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A Space Robotic System Used for On-Orbit Servicing in the Geostationary Orbit

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Abstract—**The failures of GEO (Geostationary Orbit) spacecrafts will result in large economic cost and other bad impacts. In this paper, we propose a space robotic servicing concept, and present the design of the corresponding system. The system consists of a 7-DOF redundant manipulator, a 2-DOF docking mechanism, a set of stereo vision and general subsystems of a spacecraft platform. This system can serve most existing GEO satellites, not requiring specially designed objects for grappling and measuring on the target. The serving tasks include: (a) visual inspecting; (b) target tracking, approaching and docking; (c) ORUs (Orbital Replacement Units) replacement; (d) un-deployed mechanism deploying; (e) extending satellites lifespan by replacing its own controller. As an example, the servicing mission of a malfunctioned GEO satellite with three severe mechanical failures is presented and simulated. The results show the validity and flexibility of the proposed system.**

I. INTRODUCTION

The Geostationary orbit (GEO) is very precious but limited orbit resource of the human beings. Most GEO satellites have high values and long life time. Frequent failures of GEO satellites result in large economic cost and other bad impacts; continuous increasing of GEO debris makes the GEO orbit more and more crowded. Therefore, the GEO orbital servicing technologies, whose purposes are repairing satellites and cleaning up the space debris, are comprehensively emphasized.

The GEO satellites are generally non-cooperative, i.e. neither any artificial patterns used for measurement, grappling fixtures for capturing, nor specially designed mechanism for docking, are mounted on them. The key technologies of target tracking, approaching, capturing, and docking demonstrated on ETS-VII [1] and Orbital Express [2] can not be directly used. ESA (European Space Agency) presented GSV (Geostationary Service Vehicle) to provide in-orbit inspection and robotic servicing for geostationary satellites[3], and ROGER (Robotic Geostationary Orbit Restorer)[4] to clean up the geostationary orbit of switched-off satellites and debris by transporting them into a graveyard orbit. DLR(German Space Agency) proposed the ESS telerobotic concept to repair a failed GEO satellite [5]. Orbital Recovery Limited addressed CX-OLEV (ConeXpress-Orbital Life Extension Vehicle)[6] and SMART-OLEV to extend the operational life of geostationary telecommunications satellites[7]. Another important servicing concept is FREND (Front-end Robotics Enabling Near-term Demonstration) (Spacecraft for the Universal Modification of Orbits) [8], whose purpose is to demonstrate the integration of machine vision, robotics, mechanisms, and autonomous control algorithms to accomplish autonomous rendezvous and grapple of a variety of interfaces traceable to future spacecraft servicing operations.

In this paper, a universal system is proposed for the on-orbit servicing in GEO. The system, named GEOSS (On-orbit Servicing System in GEO) has a 2-DOF docking mechanism, a 7-DOF redundant manipulator (with replaceable end-effectors) and a set of binocular cameras, as well as traditional subsystems of a spacecraft. The GEOSS can service most GEO satellites, without any artificial aids on the targets. It can serve most existing satellites in GEO, not requiring specially designed objects for grappling and measuring on the target.

The paper is organized as follows: Section two analyzes the current status and trends of the GEO environment. Section three proposes a space robotic servicing concept and designs the corresponding system. Then, as an example, an on-orbit servicing mission for a multi-malfunctioned GEO satellite is designed and simulated in Section four. Section five is the discussion and conclusion of the work.

II. THE STATUS AND TRENDS OF THE GEO ENVIRONMENT

A. The Current Status of the Objects in GEO

According to the latest status report by ESA on geosynchronous objects, till the end of 2009 [9], the total number of known objects in the geostationary ring is 1238, out of which only 391 (about 31.6%) objects are controlled. It must be pointed out that, limited by the capability of detection devices on the earth (e.g. Radar and optical telescope), only the objects above the range of 1m diameter can be detected. Smaller objects cannot be detected from the ground. Therefore, the real situation is more serious.

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B. *The Launching and Re-orbiting of GEO Satellites*

Since the launch of Syncom-3 in 1964, more and more satellites and rocket upper stages have been put into GEO ring [10]. The GEO catalogue is steadily increasing at a rate of about 30 objects per year. The GEO orbit will be over-crowded if not any measures are taken to mitigate the space debris of GEO. Typically, the control accuracy of the station keeping is within ±0.1^{o}, then the GEO orbit can accommodate maximal 1800 (=360^{o}/0.2^{o}) satellites theoretically. In order to preserve the synchronous region, professional associations, international bodies, satellite operators and space agencies developed specific recommendations and national guidelines[11].

