Structural Model of Robot-manipulator for Capture of No-cooperative Client Spacecraft

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Abstract

Reorientation, service operation of client spacecrafts etc. are very actual tasks nowadays. Most of such spacecrafts are non-cooperative. Although service operations of these satellites were held before, they are not fully automated. However, docking in manual mode needs huge amount of time and human aboard. That makes impossible to carry out the required number of service operations. In current work it is represented conceptual model of the robot -manipulator for capture and maintenance of non-cooperative client spacecraft. Mechanism of collet effector was proposed for this purpose. Payload Adapter interface PAS 1666 S, PAS 1194 C, PAS 1666 MVS, PAS 1184 VS was chosen as a docking point, because of this interface's convenience and prevalence. Proposed mechanism allows to work in conditions of client spacecraft's linear and angular dynamic position errors in a range of +/-5^0 per minute and +/-0.1 meters per minute respectively. This is achieved by design of the robot-manipulator. Problem of jogless docking and methods of shock prevention are examined. In addition, the berthing and girth operations need axes coincidence of non-cooperative client spacecraft and service spacecraft. Having this in mind, phases of berthing and girth are described and main functions of service spacecraft's control system for solving this problem are considered.

Keywords: Payload system, collet effector, telescopic console, service spacecraft, docking procedure.

1 Introduction

Nowadays on the geostationary Earth orbit (GEO) there are about 1500 satellites. However reorientation, motion or other service operations are needed for about 750 spacecrafts [1]. Almost all spacecrafts (SC) with a weight more than 500 kg were put into GEO by medium-lift and heavy-lift launch vehicles and were equipped by Payload Adapter, which is compatible with PAS PAS1666 S, 1194 C, PAS 1666 MVS, PAS 1184 VS. In most cases such design of SC and its control system did not provide docking and orbital motion in GEO after initial adjustment. So, such vehicles are not equipped by automatic docking means (IDBS) and need special methods, instrumentality and scripts for this operations.

The analysis of reports Department of Mechanical Engineering Massachusetts Institute of Technology [2], International Astronautical Congress [3], University of Nebraska - Lincoln U.S. Air Force Research U.S. Department of Defense [4] and publications [1, 5, 6], showed that at this moment there are no means of docking for service spacecraft (SSC) with non-cooperative spacecraft (NCSC) in a automated or automatic mode. Reasons for this are complexity of such operations, their cost, lack of hardware-technical solutions, common standards of interfaces and functioning of equipment operetion protocols in situations, which arise when preforming aproach, berthing, docking, undocking, departing and projection of SC [6]. Docking with NCSC in manual mode is considered in works [1, 5]. However, the duration of such operation exceeds five hours and requires availability of the cosmonaut and complex equipment on SSC.

As follows, it is obvious that with further evolution of Astronautics execution of docking operations with NCSC will appear more often and involvement of human as an object, which controls docking process, will have no any economical, social or scientific significance.

2 Formulation of the problem

Process of docking NCSC with SSC is performed using the script, which is presented in table 1. This script includes nine stages, the first five of which are essential for orbital docking of SC [5] and must be performed automatically.

Stages 1, 2 have complied technical solution [7, 8], and stages 3, 4 were conducted within Space Orbiter programs and described in publications [7-10]. Stages 6-8, which provide the process of "soft" docking, are performed only in manual mode and the process of their automation requires the development of new control tools and control systems. Table 1. Sequence of operations, which are held during docking with NCSC.

