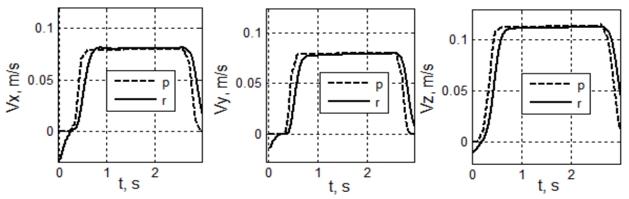

Figure 5: The gripper velocities for closed-loop velocity control

The gripper velocity coordinates have rather big errors at the beginning of the motion because of the influence of external disturbances on the load torques in the drives imitated in the block *T_L*.

The processes in a control system for the case of point-to-point motion of the robot gripper

In this control mode a human operator smoothly turns the handle from the initial position to the required position. The handle link trajectories are calculated by the polynomials of the 5th order.

Figure 6 shows the animations of the gripper and robot when the gripper is moving to a required position.

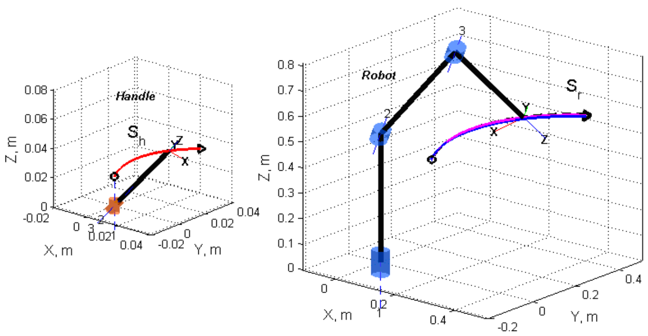

Figure 6: The handle and the robot animations for point-to-point control mode

Figure 7 represents the gripper position coordinates for a closed-loop position control system where programmed coordinates are shown with a dash line (p) and the real coordinates – with a solid line (r). As it can be seen the closed-loop position control system provides the gripper position with smaller dynamic errors. And the final position of the gripper is reached without error.

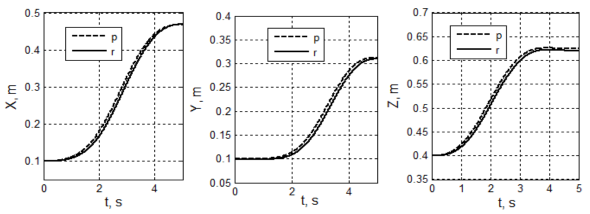

Figure 7: The gripper coordinates for point-to-point motion

The processes in a control system for the case of continuous-path motion of the robot gripper

In the continuous-path mode a skillful human operator moves the handle along the required trajectory of a complex shape, e.g. a helical line. Figure 8 illustrates the animations for the situation when the robot gripper should move along a helical line. The blue curve corresponds to the open-loop position control and the pink curve – to the closed-loop position control.

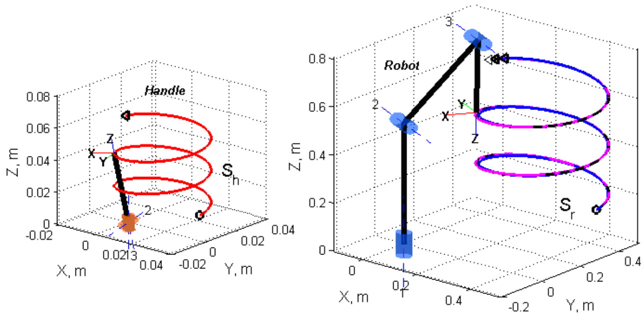

Figure 8: The handle and the robot animations for continuous-path control mode

Figure 9 represents the curves of the gripper positions for the closed-loop position control system where programmed coordinates are shown with a dash line (p) and the real coordinates – with a solid line (r).