As for the end of 2009, some satellites have been re-orbited successfully, i.e. the graveyard orbit complying with the IADC (the Inter-Agency Space Debris Coordination Committee) re-orbiting guidelines [12-13]. Integrating and analyzing the data of different information sources, the annual launching and re-orbiting GEO satellites, together with the GEO satellites which reached the EOL(end of life), are analyzed. The results are given in Table. 1.

Table. 1 The launch and re-orbiting of the GEO satellite

year	Succeed to Reach GEO	Fail to Orbit	Rocket Bodies	Reach EOL	Successfully Re-orbiting	Re-orbiting Ratio(%)
1997	35	0	-	17	7	41.2
1998	29	3	-	21	7	33.3
1999	22	6	-	12	4	33.3
2000	43	4	-	11	3	27.3
2001	22	1	-	14	2	14.3
2002	28	3	-	11	4	36.4
2003	28	0	-	16	8	50
2004	19	1	5	13	5	38.5
2005	22	0	3	18	10	55.6
2006	29	2	2	16	7	43.8
2007	25	3	2	13	11	84.6
2008	30	2	4	12	7	58.3
2009	30	1	3	21	11	52.4
Total Average	28	2	3.2	15	6.6	44.1
5-year Average	27	1.6	2.8	16	9.2	57.5

Table. 1 shows that, compared with the previous (before 2001) about 1/3 successfully re-orbiting ratio [13], the proportion of the successfully re-orbited satellites is largely increasing. In the latest 5 years, the annual average has reached 57.5%. According to Table. 1, in the last 13 years (1997~2009), there are annually 28 satellites and 3 rocket bodies were launched to GEO, but only 7 (actually 6.6) satellites were re-orbited successfully. Therefore, the GEO objects in each year after 2009 can be estimated using the following equation:

$$n_{year} = n_{2009} + \left(\overline{n}_{launch} + \overline{n}_{rocket} - \overline{n}_{reorbit}\right)\left(year - 2009\right) \quad (1)$$

Where, n_{2009} (=1238) is the identified GEO objects at the end of 2009, $\overline{n}_{launch}$ and $\overline{n}_{rocket}$ are the annual average values of the launched satellites and rocket bodies and $\overline{n}_{reorbit}$ is the annual average number of re-orbited satellites. For example, the GEO objects in 2050 can be estimated as:

$$n_{2050} = 1238 + \left(28 + 3 - 7\right) \times \left(2050 - 2009\right) = 2222 \quad (2)$$

The number of the GEO objects varies as time is shown as Fig. 1. Hence, the study on the GEO orbital servicing technologies is very important.

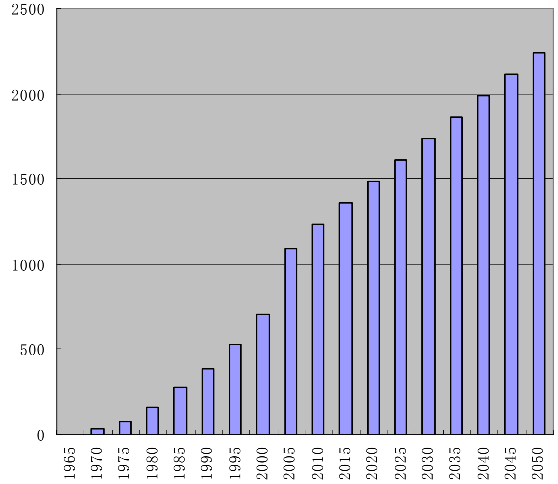

Fig. 1 The estimated numbers of the GEO objects in future

III. A SPACE ROBOTIC SYSTEM DESIGNED FOR GEO ORBITAL SERVICING

A. *The Configuration of the System*

A designed space robotic system for GEO orbital servicing is shown as Fig. 2. The total mass and power of the system are 500kg and 400W respectively.