Table 1. Sequence of operations, which are performed during docking with NCSC

№	Stage name	Stage description
1	NCSC position determination	Determination of the NCSC and SSC relative position via GPS navigation and radar tools.
2	NCSC and SSC approach at a distance up to 200 m.	Approaching SSC at a distance of the first suspension for the docking equipment preparation
3	NCSC and SSC approach at a distance up to 20 m.	Approaching SC at a distance of a second suspension for testing docking and fixing SC's continuation equipment.
4	Search for a docking plane on NCSC	SSC flight-around NCSC for searching of a docking plane. Definition of the docking point position. Coordination of dynamic characteristics of devices.
5	Berthing SSC to NCSC at a distance of 2 meters	Approaching SSC to NCSC on the position of service with further approach. The relative position of the devices are considered.
6	Definition of the position of the mechanical docking point	Optical, analytic and radio-locating determination of docking port on NCSC's docking plane. Estimation of the values of the cone of occurrence.
7	Capture and maintenance of NCSC by the means of SSC	Unstressed maintenance of NCSC by mechanical means of SSC and further fixation of NCSC linear and angular movement of NCSC.
8	Coordinating of electric and mechanic parameters of the devices	Coordination of the angles of the rotation in relative planes, electric level 0 V and digital interfaces.
9	Departing of SSC from NCSC	Departing of SSC at a distance of 20 m with subsequent return of the predetermined orbital position.

3 Conceptual Structure of Robot-Manipulator

Suitable Docking point (DP) in modern SC is apogee motor nozzle (Fig. 1) and SpaceCraft adapter ring

(S/C) Payload Adapter (Fig. 2) the technical characteristics of which are written in operating manuals [11-13]. These nodes are characterized by high rigidity and coherence of the position of center of mass of the devices what allows to move NCSC with mechanic tools, which are located in SSC [11-13].

Capture and maintenance of NCSC through the listed DP need compensation of error of the active positioning of the spacecrafts, which is caused by the features of radar sensor system, which is characterized by low resolution at the distance of up to 20 meters [15], has stationary character and is given by six degrees of freedom (DOF).

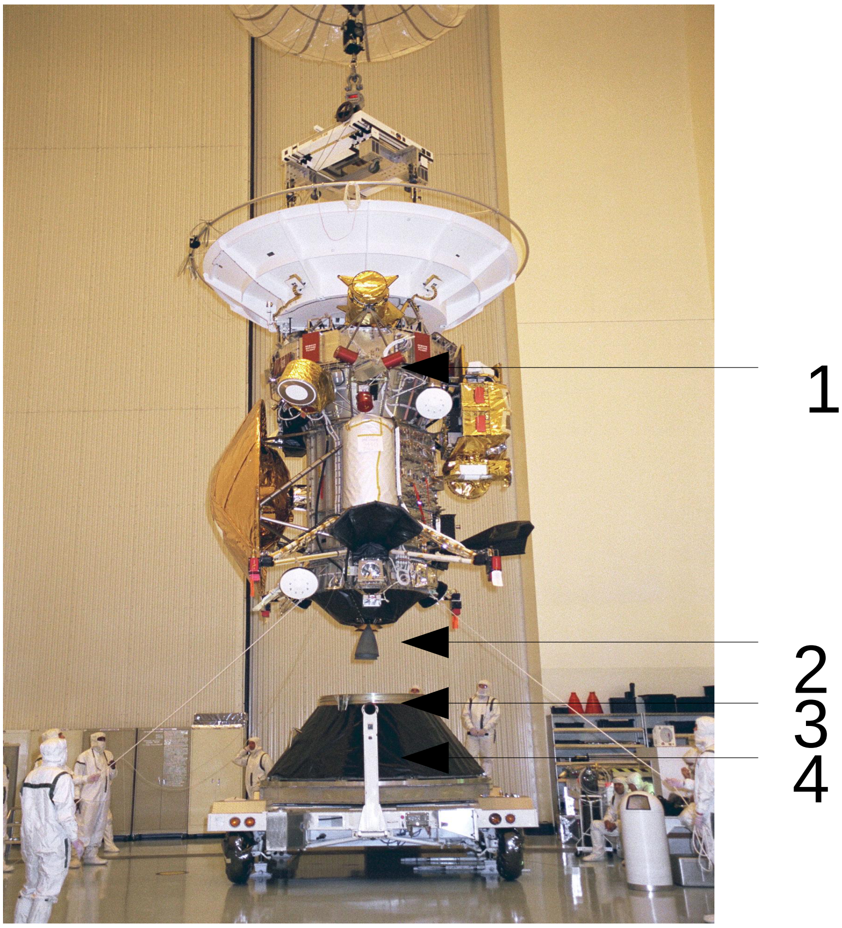


Fig. 1. Spacecraft “Cassini-Huygens” with available S/C adapter ring and apogee motor nozzle in process of connecting to PAS: 1   system block of SC; 2   nozzle of apogeum motor; 3   S/C adapter ring; 4   PAS (photo is used with permission of European Space Agency, Communication Department)

