Article

Structural Model of Robot-Manipulator for Capture of No-Cooperation Client Spacecraft

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Abstract: In this work is represented conceptual model of robot-manipulator for capture and holding no-cooperation client spacecraft, which has Payload Adapter interface PAS 1666 S, PAS 1194 C, PAS 1666 MVS, PAS 1184 VS, when there are dynamic errors of linear and angular position of client spacecraft in the interval +/-5^0 per minute and +/-0.1 meters per minute respectively.

Keywords: pay load adapter; robotic arm; no-cooperation spacecraft; suitable docking port

1. Introduction

Today on the geostationary Earth orbit (GEO) there are about 1500 satellites, 750 of which require reorientation, motion or another service operation [5]. Mostly all spacecrafts (SC) with weights more than 500 kg were placed into GEO by medium-lift and heavy-lift launch vehicle 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. Therefore such vehicles are not equipped by automatic docking means (IDBS) and need special methods, instrumentality and scripts for this operations.

The analysis of next reports: Department of Mechanical Engineering Massachusetts Institute of Technology [7], International Astronautical Congress [8], University of Nebraska - Lincoln U.S. Air Force Research U.S. Department of Defense [9] and publications [4], [5], [6] showed that at the moment there are no docking means for service spacecraft (SSC) with no-cooperation spacecraft (NCSC) in automated or automatic modes. Reasons for this are complexity of such operations, their cost, lack of hardware-technical solutions, single standards of interfaces and functioning protocols of equipment in situations, which arise during process of approach, berthing, docking, undocking, unberthing and projection of SC. [6]. Docking with NCSC in manual mode is considered in works [4], [5]. However, duration of this operation is longer than five hours and needs both presence of cosmonaut (astronaut) and complex equipment on SSC.

Thereby, 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 not have economical, social or scientific sense.

2. Problem formulation

Process of docking NCSC with SSC is performed by using a script, which is presented in table 1. This script includes nine stages. Five of them are essential for orbital docking of SC [4] and must be fulfilled automatically.

Stages 1, 2 have turn-key solution [12], [13], and stages 3, 4 were carried out within Space Orbiter programs and described in publications [12], [13], [14], [15]. Stages 6-8, which provide process of "soft" docking, are performed only in manual mode. Process of their automation needs development of new control means and systems.

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

№	Stage name	Stage description
1	NCSC position determination	Determination of the positional relationship of NCSC and SSC with GPS navigation and radio-location tools.
2	Approach of NCSC and SSC to a distance 200 m.	Approaching SSC to a distance of the first suspension for the preparation of docking equipment
3	Approach of NCSC and SSC to a distance 20 m.	Approaching SC to a distance of a second suspension for testing docking and fixing equipment of apparatus' continuation.
4	Search for the docking plane on NCSC	SSC flight-around NCSC for searching of the docking plane. Determination of the position of docking port. Comparison of apparatuses dynamic behaviors.
5	Berthing SSC to NCSC on a 2 meters distance	Approaching SSC to NCSC on the service distance with further approach. Positional relationship and orientation of apparatuses are coordinated.
6	Determination the position of docking point	Optical, analytic and radio-locating determination of docking port on NCSC's docking plane. Estimate of entering cone.
7	Capture and retention of NCSC by SSC tools	Jogless containment of NCSC with mechanical tools of SSC and further fixation of linear and angular displacement of NCSC.
8	Matching of electric and mechanic parameters of apparatuses	Matching of rotation angles in relative planes electric level 0 V and digital interfaces.
9	Unberthing of SSC from NCSC	Unberthing of SSC on a distance of 20 m with further return to the previously specified orbital position.

3. Conceptual design of robot-manipulator

Suitable Docking port (DP) in modern SC is nozzle of apogeum motor (fig. 1) and SpaceCraft adapter ring (S/C) Payload Adapter (fig. 2). Specification on them can be found accordingly in service instructions [1], [2], [3]. This nodes are characterized by high rigidity and coaxiality axis of apparatuses' mass, what allows to motion NCSC with mechanic tools which are located in SSC. [1], [2], [3].

