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SPACE ROBOTIC MISSION CONCEPTS FOR CAPTURING STRAY OBJECTS

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Abstract

The capture and recovery of an expensive satellite that has lost its attitude control function can be an important class of future missions for space robots. Moreover, there are tens of thousands of pieces of debris in orbit from previous missions. These orbiting debris such as the uncontrolled pieces of booster stages and obsolete satellites are a serious hazard to future orbiting spacecrafts. Thus, the use of robotic systems to capture and de-orbit uncontrolled materials from earth orbit has the potential to be another important future class of missions for space robots which should be technically similar to satellite capture. This paper describes on-orbit service system that utilizes multiple space robots for capturing and recovering valuable satellite system and for removing and changing the orbit to avoid collision from space debris.

1. Introduction

Researchers have suggested that robots will be crucial components of future orbital missions [1]. While human astronauts are invaluable for their judgment and intelligence, transporting and maintaining them in space is expensive and potentially dangerous. Robotic systems, while having many limitations, offer important advantages to augment or in some cases replace astronauts in orbit. Robots have lower cost, require minimal support infrastructure, and have an indefinite work life in orbit.

This paper outlines two potential orbital space missions suited to robots, and possibly teams of robots. These missions are the capture of an uncontrolled satellite and collection or deflection of space debris. The technologies required to perform these missions are currently under study as part of a joint MIT/NASDA research program. An important issue is to identify potential tasks within these missions that are most effectively done by robots.

2. Capture of an uncontrolled satellite

2.1 Motivation

Unfortunately, the launch and deployment of a satellite is not always successful. Reasons include problems with the launch vehicle propulsion system, computer malfunctions, failures in deployment of panels and antennas, power loss, and attitude control system failures (see Table 1). Such satellites often remain in orbit with limited or no useful capabilities. Only a few satellites have been repaired in orbit. In May 1992 Intelsat VI F-3, a satellite in an incorrect orbit due to a problem with the launch rocket, was captured by three astronauts in Space Shuttle Mission STS-49. The astronauts attached an orbital transfer engine that lifted the satellite to its correct orbit [3].

Failure mode / Result	Mission (Country)
Gas leak / fuel loss,	Military (Russia)
Mission hardware malfunction / fuel loss, tumbling, canceled mission	Science (USA)
Loss of power, battery failure / canceled mission	Science (Germany)
Attitude control failure / power loss	Science (USA)
Mission hardware malfunction / limited mission	Weather (India)

Table 1. Examples of satellite failures in 1999[2]

In 1993, Space Shuttle Mission STS-61 corrected an optical flaw in the Hubble Space Telescope's primary mirror. The following servicing missions in 1997, 1999 and 2002 replaced the failed gyroscopes and the exhausted solar arrays, and installed new scientific instruments.

While it might be feasible to use a Space Shuttle mission or other manned mission to capture and repair an especially valuable satellite, these missions are expensive, and require lengthy and difficult extra-vehicular activity (EVA). Satellite rescue missions could also be dangerous, especially if the satellite is spinning or tumbling out of control. These missions are thus good candidates for robotic systems.

2.2 Background

The problem of robots catching a satellite has been studied previously. The 1997 ETS-VII mission of the National Space Development Agency of Japan (NASDA) successfully demonstrated a number of satellite servicing capabilities in orbit, including capture and berthing of a 0.4 ton target satellite by a 2.5 ton chaser satellite [4], [5]. The German Aerospace Center (DLR) is developing the Experimental Servicing Satellite (ESS) using as a prototype scenario the capture and repair of TV-Sat-1, a satellite that failed to deploy a solar panel [6]. They propose teleoperation for inspection and repair of the satellite, based on the results of their ROTEX experiments. Vision-guided autonomous control is being developed for approach and capture of the satellite.

Although these research efforts have made important strides toward developing feasible robotic missions for satellite capture and repair, important problems remain. In particular, catching an uncontrolled, spinning satellite remains an important research challenge.

2.3 Mission concept

Study of past satellite failures have shown that large (1-10 ton), expensive satellites with significant spinning or tumbling are a good class of targets for a rescue mission. Apart from effects such as fuel loss or deployment failures for panels and antennas, size and inertial properties of the target satellite will be known. The locations will also be known of “hard points” most appropriate for grasping during the capture (e.g., the payload attachment fitting, the anchor points for solar panels and antenna, and thruster nozzles). The satellite's orbit will be known from Earth observation, but probably not its spin rate or tumbling motion.

The robots for performing capture missions will need thrusters to approach the satellite and stabilize it, and probably multiple arms for maintaining a firm hold on the satellite (Figure 1). Depending on the size of the satellite and the strategy to capture it, a team of several robots may be appropriate. The size of the robots or team of robots will be limited by launch considerations.

There are many possible concepts for this mission. One potential concept presented here can be broken into the following sequence of tasks.

Rendezvous and approach. The robots are first launched and transported for rendezvous with the satellite by a transfer vehicle. The transfer vehicle will release the robots 100ms from the satellite: far enough not to interfere with the capture, but close enough to observe the satellite and the capture process. Before the robots approach the satellite, they and the transfer vehicle will observe the satellite from multiple positions to determine its condition, to characterize its spinning and tumbling motions, and to estimate its inertial properties from these motions. Figure 2 depicts the expected spin axes of the satellite due to its solar panels.