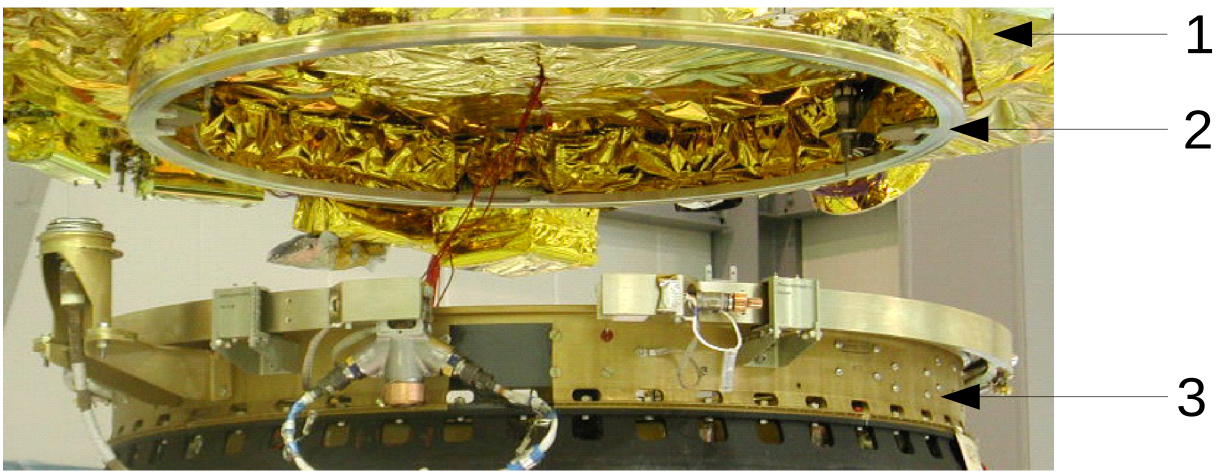


Fig. 2. Connection of SC with Payload adapter PAS 1194 C with means of S/C adapter ring:
1 - system module; SC; 2 — contact plane of SC with PAS by S/C adapter ring means; 3 - Payload adapter(photo is used with the permission of European Space Agency,
Communication Department)

Typical structure of S/C Adapter, which remains on S/C after its departing from the NCSC's launch vehicle (Fig. 3), has mounting hardware (keys) to Payload Adapter, thank to pyrotechnic fasteners is provided “departing” of SC from launch vehicle through. After departing from the launch vehicle S/C Adapter remeins on the SC and is not used repeatably for the active existence of devise on the GEO. Mechanical characteristics of pyrotechnic fasteners' mounting hardware allow the NCSC to hold the S/C Adapter 's mounting hardware in case of uncoordinated docking with the following coordination of dynamic and mechanical parameters of leaked devices.