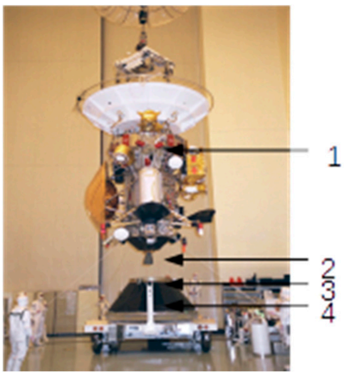

Figure1. Spacecraft "Cassini-Huygens" with available S/C adapter ring and nozzle of apogeum motor in process of connecting to PAS: 1 – system block of SC; 2 – nozzle of apogeum motor; 3 – S/C adapter ring; 4 – PAS

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(photo is used with permission of European Space Agency, Communication Department)

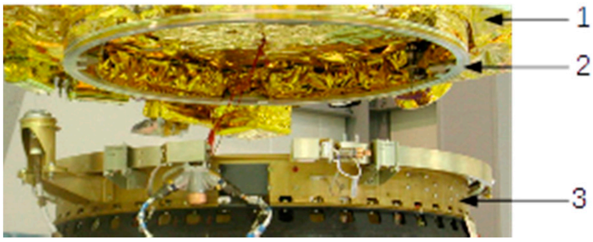

Figure 2. Connection of SC with Payload adapter PAS 1194 C with means of S/C adapter ring: 1 - system module; SC; 2 — contact plane of SC with PAS by S/C adapter ring means; 3 - Payload adapter(photo is used with permission of European Space Agency, Communication Department)

Capture and holding of NCSC by the listed above ports needs compensation of error relatively to the positional relationship, which is caused by means of radar sensor system. This system is defined by low resolution on the distance of 20 meters [11], and has stationary character and is set by six degrees of freedom (DOF).

Typical design of S/C Adapter, which remains on SC after itsunberthing from the NCSC's launch vehicle (fig. 3) has mounting hardware (keys) to Payload Adapter. Keys provides “unberthing” of SC from launch vehicle through pyrotechnic fasteners. After unberthing from launch vehicle S/C Adapter stays on SC and in not in use again for period of active existence of satellite in GEO. Mechanical characteristics of pyrotechnic fasteners' mounting hardware allow holding on NCSC to the S/C Adapter 's mounting hardware in case of uncoordinated docking with further coordination of dynamical and mechanical parameters of butt-jointed apparatuses.

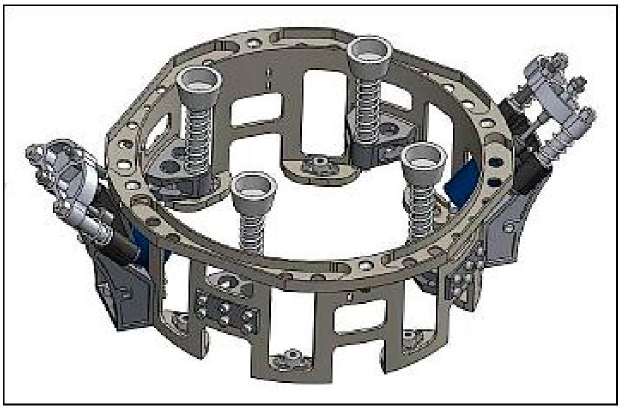

Fig. 3.Typical design of S/C Adapter

In such a way, for providing automatic capture of SC for S/C Adapter's elements it is necessary to set specification of capture adapter with range of diameters 800-1400 mm, and at the same time save the coaxiality of console, final effector, NCSC and SSC. It is important to note necessity of jogless capture in the conditions of dynamic positioning error of apparatuses. In works [10], [16] the possibility of such a capture is considered howevercoaxiality of SC is not provided.

Structure of effector has to provide the opportunity of capturing NCSC with consideration of all such factors: the presence of linear and angular error of locating; limited time of being on the distance of berthing of NCSC and SSC; huge amount of S/C Adapter's standards, that differs by sizes and design; the lack of standard markers on NCSC adapter; the lack of friction force between NCSC and environment.

Then, with taking to the account the above, capture of NCSC by RM has to meet the requirements, specified in Table 2 and described in [4].

Table 2. Conditions to th opportunities of RM for capture of NCSC

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№	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 speed of capture	to 10° per 1 min
4	Relative linear speed of capture	to 0.1m per 1 min
5	Zone of positional relationship's insensibility	to 0.1m
6	Permissible dimensions of S/C Adapter	0.6-3m
7	Permissible mass characteristics of SC	to 5000 kg

Conditions for SSC, which are listed in table 2 (it. 1 and 2) are caused by specifications of NCSC, in particular by generalized length of satellite's solar batteries, location of antennas, radius of SC's entering cone, linear and angular errors of positional relationship of SSC and NCSC. In such conditions, delivery of RM's effector to S/C Adapter is available by using telescopic console, which is equipped by two corner hinges: double-axis hinge 1 and triple-axis hinge 2, which are located in places of console fastening to NCSC (p. A) and final effector (p. B) in accordance, which kinematic structure is shown on fig 4.