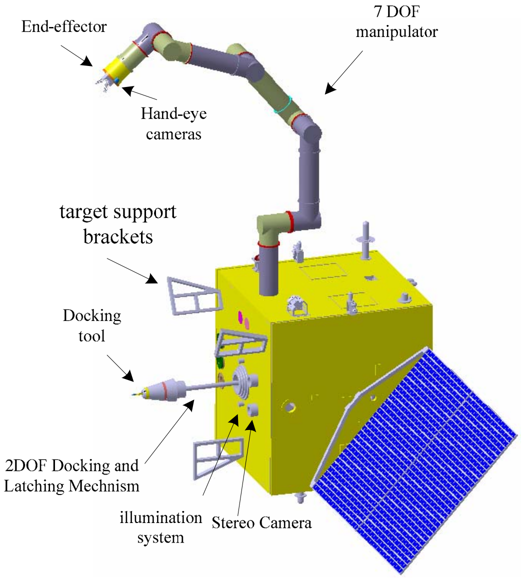

Fig. 2 A designed space robotic system for GEO orbital servicing

The system is mainly composed of the following parts:

1) a 7-DOF (Degree of Freedom) manipulator with two hand-eye cameras and a replaceable end-effector

The manipulator has 7 serial revolution joints. It is used to repair the malfunctioned GEO satellite, for example, to deploy the un-folded mechanisms, transfer and install ORUs (Orbital Replacement Unit), and so on. Compared with its

6-DOF (Degree of Freedom) counterpart, the 7-DOF redundant manipulator is very flexible for singularities handling, obstacle avoiding, tumbling satellites capturing, etc.

2) a 2-DOF docking and latching mechanism (DLM) and three target support brackets (TSB)

The docking and latching mechanism (DLM) has two DOFs ---- a translational DOF and a revolution DOF, which are respectively extend-and-retract (using the translational joint), and rotate (using the revolution joint) the docking tool. The docking tool is specially developed to capture the apogee engine nozzle of GEO spacecrafts. Once within the engine injector, the tool uses a crown locking mechanism to maintain contact. The concept comes from the classical docking tool first proposed by DLR[5]. Three target support brackets, located on GEOSS top panel and compatibility with the launch vehicle interface ring, sustain the target satellite when it is pulled down by the DLM on to them. Then the target can be tightly fixed on the chaser under the resultant action generated by the pull force of the DLM and the support force of the TSB.

3) a binocular stereo vision and illumination system

The stereo vision and illumination system, mounted on the top panel (near the DLM) of the chaser, are used to supply the relative pose measurement of the target during the close approaching and station keeping at the berthing point, where the DLM can reach the apogee engine nozzle of the target. The launch vehicle interface ring and the apogee engine nozzle are chosen as the features to be recognized. These two types of features are combined to satisfy the measurement needs, which depend on the distance to the target. When the distance is longer, the interface ring is used as the main feature. On the other hand, the nozzle is used as the main feature when the chaser is very close to the target. For the middle distance, they can be recognized at the same time, when redundant features information can be used.

4) The GNC (Guidance, Navigation and Control) System

The chaser is controlled to approach and rendezvous with the target with a desired pose for the 2-DOF DLM to easily dock with the target. During the approach, the manipulator keeps the fixed configuration and not generates disturbance on the base, i.e. the traditional navigation, guidance and control method can be used. The control loops for attitude and orbit control include the sensors for position and attitude measurement, the GNC functions, and the actuators (thrusters, reaction wheels, et al) for attitude and position control.

5) The Planner and controller of the Manipulator

The main function of the planner is to plan the motions of the manipulator according to different tasks. The planner outputs the desired joint angles and rates at 4Hz. Then, each joint controller, whose control cycle is about 5ms (i.e. the control frequency is 200Hz), interposes more path nodes between the current values and the desired values using the 3rd spline function, and drives each joint to track the desired motion.

6) Others

Except for those mentioned above, the space robotic system has the necessary sub-systems as other spacecrafts, such as the structure, power, propulsion, Telemetry/Telecommand, et al.

B. The 7DOF Redundant Manipulator

The redundant manipulator used for the on-orbital repairing mission has seven serial revolute joints; its stored configuration is shown as Fig. 3. The length is about 3m. Table. 2 lists the corresponding DH (Denavit-Hartenberg) [14] parameters of each link.