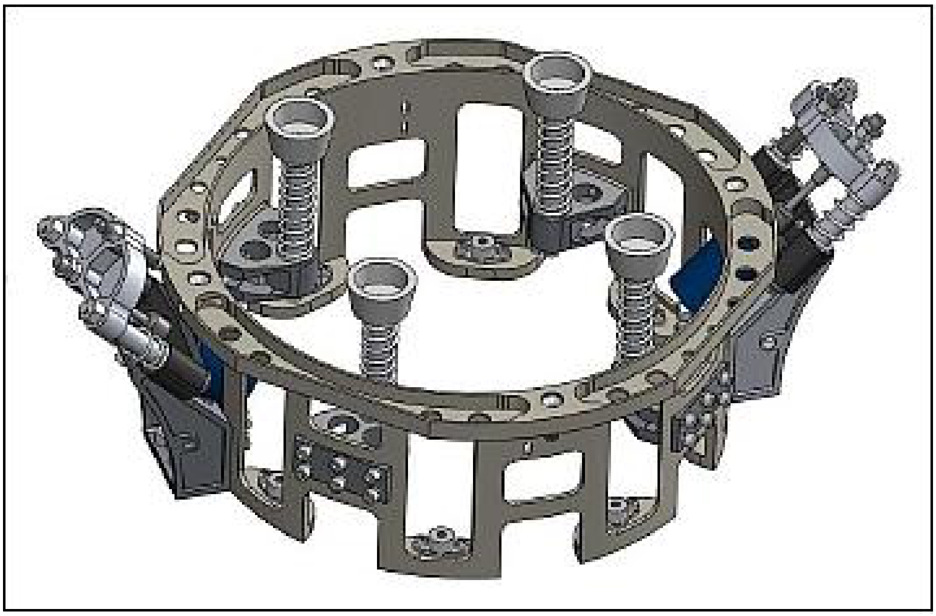


Fig. 3. Typical design of S/C Adapter

Accordingly, for providing automatic capture of SC and S/C Adapter's elements it is necessary to specify the technical capabilities of capture adapter with a diameter range of 800-1400 mm, while maintaining the coaxiality of console, finite effector, NCSC and SSC. It is also important to note the necessity of unstressed capture in conditions of dynamic positioning error of devices. In work [14], the possibility of such a capture is considered, however coaxiality of SC is not provided.

The structure of effector should provide the opportunity of capturing NCSC with consideration of such factors: the presence of errors in linear and angular desitioning; limited time of being at the distance of NCSC and SSC berthing; a large number of S/C Adapter's standards, that are diffrent at sizes and structure; the lack of standard markers on NCSC adapter; absence of friction force between NCSC and environment.

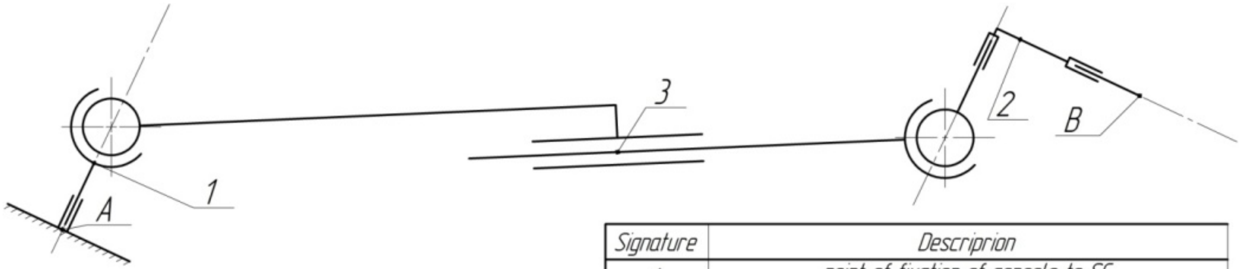
Then, taking into account the factors above, capture of NCSC by Robot Manipulator (RM) must meet the requirements, specified in table 2 and described in [4].

Table 2. Requirements to the RM’s capability to perform the capture of NCSC

№	Description	Value
1	Distance between the base point and NCSC's S/C Adapter	1.5-3 m
2	Mutual orientation	Quasispherical
3	Relative angular velocity at capture	to 10˚ per 1 min
4	Relative linear velocity at capture	to 0.1 m per 1 min
5	Zone of insensitivity of relative positioning of S/C Adapter	to 0.1 m
6	Tolerances to dimensions of S/C Adapter	0.6-3 m
7	Tolerances to mass characteristics of SC	to 5000 kg

Berthing requirements for SSC, which are listed in table 2 (points 1 and 2) are caused by specifications of NCSC, in particular, the generalized length of solar batteries of devices, arengment of antennas, the radius of cone of occurrence of SC, errors of linear and angular positioning of the SSC to NCSC. In such conditions, delivery of RM's effector to S/C Adapter is possible with the use of telescopic console, which is equipped with two angular hinges: double-axis hinge 1 and triple-axis hinge 2, which are located in places of console mounting to NCSC (p. A) and the final effector (p. B) in accordance/ kinematic structure of console is shown on Fig. 4.

