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SYSTEM FOR CAPTURE OF NON-COOPERATIVE SPACECRAFT

System for Capture of Non-cooperative Spacecraft.

Analysis and design

- Overview of existing and prospective systems of capture and docking
- Justification of methods and means to solve the problem of capture and docking
- Components of the system
- System operation modes and their duration
- System dimensions
- Energy consumption and weight of the component devices
- Requirements for ground-based processing, control and simulation system
- Timing of the system development
- System design and manufacturing costs

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The Monography contains an overview of mechanical gripper systems to make a cooperative connection between spacecraft and Rocket. The middle of the Monography presents some ideas regarding the scenario of the capture of no-cooperative spacecraft. At the end of it - the main parts of the gripper have been described. Also, there are some roadmaps to design it based on the overviewed practices.

Proceedings has been prepared by a team of authors consisting of PhD Dmytro Humennyi, Doctor of technical science, Professor Yurii Khlaponin, Doctor of technical science, Ing., Associate Professor Marek Aleksander.

The text of the monograph was prepared using materials of the open press on the experience of foreign countries and Ukraine. For specialists involved in the development, creation and operation of spacecraft, it can also be recommended to graduate students and undergraduates.

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Content

A list of conventions, symbols, units, abbreviations and terms

CM	Center of mass
CR	Carrier rocket
CS	Control system
CSC	Customer's spacecraft
DP	Docking Port
GDS	Gripping and docking system
PID controller	Proportional integral-differential controller
MGS	Mechanical gripping system
RM	Robot-manipulator
RMS	Robotic manipulation system
RS	Robotic system
SS	Service spacecraft

1. Introduction

Intensification of near-Earth space utilization brings forward the problem of building service spacecraft (SS) designed for transportation of client spacecraft (CSC) to other orbits in order to extend their service life or to safely free up advantageous orbital positions for other spacecraft.

This paper discusses the concept of building a SS equipped with a multi-purpose robotic arm (RM) to capture the CSC, bring it close to the CSC, hold it during transportation, and separate the two vehicles to a safe distance at the end of transportation.

Considering a great variety of potential CSC designs, and often the absence of standard structural units for its capture, uncertainty of parameters of its initial movement, the RM must have a developed kinematic scheme and be equipped with a universal executive device (effector), which together will provide a successful solution to the problems of manipulation.

A comparative analysis of several variants of the kinematic scheme of the RM: with one arm, with two arms, with an additional telescopic boom. The analysis was carried out according to the criteria of design complexity, maximum drive moments and total power consumption.

Based on the selected kinematic structure, the dynamic behavior of the RM, the list of typical orbital service tasks, the structure of the RM control system was proposed, which solves the following tasks:

- deploying RM from the transport state;
- introducing an RM into a working zone;
- bringing the operating body of the spacecraft closer to the points of SS pickup;
- gripping and holding the spacecraft without damaging it;
    - extinguishing of oscillation processes when matching the moments and velocities of the client and base vehicles. The paper also shows the main characteristics of the RMS operation scenario. Its mass, dimensional and energy characteristics and properties are defined. Requirements for ground equipment are described.

2. Overview of existing and prospective systems of capture and docking

Nowadays the problem of ensuring the capture and docking with unguided spacecraft is a complex scientific and technological task, the solution of which provides the technical possibility of a number of complex service operations. The relevance of this question is the economic feasibility, which is to create opportunities for the continuation of the spacecraft operation (up to its delivery to stationary orbits).

The existence of a practical experience, which confirms the use of capture and docking systems (GDS) with unguided spacecraft in automatic or automated mode today does not exist, despite the fact that this is a promising direction for such operations. All known facts of docking were performed in manual mode, ABL in telecontrol mode and were performed directly by a cosmonaut (astronaut).

The complexity of automatic or automated execution of the seizure and docking operation with an unguided CSC is related to groups of factors

- generated by the structure and condition of the spacecraft;
- related to the characteristics of the spacecraft;
- related to the ground control systems;
- related to the state and characteristics of GDS.

Difficulties in automating the docking process associated with spacecraft are determined by the following factors:

1. Lack of a single standard docking system on the spacecraft (respectively, and standard tags or beacons that characterize the suitability of a point on the spacecraft to perform a capture).
2. The error in the data about the position of the spacecraft center of mass point (CM), which is given by the working body flow rate, the complex error in the location of the peripheral equipment of the spacecraft, etc.
3. Limited working area of GDS, which is associated with the presence of peripheral offsite systems of spacecraft.

Difficulties of automation of the docking process, associated with SS, are determined by the following factors:

1. The error of relative positioning of CSC and SS, which contains a dynamic component and cannot be eliminated by the control systems (CS) of CSC and SS.
2. Limitations of linear distance (with the condition "not less than..."), time (with the condition "not more than...") and energy consumption (with the condition "not more than...") are imposed on performing the operation of capture and docking in that the specified parameters are interrelated.
3. Presence of torsion between CSC and SS.
4. Limited data about the type and location of the gripping point on the CSC relative to the SS.
5. Existing limitations of the GDS working area, related to the design features of the SS.

Difficulties in automating the docking process associated with ground-based GDS:

1. The need to develop complex hardware, and software algorithms that provide control of the GDS in automatic and automated control modes, as well as telecontrol with functions:
    a. simulation of gripping and docking processes;
    b. reorganization of the standard algorithms in the GDS functioning.
2. Necessity to provide video broadcasting of control commands, system reactions and data from complex sensors (video cameras, angle sensors, torsion sensors, current sensors, end sensors, pressure sensors, and automatic CS monitoring systems).
3. The need to build the ground complex: to provide tolerable training, which is aimed at practicing the scenarios of the system operation. The conditions of this process must be approximated to the real operation (including the available typical capture and docking points).

Difficulties of automating the docking process, associated with the development of GDS:

1. Choosing the concept of capturing and docking an unguided spacecraft with a predetermined type of capture point.
2. Solving the problem of the effector positioning error, which occurs due to the transient oscillatory process in the GDS design.
3. Elimination of the problem in the deployment (holding) of the GDS during the stages of transportation, entry into the working zone, and the movement of the spacecraft.
4. Compensation fora mismatch between the CSC and the SS with the help of means, which are available in the GDS.

The tasks listed above characterize the main problems in the development of GDS with unguided CSC, which are not typical in the construction of such systems. Despite the fact that the factors associated with CSC and SS are not solvable, their manifestations must be compensated by GDS.

2.1 Analysis of technical inspections of a completed robotic system (RS) design for grabbing and docking system

Authors Angel Flores-Abad [1], Ou Ma [2], Khanh Pham [3], Steve Ulrich [4], S. Ali A. Moosavian [5], Evangelos Papadopoulos [6], Bryan Patrick McCarthy [7], Alvar Saenz-Otero [8], David W. Miller [9] analyzed the kinematic, dynamic and structural characteristics of the SPC as of 2014. According to the analysis of the reports, the concept of using a robotic manipulation system (RMS) as a GDS originated in 1980.

2.2 Analysis of the Orbital Service Solution Set

The paper "Autonomous rendezvous and robotic capturing of a non-cooperative target in space" by Wenfu Xu, Bin Liang, Cheng Li, Yangsheng Xu [10] described the technologies of autonomous rendezvous and robotic capturing of a non-cooperative target, method of mathematical model construction and RM design.

Target and pose recognition (position and attitude), stereovision-based measurement, guidance, navigation and control were considered. The measurement algorithm includes image filtering, edge detection, line extraction, and stereo-matching. Based on the measured values, the computers determine a convergence algorithm that was designed to pursue, approach, and converge on the target. Then the algorithm, which proved advantageous over the traditional detached method, was used to plan and track the P base trajectory. A 3D simulation system was developed to evaluate the proposed method. The simulation results are verified by appropriate algorithms.

The paper "Motion Planning for the On-orbit Grasping of a Non-cooperative Target Satellite with Collision Avoidance" by the author R. Lampariello [11] described a method of capturing a moving non-cooperative target, which is based on nonlinear optimization and collision avoidance. The constraints on the angular parameters of the links of the work, as well as on the effector, are described. The paper describes a method for trimming scenarios of system behavior.

2.3 Overview and analysis of typical interface designs and adapters for potential client vehicles

The vast majority of spacecraft currently in operation does not have a uniform standard for the attachment elements, support structure locations, and labels that are needed to indicate the allowable hard grip point. Generalized variants of rigid mechanical gripping can be: nozzle and inner cavity of apogee engine, the interface of CSC attachment with carrier rocket (CR) (in most cases with application of adapter part), bracket of peripheral equipment attachment (antenna, solar panels). Of the options listed above, the CSC mounting interface is mandatory. Regardless of the type of interface available on the CSC, the appropriate adapter is used to attach the CSC to the CR. Moreover, the most common adaptations are interfaces 937, 1194, 1663, 1666, and 2624. Application of adapters like PAS 937 S (C), and PAS 1194 VS (C) provides for the existing design feature, viz:

- the typical cone design of the CSC mount (Figure 2.1);

- an appropriate interface plane between the CSC and adapter, which is equipped with a slot lock with the characteristics given in Table 2.1.

Table 2.1.

PAS, type:	937 S	937 C	1194 VS	1194 C
Length (мм)	25			
Inertia (xx)	11700 <Ixx< 69000	11700 <Ixx< 69000	12000 <Ixx< 65000	12000 <Ixx< 65000
Inertia (yy)	7480 <Iyy< 12650	7480 <Iyy< 12650	7500 <Iyy< 25000	7500 <Iyy< 25000
Material	Aluminum alloy			

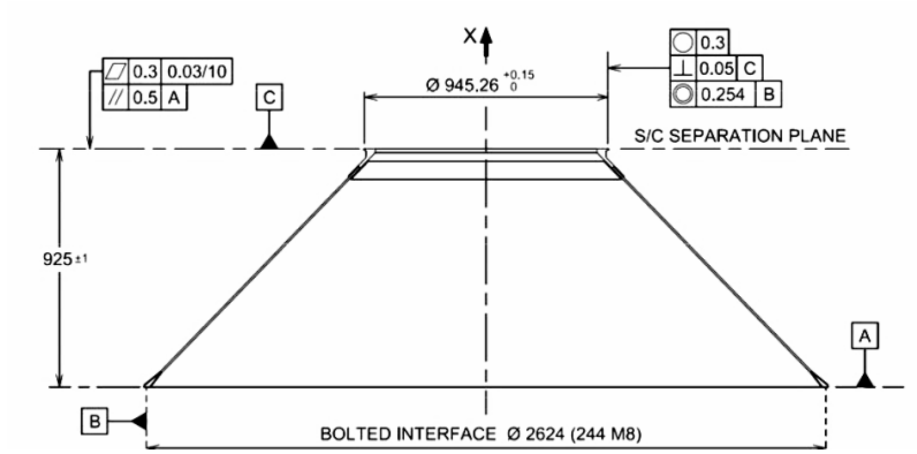


Figure 2.1 - Tapered design of the PAS 937 C (VC) adapter with pronounced radial groove area (Separate plane)

A system of locks consisting of grooves (Figure 2.2) is used to bring the spacecraft closer and bind it to the adapter, while a system of springs and pistons is used to disconnect it. As a generalized method of capturing the spacecraft proportionally modified delivery system of these locks and disconnection systems, the lock system shown in Figure 2.3 is prioritized.

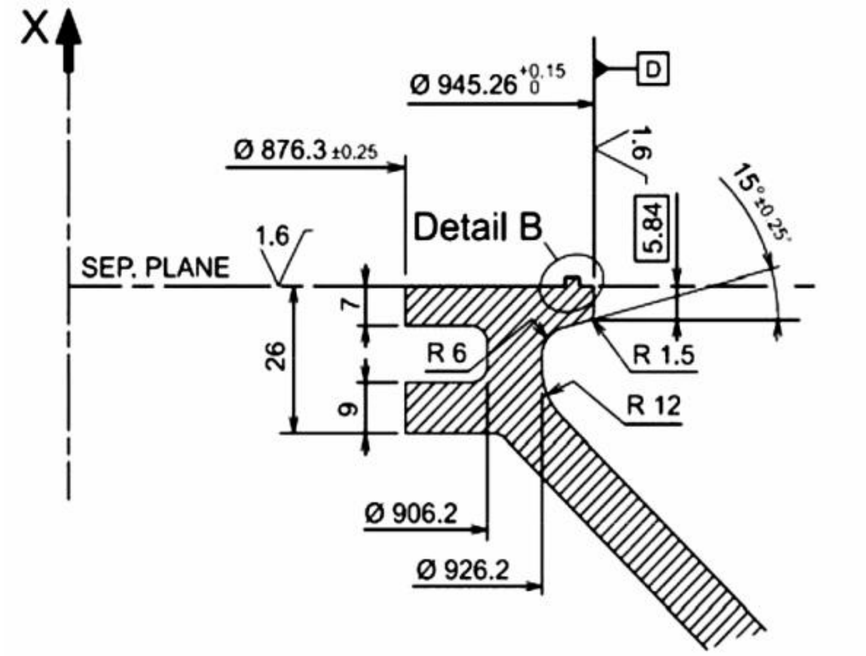


Figure 2.2 - Typical scheme of locks used to bind interfaces 947 and 1194 with corresponding adapters like PAS 937 S (C) and PAS 1194 VS ©

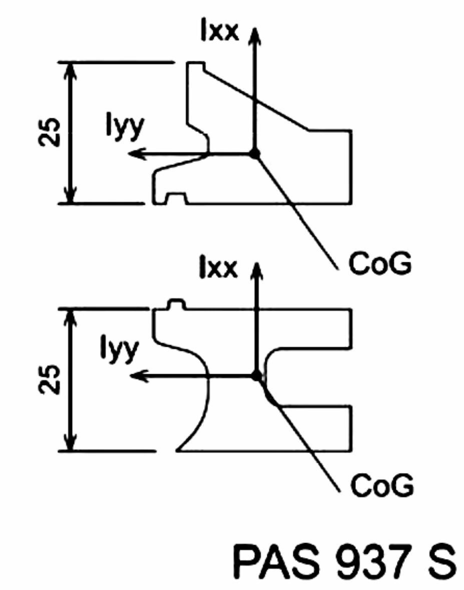


Figure 2.3 - Typical diagram of locks used to bind interfaces 947 and 1194 with the corresponding adapters of types PAS 937 S (C) and PAS937 S

Radial placement of locks (Figure 2.4) will stimulate holding the CSC and CR in the process of spacecraft moving by means of SS.

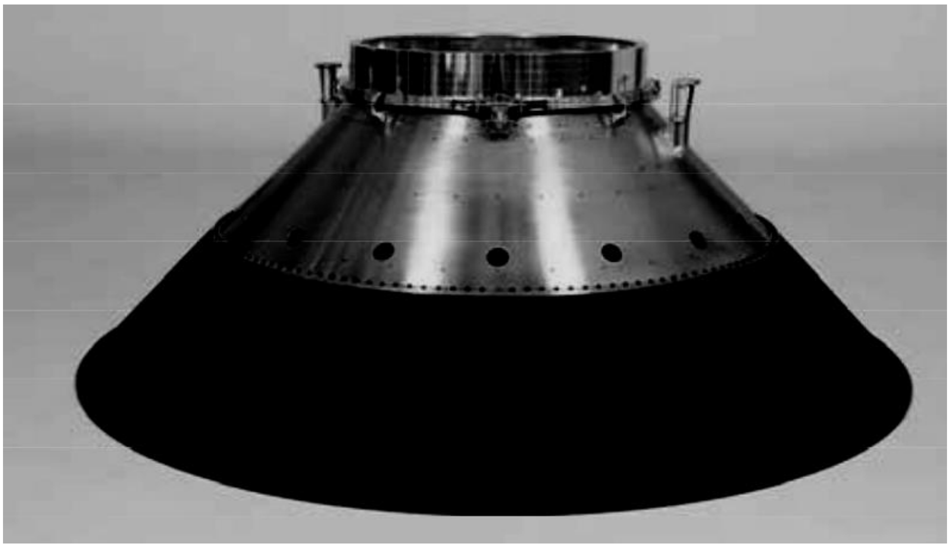


Figure 2.4 - Adapter type PAS 937 S with radial locks

According to PAS 937 S (Figure 2.4), the adapter PAS 937 C (Figure 2.5) has a cone-shaped design and the locks are arranged radially and have the gripping system shown in Figure 2.6.