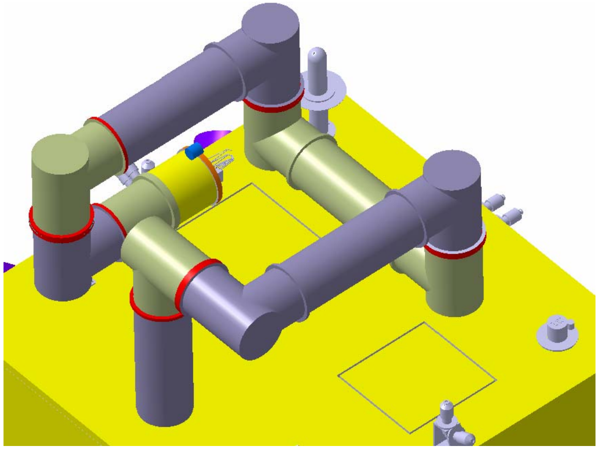

Fig. 3 The 7-DOF Manipulator (stored configuration)

Table. 2 The DH parameters of the 7-DOF Manipulator

Link i	θ_i /°	α_i /°	a_i /mm	d_i /mm
1	0	-90	0	0
2	180	90	a_2=720	d_2=320
3	-90	0	a_3=720	0
4	0	90	0	0
5	180	90	0	d_5=720
6	180	-90	0	d_6=320
7	0	0	0	d_7=475

C. The 2DOF Docking and Latching Mechanism

The 2-DOF docking and latching mechanism (DLM) has a translational joint and a revolution joint. The translational joint is used to extend and retract the docking tool, which will be insert apogee engine nozzle of the GEO target satellite. And the revolute joint can rotate the captured target when required, for example, to facilitate the manipulator repairing different devices on different panels of the target, and establishing a good orientation of the target after releasing it. The docking tool is very similar with that of the SMART-OLEV [7].

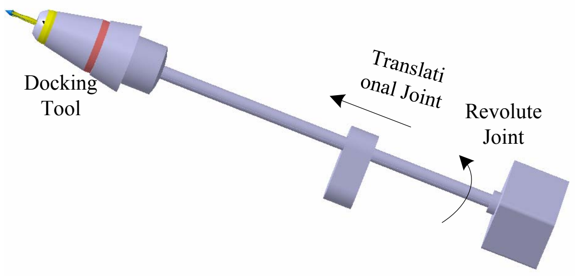

Fig. 4 The 2DOF docking and latching mechanism

D. *The Stereo Vision System*

To supply the relative pose of the non-cooperative target, we designed a binocular stereo vision system. It is well known to all, the imaging of a camera is usually modeled using pin-hole projection model. Assume a point *P*, whose coordinates whose coordinates in $\sum_W$ (the world frame) are denoted by ${}^{W}\boldsymbol{P}=[X_W, Y_W, Z_W]^T$, will project on the image plane with coordinates (u, v), then the following relationship exists:

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \boldsymbol{C} \begin{bmatrix} X_W \\ Y_W \\ Z_W \\ 1 \end{bmatrix} \tag{3}$$

where $\lambda \neq 0$ is a constant, $\boldsymbol{C}$ is the projection transform matrix, which determined by the intrinsic parameters and the extrinsic parameters of the camera. Equation (3) is the bridge between the point in 3D space and its projection on the 2D image plane. For the practical application, the process is in reverse, i.e. the 3D coordinates (X_W, Y_W, Z_W) are required to be measured according to the 2D coordinates (u, v) extracted from the camera images. However, known from (3), one point on the image plane actually denotes a line (infinite points) in 3D space. That is to say, monocular camera can not measure the 3D position of the target, if there is not any prior knowledge. This is the reason for the cooperative measurement, where artificial features (the geometrical dimensions and relative position between them are known) are designed for the monocular vision. The key for the application of the stereo vision is 3D reconstruction.

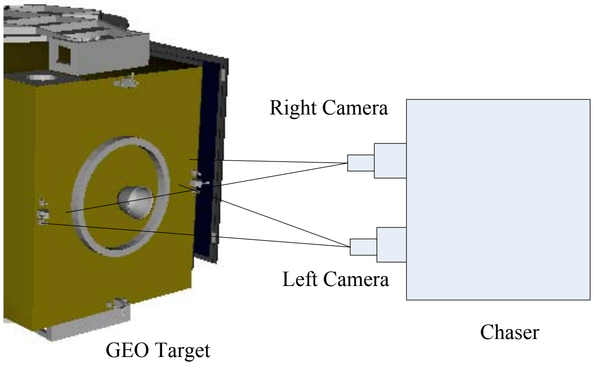

Fig. 5 The feature recognition based on binocular stereo vision system

The launch vehicle interface ring and apogee engine nozzle, which are mounted on nearly all the GEO satellites, are taken as the recognition objects. The concept is shown as Fig. 5.