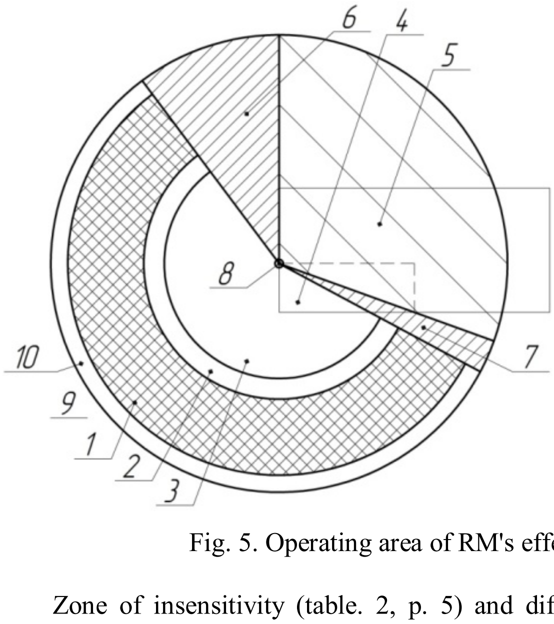
Double-axis hinge 1 and telescopic link of robotic console 3 provide the work of finite effector in the polar coordinate system. Triple-axis hinge 2 provides cardan joint of finite effector, that allows to compensate for errors of its positioning. Such kinematic structure of robotic console eliminatece the occurrence of singularity of the links, however does not solve problem of final effector positioning in S/C Adapter area for committing the unstressed NCSC capture. The solution of this problem is possible only by equipping the effector by sensor devices, which are suitable for recognition and relative position determination of finite SSC effector and NCSC S/C Adapter.



Signature	Descriprion
A	point of fixation of console to SC
B	point of fixation of effector to console
1	double-axis hinge
2	triple-axis hinge
3	linear conection of telescopic pare of links

Fig. 4. Kinematic structure of telescopic console

Taking into account the linear and angular errors of the positioning of the devices, guaranteed effector's positioning for its further girth and capture of S/C Adapter is possible in the segment of work zone (Fig. 5 p. 1). The ability to capture NCSC with deviation close to zero is also possible in zones, which are shown on Fig. 5 (p. 2 and 10). Another zones, which are shown on Fig. 5 are intended for the equipment SC or used as a part of device work in the technical operations.