Double-axis hinge 1 and telescopic link of robotic console 3 provides work of final effector in polar coordinate system. Triple-axis hinge 2 provides cardan joint of final effector. That allows to compensate errors of its locating. Such kinematic structure of robotic console prevents the emergence of link's singularity, however does not provide problem of final effector locating in S/C Adapter area for committing the jogless NCSC capture. Solution of this problem is possible only by equipping the effector by sensor means, which are suitable for cooperation and relative position of final SSC effector and NCSC S/C Adapter.

Considering available linear and angular errors of apparatuses positional relationship, guaranteed effector positioning for its further girth and capture of S/C Adapter is possible in segment of work zone (fig. 5 it. 1). Opportunity of capturing NCSC with deviation close to zero although possible in areas, which are shown on fig. 5 (it. 2 and 10). Another zones, which are shown on fig. 5 are assigned for equipping SC or used as a part of technical operations of apparatus work.

Zone of insensibility (table. 2, it. 5) and odd of S/C Adapter's radii (table. 2, p. 6) impose restrictions on the choice of the effectore's design and set of sensor system means. “Zone of insensibility” implies impossibility of sensor system means, which are located within the SSC control system (CS), give accurate coordinates of distance and orientation of NCSC. Error with per minute can cause a collision of effector with S/C Adapter and give it relative acceleration.

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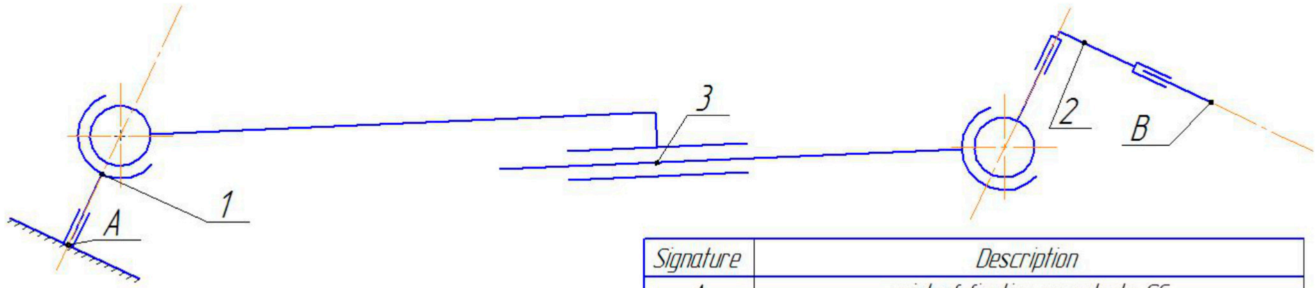
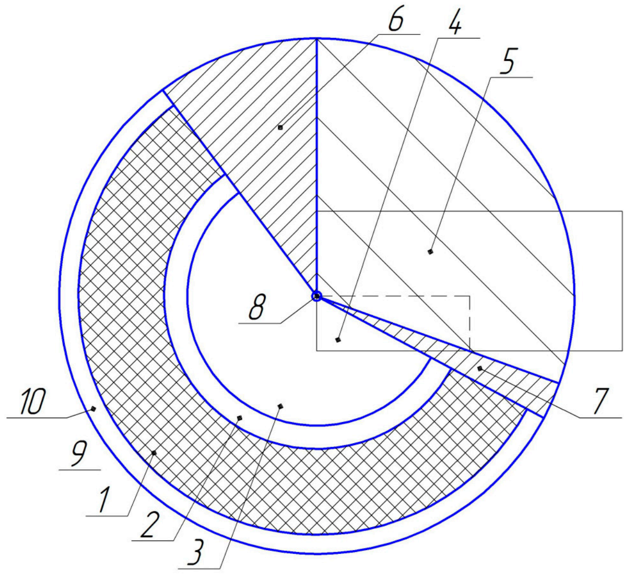


Signature	Description
A	point of fixation console to SC
B	point of fixation effector to console
1	double-axis hinge
2	triple-axis hinge
3	linear conection of telescopic pare of links

