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Robot Master Slave and Supervisory Control with Large Time Delays of Control Signals and Feedback

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Abstract

In this paper the methods of remote control over space robots with large delays of the transmission of control signals from the Earth to the local robot control system are theoretically and experimentally substantiated.

1 Introduction

At this time an indisputable fact is an assertion that the most efficient, effective and safe for human way of further space exploration is based on wide use of space robots remotely controlled from the ground control center.

The researches in this field and close to it directions are hold by the German Space Agency (DARA) [1, 2], the National Aeronautics and Space Administration (NASA), as well as in Canada and Japan. This article presents the results of searches in St.-Petersburg National Research University (ITMO) [3-5], St.-Petersburg Institute of Informatics and Automation of RAS (SPIIRAS)[6-10] and in St. Petersburg State University (SPSU) [12-19]. The main crucial obstacle while constructing efficient systems of remote control over space robots is a significant delay of control signals transferring to the space robots from the ground control center, as well as delay of feedback signals receiving mainly in case of control over robot manipulators moving objects with constraints, in particular, holonomic [9,10].

When implementing these operations it is necessary to use the feedback constraints by forces and moments of the mechanical constraints reactions that influence on the mechanical manipulator gripping by the captured and moving by it "constrained" objects.

In case of implementation of such operations by robots on the Earth in the nondeterministic external environment in the absence of delay of control signals transferring it is conventional to use the master-slave control with representation of reaction constraint forces in which this forces and moments are instantly perceived by a human arm moving a control handle [3]. This is the only way to implement such operations. Any delay hinders their implementation. And the delay of kinesthetic information for more than 0.2 seconds makes this impossible.

Therefore the classical master-slave control can not be applied for space robot, even though at this time this method of control is the only possible and the most reliable in case when the robots have to implement complex assembly efforts on the Earth in a non-deterministic environment [15-19]. To resolve this contradiction it was necessary to improve the method of master-slave control by overcoming the problem of delay.

2 The approach to construct the system of remote control over space robot

The proposed way to improve a convetional master-slave control to use it for remote control over space robot involves constructing a sufficiently accurate model of space robot and its external environment on the ground control complex with simulation of the weightlessness effect. In this modeled environment a human operator must implement the required operation in master-slave control mode using the control handle. This is possible, since there is no the delay of transferring the model control signals and receiving feedback signals. During this operation, there is formed a programmed trajectory for ground model of space manipulator, that is a vector of changing the position of control handle in space and time. If ground models of external environment and the robot itself would be ideal, i.e. in particular, would absolutely correctly represent space manipulator and its external environment, as well as their dynamic properties, then as a result the required operations would be implemented by space robot in the same way as by its model on the Earth. And a human operator controlling the robot model at the respective visualization of a model using techniques of virtual and augmented reality, would experience the same kinesthetic and visual sensations as while controlling a real robot operating in a real external environment with no delay in transferring the control and feedback signals.

Unfortunately, constructing ideal models of robot and its external environment is unreal. Therefore, it is necessary to correct a programmed trajectory while using a local system control over space robot (SR) to illiminate its erroneous actions caused by the inaccuracy of environment model.

We assume that external environment of SR is stationary. The inaccuracy of its model is in difference of the spatial position and orientation of object models from their real position in the modeled and real system of coordinates associated with the body of SR and its model. As for the shape and dimensions of real objects, their difference from the models can be considered sufficiently small to neglect them. To eliminate the effect of these differences while assembly operations it is necessary to correct the position and orientation of the SR operation tool so that the position and orientation of objects in real external environment that this operation tool is interacting with in the tool coordinate system to be identical to the position and orientation of the objects models in external environment in the coordinate system of operation tool model. In addition, it is necessary a law of variation in time of real constraint reactions vector to be identical to the"modeled" law while required operations. To this end, during the execution of a required operation using the model of SR and its external environment, it is necessary to obtain additional information to determine a position of operation tool model of space robot in relation to models of external environment objects interacting with the tool model. Analogical information on the real position of tool in relation to real object is also necessary to be found, as well as data on modeled and real force of this interaction. Finally, the data on "modeled" and real holonomic constraints, that have an operation tool of the robot and its model are necessary, too. They may be normals to hypersurfaces of constraints or so-called normalizing matrix.

For more information, a variety of sensors that must be installed on the model of space manipulator should be used. These can be location, force-torque, tactile sensors, as well as TV-cameras necessary for the implementation of machine vision systems. Generation of correction signals also implies the use of additional information obtained during execution of the required operation by space robot using the sensors, identical to ones of the robot model that are located on it in the same manner as on the model.