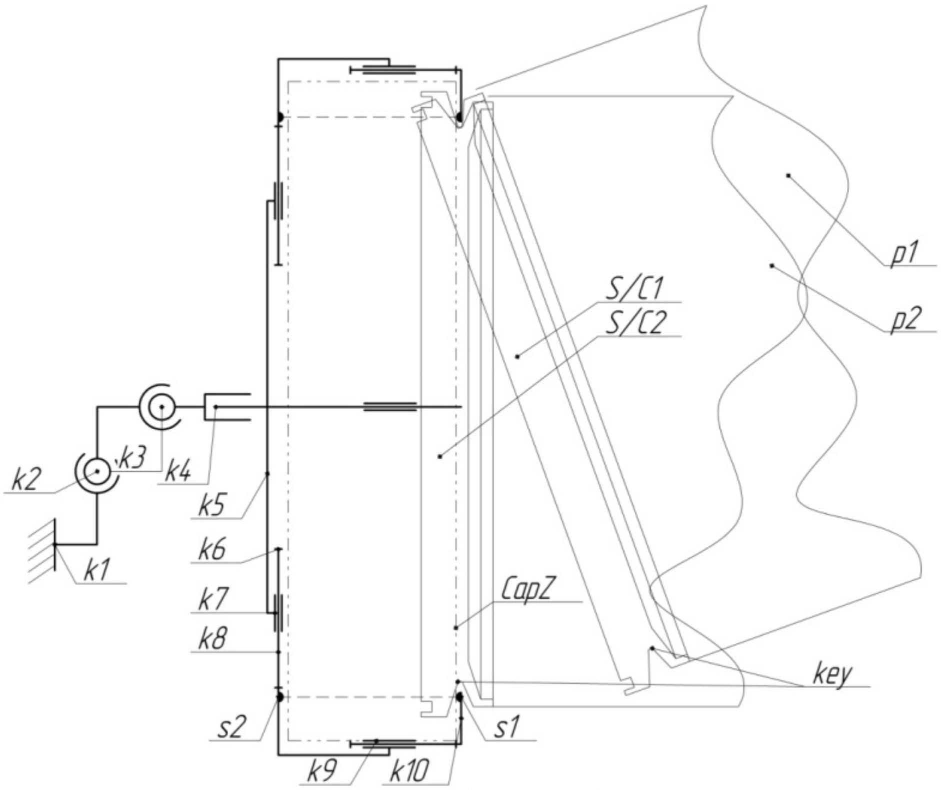


Signature	Description
1	Work zone of RM
2,10	Restriction of access angles to the work zone
3, 9	Outside the work zone
4	Outside the work zone Container with RM as a part of SC
5	Outside the work zone. Design of SC
6, 7	Outside the work zone Equipmet of SC
8	Base point of RM

Fig. 5. Operating area of RM's effector in the pale of longitudinal section.

Zone of insensitivity (table. 2, p. 5) and difference of the S/C Adapter's radii (table. 2, p. 6) impose restrictions on the choice of the effectore's construction and the set of sensor system tools. "Zone of insensitivity" means impossibility of the sensory system, which consisting of the SSC control system (CS), to give accurate distance coordinates and NCSC's orientation. Fault 1 m with the speed 1˚ per minute can cause a collision of effector with S/C Adapter and give them relative acceleration.

Compensation of error may be achieved due to the physical impact of the effector on S/C Adapter after its girth. Adaptation to diameter PAS is achieved by applying effector with chain compression principle. Kinematic structure of such effector is shown in Fig. 6. The contact area of effector has a constant shape due to unification of the key construction of PAS S/C Adapter. Shape of the adapter's key is shown on Fig. 7.



Signature	Description	Signature	Description
k1	Base point of effector	s1	Source of laser ray
k2, k3, k4	corner hinges of effector's orientation	s2	Optical diode
k5	Base link of kinematical link pair of effector	S/C1, S/C 2	Position of S/C Adapter in the groove of effector and behind the groove
k6	Damper system	p1, p2	Body of SC in case of S/C1 and S/C2
k7,k9	Translational connection of links	key	Element of key for S/C1 and S/C2
k10	L-shaped link	CapZ	Field of capture/girth of the object