E. *The Motion Planning of the 7-DOF Manipulator*

As is known to us, there are two types of Cartesian motion control for space robot [15]. The first, called *Spacecraft-Referenced End-Point Motion Control (SREMC)*, is the form of control in which the manipulator end point is commanded to move to a location fixed to its own spacecraft, or when a simple joint motion is commanded, such as when the manipulator is to be driven at its stowed position. For this control, nearly any path planning and control algorithms that can be used for fixed-based manipulators can also be used for the space manipulator systems. The second, called *Inertially-Referenced End-Point Motion Control (IREMC)*, is the form of control where the manipulator end-point is commanded to move with respect to inertial space.

For the application of the proposed system, the manipulator is used after the target is docked with its base. Therefore, the motion control of the manipulator belongs to *SREMC*, i.e. the path planning and control methods of the fixed-based manipulator can be directly used. Here, we apply the resolved motion rate control (RMRC) algorithm to plan the motion of the manipulator. The method is based on the following differential kinematic equation:

$$\begin{bmatrix} \boldsymbol{v}_e \\ \boldsymbol{\omega}_e \end{bmatrix} = \boldsymbol{J}_m(\boldsymbol{\Theta})\dot{\boldsymbol{\Theta}} \tag{4}$$

where, $\boldsymbol{v}_e, \boldsymbol{\omega}_e \in R^3$ are the linear and angular velocities of the end-effector with respect to the base; $\boldsymbol{\Theta}, \dot{\boldsymbol{\Theta}} \in R^7$ are the joint angles and rates; and $\boldsymbol{J}_m \in R^{6\times 7}$ is the traditional Jacobian matrix of the manipulator. The gradient projection method (GPM) is utilized to resolute the redundant kinematic problem. Firstly, the general solution of (4) is expressed as follows:

$$\dot{\boldsymbol{\Theta}} = \boldsymbol{J}_m^{+}(\boldsymbol{\Theta}) \begin{bmatrix} \boldsymbol{v}_e \\ \boldsymbol{\omega}_e \end{bmatrix} + \left[\boldsymbol{I} - \boldsymbol{J}_m^{+}(\boldsymbol{\Theta})\boldsymbol{J}_m(\boldsymbol{\Theta})\right]\boldsymbol{z} \tag{5}$$

$$\boldsymbol{z} = \alpha \bullet \nabla \boldsymbol{\varphi} \tag{6}$$

where, $\boldsymbol{J}_m^{+}(\boldsymbol{\Theta}) \in R^{7\times 6}$ is the pseudoinverse of $\boldsymbol{J}_m(\boldsymbol{\Theta})$, $\boldsymbol{z} \in R^7$ is an arbitrary vector in null space, α is a scalar, and $\boldsymbol{\varphi}$ is a performance criterion. To optimize the performance criterion (secondary task), the gradient of a performance criterion $\boldsymbol{\varphi}$ is used. The gain α is positive to maximize $\boldsymbol{\varphi}$ and negative to minimize $\boldsymbol{\varphi}$. If $\boldsymbol{\varphi}$ is assigned to be zero, then (5) becomes

$$\dot{\boldsymbol{\Theta}} = \boldsymbol{J}_m^{+}(\boldsymbol{\Theta}) \begin{bmatrix} \boldsymbol{v}_e \\ \boldsymbol{\omega}_e \end{bmatrix} \tag{7}$$

which is the least-norm solution of (5). This will be the simplest approach. However, the singularities cannot be avoided by this method. Several approaches for formulating the performance criterion to avoid escapable singularities of redundant manipulators are summarized in Ref.[16].

IV. The Mission Designed of the On-orbit Servicing for a Multi-Malfunctioned GEO Satellite

A. The Case of Multi-Malfunction

The target to be serviced is assumed a malfunctioned satellite, shown as Fig. 6. It has two solar swings, mounted on the +Y and -Y panels respectively, and two large antennas on the +X and -X panels. We assume that a very severe case happens after the GEO communication satellite reaches the GEO orbit successfully, i.e. the satellite encounter three mechanical malfunctions: (a) The +Y solar swing fails to deploy; (b) The +X communication antenna fails to unfold; (c) The -X communication antenna fails to unfold. To resume the normal function of the communication satellite, theses malfunctions must be resolved. The on-orbit servicing mission will be given in the following parts.