Figure 4. Kinematic structure of telescopic console



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

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

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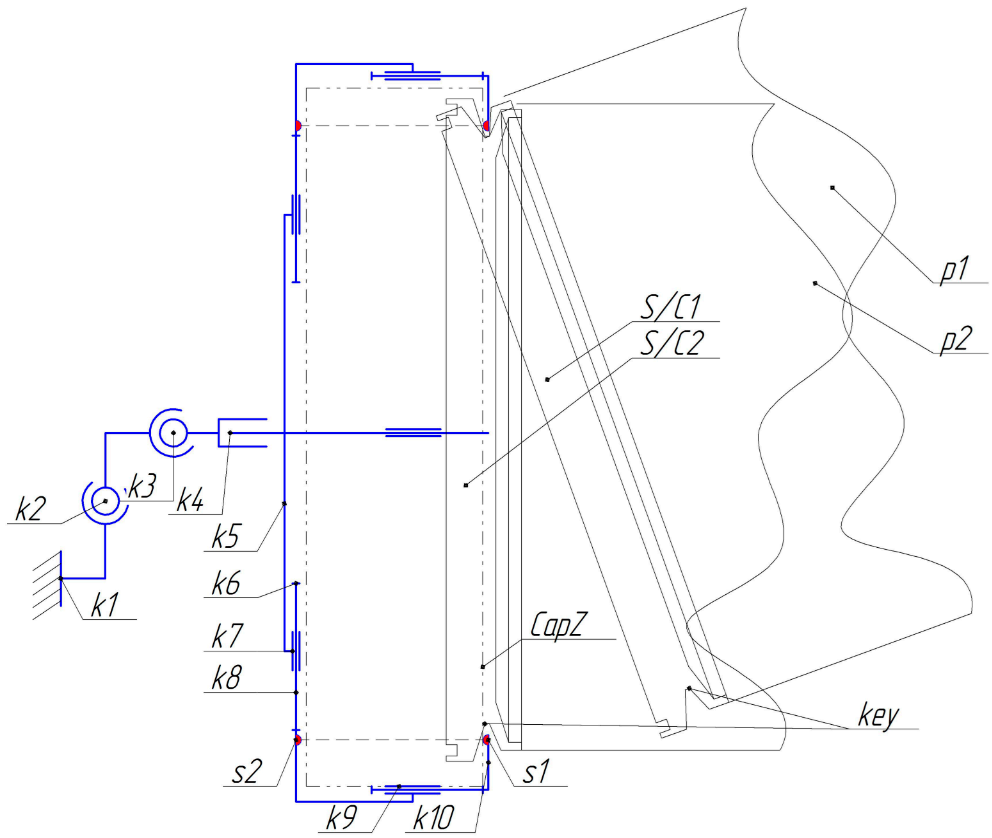

Signature	Description	Signature	Description
k1	Base point of effector	s1	Source of laser ray
k2, k3, k4	corner hinges of effector's orientation	s2	Optical diode
k5	Base link of kinematical link pair of effector	S/C1, S/C 2	Position of S/C Adapter in the groove of effector and behind the groove
k6	Damper 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

Figure 6. Kinematic structure and main node of such collet effector.

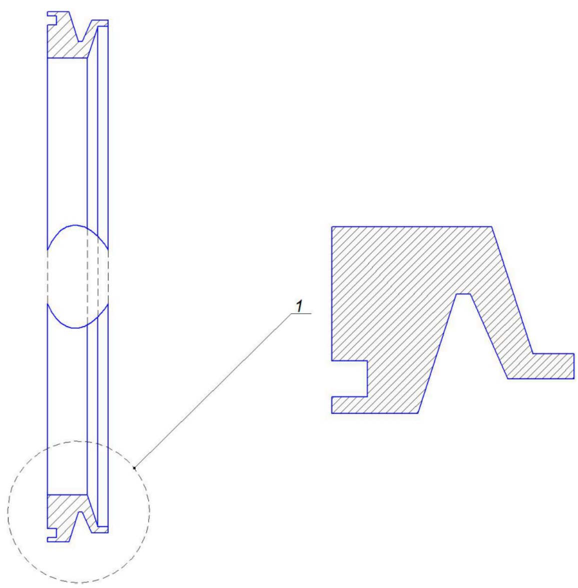

Figure 7. Design of key in composition of adapter PAS C/S Adapter: 1 — groove of a key.