Since the above-mentioned additional information is the result of the robot sensory system work, further it is named "sensory images".

The correction value of programmed trajectory transferred from the ground model is a function of mismatch value between "modeled" and real sensory images. It vanishes if mismatch value between them equels to "zero". The simple example of a visual sensory image can be images of set of characteristic points belonging to objects of the robot environment model. For instance, these can be images of polyhedron verteces (Fig. 1).

They are defined by a special "identifying program" from the external environment image obtained by using TV-cameras located on the model of operation tool. The images of similar points of real external environment are obtained at the stage of program implementation with the use of TV-cameras located on real opertaion tool, as on its model. Therefore, the images of these points must coinside with the images of "modeled" points at the ideal motion of robot operation tool forming in the process of programmed path following. However, due to possible inaccuracies model of external environment they may not coincide. Mismatch value in positions of modeled images and corresponding to them real points is used to generate the correction value for position of space manipulators operation tool during programmed trajectory following by its control system.

The "force" images obtained by using wrist force-torque sensors of robot and its model can be also the sensory images. The processing of these signals gives vectors of interaction forces betveen the model of operation tool of space manipulator with constrained objects models of its external environment. The mismatch signals of modeled and real vectors of interaction forces are transformed by space robot control system to additional offsets of its operation tool which eliminates erroneous interaction forces.

The ground system of master slave control over the model of space robot (GSMSCM) acts as an interface which programmed trajectory for local control system is generated through. The more accurate the model of robot and its external environment is, the more effectively GSMSCM works. This fact implies similarity of kinesthetic and visual perceptions of operator to perceptions experienced at master slave control over a real robot operating in real external environment. This would allow implementing one useful function more consisting in using GSMSCM as a simulator for training operators in space robot control. To improve the accuracy and reality of the model of robot and its

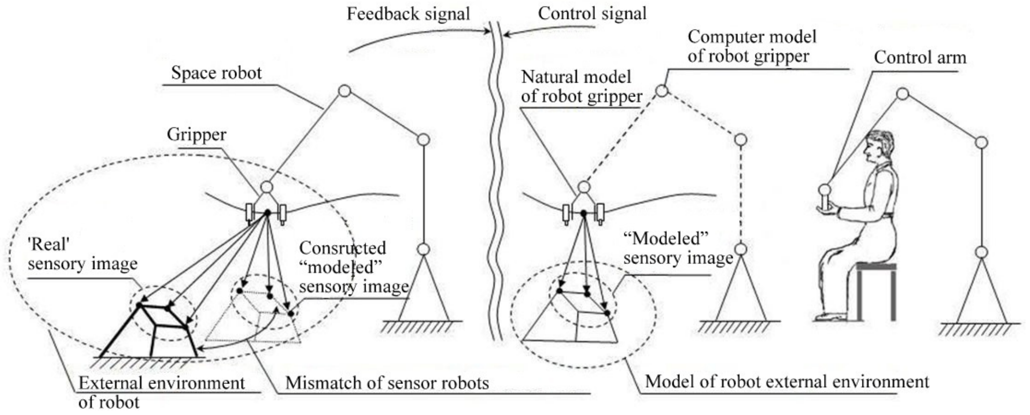

Figure 1: Scheme of remote control over space robot

external environment it is preferable to use real elements as much as possible. It primarily refers to the models of external environment objects and to control arm denoted on the block diagram of GSMSCM (Fig. 2) as block I. These can be also objects stimulants, i. e. their physical model. As concerns a model of SRs mechanical arm (block II), in the most cases it may not be made as a real physical model, since the real mechanical arm, that is usually designed to operate in weightlessness, can not be used on the Earth because of its ”weak” drives and insufficient rigidity of its construction. An obvious solution is to construct it as a computer model. However, more rational way is to construct so-called combined model of mechanical arm consisting of two parts.

The first one is supposed to be virtual. This is a dynamic model of space manipulator construsted on the basis of some known software package such as Webots. Webots is designed to simulate the behavior dynamics of controlled multi-element mechanisms and has a function of visualizing the model with the use of OpenGL library, without image of operation tool attached to the end of manipulator. A virtual part is denoted on Fig. 2 by dotted lines.