Figure 2.5 - Adapter type PAS 937 C with radial locks

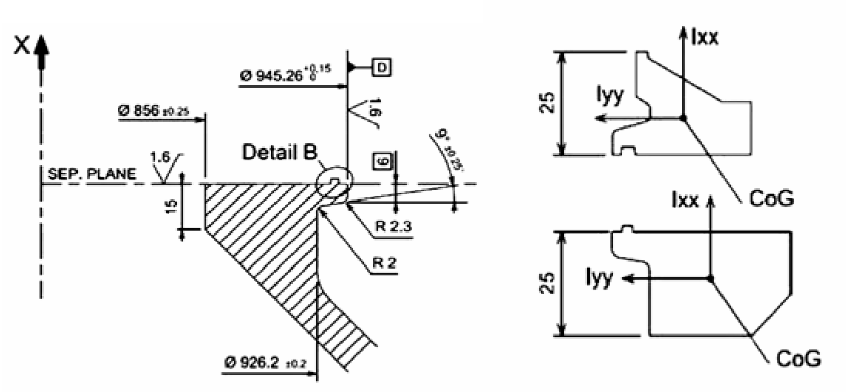
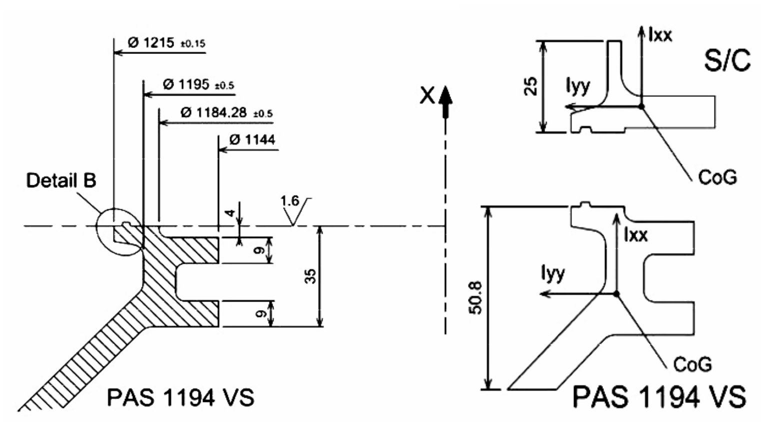
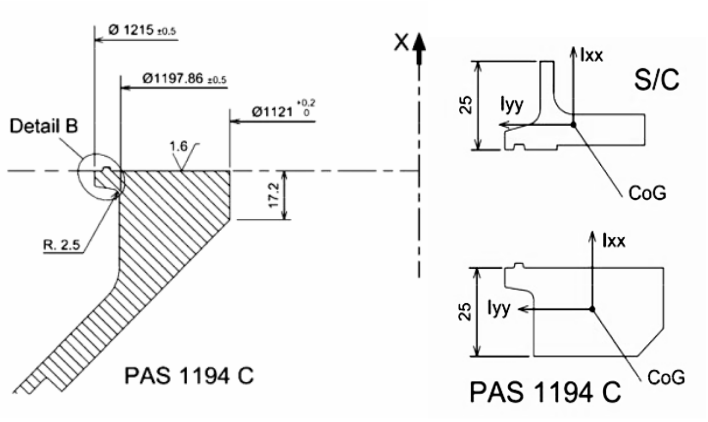


Figure 2.6 - Adapter locking system type PAS 937 C

Corresponding to the designs of the PAS 937 C (S), PAS 1194 VS (C) devices have a conical structure and are characterized by a larger interface diameter. The locking system of the adapters is shown in Figure 2.7.



a)



б)

Figure 2.7 - Design of PAS 1194 VS (a) and PAS 1194 C (b) locks

In accordance with the drawings shown in Figures 2.1, 2.2, 2.6, 2.7, it can be seen that on the side of the SS interface, the adapter has an identical structure, which is expressed:

- in the presence of slot Detail B, Figures 2.7, a, b;
- in the presence of a flange on the outer side of the adapter.

The use of these design features makes it possible to develop a strategy in determining the kinematic and design diagrams of the effector SPC for satellites with mechanical communication interfaces such as PAS 1194 VS, C, PAS 947 S, C.

But adapters of PAS 1663, and PAS 1666 MVS (S) type have a cylindrical structure. Attachment of the spacecraft to the adapter is carried out by means of the appropriate interface. The adapter optionally allows the use of interfaces such as ACY 1780. Unlike aluminum adapters (PAS 1194 VS, C, PAS 947 S, C) the adapter PAS 1663 is made of plastic, carbon and aluminum. The general view of the design is shown in Figure 2.8a, b.

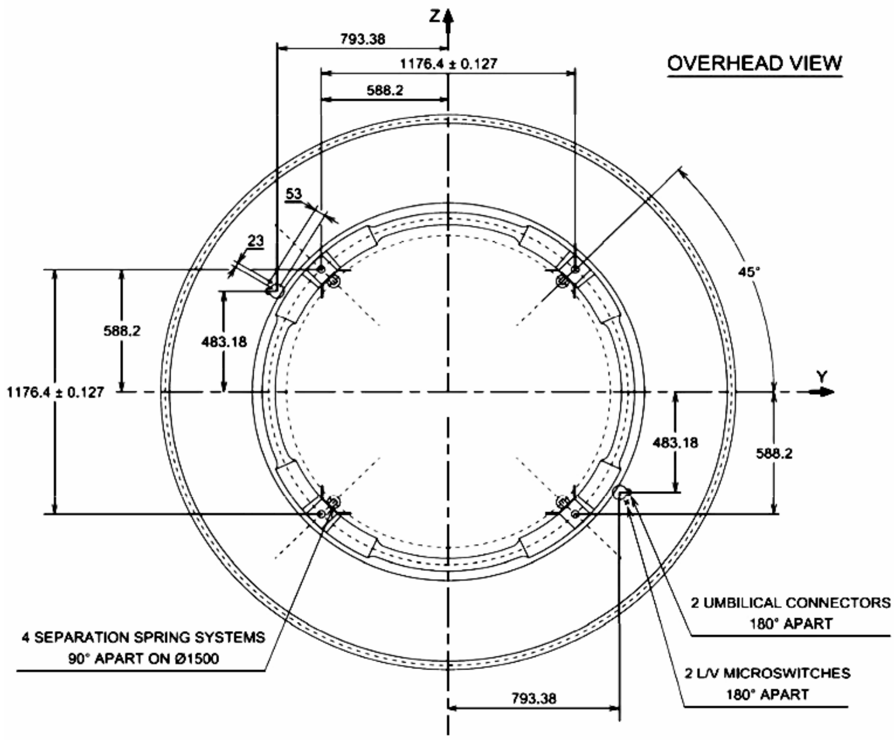


Figure 2.8 a - General view of the adapter PAS 1663 (top view)

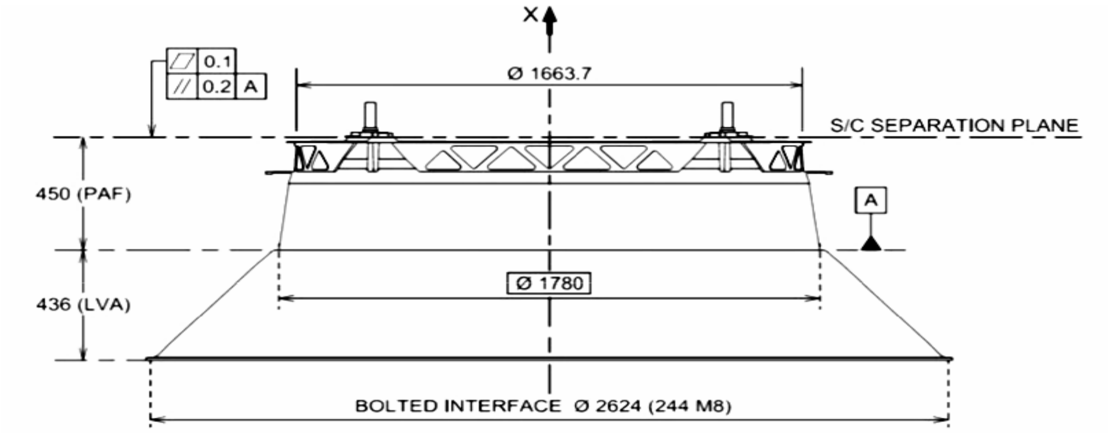


Figure 2.9b - General view of the adapter PAS 1663 (side view)

CSC detachment is carried out with the help of spring system (Figure 2.9 a, b). On the side of the CSC the fastening elements are four radially arranged bolt connections (Figure 2.8), further use of which for the purpose of gripping and docking is complicated.

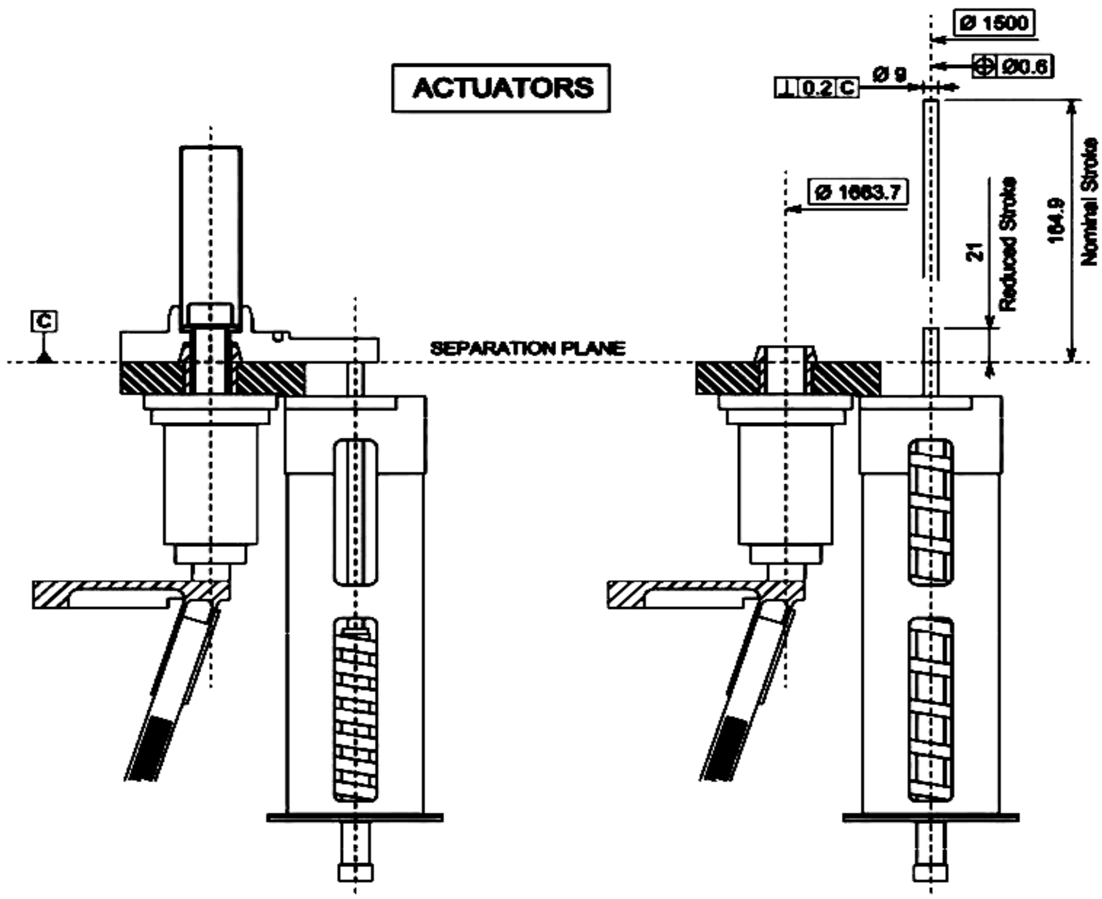


Figure 2.9 - Spring-loaded system of the spacecraft interface withdrawal from the PAS 1663.adapter

The PAS 1666 MVS adapter has a combined cone-cylindrical structure and like the PAS 937 C (S), PAS 1194 VS (C) is equipped with a locking system for holding the SS. The general view of the adapter is shown in Figure 2.10.

The lock design is shown in Figure 2.10 and a typical retention pattern is shown in Figure 2.11.

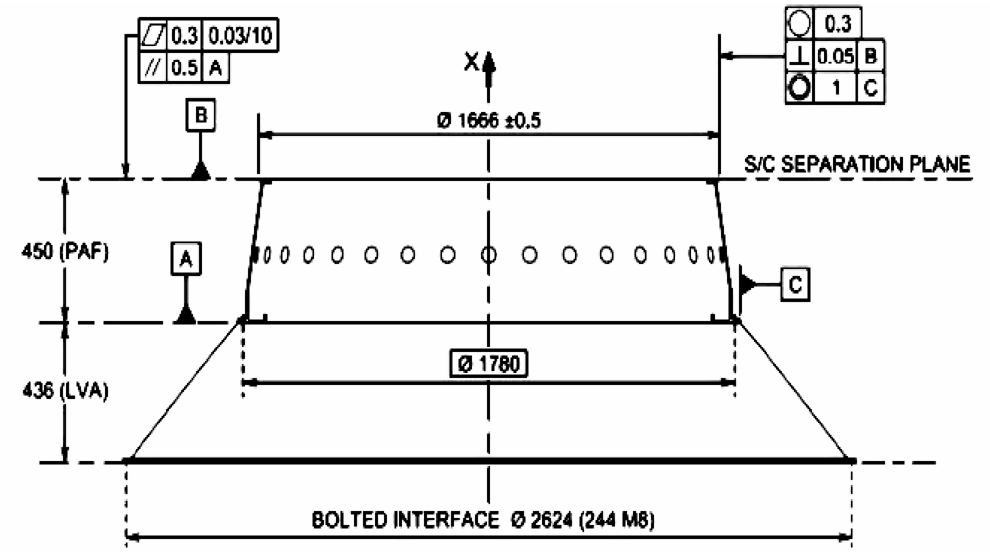


Figure 2.10 - General view of the PAS 1666 MVS adapter with locking system ofCSC maintenance

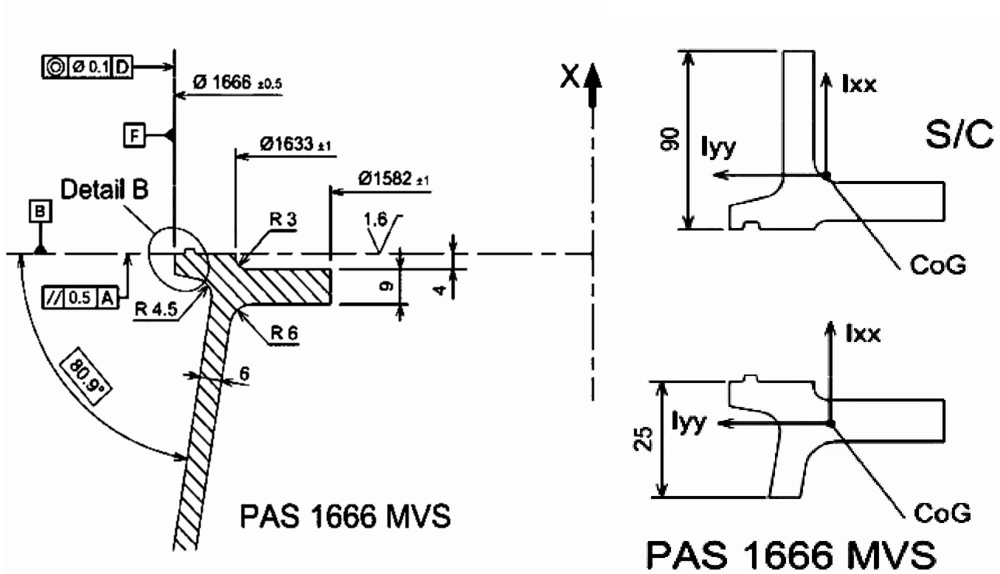


Figure 2.11 - Design of the slot lock of the PAS 1666 MVS adapter and D2624 interface

The general characteristics of the adapter are discussed in Table 2.2.

Based on the characteristics of PAS adapters (937 C, 937 S, 1194 VS, 1194 C, 1663, 1666 MVS) and corresponding interfaces with diameters 937, 1194, 1666, 2624, the possibility to assume the design feasibility of the gripping and docking system effector becomes real. It will function accordingly to the slot lock system of the PAS adapters (937 C, 937 S, 1194 VS, 1194 C, 1666 MVS).

Table 2.2

PAS, type	1666 MVS
Length (мм)	90
Inertia (xx)	191649±15%
Inertia (yy)	988604±15%
Material	Aluminum alloy

Kinematic scheme of the effector must provide a sufficient number of touch points of CSC interface. Dynamic characteristics should be within the limits of Tables 2.1, 2.2 (according to the output data). Based on the effector's design features, according to the specified conditions of stiffness accuracy and compression force, the interface is captured. The effector is brought to the interface by the console, the kinematic, structural and dynamic characteristics of which are set further in the text. The effector's sensor system is designed to display the qualitative characteristics of gripping and holding, and to record errors in the gripping, holding, and disengaging states. The design and specification of CSC interfaces impose restrictions on the construction and operation principle of the GDS. The polymorphic nature of the interface implies a complex effector device, which is designed according to the locks of the interface. The range of placed locks (937-2624 mm) characterizes the linear dimensions of the effector part of the capture and docking system.

Despite the limitations of inertia, the effector approach to the CSC interface requires a thorough analysis and selection.

The unsteady error of mutual positioning of the SS relative to the CSC during uncontrolled approach, capture and docking of spacecraft makes it impossible to use the adaptor design of the GDS. The presence of six degrees of relative mobility between the CSC and SS sets design requirements to the console of the GDS. The requirements regarding the minimum approach distance (between CSC and the SS) determine the mass-dimensional and energy limitations that characterize this system.

In order to meet the above conditions, the GDS design must have at least six degrees of mobility, which is set by the articulated joints. It should be said that the articulated joints themselves must form kinematic chains of links, the total length of which must meet the requirements of the minimum size of convergence of CSC and SS, described in the "Terms of Reference", "Technical requirements" and decisions that are made at the meetings of working groups.