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It is possible to compensate error on account of effector's physical influence on S/C Adapter after its girth. Adaptation to the diameter of PAS is reached by usage of effector with collet principle of a squeeze. Kinematic structure of such effector is shown on fig. 6. Contact area of effector has unchangeable form because of unification of key design in PAS S/C Adapter. Form of the adapter's key is shown on fig. 7.

Jogless capture of PAS S/C Adapter is achieved by compensation of force, which effector has applied, and opposite jet force, which adaptor has applied to effector. This effect is reached due to limitations that are imposed by effector's links, after effector girth adaptor until the approach of capture. Boundary values of the squeeze of S/C Adapter are determinate by the selected algorithm of capture, force sensors, which are integrated in the composition of effector's actuators and sensors of optical interruption of the ray (fig. 6, s2), which goes off when the ray crosses elements of S/C Adapter. Prevention of not full capture (fig 6, S/C1) is provided by coordinated action of SSC's vision means.

Residual fixation during capture is due to reduction of the free movement zone of adapter within the board lines of effector's zone (fig 6, CapZ), what comes as the result of translation motion in the matching hinge (fig. 6, k7, k9).

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

4. Docking program of SC

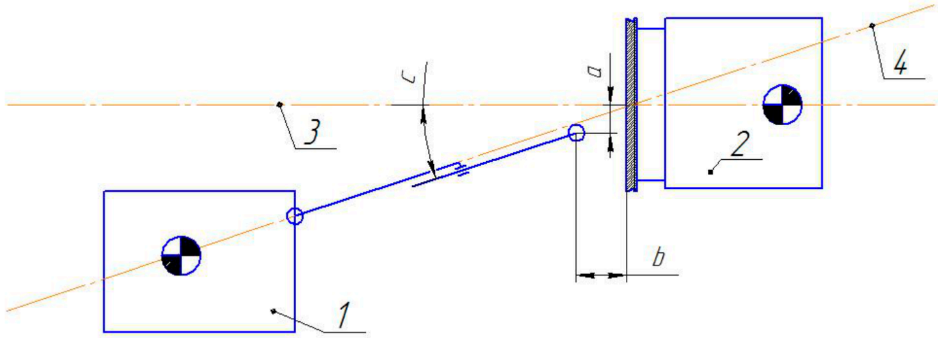
In docking program of SCs, that provides joint movement of apparatuses, prerequisite is prior alignment of their axes. At the same time, design of apparatuses provides axial of mass center point (MCP), that provides positional relationship of shared MCP on a thrust vector of the main SC's engine. For the convenience, process of berthing is divided into two phases:

- berthing with capture;
- orientation of SC by one shared axis.

During the first phase RM CS initiate execution of effector preparation operations for capture. Occurs adjustment of effector's and S/C Adapter axes.

Berthing SSC to NCSC, their positional relationship is set by service spacecraft CS, however CS sets positional error, which can call invariant of SC position. In this case there is a need for error compensation through mains of console and effectore, which are part of the robot-manipulator.

Through pair of hinges, which are placed on the base and on 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. Process of compensation of linear and angular errors within the plain is shown on fig. 8.



Signature	Description
a,b	linear positional errors
c	angular posotional errors
1	servise spacecraft
2	no-cooperation spacecraft
3	axis of the optimal berthing
4	actual axis of bearthing

Figure 8. Rendering of positional relationship error of SSC and NCSC

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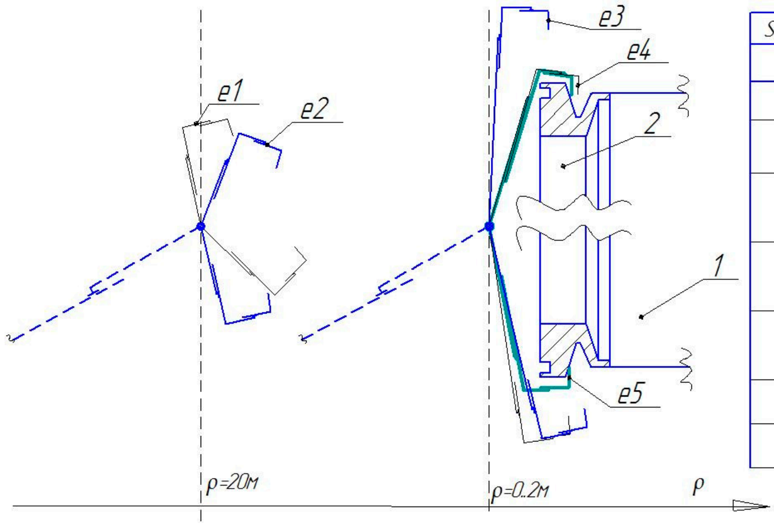