The second part of the model is a full-scale (physical) model of operation tool. It is moved by a very dynamic manipulator mechanism with quite rigid construction (block III). The motion trajectory is formed by the first part of the model taking into account that space manipulator operates in weightlessness. Using an augmented reality technology [4] it is possible to augment the video of the real physical model of operation tool by computer-synthesized image of virtual part of the manipulator model without operation tool at its end. This allows to a human to perceive an image of space manipulator as a whole. The remaining blocks shown in Fig. 2 implement augmented reality technology to create for a human a realistic illusion of interaction with the space robot, operating in a real external environment [5-7].

Programmed trajectory correction attended by developing of corrected tra-

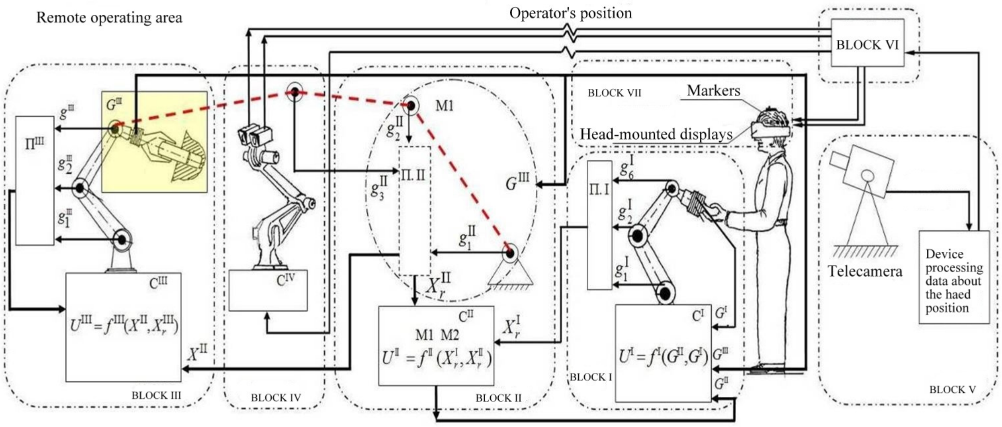

Figure 2: Block diagram of the ground master slave control system (GMSCS)

jectory is implemented by a local control system over space robot (LCSR). Its structure differs from the ground master slave control system over space robot model (GMSCSM) because of absence of human in a closed control circuit. This difference in structures of the ground master slave control system and the local one can lead to the difference in dynamic processes in these systems and, consequently, lead to erroneous actions of SR. In this regard, it is rational to execute preliminary verification on perfoming the required operations by SR model on the ground control center using an exact copy of the local control system over space robot (CLCSR). The input data for CLCSR is information obtained with help of GMSCSM for local control system over the real robot that is a programmed trajectory and sensory images. Only successful verification on performing the required operation by space robot model controlled by CLCSR makes it possible to transfer data mentioned above for the local control system over the real robot.

Fig. 3 shows a block diagram of CLCSR with controlled by it a combined SR model. The difference between CLCSR and GMSCSM mentioned above is in absence of control arm. As a substitute for it the so-called programmed trajectory corrector (PTC) is used. It forms a new corrected trajectory by conforming processing of old programmed trajectory received from GMSCS, as well as by processing modeled sensory images: visual BCO1 and force CCO1 with similar sensory images BCO2 and CCO2 formed with help of visual and force sensors. These sensors are installed on a physical model of space manipulator gripper moved by an optional manipulator mechanism. The model of environment should be different from the model of environment which the SR model as a part of GMSCSM was operating in. It is necessary for verification of quality and correction results caused by inaccuracy of the model.

Theoretical justification of efficiency of the proposed approach to remote control requires the solution of some principle problems. These primarily are the problems of determining the stability conditions of perturbed GMSCSM, LCSR and CLCSR motions. It is also important to solve the problem of correction for programmed trajectory formed by GMSCSM to eliminate the erroneous actions of robot caused by inaccuracy of its model environment.