Summarizing the above requirements, it can be argued that the GDS is a RM, consisting of consoles, effectors and auxiliary systems (the bases of the cantilevers are placed on the rigid structural elements of the SS).

The development of fundamental and practical robotic gripping and manipulation systems (including for docking tasks) in space conditions takes place in working groups, the composition of which is given in Appendix A.

2.4 Analysis of mathematical, software algorithmic, and technological solutions for building orbital service robotic manipulators

In "Motion Planning for Vibration Reducing of Free-floating Redundant Manipulators Based on Hybrid Optimization Approach" by LIAO Yihuan, LI Daokui, TANG Guojin [12], a fundamental study on analyzing and calculating the dynamic behavior of GDS under vibrational transients was conducted. A multilink system of solids connected by appropriate joints was chosen as the kinematic scheme of the GDS.

In this case, the GDS forms the structure of an anthropomorphic RM with four degrees of mobility. The client apparatus and service apparatus are represented by objects with given CM coordinates. The analytical model of the GDS is described by the Lagrange equations for the second-order equation, which makes it possible to take into account all three characteristics of motion. To analyze the vibration behavior, a breakdown of the vibration in three planes is used. The phase and amplitude of the vibration given by the Euler angle and two generalized force parameters. The paper considers the method of minimizing the amplitude of the oscillatory process through the correction of the input parameters of the PM control. To model and analyze the results obtained by the authors, an analytical experiment with a four-parameter PM, whose linear vibration characteristics were reduced by 30% compared to the controlled PM (without compensation for the vibration dynamic component), is proposed.

Application of the proposed (or similar) method of compensation control makes it possible to reduce the amplitude of oscillation of the PM console when bringing it to a given point of space. However, based on the experiment conducted by the authors, application of the method will lead to increase of time characteristic of transient process use (Figure 2.12).

In the paper "5-DOF Manipulator Simulation based on MATLAB- Simulink methodology" the authors Velarde-Sanchez J. A., Rodriguez-Gutierrez S. A., Garcia-Valdovinos L. G., Pedraza-Ortega J. C. [13] presented the methodology of kinematic, dynamic modeling and graphical simulation of the GDS.

The kinematic diagram of the GDS is a robotic anthropomorphic manipulation system. The methodology is based on the application of software tools Matlab, MatLAB-Simulink, Cpp, and OpenGL. The work shows the application of Real-Time control of real RM by means of a universal computer. The industrial ground-based RM Catalist-5 was chosen as a control object.

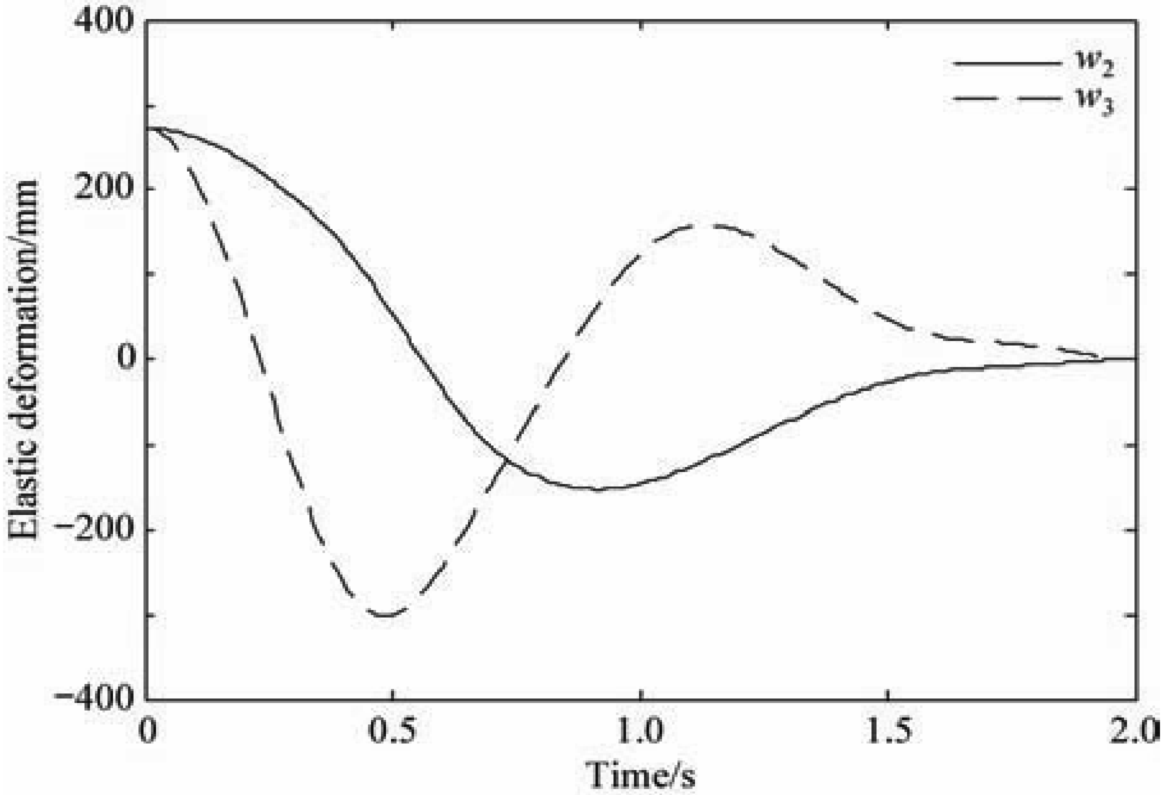


Figure 2.12 - Functional dependence between the amplitude and travel time of the transient damping using the method proposed in the paper

The compliance of the computer model of kinematics and dynamic behavior with the physical characteristics and properties of the RM Catalist is ensured by the accuracy of model description: the length of links, the location of TCM of each of the links, the structure of hinges, the characteristic of drives and the typing of feedback system. Simulation of the RM characteristics is defined by the Simulink functions (Fig. 2.13), and visualization is provided by the built-in Simulink functions and three-dimensional systems' editor tools AutoSSD, SolidWorks, and Kompas 3D.

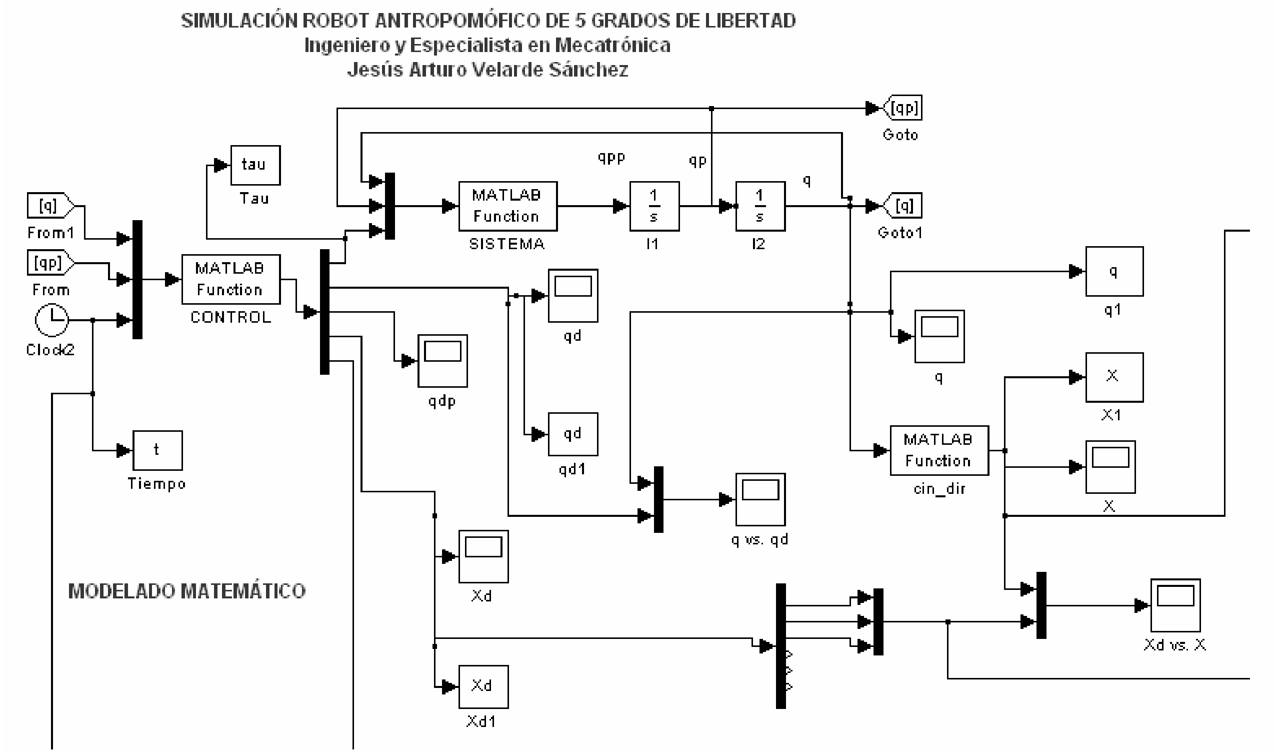


Figure 2.13 - RM model in MatLAB Simulink environment

Thus, the accuracy of model reproduction can be high. The reproduction position error of RM is given by forces and moments, which cannot be read out and transferred to the model by real Catalist RM. However, the use of similar method for modeling of space application RM can have more accurate description. The proposed method finds its reflection in declared methods of MathWorks corporation "PIL" and "HIL". The use of these techniques as a complementary method of GDS control allows modifying the existing RM control system in out-of-step situations. Among the disadvantages of the system are its superdimensional complexity (the need for a controlling universal computer arises) and the presence of a lag in the control process. Visualization, which finds its application in the method, allows us to effectively implement the proposed technology in the construction of ground-based methods of diagnostics and analysis of RM behavior.

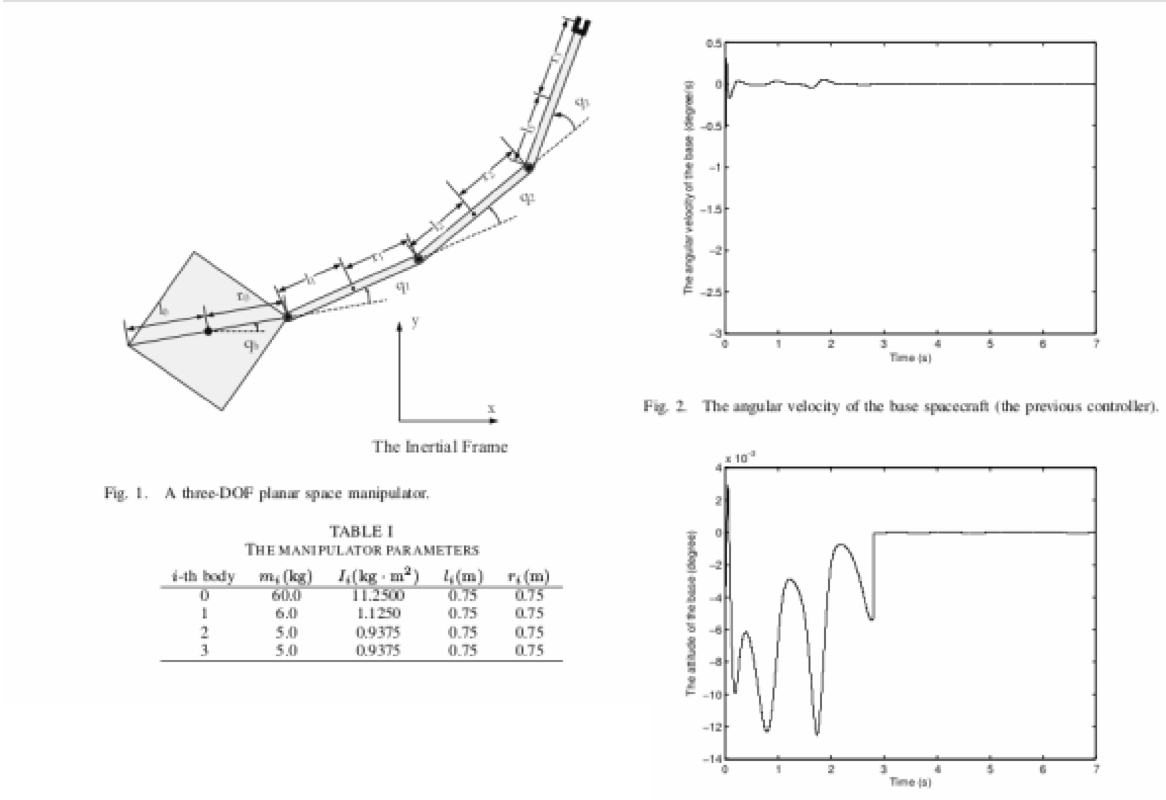
The paper "Methods of control of space robots" by V. P. Makarychev [14] proposes a structure of telecontrol and control with elements of artificial intelligence on the example of analytical model of space RM, which has characteristics close to the characteristics of RM of space systems ISS and "Buran". The author considers the application of automated RM control systems using control scenarios, and the application of the control console of the robot is disclosed. The analytical model, which is presented in the paper, is a system of second-order differential equations disclosing moments for a dynamic system with six degrees of freedom. The model of the position of the links is presented in general form. The analytical form of the drive model proposed in the paper characterizes the RM drive as a DC motor with an independent start. The drive is controlled by a digital control system of the H-bridge type (the control circuit is not presented in the work). A standard proportional integral differential regulator (PID regulator) is used to control the H-bridge circuit.

The author shows analytical methods for smoothing the impulse components of control, which can lead to the transition of the drive into "deep reversal mode". To solve this problem, it is proposed to apply an integrating link, and presented methods and algorithms for trajectory tracking are actually the distribution in power series of the Lagrange equation.

The use of the proposed methods of DC electric drive control is classical and can provide the lower program level of drive overload protection. Application of trajectory tracking methods is actually a decomposition of RM motion laws. Application of similar methods can take place when formalizing the state of RM under conditions of changing the scenario of its behavior.

In "Adaptive Reactionless Motion Control for Free-Floating Space Manipulators" the authors Shuanfeng Xu, Hanlei Wang, Duzhou Zhang, Baohua Yang [15] consider modeling of kinematic relations and dynamic behavior of an anthropomorphic RM with four links and three degrees of mobility. In this work, the emphasis is focused on the synthesis of analytical model of dynamics (?) for an orbital RM (using gliding methods of setting its working area).

It is worth to pay attention to the proposed methods of synthesis of the adaptive control unit, based on momentum control. Moreover, the dynamics of the RM is defined by its transfer function, described using the Laplace transform, based on the obtained results, the graphs of RM stabilization with parameters, which are given in Figure 2.14.



i-th body	m_i (kg)	I_i (kg · m^2)	l_i (m)	r_i (m)
0	60.0	11.2500	0.75	0.75
1	6.0	1.1250	0.75	0.75
2	5.0	0.9375	0.75	0.75
3	5.0	0.9375	0.75	0.75

Figure 2.14 - Kinematic diagram and parameters of the RM equipped with adaptive regulator

In the paper "Experimental Simulation of Manipulator Based Compliance" by Harry West, Norbert Hootsmans, Steven Dubowsky, Nathan Stelman [16] presented the development of a mathematical model of manipulation system to solve the problems of dynamics in the case where the PM base is located on a non-rigid basis (this case is observed at uncontrolled docking of SS and CSC). Authors show the methods of solving the problem of positioning the effector in the case of various errors of the base point position.

The methods of RM positioning for two cases of its kinematics are considered:

- If the RM is characterized by a single degree of mobility;
- if the cases of degrees of mobility are generalized.

The method is based on the principles of tracking moments of a link related to the base point. While moments are expressed from the position of the CM of the link and the displacement of the selected frame (the group of points experiencing uncontrolled displacement). Taking into account the relative angles and moments that act in the body system and the action of gravity, a matrix transformation (matrix of guiding cosines) of the basic link position is formed. This link corresponds to the value of certain moments. Based on the method of recalculating the moments, which is presented in the publication, it becomes possible to determine the relative allocation of the base point. However, given that the calculations are performed with respect to the parameters of the gravity vector, the position of all links of the apparatus, the solution of the problem of finding the coordinates by the deviation of the base point has duality.

The second important result, which was obtained in this study, is to solve the problem of positioning the effector RM if the following conditions are satisfied:

- the base point positions can be unspecified;
- the effector approach point must be in the working area of the RM;
- the relative positions of the base point and the capture point may have one or two unknowns in the location.

The paper shows the simulation results of the described method on the basis of industrial RM PUMA.

In particular - these are the results of RM positioning in cases of available base point torque (figure 2.15).