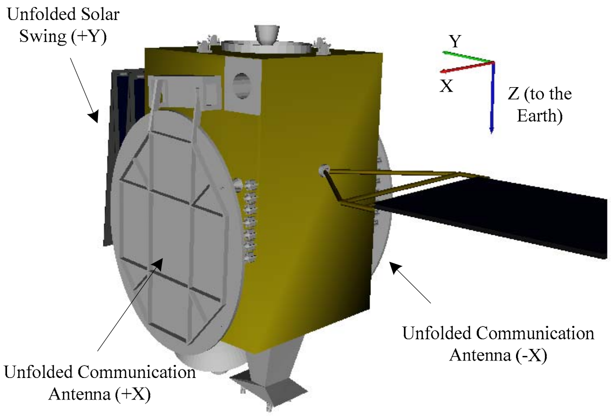

Fig. 6 The malfunctioned target to be repaired

B. The On-orbit Servicing Mission

1) The Launching and Inserting GEO

The on-orbit servicing mission is shown as Fig. 7.

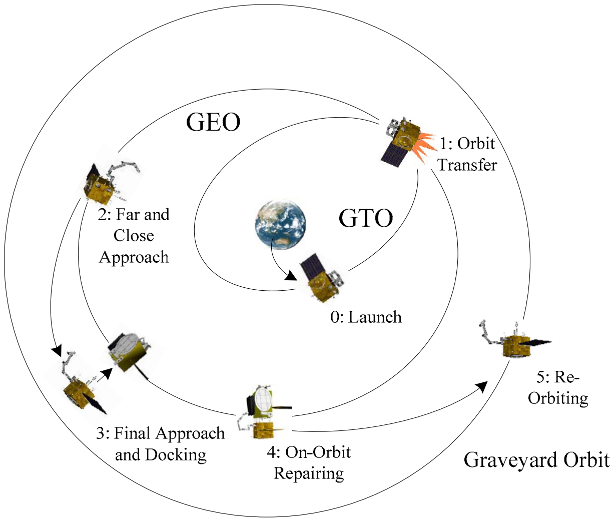

Fig. 7 The on-orbit servicing mission

The main phases are as follows:

(a) Launch and early orbit phase (LEOP): the space robotic system is launched to GTO (Geostationary Transfer Orbit);

(b) Orbit Transfer: The space robotic system transfer from GTO to GEO parking orbit. During this phase all spacecraft systems including 7-DOF manipulator and 2-DOF docking and latching mechanism will be tested.

(c) Far and close approaching: This stage will take a few days and can occur anywhere within the geostationary arc but not 24 h a day due to specific illumination needed by the sun. The space robot can be guided from the ground to within 2km with respect to the target satellite[17]. Then, the space robot can autonomously rendezvous with the target at about 5m position via a series of “stationary points” using the reaction control subsystem, based on the relative measurement supplied by the target measurement sensors (such as Far field cameras) on the chaser.

(d) The final approaching and docking (see Fig. 8): The final approaching and docking will take place from a relative distance of 5m. The space robot will switch to use a near field stereo camera and illumination system. Once the docking tool is within the nozzle of the apogee engine, laser and inductive sensors will become operative to guide and ensure satisfactory docking.

(e) On-orbit repairing: After the target is docked and latched, the space robotic system can perform the repairing mission to resume the normal function of the malfunctioned target. The details will be introduced in the next section.

(f) Target Releasing and Chaser Re-orbiting: After the target spacecraft is successfully repaired, the space robot will first adjust its attitude (such as earth-orientated) and then release it, using the 2-DOF docking and latching mechanism. Now, the target satellite can work normally and the on-orbit servicing mission is finished. The space robot can manoeuvre to the next mission orbit and perform the new repairing mission, or it will re-orbiting to the graveyard orbit if no further tasks.