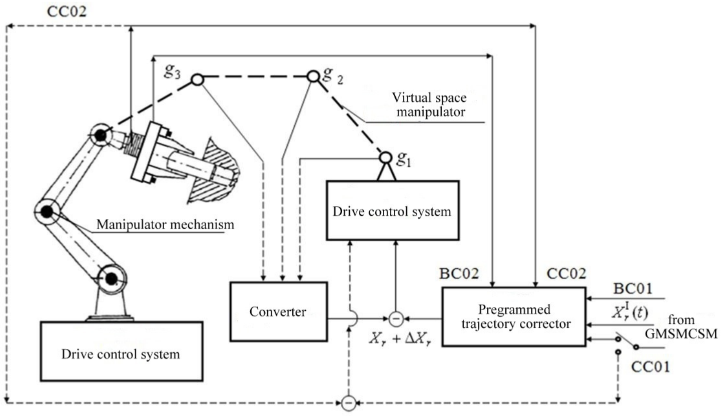

Figure 3: Block diagram of the local control system copy through the Combined model of space robot

3 Dynamic analysis of ground master slave control system over robot

The dynamics of behavior of ground space robot model with master slave control may be described by the following system of differential equations:

$$A^i\ddot{q}^i + B^i\dot{q}^i + C^iq^i + D^i = H^iU^i + Q^i, \quad i = I, II, III. \tag{1}$$

The constraint equation for the operation tool of manipulator mechanism has the form:

$$p\dot{X}^{III} = pJ^{III}\dot{q} = pJ_r^{III}\dot{g} + pJ_e^{III}\dot{e} = 0, \tag{2}$$

where $q^i = (g^i, e^i), \quad i = I, II, III$ — (n^i+m^i) are the generalized coordinates vectors of controlled objects: control arm, space manipulator model, manipulator mechanism, respectively, g^i and $e^i, \quad i = I, II, III$, n^i and m^i are the joint coordinates vectors of controlled objects and the deformation vectors of all the elastic structure elements, $e^{III} = 0$, $H^i = \left[\begin{array}{c:c} O & E \end{array}\right]$ — $n^i \times (n^i+m^i)$ is a block matrix, E — (n^i+n^i) is an identity matrix, A^i and B^i — $(n^i+m^i)\times(n^i+m^i)$ are matrices of inertia and of dissipative, Coriolis, centrifugal forces of controlled objects, $J^i = \left[\begin{array}{c:c} J_r^i & E_e^i \end{array}\right]$ are Jacobi matrices, where $i = I, II, III$.

$C = \left[\begin{array}{c:c} 0 & 0 \\ \hdashline 0 & C_e \end{array}\right]$, $i = I, II, III$, C_e^i — $(m^i + m^i)$ is a stiffness matrix of controlled objects structure; D^i — $(n^i + m^i)$ are vectors of generalized weight forces; $D^{II} = 0$, $Q^I = (J^I)^T(C_r J^I \Delta q^I + k_r J^I \dot{q})$ is a vector of generalized force of retention by hand, C_r and K_r are matrices of stiffness and damping a hand of a human being an operator of control handle, $Q^{II} = -J^{II}G^{III}$ is a vector of generalized constraint reaction force of SR operaton tool, $Q^{III} = (J^{III})^T p\lambda = (J^{III})^T G^{III} = (J^{III})^T p^T cpJ^{III} q^{III} \quad (c \to \infty)$ is a vector of generalized constraint reaction force of optional manipulator mechanisms operation tool, G^{III} and G^I are six-dimensional vectors of constraint reaction force in coordinate system of full-scale operation tool and retention force vectors of control arm that are measured by wrist force-torque sensors. $U^I = (J_r^I)^T(G^I + G^{III})$, $U^{II} = (J_r^{II})^T k_{pf}(X_r^I - X_r^{II})$, $U^{III} = (J_r^{III})^T k_p(X_r^{II} - X_r^{III})$ are control laws for control arm, manipulator model and optional manipulator mechanism. $X_r^i, \quad i = I, II, III$ are six-dimensional position vectors of control arm, operation tool of manipulator model and operation tool of optional manipulator mechanism, respectively, generated by joint coordinates $g^i, \quad i = I, II, III$, p is a normal to the hypersurface formalizing a mechanical constraint imposed on the operation tool of manipulator mechanism.

The behavior dynamics of space robot is described by system of equations of the form (1) at $i = II$, where q^{II} is replaced by $q^M = (g^M, e^M)$, $Q^{II} = (J^{II})^T G^{III}$ is replaced by $Q^M = (J^{II})^T G^M$ and U^{II} is replaced by $U^M = k_{pf}(X_r^I - X_r^M)$ where X_r^M is a six-dimentional vector, that is a function of joint coordinates g^M.

In [4-7] it is shown that the dynamic processes in GMSCSM are stable at perturbations. Moreover, the following requirements on the parameters of controlled laws over controlled objects are true.

Amplification matrices k_{pf}, k_p, k included in the control laws U^I, U^{II}, U^{III} should be symmetric and positively definite and be permuted with matrices p and p^T defining the type of constraints for the space manipulator and its model. In addition it is necessary to consider the following requirements to the values of control law parameters: $k_p >> k_{pf}; k_{pf} >> C_r; k >> E$.