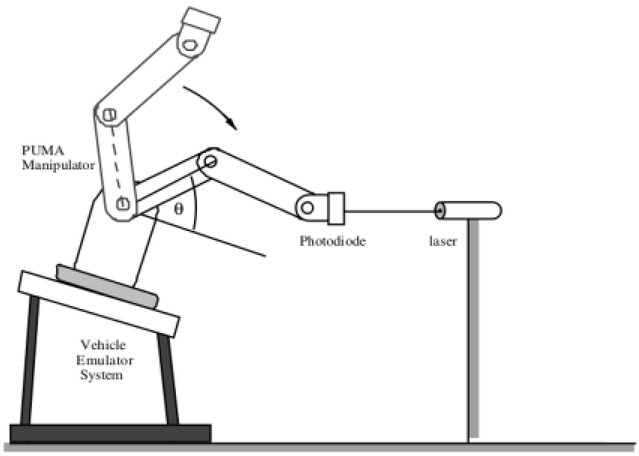


Figure 2.15 - Application of the effector positioning method in the case of a given location of the RM base point

Similar to the previous publication that we analyzed, the study "Parameter Identification of Free-Floating Robots with Flexible Appendages and Fuel Sloshing" by Wolfgang Rackl and Roberto Lampariello [17] presents the situation of compensatory control of the RM in the case when the base point of the robot is connected to a non-stationary body. Attention in this work is paid to the phenomenon when the base point of the RM has an oscillatory motion. Moreover, that this base point also has its own parameters of motion, known a priori (figure 2.16).

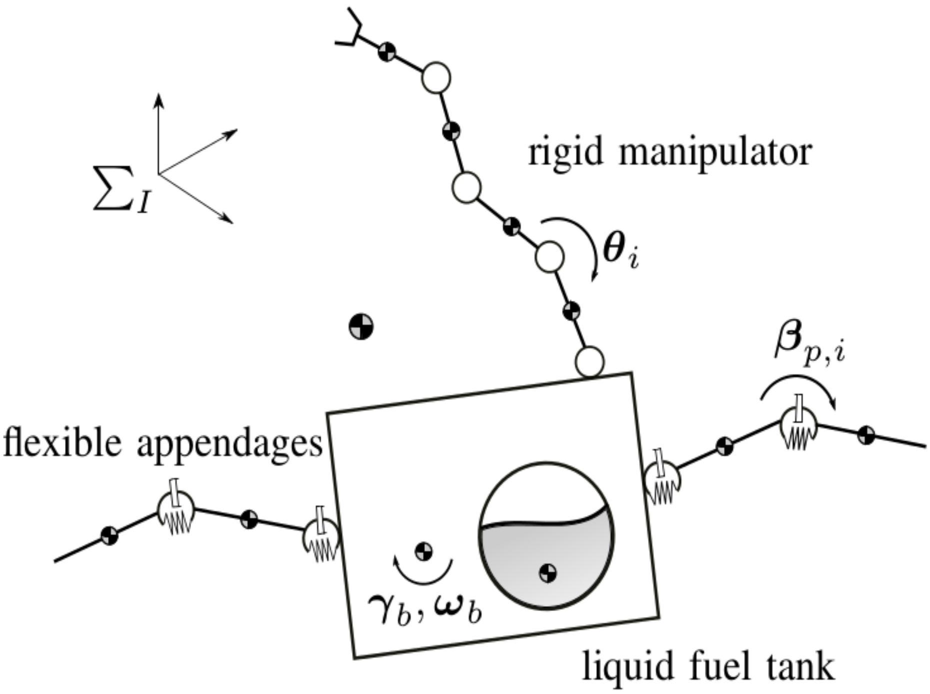


Figure 2.16 - Schematic representation of RM with stationary basic point and characteristic a priori - given motion

In contrast to the previous publication, in this source the given point positions are characterized by its linear and angular positions, linear and angular accelerations.

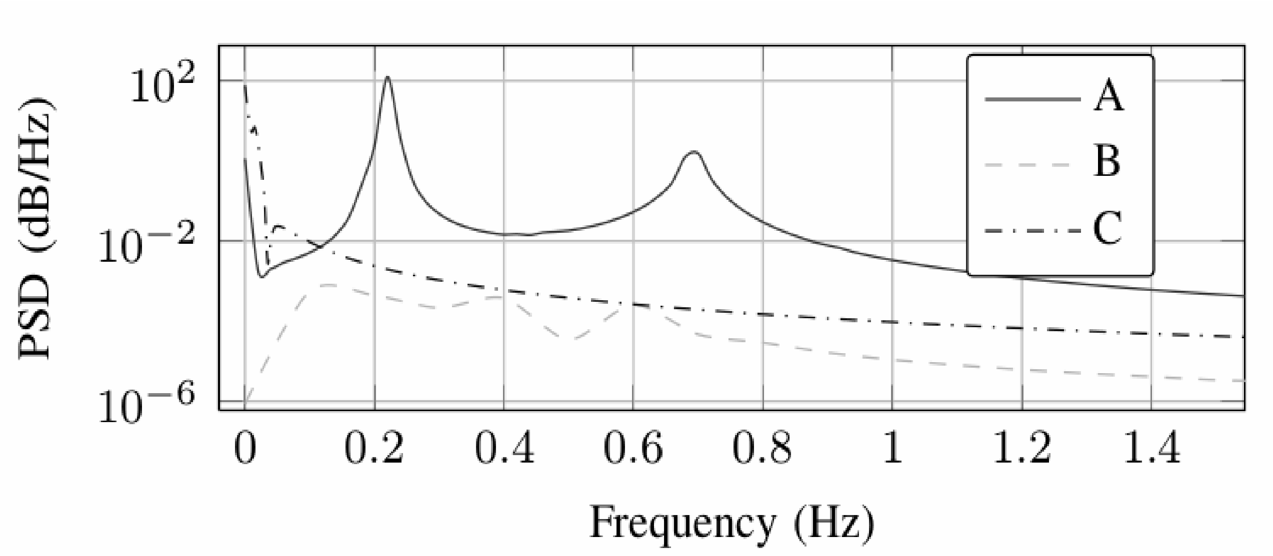
To formalize the object, n equations and m links are applied. The description of the turnover of the model bodies is given by the Lagrange differential equation for the equations of the second kind in matrix form.

We have also used methods of optimal control (nonlinear programming methods) to solve the trajectory optimization problem. Thus, the parameters of the oscillatory motion of the base point can be set in k-dimensional space, which allows to set arbitrary factors of compensatory influence on the control system of the RM.

As parameters of the control system, it is proposed to apply such characteristics:

- frequency of natural vibrations of the base point;
- tensor of inertia and location of the CM of the base point of the apparatus;
- matrix of stiffness characteristics of the RM;
- matrix of braking capabilities (inverse moments, which can be given by RM prepositions).

To verify the results of the hypothesis, the authors performed a mathematical computer simulation of the compensatory effects on the control system of the PM. To simulate the developed system of solids with seven degrees of mobility and the maximum removal of the RM console at a distance of 3 m. As a result of simulation the data of frequency simulation at different values of oscillation frequency were obtained (figure 2.17).



A - response to oscillatory influences,B - excitation trajectory in the vibrational mode,C - trajectory of reversal for the system of solid bodies.

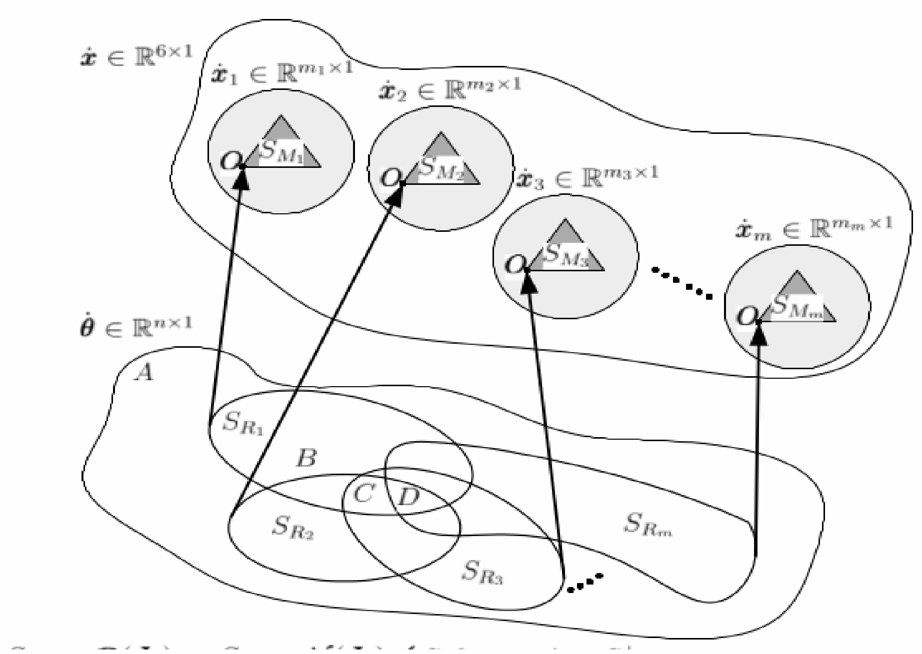
Figure 2.17 - Frequency analysis of oscillatory process of compensating influence on RM control system.

In the source "Kinematic Analysis of Free-Floating Redundant Space Manipulator based on Momentum Conservation" by the author Mingming Wang [18] considered the fundamental, classical methods of describing the kinematics of robotic manipulation systems. The outlined methods of formalized description were applied in a number of projects, including "Engineering Test Satellite VII (ETS- VII)" and "Orbital Express (OE)". The basic concepts of object suitability for manipulation are formulated. Characteristics of the degree of mobility and minimum characteristics of RM for service operations are introduced and justified.

The paper also shows variants of CR kinematics for equal situations of base point description, typing of manipulation object, etc.

One of the variants of the description of the direct kinematics problem is proposed to use the Jacobian matrix. It makes it possible to avoid the problem with degeneracy of matrices of guiding cosines and Euler's method.

A large part of the publication concerns the description of the variational position of the base point, in order to perform an equivalent service (Figure 2.18).



Sr - zones are suitable for performing a service over the Sm object,

B, C, D - cross-sections of the orbital service execution zones.

Figure 2.18 - The position invariant of the base point of the RM to perform an equivalent orbital service

The paper "New planar air-bearing microgravity simulator for verification of space robotics numerical simulations and control algorithms" by Tomasz Rybus, JanuszNicolau-Kukliński, Karol Seweryn et al. [19], show the construction of a model RM and a ground-based microgravity simulation system made in glider form. The authors proposed the development of a two-link anthropomorphic RM with single-stage rotary joints and an unloading system based on the air cushion effect.

Here you can also see the development of an electric drive for angular movement of the links, based on a DC motor, reduction unit, decoder, housing (figure 2.18) and digital control system (figure 2.19).

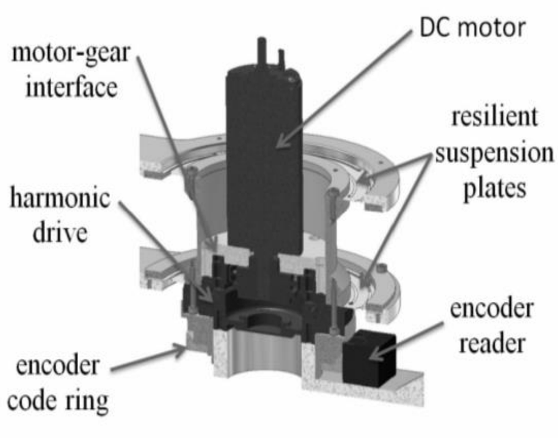


Figure 2.18 - Electric actuator of angular movement Lanco RM

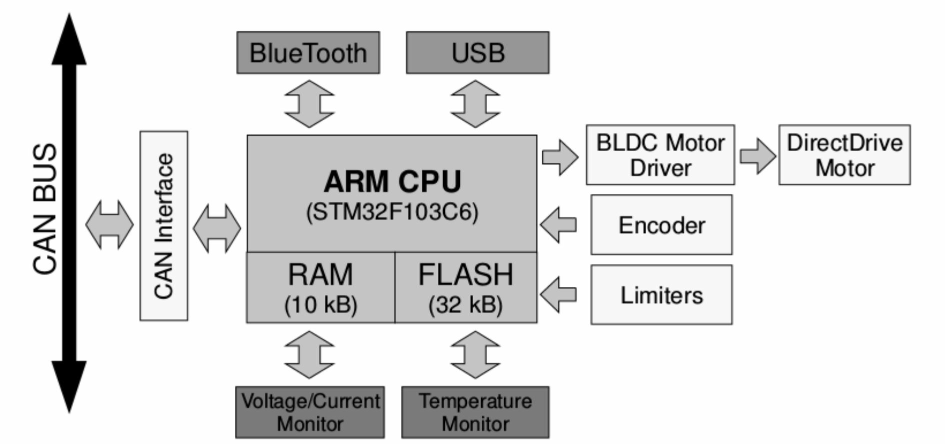


Figure 2.19 - Diagram of the digital control system of the actuator

Reading data about the current state and position of the RM is performed by means of feedback of the electric drive. The bench component of the development provides the function of unloading of kinematic pairs of RM.

In the paper "Improving the Absolute Positioning Accuracy of Robot Manipulators" the authors S. Hayati and M. Mirmirani [20] proposed methods of program control to compensate the error in positioning of RM. It is based on the method of inverse kinematics problem, which consists in the statement about the known positions of the base point of the RM and the location of the desired point of manipulation. The method involves minimizing the deviation of the manipulation point by calibrating the angular position of the robot links. The analytical and experimental part was based on the industrial characteristics of the Puma RM.

In the paper "On the Nature of Control Algorithms for Space Manipulators", the authors EvangelosPapadopoulost and Steven Dubowsky [21] proposed a modification of the kinematic and dynamic models of the RM for the case of non-stationary base point operation. Also, a new RM control algorithm based on the presence of a non-stationary RM base point is proposed.

The described models concern planar (can-planar) RM with specified characteristics of all links and SS (figure 2.20).

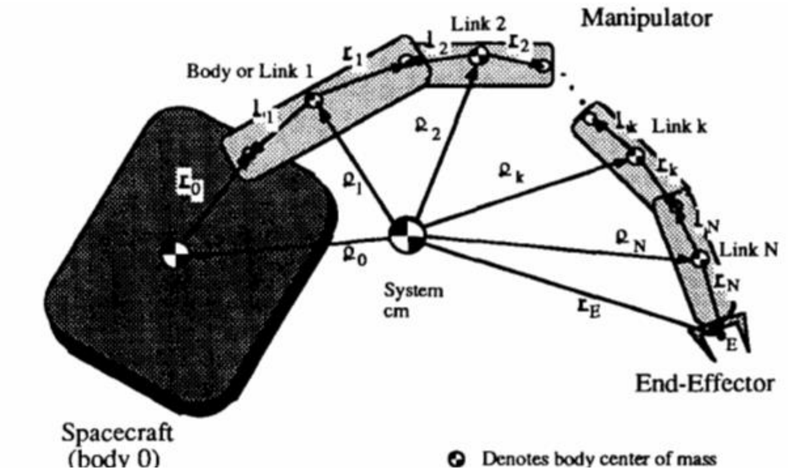


Figure 2.20 - Typical planar model of RM with given parameters of links

The analytical model of the RM is characterized by kinematic energy of the system of bodies expressed through their mass-inertial characteristics. Despite the fact that the model is presented as a planar model, the analytical component contains a description of only two projections. The method proposed by the authors consists in determining the mass values of RM bodies, at which the position of its effector remains constant. In general, the conceptual model is shown in Figure 2.21.

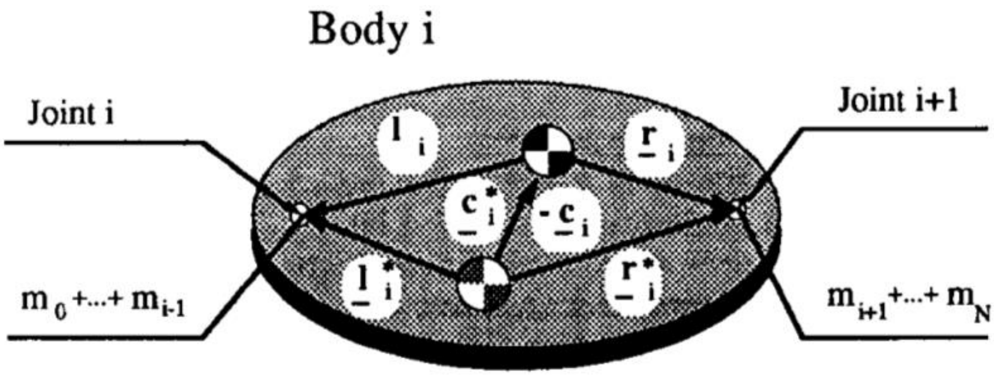


Figure 2.21 - General view of variables of mass-inertial characteristics of the RM without changing the position of its effector

As a result of analytical transformations described in the publication, the authors proposed a form of expression of the generalized vector of forces acting in the system through the Coriolis acceleration and inertia of the RM links. Based on the analytical transformations performed and the known criteria for positioning the RM (kinematics problems), the authors propose a new algorithm for its positioning.

In particular, the paper shows methods:

- compensating influences on the base point of the RM to maintain its relative position;
- recalculating the inertia of the object of manipulation;
- analysis of the deviation of the RM base point.

To verify the hypotheses and methods proposed in the paper, the authors performed analytical modeling of control of a RM with three links. The RM has no fixed base point, and its dynamics, described using the Jacobian matrix, is expressed in the form of a cosine matrix. As a result of the analytical check the results of compensation of the base point displacement due to the complex angular displacement of RM links are shown (Figure 2.22).