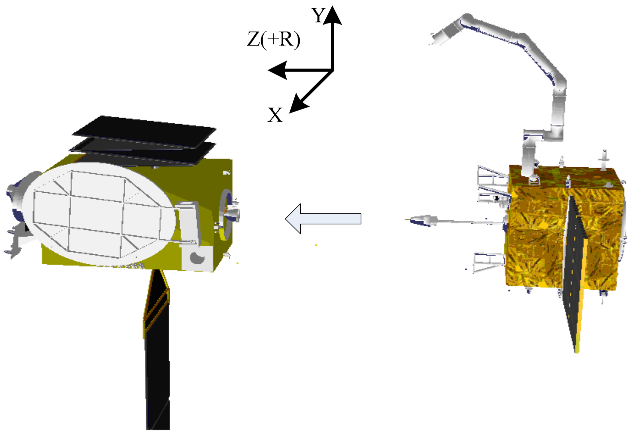

Fig. 8 The final approaching (+R bar)

2) The On-orbit Repairing of Multi-Malfunctioned Target

After the target is docked and latched, the space robot can perform the repairing tasks for the multi-malfunctioned target. The steps are as follows: (a) The 7-DOF manipulator moves to the 1st malfunction point from its ready-configuration, and get rid of it, i.e. deploy the un-deployed solar swing; (b) The 7-DOF manipulator moves back to its ready configuration;(c)

The 2-DOF docking and latching mechanism rotates the target to facilitate the 7-DOF manipulator repairing the 2nd malfunction; (d) The 7-DOF manipulator moves to the second malfunction point from its ready-configuration, and get rid of it, i.e deploy the +x un-deployed antenna; (e) The 7-DOF manipulator moves back to its ready configuration; (f) The 2-DOF docking and latching mechanism rotates the target to facilitate the 7-DOF manipulator repairing the 3rd malfunction; (g) The 7-DOF manipulator moves to the second malfunction point from its ready-configuration, and get rid of it, i.e deploy the -x un-deployed antenna; (h) The 7-DOF manipulator moves back to its re-orbiting configuration; (i) The 2-DOF docking and latching mechanism re-orientate the target and releases it; (j) The space robotic system re-orbits to the next mission orbit or to graveyard orbit.

Some steps are shown as Fig. 9~Fig. 10.

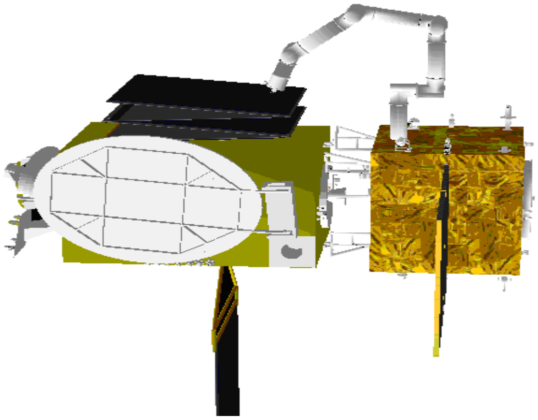

Fig. 9 The first repairing mission ---- deploy the un-deployed solar panel (+Y solar swing)

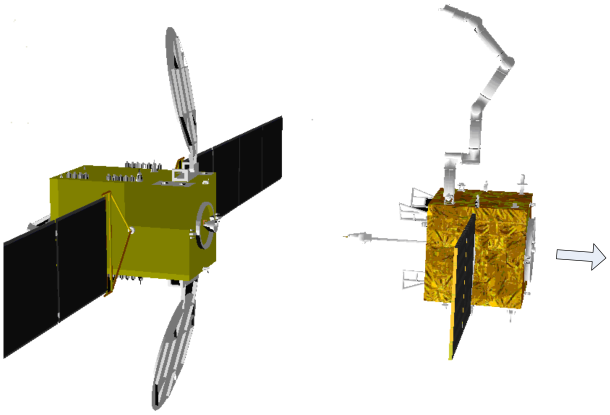

Fig. 10 The space robot separates from the target after the repairing mission finished

V. DISCUSSION AND CONCLUSION

In this paper, we designed a universal system for the on-orbit servicing in GEO. The system consists of a 2-DOF docking mechanism, a 7-DOF redundant manipulator, stereo vision, GNC subsystems, etc. It can serve most existing satellites in GEO, not requiring specially designed objects for grappling and measuring on the target. The servicing contents include visual inspecting, ORU replacement, malfunctioned mechanism deploying, spacecraft life extension, re-orbiting and so on. The mission simulation of a typical satellite with multi-malfunction shows the flexibility and validity of the system. In the future, we will further develop the system, and perform the main experiments at the air-bearing table, including 2-DOF docking and latching, redundant manipulator operation, and so on.

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