Furthermore, while constructing controlled objects of the simulator it is necessary the stiffness matrix C^r of manipulator mechanism structure to satisfy an inequality $C_r >> k_p$ and the stiffness matrix of control arm structure C_{oe}^I to be much greater than the stiffness matrix of its force-torque sensor construction C_w^I.

Thus, if the mentioned above requirements are satisfied, then one of the aspects for efficiency of the proposed approach to the organization of remote control over space manipulator is satisfied.

4 Methods of SR programmed trajectory correction

Another aspect to achieve sufficient efficiency of suggested approach to the organization of remote control over SR consists in solving the problem of SR erroneous actions elimination. These errors may be caused by "non-ideal" SR ground model the model of its external environment. This "non-ideality" is caused by probable differences of real objects positions in coordinate system of robot trunk from positions of their models. To minimize this effect during operation the control over robot should be constructed so that the position of robot operation tool relative to object of external environment, that the robot interacts with, to be identical to the position of full-scale tool model relative to object model. In case of interaction between operation tool and object, such as a gripper and a rod movable in hole, the "forces" of interaction must be identical. The information mentioned above on relative position and force of interaction between operation tool and object which is presented as a function of time is a "passport" of operation and gives a complete concept of it. With this purpose the movement of control arm by human operator allows forming data to determine the position of operation tool relative to external environment object, as well as force and torque vectors of interaction between operation tool and object model. These data must be generated by processing of relevant information obtained from various sensors of robot model (sensory images). These sensory images can be presented by position vectors of some characteristic points of external environment in coordinate system associated with manipulator operation tool, as well as vectors of forces and constraint reaction torques occurring during movement of external environment objects by operation tool.

A possible approach to correction is based on images obtained by "pair" of CCD cameras associated with full-scale model of operation tool (Fig. 4), in other words by so-called reference points. At least three such points are extracted from the image of external environment model in the vicinity of full-scale operation tool model with the help of special software tools included in software of simulator interface.

Two-dimensional vectors of images positions of reference points on perceivable surfaces of each CCD cameras are the values proportional to projections of reference points vectors on the plane x_1, O, x_2 formed by coordinate axes x_1, x_2 of coordinate system associated with the full-scale model of operation tool. Position vectors of the i-th reference point obtained by the first and second CCD cameras are denoted as $x^i_{p.t.}$ and $\bar{x}^i_{p.t.}$, respectively. These values must be transferred from the ground control center to the local space manipulator control system and used to calculate the values of correction vector ΔX^M to the position of its operation tool of space manipulator.

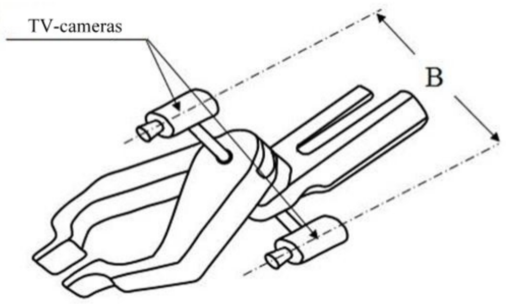

Figure 4: Possible location of CCD cameras on operation tool model

To find an expression to calculate the correction ΔX_r^I mentioned above to the programmed vector X_r^I the formulas of optical transformation shoud be used. These formulas assosiate two-dimensional vectors $x^i_{p.t.}, \bar{x}^i_{p.t.}, x^i, \bar{x}^i$ with the vectors of reference points positions in modeled $x^i_{p.t.}$ and real $X^{(i)}$ external environments of the simulator and space robot, respectively [4-6].

The essence of these formulas is easy to understand with the help of Fig. 5. This illustrates an optical conversion for one of two TV-cameras located on operation tool of space manipulator.