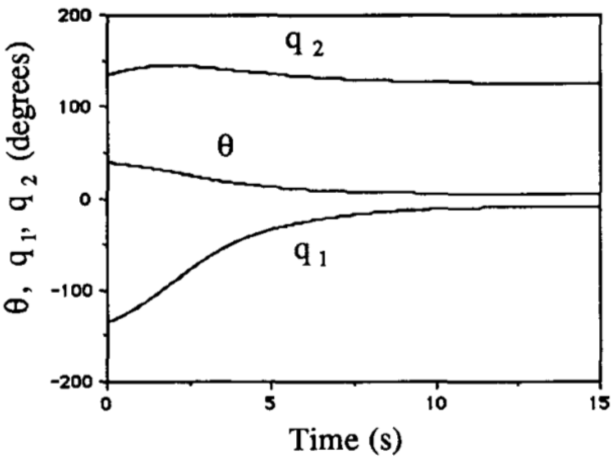


Figure 2.22 - Compensation of movement of the RM base point due to angle change at displacement of RM links, where Θ - displacement of the base point of RM where Θ - displacement of the base point of PM; q1, q2 - angular displacements of RM links

In the paper "Space Manipulator Motions with No Satellite Attitude Disturbances" by the author Z. Vofa [22] shows the application of classical methods of modeling of kinematics and dynamics of 6 and 9 section RM to solve trajectory problems. The author proposed to change the position of the RM base point in a parametric way. The relevance of the shown work lies in the complexity of the working area of the RM, which is associated with the presence of peripheral equipment of spacecraft.

In the paper "Control of Free-floating Space Robotic Manipulators base on Neural Network", the authors ZHANG Wenhui and ZHU Yinfa [23] proposed the use of self-learning algorithms to solve the trajectory control problems of the RM in conditions of non-stationary base point of the robot. The method is based on the use of neural networks with a backward distribution of error (deviation) correction.

To describe the dynamics of the object the differential equations of the second kind are used, which describe: the position, velocity and acceleration of movements of the RM joints; the inertia of the links; the Coriolis centripetal forces and the control values of moments. The control quantity is the position of the RM effector, which is set in the Cartesian coordinate system. The concept of the proposed method of adaptive control consists in gradient approximation of the effector's position (may I remove this word?) to the desired point (the point is preferably set). This is done by correcting the values of moments in the joints. Depending on the number of learning interactions, the positioning error will decrease. However, it is worth noting that a change in the initial properties of the RM will result in the need for re-learning. Given the probability of constant property changes (degradation processes), the proposed method for solving the trajectory problem can be used as an auxiliary system. Such a system is able to calibrate the orientation of RM at the stage of coordination of different-type feedback systems (which is included in the typical scenario of GDS and RM operation in particular).

To visually check the effectiveness of control systems, the authors show the solution of trajectory problem for moving the RM effector along a certain trajectory (Figure 2.23).

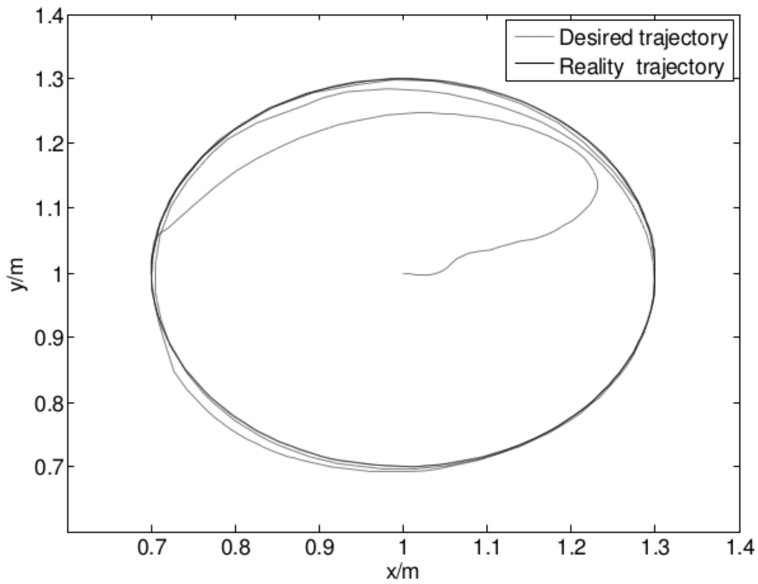


Figure 2.23 - Approximation of the trajectory solution to the reference value

In "Composite Sliding Mode Control for a Free-Floating Space Rigid-Flexible Coupling Manipulator System" by Wang Congqing, Wu Pengfei, Zhou Xin and Pei Xiwu [24], a comprehensive solution of the RM control problem under non-stationary base point conditions and under the existing oscillatory transient processes on the robot links is shown.

The analytical description of the object model is performed by classical methods with separate consideration of kinematics, dynamics, and control parameters. The kinematic component is based on the Newton-Euler equation and connections in kinematic chains according to the Denavit-Hartenberg principle. The dynamic model of the apparatus gives a description of the Lagrange equation of the second kind, which are used in it. The control parameters are the moments in the joints. A sinusoidal function is used as a typical oscillatory process.

As a result of recalculation, the authors have determined the nominal characteristics of the links (including - materials, lengths, masses), energy characteristics of drives, nominal and extreme characteristics of the frequency and amplitude of oscillation of the links. The authors have also synthesized a structural diagram of the effector position control system that takes into account the amplitude-frequency characteristics of the link transients (Figure 2.24).

Based on the proposed method, the authors simulated the stabilization of the RM base point in a given area (Figure 2.25) and the movement of the RM effector along the specified trajectory (Figure 2.26).

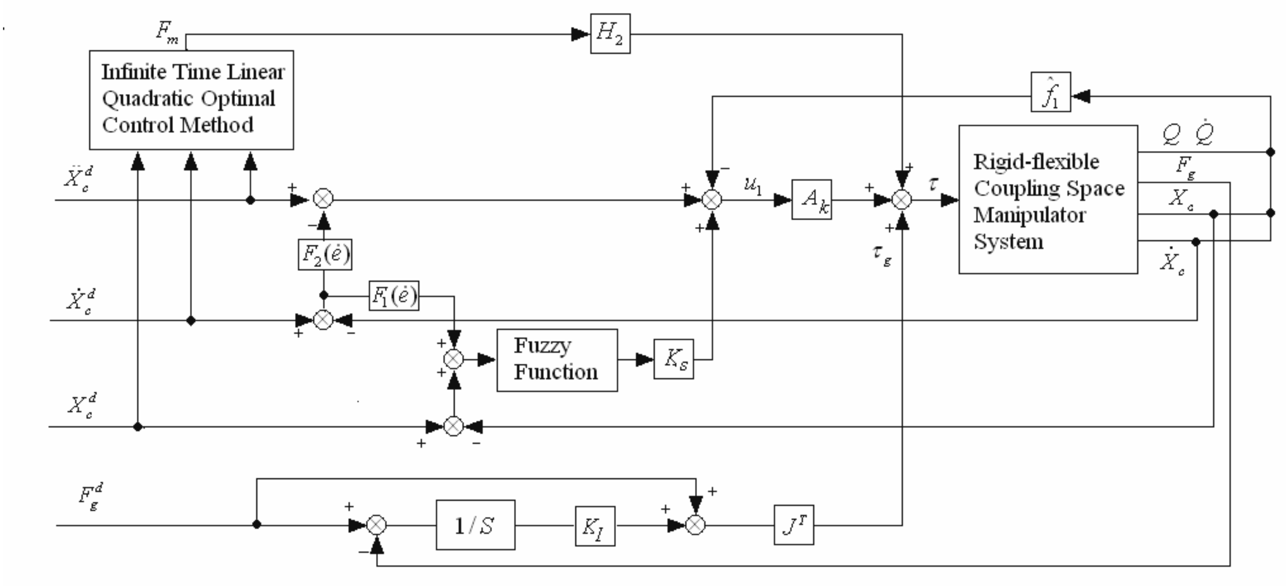


Figure 2.24 - Computer model and block diagram of RM control system of RM control system taking into account oscillatory processes of links

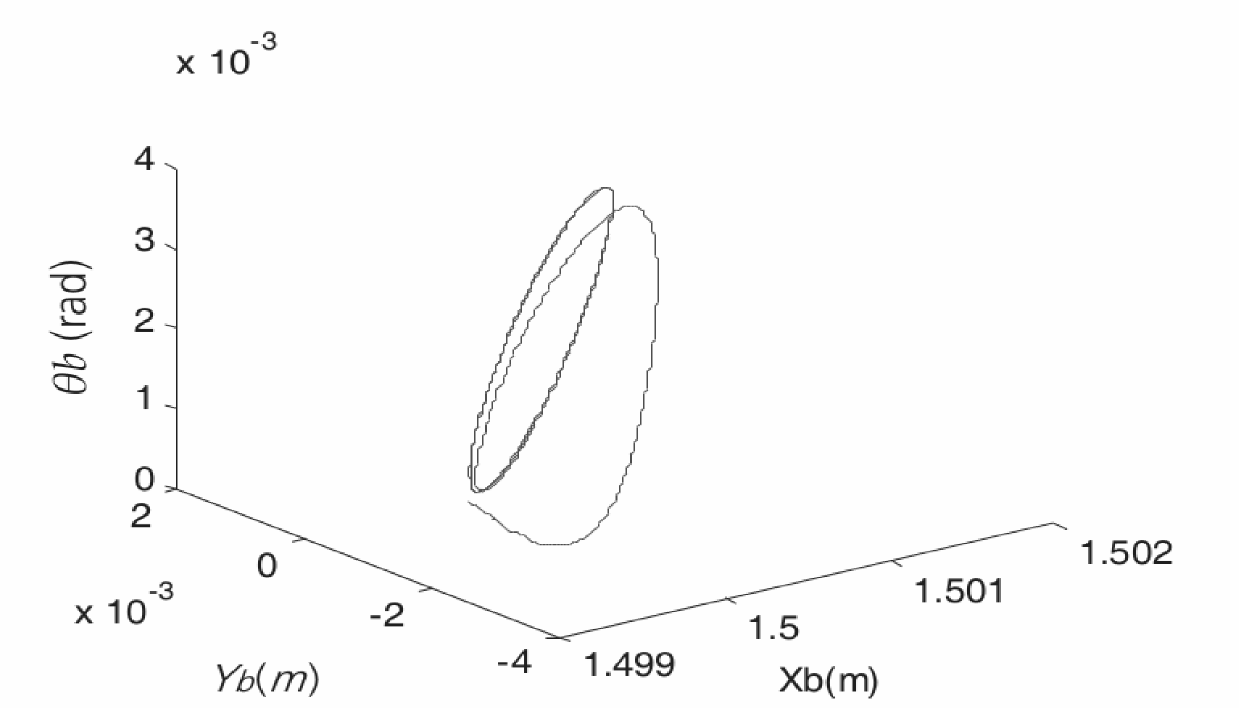


Figure 2.25 - Positioning of the RM base point

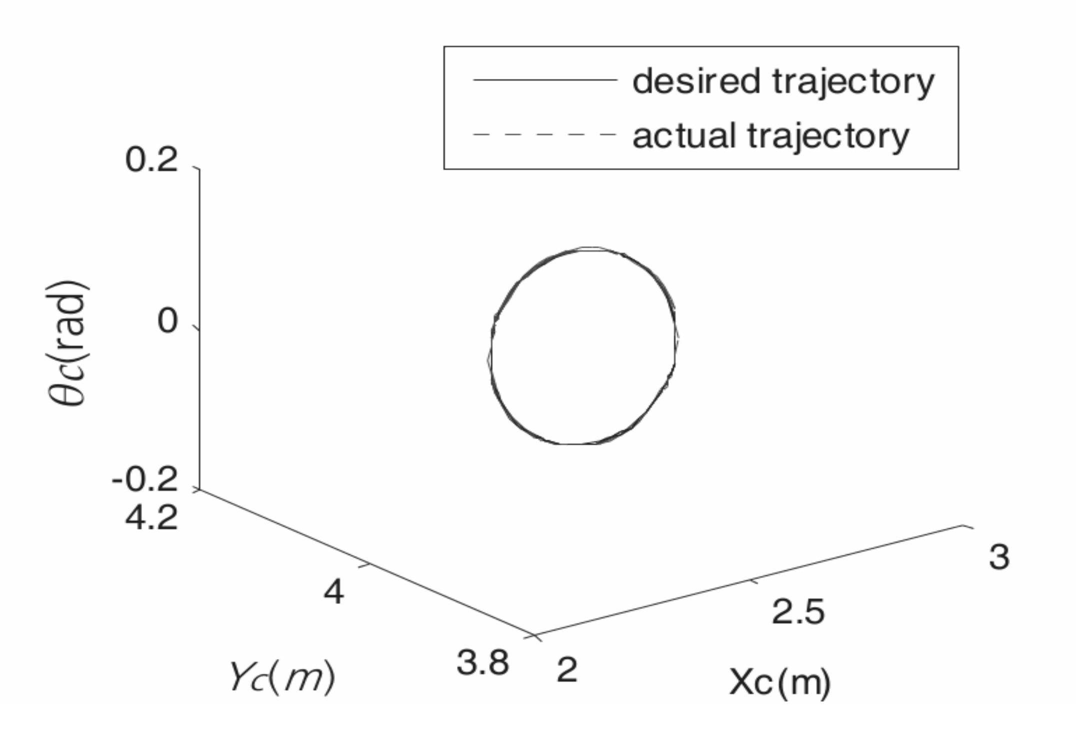


Figure 2.26 - Moving the RM effector along the specified trajectory

The paper "Momentum Distribution in a Space Manipulator for Facilitating the Post-Impact Control" by Dimitar Nikolaev and Kazuya Yoshida [25] considers the problem of redistribution of forces and moments in kinematic pairs of the RM before, during and after contact of the effector with the CSC. The model proposed in the publication uses a damping device on the RM effector, while the robot arm contains no damping mechanisms (Figure 2.27).

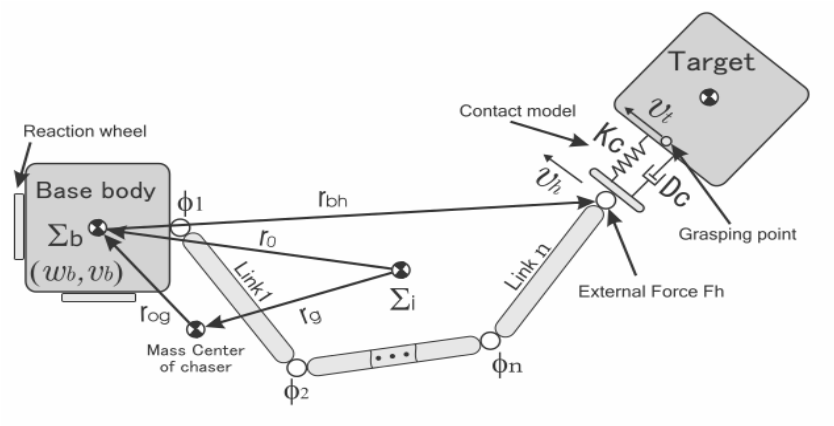


Figure 2.27 - Robot with a damper mechanism on the effector part of the console

Classical methods of computer and analytical dynamics were applied to describe the RM. The results are presented in the form of a functional relationship between the moments in the effector and the phase of the scenario.

The results are presented as graphs of moment (angle) dependence on time (Figure 2.28).

A number of works, in particular, "Resolved Motion Rate Control of Space Manipulators with Generalized Jacobian Matrix" by YojiUmetaniand Kazuya Yoshida [26], "The Kinematics, Dynamics, and Control of Free-Flying and Free-Floating Speca Robotic Systems" by Steven Dubowsky, EvangelosPopadopoulos [27] show analysis of completed robotic systems.