Signature	ρ	Description
ρ	–	Distanse between NCSC and SSC
e1	20	Stage 1. Alignment of axes of NCSC and SSC
e2	20	Stage 2. Effector orientation parelel to the plane of S/C Adapter
e3	0.2	Stage 3. Grasping of S/C Adapter by effector with taking into account errors of positional errors
e4	0	Stage 4. Insertion 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)

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

It is significant to note that on 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 cooperation of SSC and NCSC mass center points (MCP) without their displacement through forces, which are applied by effector and are equal by value and opposite by direction. 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 step is held on the “decision-making” distance (20 meters between NCSC and SSC). On this step initialization operations of sensor system, executive devices and RM CS are performed. On the distance ϱ=20 meters effector of RM insert into the manipulation work zone. According to data from RM CS, vision, sensors of links orientation and position concordance of effector's position by three coordinates is carried out. At the same time, angular orientation of effector is remains random. (fig. 9, e1).

On the second step effector places in parallel with plane of S/C Adapter. Second step is carried on the distance of “berthing” (about two meters between NCSC and SSC). On this step takes place calibration of vision according to sensors of orientation and position of RM's links. The S/C Adapter is classified. Algorithm of berthing and capture is determinate (fig. 9, e2).

On the third, forth and fifth steps (fig. 9, e3 e5) operations of girth and capture of structural part of S/C Adapter are carried by effector. Taking into consideration huge number of S/C Adapter versions, effector can change zone of girth and capture in dependence of determinate algorithm, which was chosen of the second step.

During the second phase CS of RM initiate coordination of SSC and NCSC axes. For this angle (fig. 8) leads to zero. After coordination of axes hinge joint of SSC, RM, NCSC design is fixed, what confine relative displacement. This gives new position of MCP of all the design. Position of MCP coincide with axis of apparatuses (which goes through their apogeum motors). This orientation of the apparatuses allows to use apogeum motor of SSC as the motor of whole construction.

5. Conclusion

Researches, that were held in this work, showed, that procedure of no-cooperated capture and docking operations is economically and scientifically actual engineering problem, and development of space industry of the human menage needs technologies for satellites extirpation, their recycling, execution of mechanical operations etc.

The proposed principle and design conception of service of the spacecraft robot-manipulator allows to carry out capture procedure of spacecraft with wights up to 5000 kilos in conditions of incomplete definition of their spatial position and suggested adapter design, which works on the principle of collet. This conception allows to make girth, capture and holding of SC which is equipped by PAS 1666 S, PAS 1194 C, PAS 1666 MVS, PAS 1184 VS with positional error 10° per minute and

The proposed solutions needs further development and solving of such actual problems:

development of kinematic structure of robotic console and effector, which have to consider features of fastening console to basic structure of SSC, and principle approaches to provide linear and angular motion of the links;

(a) calculation of angular and linear position of the links and effector, determination of speeds and accelerations of links, calculating moments and determination of work zone and singularity zone;
(b) selection of the engines and actuators types, which allows effectively provide linear and angular motion of the colsole's and effectore's links in terms of space. In particular, chosen engines must be characterized by low wight, huge moment, low consumption, working voltage range less that 20 Volt, minimum requirements to climatic conditions and possibility of accurate refining of angles and rotation speeds. Furthermore, actuators have to provide translational motion of the links in space conditions as well as angular motion of the links in two or three planes;
(c) choice of the materials for console's and effector's links has to provide minimal weight with high rigidity. Important is appropriateness of chosen materials in application conditions and with minimal level of capacity, permeance and radio-wave absorption;
(d) development of action script of the robot-manipulator system, which contains control algorithm of RM and process of its co-operation with SSC CS ;
(e) development of technical equipment and script of output from transfer position;
(f) development of mathematical and computer methods of simulation RM actions and control.
(g) development of methods and means of vision for RM;
(h) development of interaction protocols between RM CS and SSC CS;
(i) development of hardware for RM CS, sensor system and power supply means;
(j) development of ground part of diagnostic, arrangement and management equipment as well as equipping of auxiliary service;
(k) development of marking standards of S/C Adapter and improvement systems for burial of SC;
(l) determination of spacecraft's orientation engine location for cases of variable position of MCP.

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