Fig. 6. Kinematic structure and main nodes of the effector of the chain type

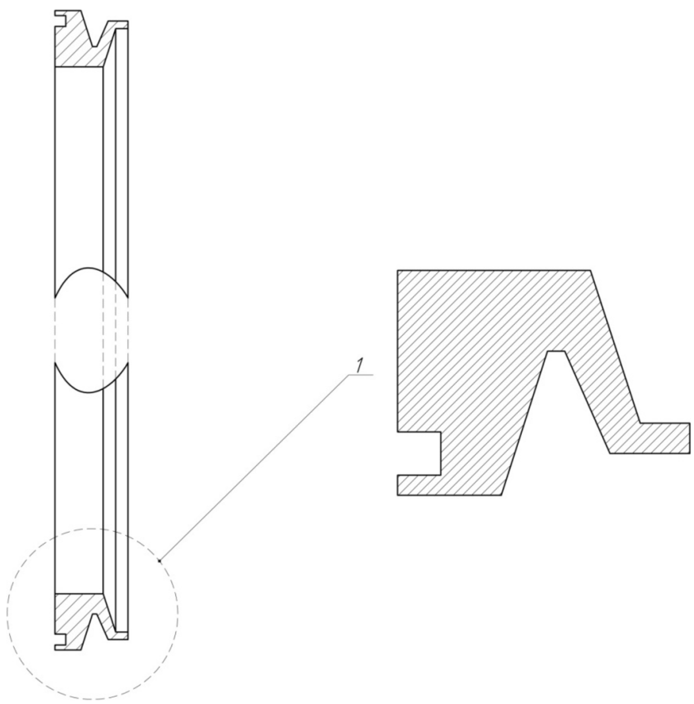


Fig. 7. Key thumbnail in the adapter PAS C/S Adapter: 1 — groove of a key

Unstressed capture of PAS S/C Adapter is achieved by compensating force, which effector has applied, and the counteracting reactive force applied by the adapter in relation to the effector. Such phenomenon is achieved through the restrictions that are imposed by effector's links, after effector girth adapter and until the approach of capture. Monaural compression values of the S/C Adapter are determinate from the selected capture algorithm, force sensors, which are integrated in the composition of effector's actuators, and sensors of the optical leane interruption (Fig. 6, s2), which works when the ray crosses S/C Adapter elements. Prevention of incomplete capture (Fig 6, S/C1) is ensured by a coordinated action of SSC's vision and technical means.

The final fixation when capture arises due to the to reduction of the free zone of the adapter movement zone within the board lines of effector's zone (Fig. 6, CapZ), which occurs as a result of translation motion in the effector units in the corresponding hinges (Fig. 6, k7, k9).

Process of S/C Adapter's fixation is accompanied by mutually rotation of the effector, which prevents the occurrence of angular momentum between effector and the adapter. Such rotation is provided by hinges, which are shown on Fig. 6 (k2, k3, k4).

4 Program of the connection of the SC

In program of the connection of SCs, that involves the joint movement of devices, a required condition is preliminary alignment of their axes. Moreover, design of satellites involves the axial position of the point mass center (MCP) that provides position of a common MCP on a vector of the main SC's engine. For convenience, process of berthing is divided into two phases:

1. berthing with capture;
2. orientation of SC on one common axis.

During the first phase RM CS initiate the execution of operations of effector preparation for capture. Coordination of axes of effector and S/C Adapter is achived.

Berthing SSC to NCSC and their relative position is determinated by service spacecraft Control System (CS), however CS sets positioning faults, that can cause invariant of SC position. In this case there is a need compensation of the fault by means of the console and the effector that are part of the robot-manipulator.

Due to the pair of hinges, which are placed at the base and at the end of the RM's console and thanks to the telescopic pair of links, final effector can be positioned in the plane of S/C Adapter. Control of effector positioning is possible due vision means. The process of compensation of linear and angular faults within the plain is shown on Fig. 8.