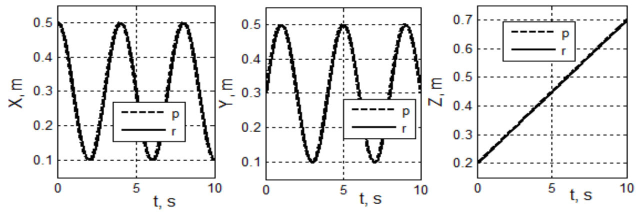

Figure 9: The gripper coordinates for continuous-path motion

The processes in a control system when the robot performs a contact operation

Figure 10 illustrates the animations when the robot performs a contact operation and applies the required force in the given gripper position without motion of the gripper. The vector of programmed force in Figure 10 is shown with red color. The green and pink color vectors correspond to real force for open-loop and closed-loop control respectively.

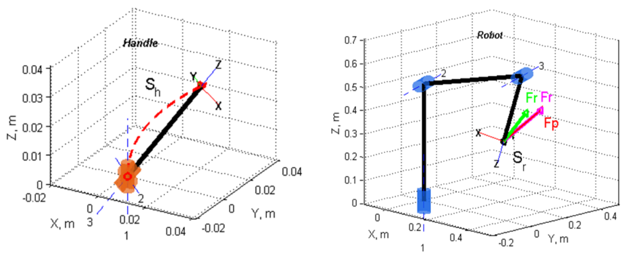

Figure 10: The handle and the robot animations for contact operation mode

Figure 11 represents the curves of programmed and real forces in the closed-loop control system when the robot applies force to a given contact point without motion of the gripper. The programmed forces are shown with red color. The real forces corresponding to the closed-loop control system are shown with pink color.

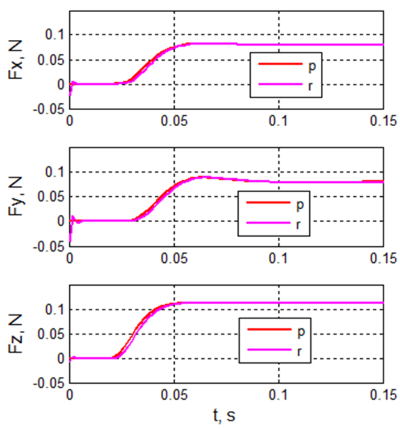

Figure 11: The gripper forces for contact operation mode

EVALUATION OF DYNAMIC ERRORS IN ROBOT MOTION CONTROL SYSTEMS

The dynamic errors of the gripper velocity, position trajectory and force for the open-loop and closed-loop control systems are calculated by the following formulas:

$$E_V = \sqrt{(V_{xp} - V_x)^2 + (V_{yp} - V_y)^2 + (V_{zp} - V_z)^2} \quad (17)$$

$$E_S = \sqrt{(X_p - X_r)^2 + (Y_p - Y_r)^2 + (Z_p - Z_r)^2} \quad (18)$$

$$E_F = \sqrt{(F_{xp} - F_x)^2 + (F_{yp} - F_y)^2 + (F_{zp} - F_z)^2} \quad (19)$$

As it can be seen from the results of simulation, the closed-loop velocity, position and force control systems provide the smaller dynamic errors.

Also, the analysis of the gripper trajectories in Figure 8 shows that the closed-loop position control system gives a smaller contour (geometrical) error compared to the open-loop position control system due to multivariable coordinated position control of the robot link drives.

The robot with the closed-loop force control system applies the required force in a given gripper position without static error.

CONCLUSION

The design of a robot motion control algorithms has shown that it is necessary to build biotechnical control systems with reconfigurable structure.

The results of simulation of dynamic processes have proved that closed-loop algorithms of velocity, position and force control give smaller dynamic errors in comparison with open-loop algorithms. The evaluation of the gripper errors for velocity, position and force control which were obtained in the process of computer simulation is approximate because the purpose of the work was to investigate robot motion control systems in general rather than assess characteristics for a particular robot.

The developed computer models of the velocity, position and force control systems allow to perform motion and contact force operations set by a human operator. In the developed models a human operator is represented as a vector of linear dynamic elements with dead time.

The developed models can be utilized in simulators for training human operators and supervisors of biotechnical robot control systems in real time mode.

From a practical point of view, the animation of both a handle and a robot on a control panel monitor with trajectories and force vectors can make the work of a human operator more effective and convenient.

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