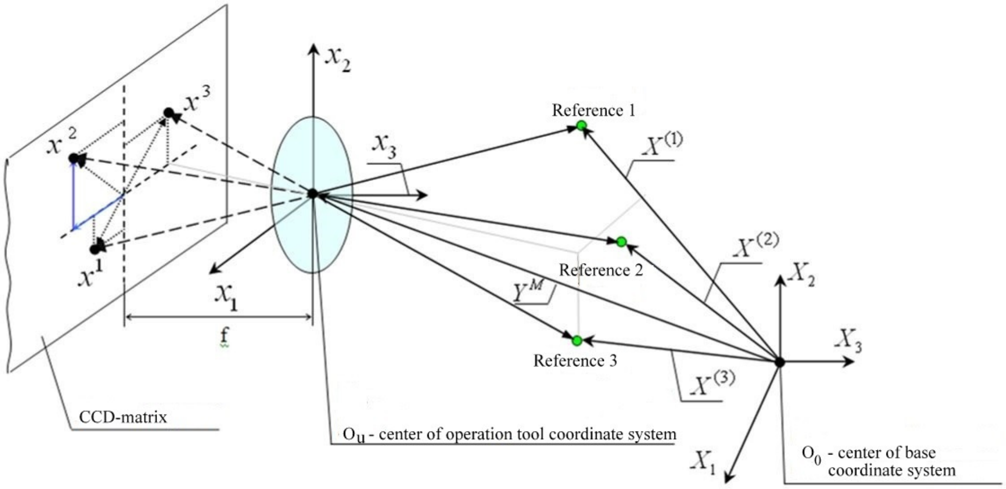

Figure 5: Formation of reference points images

The process of remote control can be performed in two ways: incrementl and continuous ones. An incremental approach is more appropriate to be used for very important operations, as well as in cases of uncertainty about simulation correctness of real external environment of controlled space manipulator.

This way has the form of a sequence of steps, which the motion of manipulator stops between. On each step a small piece of programmed trajectory is tested. Then if the real sensor image is different from the modeled one, manipulator position is corrected.

The approach of continuous control does not involve stopping of manipulator motion. The time duration of the "step" mentioned above is reduced to a value at which the generated output PTC data on programmed trajectory of operation tools position vector and the value of constraint reaction force are perceived by the local SR control system as analog quantities. An operational buffer of PTC must be loaded with all input data required to perform the desired operation. The input data involes a formed by GMSCSM programmed trajectory X_r^I and model and real sensory images of interaction between manipulator operation tool and objects of external environment. It is also reasonable to make some changes in processing of this data to obtain a correction signal. At the "incremental" control this data is recalculated by the corrector to the correction of program trajectory considered in local control system, while at "continuous" control only data on visual sensory images is recalculated: modeled and real one. Force modeled sensory image CC01 is programmed itself.

On Fig. 3 there is a block diagram of CLCSR with controlled by it SR model. This block diagram is similar with a block diagram of LCSR with controlled SR model. Fig. 3 illustrates this difference in methods of input data processing. At the "incremental" control mode all the data obtained by GMSCSM on programmed trajectory X_r^I and visual (BC01) and force (CC01) sensory images, as well as on analogical images BC02 and CC02 is recalculated for the new corrected programmed trajectory. BC02 and CC02 are generated by sensors installed on a physical model of SR operation tool.

At the "continuous" control mode CC01 is not getting to PTC, which is shown on Fig. 3 with a pecked line. CC01 is a programmed value itself and is compared with the current value of CC02 formed by wrist force-torque sensor.

In this case control system over SR drives that is servo control system with proportional control law "by position" turns into a so-called hybrid control system [11, 12] registering as a position as an interaction force. Control law of the hybrid system is following:

$U^{II} = (J_r^I)^T k_{pf}(E = p^T p)(X_r^I - X_r^{II}) + (J_r^{II}) k_G p^T p(G_d^{III} - G^{III})$ for CLCSR and $U^M = (J_r^I)^T (E - p^T p)(X_r^I - X_r^M) + (J_r^{II})^T p^T p(G^{III} - G^M)$ for LCSR.

G_d^{III} and G^{III} are programmed (desired) and current forces of interaction between physical model of operation tool and model of environmental object having a mechanical constraint; G_d^{III} is formed by GMSCSM in the process of training a required operation by SR and G^{III} is formed when performing this operation by CLCSR; G^M is a vector of force and moment of interaction between SR gripper and environmental object having a mechanical constraint; X_r^I is a programmed trajectory of changing in time of SR operation tool position or of its model obtained by PTC.

Experiments carried out on a computer model showed that transfer processes during incremental perturbations damp for this control systems, though the quality of these process is not high.

5 Conclusion

These fundamental results make this possible to successfully construct a real full-time sample of the simulator interface, though the construction implies a number of difficult engineering problems to be solved. However, it is reasonable to construct such a device, in spite of significant intellectual and financial costs, because the various modifications of the simulator interface will be needed to control robots operating not only in space, but also in other extreme environments [20-22].

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