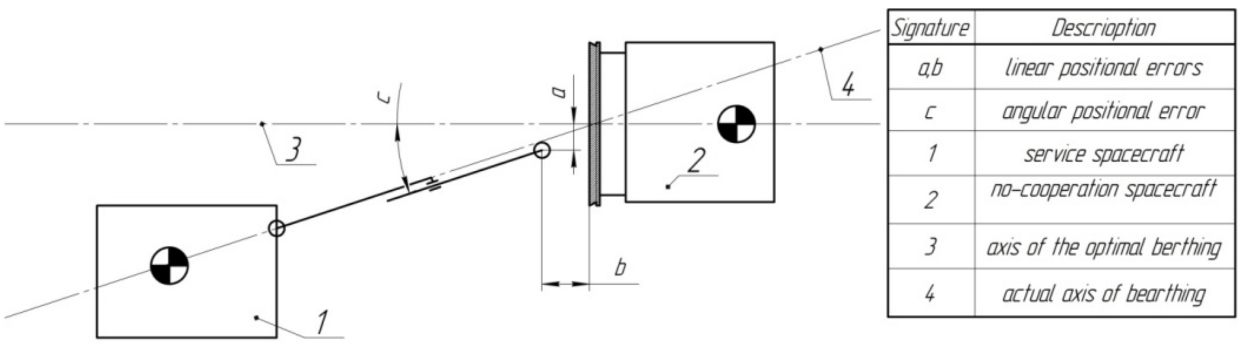


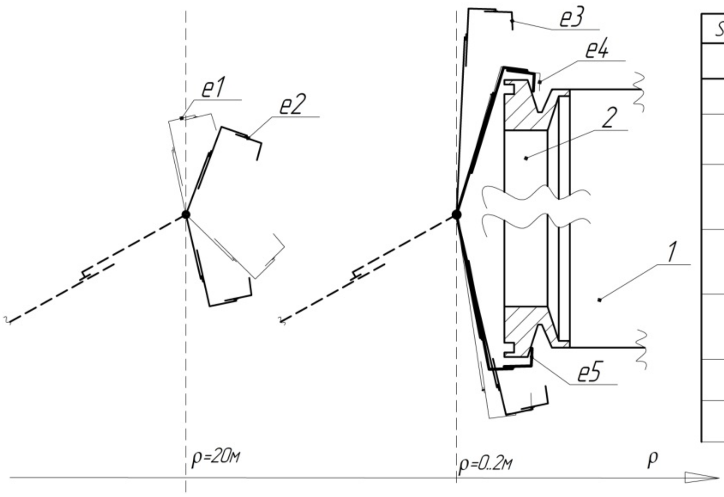
Fig. 8. Visualization of faults of relative position SSC and NCSC

It is important to note that at the stage of berthing robot's effector does not interact with NCSC, which leads to preservation of the Newton's first law.

Capture procedure provides aligment of SSC and NCSC mass center points (MCP) without their displacement by applying an equal number in magnitude and opposing forces in the direction of the effector. During the berthing RM can act on NCSC with essential force, which in the case of inaccurate capture, will give NCSC uncontrolled movement. For the capture of NCSC without increase acceleration to it, effector of RM has to cover structural components of S/C Adapter without contacting them. This procedure is shown on Fig. 9.

First stage is held on the “decision-making” distance (20 meters between NCSC and SSC). At this stage operations of initialization of sensory system, executive devices and RM CS are performed. At a distance ρ=20 meters, effector of RM is introduced into the work zone of manipulator. According to data from RM CS, means of technical vision and sensors and the position of links is carried out by coordinating the position of the effector in 3 coordinates. At the same time, angular orientation of effector stays random. (Fig. 9, e1).

On the second stage effector places in parallel to the plane of S/C Adapter. Second stage is carried at the “berthing” distance (about two meters between NCSC and SSC). At this stage the calibration of vision devices is performed according to sensors of orientation and position of RM's links. The classification of the S/C Adapter is carried out. Algorithm of berthing and capture is determinate (Fig. 9, e2).



Signature	ρ	Description
ρ	-	Distanse between NCSC and SSC (m)
e1	20	Stage 1. Alignment of axes of NCSC and SSC
e2	20	Stage 2. Effector orientation parelel to the plane of S/C Adapter
e3	0.2	Stage 3. Grasping of S/C Adapter by effector with taking into account errors of positional errors
e4	0	Stage 4. Insertion of the capture mechanism in the groove of the S/C Adapter
e5	0	Stage 5. Capture the S/C Adapter by effector through contraction of the effector's links
1	-	S/C Adapter
2	-	No-cooperation spacecraft (NCSC)

Fig. 9. Capture procedure S/C Adapter of NCSC by effector of RM

At the third, forth and fifth stages(Fig. 9, e3 - e5) operations of girth and capturing the S/C Adapter's construction part are performed by the effector. Taking into consideration huge number of S/C Adapter versions, effector can change zone of girth and capture in depending on the chosen algorithm, which is selected in the second stage.

During the second phase CS of RM initiate coordination of SSC and NCSC axes. For this angle c (Fig. 8) reduces to zero. After aligment of axes hinge joint of SSC, RM, NCSC design is constant, and limiting relative displacement new position of the all MCP are considered. MCP position coincides with axis of the devices (which passing through their apogee engines). This orientation of the devices allows to use apogee engine of SSC as the motor of whole construction.

5 Conclusion

Researches, which were held in this work, showed that procedure of non-cooperative capture and docking operations are economical and scientific actual engineering problems and the development of the space industry of the human management requires the technical means for carrying out satellites, their recycling, execution of mechanical operations etc.
The proposed principle and the concept of the structure of the robot-manipulator of a service spacecraft will allow the procedure of capturing spacecraft with the mass up to 5000 kilograms in conditions of uncertain definition of their spatial position and proposed structure of the adapter design. Working on the principle of chain will allow to carry out girth, capture and holding of SC, which is equipped by PAS 1666 S, PAS 1194 C, PAS 1666 MVS, PAS 1184 VS with positional fault 10° per minute and 0.1 m3.

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