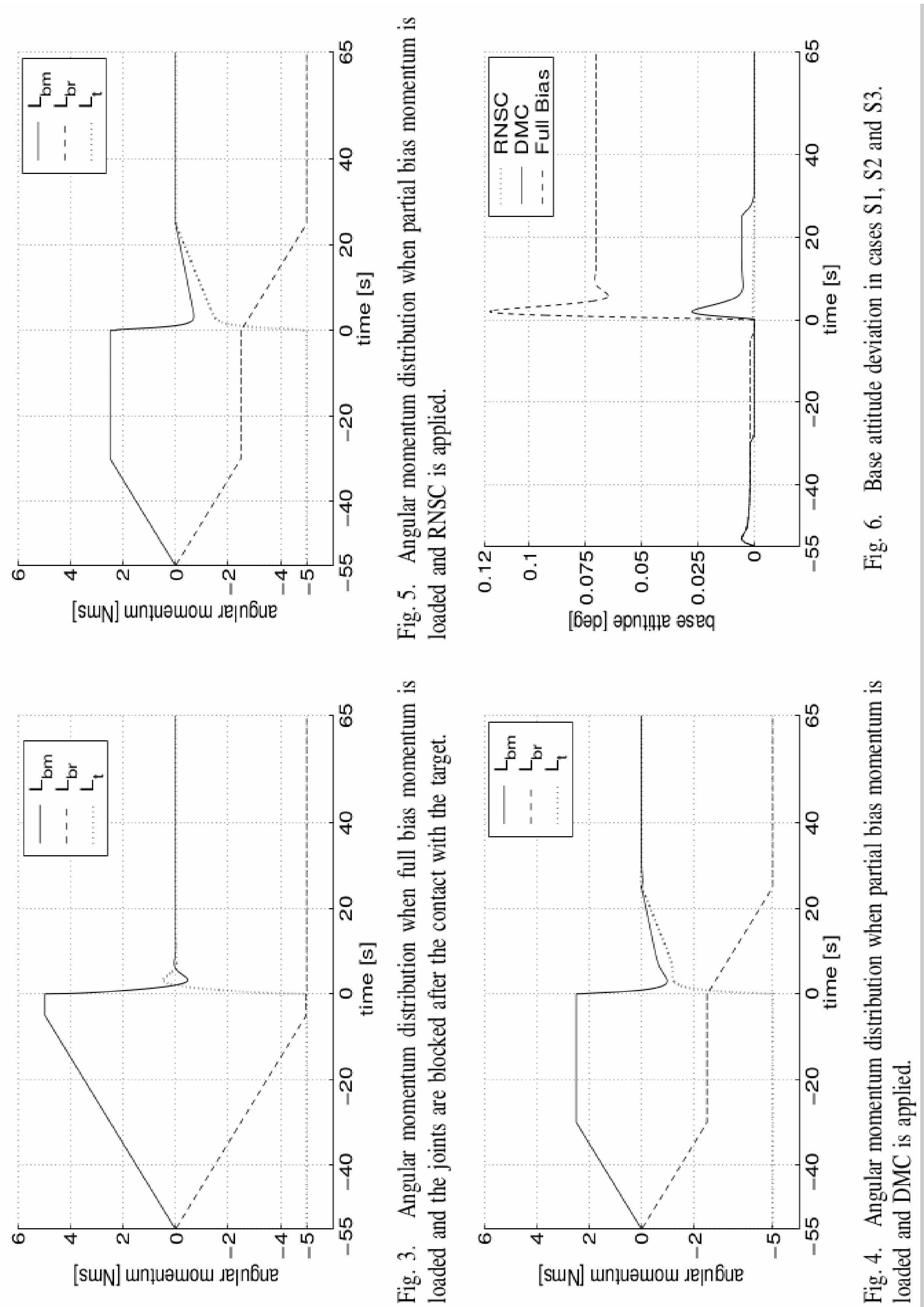


Figure 2.28 - Change of RM characteristics before and after interaction with the spacecraft

3. Justification of methods and means to solvethe problem of capture and docking

The solution of the problem of rendezvous, capture and docking with unguided CSC is carried out with the use of robotic systems. Considering the application conditions, it was found that the only satisfactory design solution for performing an orbital service is a robotic manipulator with six or more degrees of mobility. The technical solutions existing today are complete and represent structural and software algorithmic software for grasping and manipulating mechanical objects.

However, these design solutions have not been developed and cannot be used to perform a service with an unplanned object in advance. Thus, the actuators, feedback systems and the corresponding software for controlling the RM are not suitable for solving the assigned tasks of capturing, holding and docking with an unguided CSC.

The analyzed variants of construction of actuators, console designs, sensor system means, as well as methods and principles of control in conditions of unsteady base point of the RM, under conditions of jump changes of moments in actuators, etc., allow positively assess the possibility of building an own RM, which can solve the assigned tasks.

Analysis of publications and descriptions of finished products characterizes the lack of complete solutions for the construction of the effector part, which could be used for the capture and retention of different types of CSC. However, the analysis of standard interfaces and adapters allows us to specify the characteristics of the device for CSC capture. Also, based on the analysis, some types of CSC, which are equipped with pyrotechnic means of separation from the adapter, cannot be captured and held by the effector part, suitable for interaction with the interface. The use of an additional effector, which is equipped with a universal gripper, has been suggested for gripping in such a CSC. Despite the wide range of mass-size characteristics of the CSC, it makes sense to use a complex of two RMs, which are equipped with different-type effectors and are characterized according to the telescopic and anthropomorphic principle of kinematic console pairs. In order to quickly solve the problem concerning the construction of a robotic system of capturing and holding the CSC, the methods of modeling, control and some elements of construction are proposed. The analysis and description of these techniques is given in the publications.

It is also recommended to cooperate with the corresponding authors to solve the following problems:

- Modeling and optimization of transient flow. LIAO Yihuan, LI Daokui, TANG Guojin;
- Analytical modeling of RM. Shuanfeng Xu, Hanlei Wang, Duzhou Zhang, Baohua Yang, and Mingming Wang and Z. Vofa;
- Modeling and control of RM in the case of unsteady basepoint support. Harry West, Norbert Hootsmans, Steven Dubowsky, Nathan Stelman, Wolfgang Rackl and Roberto Lampariello;
- Capture problems in the situation of capture point invariant and base point position invariant. Mingming Wang and EvangelosPapadopoulost, Steven Dubowsky;
- Design of a ground experimental bench and RM actuators. Tomasz Rybus, JanuszNicolau-Kukliński, Karol Seweryn;
- Trajectory problem solving and optimisation. ZHANG Wenhui and ZHU Yinfa and Wang Congqing, Wu Pengfei, Zhou Xin and Pei Xiwu;
- Modeling and formation of the scenario of the RM docking in unity with CSC. Dimitar Nikolaev, Kazuya Yoshida.
- Comprehensive solutions for the docking scenario and the RM design.
  Wenfu Xu, Bin Liang, Cheng Li, Yangsheng Xu and R. Lampariello.

4. Components of the system

The MTA RM consists of:

- robotic arm with a telescopic link;
- an anthropomorphic manipulator robot;
- a control system unit for coordinated operation of robots and the MTA control system.

4.1. The telescopic link manipulator robot includes:

- Actuators:
  - three angular actuators based on stepper motors with torque reduction;
  - linear translational drive based on stepping motor with torque reduction transmission;
  - two angular drives based on stepper motors with torque reduction transmission, which serve to orient the link together with the effectors.
- Links:
  - a telescopic kinematic pair of links:
    - structural means of ensuring translational motion: base cantilever; sliding cantilever; toothed rack guides; guide system with slide bearings; damping mechanisms; fastening elements;
    - structural means of power transmission and drive controls;
    - structural means of heat transfer.
  - effector-compatible link:
    - structural means of power transmission and actuator controls;
    - constructive means of heat transfer;
    - structural means of grafting with the effector;
    - damping mechanisms;
    - fixing elements.
- Effector with the system of capturing and fixing the CSC interface:
  - the effector sensor system:

        - gripping force monitoring means;
        - means of vibration monitoring;
        - means of grip release;
        - means of gripping marking;
        - means of measuring relative distance.
    - effector drives;
    - heat exchange system;
    - structural components of the gripper device.
- Sensor system:
    - sensors of angular motion of links;
    - sensors of translational motion of links;
    - end sensors;
    - current sensors on actuating elements of RM;
    - linear and angular effector acceleration sensors;
    - tension sensors;
    - vibration sensors;
    - sensors of RM location in transport state;
    - temperature sensor.
- Docking Port (DP) lighting means;
- Control system unit:
    - digital fan base control system;
    - digital microcontroller script control system;
    - interface part;
    - thermal management unit;
    - block of technical malfunction diagnostics.
- Means of interaction between the MTA power system, its control system and video cameras;
- Fastening elements:
    - attachment elements of the RM base link to the MTA hull;
    - elements of attachment of the RM with pyrotechnic release (for transport

mode of insertion into orbit);
    - pyrotechnic means of separation of the RM from the MTA hull.

4.2. The anthropomorphic robotic arm structure includes:

- Actuators:
    - two angular drives based on stepper motors with torque reduction based on the RM;
    - an angular actuator based on a stepping motor with a torque reduction transmission for movements of a kinematic pair of elbow joint links;
    - three angular actuators based on stepper motors with torque-reduction transmission for orientation of a link that is compatible with effectors;
- Links:
    - the basic and compatible links:
        - thermal management system;
        - constructive means of power transmission and actuator control means;
        - constructive means of grafting with the effector;
        - damping mechanisms;
        - fastening elements;
    - link compatible with the effector:
        - constructive means of power transmission and actuator controls;
        - structural means of heat transfer;
        - structural means of grafting with the effector;
        - damping mechanisms;
        - attachment elements.
- Anthropomorphic effector:
    - sensory system:
        - means of diagnosing gripping force;
        - torsion diagnostics means;
        - vibration diagnostics means;

        - means of grip release;
    - heat exchange system;
    - effector drives;
    - structural components of the gripper device;
    - additional tooling equipment (tool changers).
- Sensor system:
    - link angular displacement sensors;
    - end sensors;
    - current sensors on actuators of RM;
    - sensors of linear and angular acceleration of the effector;
    - tension sensors;
    - vibration sensors;
    - sensors of RM location in transport state;
    - temperature sensor.
- DP lighting means;
- Control system unit:
    - digital fan base control system;
    - digital microcontroller script control system;
    - interface unit;
    - thermal management unit;
    - technical malfunction diagnostic unit.
    - means of interaction between the MTA power system, its control system and video cameras;
- Fastening elements:
    - attachment elements of the RM base link to the MTA hull;
    - elements of attachment of the RM with pyrotechnic release (for transport mode of insertion into orbit);
    - pyrotechnic means of separation of the RM from the MTA hull.

4.3. The control system unit for coordinated operation of robots and MTA control system includes:

- a transport container (located in the MTA hull) with a capacity of two RMs and their effectors in transport condition;
- two video cameras to provide technical vision;
- technical and software means for ensuring a communication channel between the RM control and the MTA control;
- technical and software means for providing a communication channel between the RM control and the RM ground stations of telecontrol;
- complex of ground means of RM tracking and control.

5. System operation modes and their duration

5.1. The interaction scenario describes the behavior of the RM depending on the stage of approaching the SS and CSC to perform orbital service.

5.1.1 Behavior of RM when approaching a SS and CSC

The 7 actual stages of approach are described:

1 - distance between the SS and CSC is greater than 100 m;

2 - The distance between SS and CSC is equal to 100 m and the approaching axis is defined;

3. - distance between SS and CSC is more than 20 m and less than 100 m;

4. - the distance between SA and CSC is equal to 20 m;

5. - The distance between SS and CSC is more than 2 m and less than 20 m;

6. - The distance between SS and CSC is equal to 2 m.

Negative approach status is also described:

1 - distance between SS and CSC is less than 2 m.

At stages (1-3) the RM is in transport position.

At stage 2 the RM is removed from the transport container. Test program No. 1 (all test programs and control programs are given in Appendix B) is executed to check the possibility of further use of the RM in the manipulation working area.

Based on the results of test program No. 1, the RM control system generates and transmits report No. 1 (all reports are given in appendix C) confirming the success of test program No. 1.

If test program No. 1 is successful, test program No. 2 is executed to check the operability of the RM tool (effector). Report No. 2 on the effector operability is sent to CS of the SS.

If test programs #1 and #2 ended with errors, report #7 is generated and the RM control system loads control program #14 to switch to the telecontrol mode.

After exiting the telecontrol mode, report No. 15 is generated and reports Nos. 1, 2 are set in the manual mode.

After successful testing of the RM and the effector, the control program #1 starts, which positions the RM at the rear boundary of its working area.

After positioning is completed, the CS of RM generates report No. 3, which indicates that at the specified time interval the RM has taken the specified position and is ready to complete the stage.

At stage 2, the RM is removed from the transport container, its effector is on the rear border of the working zone. The RM control system executes control program No. 2.

At stage 4 the RM control system performs operations in the following sequence:

- running the test program No. 3, and balancing the RM feedback system by the control program No. 5;

- start of control program № 3 and determination of DP position relative to the effector. At that, the PM console keeps constant position;

- in case of successful determination of DP position, a report № 5 is generated in CS of the SS about readiness to start automatic approach of the effector to the DP spacecraft;

- in case of failure to locate DP - report № 5 notes this fact;

- in case of equipment failure and in other abnormal situations, Report No. 7 is generated.

Based on the results of reports Nos. 5 and 6, the control system SS confirms the launch of control program No. 4 of the control system RM about the start of bringing the effector to DP in automated mode, or in telecontrol mode. If the received report No. 7 does not confirm the start of control program No. 4, the control system shall proceed to stage No. 5. In step No. 5, the control system executes test program No. 4. Report No. 8 describes the full technical condition of the RM and its control system and is received by the SS control system.

Further work plan is performed in accordance with additional interaction protocols and is not described in this document.

With completion of control program #4, the effector PM is in the immediate (without the possibility of applying moments and forces) vicinity of the DP of CSC. After that, the corresponding report No. 9 is generated. As a result of processing report #9, the SC of SS generates a directive to capture or cancel capture by the DP of SS effector, which is fed into control program #6 of the RM control system.

If the response to report #9 is an override directive, control is transferred to control program #12, which causes the effector to retract to the initial position (to the boundary of the RM's working area). Report #11 is sent about the results of RM withdrawal, and control is returned to the CS of SS.

If the response to report No. 9 is a capture directive, control program No. 11 is executed, which results in DP capture. With the completion of control program No. 11, the CS of RM generates capture report No. 10. If the capture has not been completed and report #10 contains an appropriate message, the CS of SS may provide a recapture directive, which is executed by control program #11, or a RM effector retraction directive, which is executed by control program #12.

Based on the data on the execution of control programs No. 11, 12, reports No. 10, 11 are generated, respectively.

If report No. 10 contains information about fulfillment of capture, the RM fixes its spatial position by executing control program No. 2. After that, the RM control program submits report No. 12 on the readiness of spacecraft transportation by means of SS. If reports #10, 11 describe the absence of capture and unsuccessful withdrawal of the effector, report #7 is generated. After receiving report No. 7, the CS of SS can repeat control program No. 2 and fix the spatial position of the RM by applying control programs No. 12, 2 or withdraw the RM to the initial position according to control program No. 12. Execution of the programs is confirmed by corresponding reports.

If the gripping is not performed, the CS of SS decides to withdraw the RM to the limit area of the working zone (control program № 1) and return the RM to the stage № 4 or retry the gripping using the RM telecontrol mode (control program № 14).

After receiving report #12, the RM maintains the current position, while the SS performs a move. With the completion of the movement the SS starts the control program № 15, as a result of which the effector RM opens the capture of the spacecraft. Based on the results of this program a report #14 is generated. If the opening of the gripper is completed, the CS of RM starts control programs #12, 1, which results in report #3. If report No. 3 is negative, the RM control system calls control program No. 14 and forms reports No. 7 and No. 15, which describe the technical condition of the RM and informs the SS control system that the RM has completed its telecontrol mode.

After successful report #3 or report #15, the RM maintains its spatial position until the start of step #6. After that, the RM control system starts control program #16, as a result of which the RM is placed and fixed in the transport position.

After completion of control program #16, report #16 is generated, confirming completion of the manipulation stage.

If negative report No. 3 or No. 15 occurs, it is recommended to operate the RM in the telecontrol mode.

6. System dimensions

6.1 Approximate configuration of the manipulator in transport position is shown in Figure 6.1.

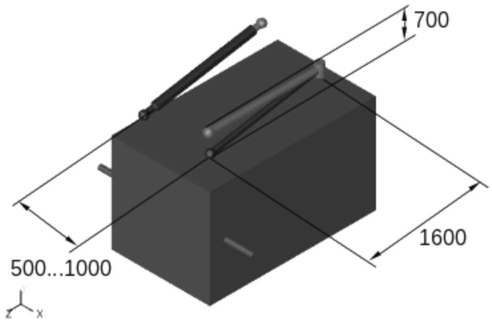


Figure 6.1 - Configuration of the manipulator in the transport position

For the design scheme the dimensions of the manipulator in the transport position are estimated by the following values:

- length 1600 mm;
- width (500 - 1000) mm depending on the distance to the mounting points of the two working elements (the necessary distance will be specified in the process of modeling the docking process);
- height 700 mm.

6.2 Dimensions of the working area

The configuration of the working area is shown in Fig. 6.2.

In the space around the apparatus, we allocate 3 areas:

- area 1 - is overlapped by the structural elements of the manipulator when it is transferred from the transport position to the ready position and has the shape of a quarter cylinder with a radius equal to the length of the manipulator's working elements in the transport position. According to preliminary estimates the radius of the working area R1=1.2 m;

- Area 2 - the working area of the manipulator, that is the area of space in which it is possible to grab with the docking device of the CSC. It has the form of a sphere or two spheres, intersecting for the manipulator with two working bodies. The working area is limited by the radius from above, which corresponds to the maximum removal of the docking unit due to the deployment of manipulator links. According to preliminary estimates the working area R 2 = 2.2 m;

- region 3 - "dead" zone, i.e. the zone near the hull of the SS, in which manipulations are impossible, is limited by the range of values of the radius R3 from 0.7 to 1.2 m (Figure 6.2).

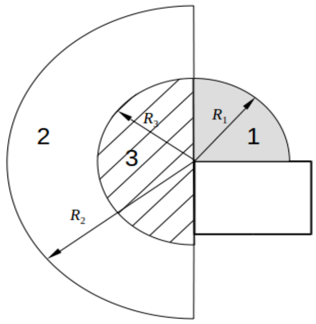


Figure 6.2 - Configuration of the working area

7. Energy consumption and weight of the component devices

Energy consumption and weight of the system components are given in Table 7.1.

Table 7.1

Consumer Group	Description	Quantity;Power(W); Weight (kg)
Actuator	Angular drive based on stepper motors with torque reduction with integrated feedback sensors	11 items; 150; 1,7
	Linear actuator based on a stepper motor with torque reduction with integrated feedback sensors	1 item; 150; 1,7
Sensor system	Link angular motion sensor	11 items; <1; 0,1
	End sensor	24 items; <1; 0,1
	Progressive link sensor	1 item; <1; 0,1
	Current sensor on the RM actuators	15 items; <1,0; <0,1
	Effector linear and angular acceleration sensor	2 items; <1; <0,1
	Tension sensor	15 items; <0,5; <0,1
	Vibration sensor	8 items; <1; <0,1
	RM location sensor in transport state	2 items; <1; <0,1
	Thermal sensor	60 items; <3; <0,1
	Grip splitting tool	2 items; 10; 2
	Vibration diagnostic tool	2 items; <1; 0,1
	Torsion diagnostic tool	1 item; <1; 0,1
Sensor system	Gripping force diagnostic tool	2 items; <1; 0,1
	Grip marking tool	1 item; 5; 1
	Relative distance measuring instrument	1 item; 20; 3
	Video camera to provide technical vision	2 items; 25; 3

Table 7.1. Continue

Consumer Group	Description	Quantity; Power(W); Weight (kg)
Effector system	Heat exchange system	2 items; 15; 3
	Effector drive	6 items; 100; 1,3
	Stage lighting tool	1 item; 1,5; 0,5
Control System	Diagnostic unit of technical malfunction	2 items; 4; 0,2
	Digital valve system for basic control	2 items; 4; 0,2
	Digital microcontroller script control system	2 items; 4; 0,2
	Interface part	2 items; 2; 0,2
	Temperature control unit	2 items; 3; 0,2
	Control unit for coordinated operation of robots and CS of SS	1 item; 4; 0,2
Mounting system	RM fixing element with pyrotechnic release of RM from SS	2 items; 5; 1,5
Console and structural elements	Telescopic kinematic pair of links with constructive means of translational motion	1 item; - ; 2,5
	Polycarbonate beam	2 items; - ; 5
	Base link and angular alignment link	1 item; - ; 6
	Structural component of the gripper device	2 items; - ; 3
	Structural component of tooling (tool changer)	1 item; - ; 2
	Attachment of the RM base link to the SS body	2 items; - ; 0,5
	Telescopic kinematic pair of links with constructive means of translational motion	1 item; - ; 25
	Polycarbonate beam compatible with effectors	2 items; - ; 5
	Base link and angular alignment link	1 item; - ; 6
	Constructive components of the gripper	2 items; - ; 3

Table 7.1. Continue		
Consumer Group	Description	Quantity; Power(W); Weight (kg)
Console and structural elements	Constructive components of tooling (tool changers)	1 item; - ; 2
	Elements for attaching the RM base link to the SS body	2 items; - ; 0,5

Energy consumption of the robotic system under typical modes of its operation

Power consumption characteristics during typical operation modes of the CSC capture and restraint system are given in Table 7.2.

The power consumption of the robotic system depends on the stage of the CSC capture and restraint operation. According to the results of approximate modeling of the robotic system operation scenario, the maximum power consumption is observed at the stage of "capturing and holding the client spacecraft's RM" and can be up to 485W. If the operation time increases up to 10 min, the maximum power consumption will be up to 151 W.

Table 7.2			
Mode of operation	Consumer	Consumption, W	Total maximum consumption, W
Transport mode; diagnostics in folded mode	Sensor system	10	36
	Effector. Effector heat exchange unit	5	
	CS. Diagnostic system for technical failures. CS. Interface. CS. Control System unit for coordinated operation of the RM	16	
	Mounting system	5	

Table 7.2. Continue

Mode of operation	Consumer	Consumption, W	Total maximum consumption, W
Taking the robotic system out of its transport state	Actuators	60·K, K=1	195
	Sensor system (without relative distance and vision aids)	100	
	CS	25	
	Mounting system	10	
Entering the RM into the manipulation working area	Actuators	90·K, K=1	215
	Sensor system	100	
	CS	25	
RM diagnostics	Actuators	50·K, K=1	323
	Sensor system	100	
	Effector systems	133	
	CS	40	
Positioning RM	Actuators	100·K, K=1	243
	Sensor system	100	
	Effector systems. Stage lighting	3	
	CS	40	
Capturing and holding the client machine's RM	Actuators	150·K, K=1	483
	Sensor system	100	
	Effector systems	233·K, K=1	
Disconnecting the RM from the MTA	Actuators	30·K, K=1	60
	Sensor system	20	
	Mounting system	10	

K is the correlation coefficient between the operation time and drive consumption

The power consumption of the drives depends on the imposed time limits for performing the operation of capturing and holding the CSC through the parameter K. The consumption characteristics shown in the table correspond to the time limits specified in the Technical Requirements.

8. Requirements for ground-based processing, control and simulation system

8.1 The ground component of the system of capture and docking with an unguided CSC involves a set of complex operations, namely:

- conducting a bench simulation of the system operation;
- synthesizing and refining scenarios;
- bench-scale preparation of GDS robotic equipment;
- ensuring communication between GDS and other systems of the SS;
- provision of telecontrol functions;
- performing automated control functions using Processor in the Loop, HardWare in the Loop technologies;
- backing up and accumulation of control data;
- remote access to simulation and control workstations;
- high-performance scenario processing for finding the best solution in a non-standard control situation;
- interaction between ground service units for set-up and control;
- ground service administration.

To perform the tasks, the ground service structure must comply with the structural diagram shown in Figure 8.1.

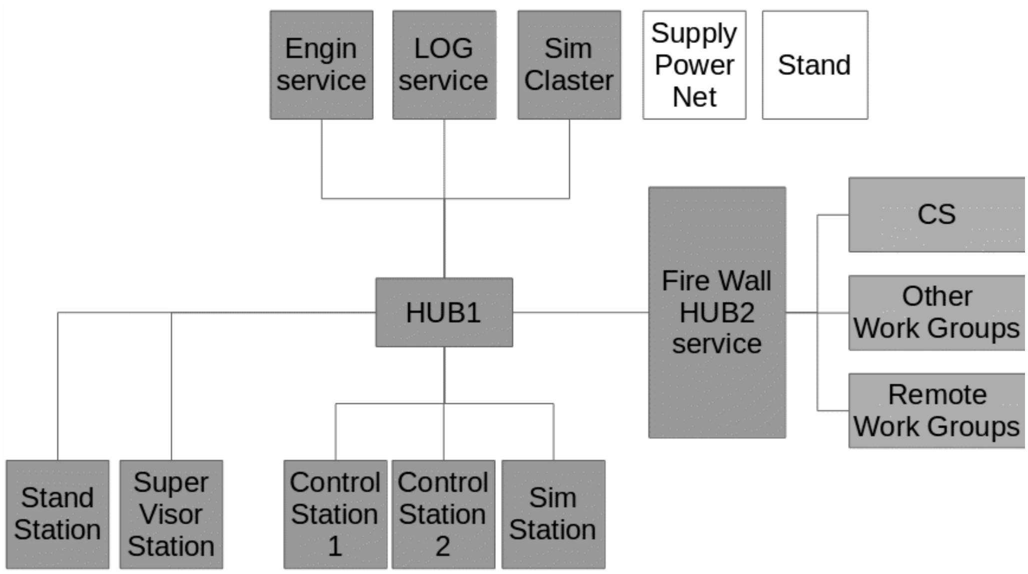


Figure 8.1 - The structurel diagram of the ground service

Figure 8.1 shows the following designations:

- CS - ground structure of the superior SS control system;
- Other Work Group - other work groups involved in the SS bench development process;
- Supply Power, Net - means of uninterrupted power supply and network maintenance;
- Stand - ground RM stand, which includes in its list the means to simulate climatic conditions, microgravity, load, block of spacecraft simulators with typical interface parts for interaction with the operating RM, etc;
- Remote Work Group - remote parallel (or auxiliary) units;
- Firewall, HUB2 service - server (hardware and software platform) to perform access control and arbitration of data and commands;
- HUB1 - hardware system of arbitration and access control;
- Engin service - workstation, server and switching equipment administration service;
- LOG service - server (hardware and software) for backup recording of all data and events occurring in the system;
- SIM Claster - a high-performance computing cluster for simulating the behavior of robotic equipment;
- Stand Station - a workstation for control and simulation of the ground stand operation;
- Super Visor Station - a workstation to monitor and diagnose the state of the system and the actions of other workstations;
- Control Station 1 - workstation to control robotic equipment in modes of automated RM operation;
- Control Station 2 - backup (auxiliary) workstation to control robotic equipment in modes of RM automated operation;
- Sim Station - workstation for testing RM functioning scenario in preparation for RM telecontrol.

It is recommended to use workstations as the basic application software:

- OS family: LINUX;
- Simulation tools: MATLAB Simulink;
- standard language: M, C/Cpp, Python;

Characteristics of hardware and software of the server components of the system, as well as switches will be defined later.

It is recommended to arrange the ground service structural subdivisions as shown in Figure 8.2.

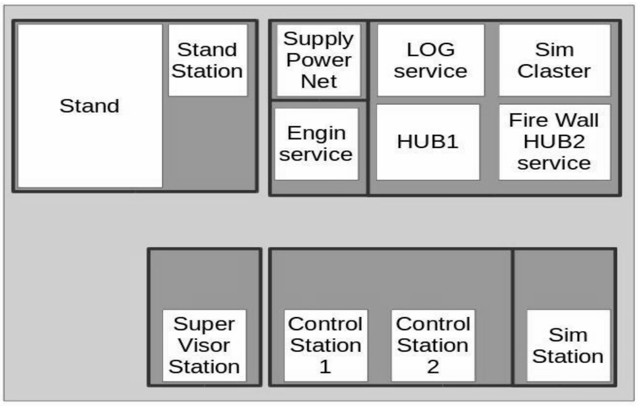


Figure 8.2 - Ground service structural subdivisions

To perform the tasks of bench preparation and management of the RM in the scenario, it is recommended to include in the staff the workers whose responsibilities will include

- control of RM in automatic and automated modes;
- control and telecontrol - 7 jobs;
- simulation of the RM behavior in case of emergency situations and for performing the bench simulation - 7 jobs;
- monitoring and control of the work group - 5 workplace;
- system and network administration - 5 jobs;
- technical support of the stand and power equipment - 5 workplace;
- support personnel - 11 jobs.

8.2 Aspects of checking the product performance

Acceptance of the prototype version of the robotic gripping and restraint system requires a cycle of diagnostic procedures, which must take place in the order shown in Table 8.1.

Table 8.1.

item no.	Name of diagnostic stage	Location	Evaluation and diagnostic criteria
1	Diagnostics of the integrity and serviceability of the robotic system	Manufacturer	Compliance of mass-dimensional characteristics of the product in folded and unfolded positions with reference values
			Compliance of the energy characteristics of the product with the reference values
			The product is completed in accordance with the stated position and composition
2	Diagnosis of the robotic system's ability to perform typical operations described in the scenario	Bench installation	Taking the RM from the transport state to a given point of the working area
			Relocation of the effector part of the RM in the working area, taking into account time factors
			The program movements of the RM are coordinated by time and position
3	Diagnostics of correctness of coupling of electrical subsystems, control system and sensor subsystem as a part of robotic system with bench version of hardware and software interface between SS and RM		Ability to physically connect mechanical and electrical interfaces
			Exchange of test data packets between control system subsystems
			Transmitting non-standard directives. Receiving appropriate reports
			Transmitting status queries. Receiving reports
			Transmission of data about simultaneous control of a group of PM links. Receiving the sequence of movement processing
			Transmission of data on the movement of the RM and the holding of the spacecraft by the effector
			Transmission of RM mechanical opening data from the MTA. Monitoring of opening data

Table 8.1. Continue

item no.	Name of diagnostic stage	Location	Evaluation and diagnostic criteria
			Transmission of control data. Receiving confirmation of successful control
			Transmission of requests with different exchange rate error. Obtaining the value of the corridor of acceptable error values
4	Diagnostics of robotic system performance under stimulated microgravity, climatic conditions and external forces		The removal of the RM from the transport position under: - variable effects of external forces; - Limit values of operating temperature.
			Positioning of the RM in a given point of the working area under: - Variable influence of external forces; - Limit values of working temperature.
			Correction of positioning error of MTA by means of RM at: - Variable exposure to external forces; - Limit values of operating temperature.
			Capture and retention of a CSC under: - Variable exposure to external forces; - Limit values of operating temperature.
			The release of a CSC under: - Variable exposure to external forces; - Limit values of operating temperature
			The removal of the RM from the CSC to a given point in the working area under: - Variable influence of external forces; - Limit values of the working temperature

Table 8.1. Continue

item no.	Name of diagnostic stage	Location	Evaluation and diagnostic criteria
			Transfer of the RM to the transport position under: - Variable exposure to external forces; - Limit values of operating temperature.
5	Diagnostics of the robotic system's ability to perform the typical procedures described in the scenario using a bench version of the appropriate hardware and software interface between the SS and RM. All stages of RM operation are performed separately. Diagnostics of the robotic system performance at load and performance peaks is performed. Diagnostics cycle of feedback		Passage of RM with specified coordinates of the working area during standard turning, RM approach to the CSC, grabbing, holding, transporting, releasing, leaving, transition to the transport state. Checking coordinate deviation during passage depending on: - the payload mass by which the RM is loaded; - speed of positioning of the RM; - climatic conditions; - influence of external forces.
	means (including optical ones) is performed		Formation of the deviation dependence on the parameters obtained from the sensor system of the RM and the stand
6	Diagnostics of the robot system control in all modes (automatic, automated, telecontrol). A separate analysis of the operability of the digital control systems with the ability to switch between basic and secondary digital systems is performed		Passing of the RM with the specified coordinates of the working area during the execution of the standard capture scenario.
			Switching of control modes of the control system
7	Diagnostics of the robotic system performance as a part of the MTA. Verification of hardware and software interface compatibility between the MTA and the RM. Execution of all typical scenarios of system operation	Main factory	Execution of the testing schemes specified in paras. 1,2,3,5,6 in conjunction with the corresponding tests

To perform all stages of diagnostics of the gripping and restraining system, workstations must be equipped with the experimental base shown in Table 8.2.

Table 8.2.

test step no.	Necessary experimental basis
1	Reference values of mass-dimensional andenergy values of the product and its configuration
	Tooling for mounting / dismounting of product units, according to the specifics of design, mounting, etc.
	24 V-36 V, 250 W power supply with ammeter, voltmeter, means of connection to connectors and pins used in the structures and circuits of the robotic system
	Interfaces identical to those used in SS for interaction with the robotic system
	Computer equipped with software compatible in protocols with the RM control system
	Interface conversion unit for combining RM and computer
	Computer power supply
2	Bench installation to simulate the interface part of the SS and the operating conditions of the RM
	Passing scenario data of the SS robotic system
	Tooling for mounting/dismounting the product units, according to the specifics of design, mounting, etc.
	24 V-36 V, 250 W power supply with ammeter, voltmeter, means of connection to connectors and pins used in robotic system designs and circuits
	Interfaces identical to those used in SS for interaction with the robotic system
	Computer equipped with software compatible in protocols with the RM control system
	Interface conversion unit for combining PM and computer
	Computer power supply
	Cinematograms tool
	Dual-beam oscilloscope (1 Hz - 2 MHz)
	Multimeter
2, 3, 5, 6, 7	Bench installation to simulate the interface part of the SS and the operating conditions of the RM
	Passing scenario data of the SS robotic system
	Tooling for mounting / dismounting of product units, according to the specifics of design, mounting, etc.

Table 8.2. Continue	
test step no.	Necessary experimental basis
	24 V-36 V, 250 W power supply with ammeter, voltmeter, means of connection to connectors and pins used in the structures and circuits of the robotic system
	Interfaces identical to those used in the MTA for interaction with the robotic system
	Computer equipped with software compatible in protocols with the RM control system
	Interface conversion unit for combining RM and computer
	Computer power supply
	Cinematograms tool
	Dual-beam oscilloscope (1 Hz - 2 MHz)
	Multimeter
4	Bench installation to simulate the MTA interface and operating conditions of the RM
	Passing scenario data for the MTA robotic system
	Tooling for mounting/dismounting product units according to design features, mounting, etc.
	24 V-36 V, 250 W power supply with ammeter, voltmeter, means of connection to connectors and pins used in the design and circuitry of the robotic system
	Interfaces identical to those used in the MTA for interaction with the robotic system
	Computer equipped with software compatible in protocols with the RM control system
	Interface conversion unit for combining RM and computer
	Computer power supply
	Cinematograms tool
	Dual-beam oscilloscope (1 Hz - 2 MHz)
	Multimeter
	Infrared thermometer
	Displacement sensors 0.2-15 g (6 steps) with standardized interface
	Pressure sensors with standardized interface

9. Timing of the system development

9.1 Timeline for system development is given in Table 9.1.

Table 9.1

Stages	No	Task name	Workload (Sprints)
1. Data collection, analysisand construction of RM physical model	1	Signing a cooperation agreement	
	2	Agreement of technical specifications	1
	3	Analysis of existing RMs for the relevant industry, the main developers and identify the current stages of their development	11
	3.1	Analysis of kinematic models of existing RMs	2
	3.2	Analysis of the dynamic properties of existing RMs	2
	3.3	Analysis of drive types used in existing RM solutions	2
	3.4	Analysis of the mass-dimensional and energy characteristics of the RM	1
	3.5	Formation and argumentation of the qualitative choice of the RM structure, its kinematic scheme, dynamic properties, drives and feedback means	3
	3.6	Stage 3 report	1
	4	Analysis of modern approaches to the selection and construction of such systems	19
	4.1	Analysis of existing factors that apply in the field for similar tasks related to the capture, docking or docking of spacecraft	2
	4.2	Analysis of effector kinematic diagrams	2
	4.3	Analysis of the principles of action of the effectors. Determination of their suitability for the specified area of application according to the criteria defined by the environment	2
	4.4	Defining the requirements for the client machine effector capture interfaces	1
	4.5	Search and analysis of information about the mass-dimensional and energy characteristics of effectors. Determination of the possibility of their reuse, automatic repair and replacement	3
	4.6	Determination of dynamic loads on the effector in the process of spacecraft manipulation	1

Table 9.1. Continue

Stages	No	Task name	Workload (Sprints)
	4.7	Analysis of the possibility of using feedback and sensor systems for local positioning of the effector, its safe approach to the object of manipulation	3
	4.8	Formation and argumentation of the choice of the effector design scheme, its kinematic scheme and power characteristics. Determination of feedback means	4
	4.9	Stage 4 report	1
	5	Model synthesis of the RM control system	19
	5.1	Development of regulatory mathematical means of controlling the position of the PM console	1
	5.2	Development of basic trajectory control algorithms for RM	1
	5.3	Development of algorithms for optimal control of the trajectory motion of the RM according to such optimality criteria: - energy efficiency; - performance; - torsion of the RM console	2
	5.4	Development of a control system for complex manipulation. Development of a superstructure over the control system to enable telecontrol of the RM	2
	5.5	Development of mathematical and algorithmic support for the positioning of the PM effector at the unsteady position of its base point	8
	5.6	Development of an optical guidance system for the CSC interface	2
	5.7	Development of algorithmic and software scenarios for automated operation of the RM control system	2
	5.8	Stage 5 report	1
	6	Analysis of interaction between SS and RM control systems for their interaction	5
	6.1	Development of the conceptual model of the RM and effector AC. Determination of typical information about RM, SS, CSC and effector, which will ensure effective operation of RM CS and SS CS	1
	6.2	Analysis of sensory system means of SS, which can be used to control RM. Analysis of the dynamic capabilities of the SS that can be used by the RM for manipulation tasks	1
	6.3	Distribution of functions between actuators and sensor systems of SS and RM in order to maximize the effect of control	1

Table 9.1. Continue

Stages	No	Task name	Workload (Sprints)
	6.4	Development of a model of RM and SS behavior under the existing model of sensory and executive systems	1
	6.5	Stage 6 report	1
	7	Development of effector and RM layouts	10
	7.1	Construction of a computer model of the kinematics and dynamics of the effector and RM	1
	7.2	Testing the effector model and PM. Definition of requirements for the product. Development of design documentation. Formation of requirements to the RM ground testing system	1
	7.3	Reconciliation of mass-dimensional characteristics with subsequent design changes	1
	7.4	Bundling of the design model with actuators and sensor systems, as well as digital control system	1
	7.5	Making a 3D model of the effector and RM	1
	7.6	Development of the electrical system of the effector and RM	1
	7.7	Development of a digital control system of actuators and feedback system and its interface with the computer. Development of a digital control system for actuators and feedback system and its interface with a computer and effector	2
	7.8	Testing the model design to capture typical CSC interfaces. Analysis of test results. Correction of design and calculations. Testing of the model design for positioning the effector at a given point with typical obstacles present	1
	7.9	Stage 7 report	1
2. Building and handing over the first product sample	8	Approval of incoming documents on RM development	1
	8.1	Formation of the terms of reference and technical requirements. Selection of the production site. Agreement of requirements for the production process, logistical support, etc.	1
	9	Formation of the preliminary design of the RM and the effector	9
	9.1	Product design and development of working documentation	8
	9.2	Stage 9 report	1
	10	Development of design, schematic and design documentation for the construction of RM and effector	29
	10.1	Synthesis of the structural diagram of the electronic control system of the RM and effector	1

Table 9.1. Continue

Stages	No	Task name	Workload (Sprints)
	10.2	Synthesis of the layout of actuators, sensor system means, climate system and interfaces of RM and effector	2
	10.3	Formation of RM cable paths scheme	1
	10.4	Formation of the effector cable paths scheme	1
	10.5	Design of electronic control systems of RM and effector	5
	10.6	Design of climate system RM and effector	5
	10.7	Production of design documentation for the product	13
	10.8	Stage 10 report	1
	11	Forming the base of blocks and parts for the product	10
	11.1	Purchase of RM and effector block equipment	2
	11.2	Formation of the protocol of assembly and testing of products	1
	11.3	Manufacturing of RM and effector component assemblies at the manufacturing plant. Acceptance of the manufactured RM and effector component assemblies to make a complete product	6
	11.4	Stage 11 report	1
	12	Product assembly	11
	12.1	Making up the basic design of the RM and the effector	2
	12.2	Control tools intergation	1
	12.3	Integration and calibration of the sensor system tools	1
	12.4	Integration of effector control systems and cable paths	1
	12.5	Integration of the climate system	1
	12.6	Coordinating and combining the RM and the effector	1
	12.7	Coordinating a robotic system with a SS-compatible interface	1
	12.8	Testing and debugging	2
	12.9	Stage 12 report	1

Table 9.1. Continue

Stages	No	Task name	Workload (Sprints)
3. Diagnostics of RM and effector operability. Interface harmonization and checking work scenarios	13	Product diagnostics	10
	13.1	Diagnosing the integrity and serviceability of the robotic system.	1
	13.2	Diagnosis of the robotic system's ability to perform the typical operations described in the scenario.	2
	13.3	Diagnostics of correctness of coupling of electrical subsystems, control subsystem and sensor subsystem as a part of robotic system with bench version of hardware and software interface between SS and RM.	1
	13.4	Diagnostics of robotic system performance under simulated microgravity, climatic conditions, and conditions of extraneous forces.	2
	13.5	Diagnostics of robot system control in all available modes	2
	13.6	Diagnosing the performance of the robotic system as part of the SS	1
	13.7	Stage 13 report	1
	14	Formation of instructions for the use of RM and effector	3

10. System design and manufacturing costs

The cost projections for the timeline described above are as follows.

Table 10.1 shows the cost of purchasing the block elements and structures for the production of the robotic system model and the effector for capturing and holding the spacecraft.

Table 10.2 shows the costs for the purchase of block structures for the manufacture of the prototype of the robotic system of capturing and holding the CSC.

Table 10.2

o	Purpose of financing	Description
1	Acquisition of block elements of the RM model structure	Telescopic kinematic pair of links with structural means to ensure translational motion, such as: - base console; - sliding console; - rack and pinion guiding system; - guide system with plain bearings; - damping mechanisms; -fastening elements with power transmission and drive controls, as well as heat transfer elements
		Polycarbonate beam compatible with effector
		Base link and angular alignment link
		Angular drive based on stepper motors with torque reduction with integrated feedback sensors
2	Acquisition of sensor system components	Angular motion sensor for links
		End position sensor
		Progressive motion sensor for links
		Current sensor on the RM actuators
		Effector linear and angular acceleration sensor
		Tension sensor
		Vibration sensor
		RM location sensor in transport state
		Temperature sensor
		Grip splitting tool
		Vibration diagnostic tool

Table 10.2. Continue

o	Purpose of financing	Description
		Torsion diagnostic tool
		Gripping force diagnostic tool
		Grip marking tool
		Relative distance measuring instrument
		Video camera to provide technical vision
3	Acquiring the block elements of the model construction of the effector	Heat exchange system
		Effector drive
		Elements of the gripping device
		Tooling assemblies (tool changers)
4	Making CS blocks	Technical troubleshooting unit
		Digital valve system for basic control
		Digital microcontroller script control system
		Interface part
		Temperature control unit
		Control system unit for coordinated operation of robots and SS CS
5	Acquisition of fastening elements	Attachment of the RM base link to the SS body
		RM mounting element with pyrotechnic release of the RM from the SS body

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APPENDIX

APPENDIX A

Scientific and production units with current or completed developments in the field of HHS

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PICYT-CIDESI, CIDIT-Facultad de Informatica, Universidad Autonoma de Queretaro, Queretaro, Mexico;

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Department of Technical Cybernetics, National Technical University of Ukraine "Kyiv Polytechnic Institute," Kyiv, Ukraine;

Defense Advanced Research Projects Agency;

InstitutfürRaumfahrtsysteme, Technische Universität Braunschweig, DE;

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, SS;

California State University, LA, SS;

Departament of Mechanical Engineering Massachusetts Institute of Technology Cambridge, MA;

GE Corporate Research and Development P.O. Box 8, Schenectady, NY;

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College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China;

Manufacturing Systems Engineering State Key Laboratory, Xi'an Jiaotong University, Xi'an, China;

Dept. of Aeronautics and Space Engineering Tohoku University Aoba01 Sendai 980-8579, Japan;

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Robotic Industries of America, Japan Society for Aeronautical and Space Science, the Robotic Society of Japan;

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Department of Mechanical Engineering, National Technical University of Athens, 15780 Athens, Greece;

Automation School, Beijing University of Posts and Telecommunications, Haidian, Beijing, 100876, China;

The Institute of Space Intelligent System, Harbin Institute of Technology, Harbin, P.R. China;

Shenzhen Academy of Aerospace Technology, Shenzhen, P.R. China;

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German Aerospace Center DLR, Institute of Robotics & Mechatronics, Münchner Strasse 20, 82234 Wessling, Germany.

APPENDIX B

Automatic RM programs

- Test programs:
- - program #1 performs a test of the response of the RM nodes;
- - program №2 performs test of response and mechanical operability of the effector;
- - program №3 performs balancing between different types (means) of feedback that are used to control RM;
- - program #4 performs a full analysis of the technical condition of the RM;
- 2 Control programs:
- - program #1 positions the RM at the rear boundary of the working area, while ensuring equidistance from the MTA structural objects;
- - program No.2 - stabilizes and holds RM in its current position;
- - program №5 - balancing of feedback systems by means of moving RM by coordinates;
- - program №3 provides determination of relative position and orientation of the effector RM and PD;
- - program #4 - bringing RM effector to DP spacecraft without forces and moments between them;
- - program №6 - bringing RM effector to DP without appearance of forces and moments between them;
- - program №12 - withdrawal of the effector to the start position;
- - program №11 - capture of DP by the RM effector;
- - program #14 - change of the control mode, entering the RM control system in the telecontrol mode;
- - program №15 - disconnection of RM effector;
- - program №16 - transfer of RM to the transport state.

APPENDIX C

Protocol of reports from RM SC to MTA CS

Report #1 contains typical results for test program #1: describes possibility of further use of RM for manipulation execution; characterizes availability of technical recall of executing devices, sensor system and auxiliary equipment. It is submitted to the MTA CS processing in "true/false" format.

Report #2 contains typical results for test program #2: it describes the possibility of further application of the effector in the RM; it characterizes the presence of technical recall of the executing devices, sensor system and auxiliary equipment. It is submitted to the MTA CS processing in the "true/false" format.

Report #3 contains typical results for the control program #1: it describes the RM positioning compliance on the area of the working area boundary; it characterizes the spatial and temporal positioning compliance. It is submitted to the MTA control system for processing in "true/false" format.

Report #5 contains confirmation of successful calculation of relative position and orientation of the effector and DP. It is submitted to the MTA control system for processing in "true/false" format.

Report #7 contains confirmation of equipment failure and occurrence of other abnormal situations. Submitted for processing MTA control system in the format "[error code]/false".

Report #8 contains full description of technical condition of RM, including confirmation of access to working area, confirmation of operation of actuators and sensor system, describing climatic and energy characteristics. It is submitted to the MTA control system for processing in the format "[state, report source]/[state, report source]".

Report #9 contains confirmation of successful positioning of the RM effector directly at the DP. It is sent to the MTA control unit for processing in true/false format.

Report #10 contains confirmation of successful DP capture. Report #10 contains confirmation of successful DP capture.

Report #11 contains confirmation of successful removal of the PM effector from the DP to the initial position at the boundary of the working area. It is submitted to the MTA control system for processing in "true/false" format.

Report #12 informs MTA CS about readiness of RM to move MTA with RM and CS that are in rigid coupling. It is submitted for processing to the MTA CS in "true/false" format.

Report #14 contains confirmation of successful completion of DP unhooking. Submitted for processing MTA CS in "true/false" format.

Report #15 contains a confirmation of completion of the RM control system in telecontrol mode. It is submitted for processing of MTA control system in "true/false" format.

Report #16 contains confirmation of successful positioning of RM in transport state. Submitted to the MTA control system for processing in "true/false" format.

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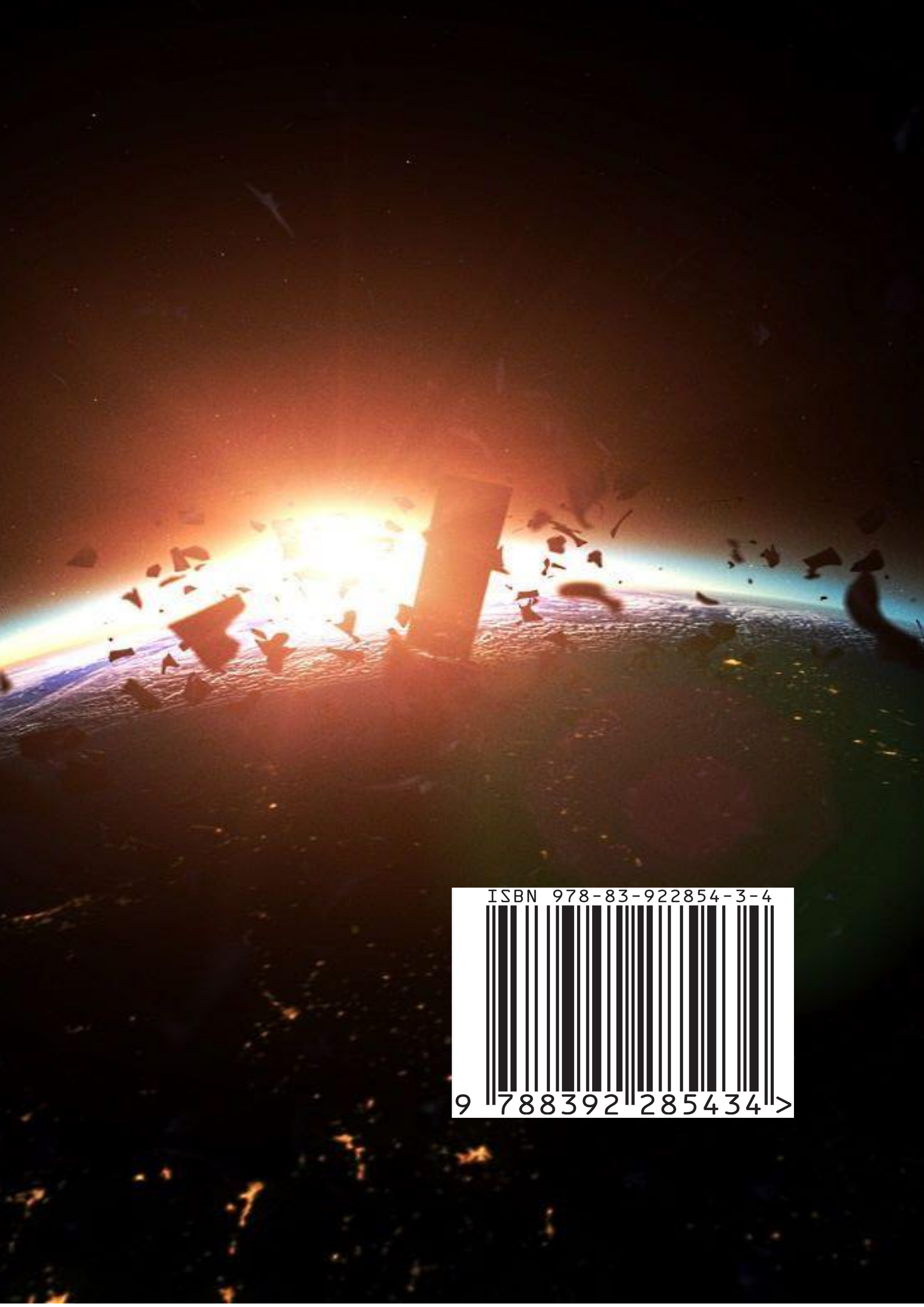

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