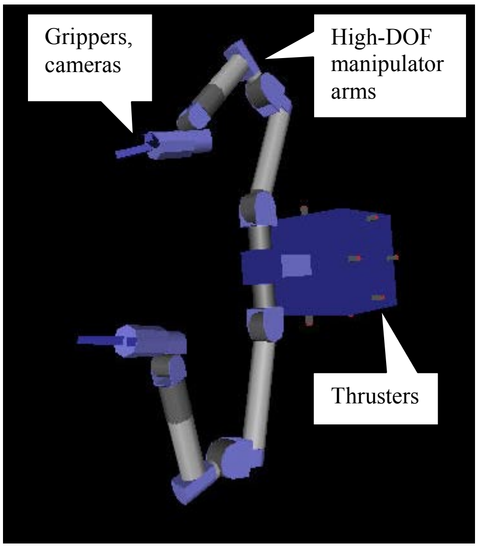

Figure 1: Example robot concept for capture mission

Next, the robots approach the satellite. The approach must be carefully planned so that the robots reach the satellite with a position and velocity suitable for grasping the satellite's hard points while avoiding collisions with the solar panels. The robots must not fire their thrusters at the satellite from close range (to avoid contamination from plume impingement). The trajectory should minimize the attitude control subject to the force constraints of the robot's thrusters. Should a problem arise at any stage in the approach, there must be a safe escape path for the robot.

The robots must execute the planned motion with only on-board sensors, presenting some interesting control problems. For example, each robot must visually track its grasp points, bring these within its manipulator workspace, and track the relative location of the grasp points from its end-effectors with a precision sufficient to perform the grasp.

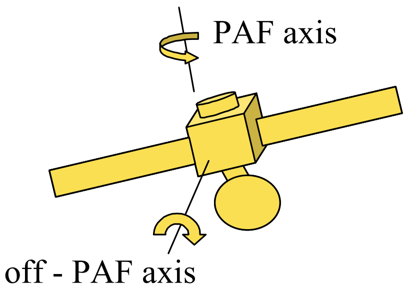

Figure 2.: Possible spin axes

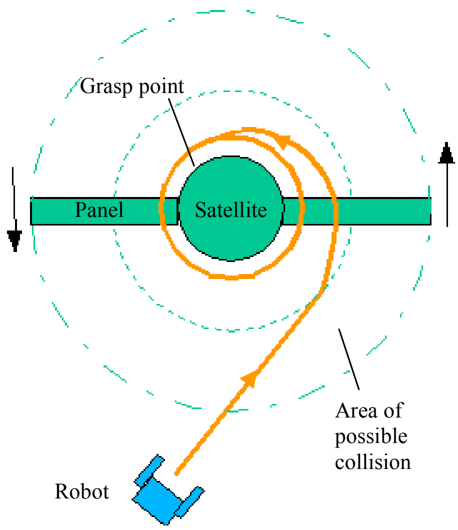

Figure 3. 2D Approach: robot approaches satellite in plane of panels and rotation.

Figure 3, a robot in the plane of the satellite's panels might approach the satellite by spiraling toward it. A simple analysis shows that while the fuel usage during the approach is not large, a large radial thruster force is necessary to keep the robot in orbit about the satellite during the grasp. For three-dimensional cases, approach path will be defined as a cost function based on performance metrics, and an optimization method will be used to find the best safe path.

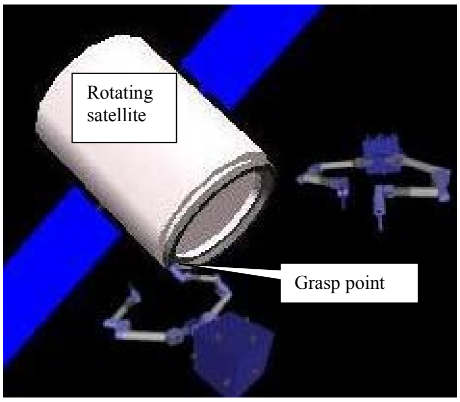

Figure 4: Robot grasps satellite on payload attachment fitting (PAF) Grasp, stabilization, and service.

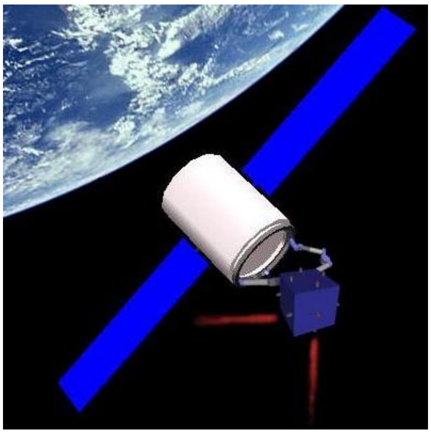

Figure 5: Robot uses its thrusters to stabilize the satellite's motion.

Satellite capture and stabilization. Next, one or more robots grasp the satellite at specified hard-points (Figure 4), and then stop its spinning (Figure 5) subject to a number of practical constraints such as fuel usage. The robot body will have a different velocity from the satellite during the grasp, due to thruster limitations, sensor errors, and constraints from avoiding damage to the satellite through plume impingement. The velocity difference limits the time window for the target hard point to remain within the workspace of the robot. To avoid damage to the satellite or the robots, the grasps and subsequent motion control must be performed without imparting dangerous torques. Dual arms of robots might greatly reduce torques at robot joints during stabilization phase.

Satellite retrieval/servicing. Once captured, the satellite is serviced and returned to operation (e.g., aligning its solar panels to recharge its batteries). The transfer vehicle may be required to carry the satellite along with the robots to a different orbit, to Earth, or to the Space Station for repair. In the future, the robot may be returned to operation by replacing an orbital replacement unit (ORU) or by refueling.

2.4 Conclusion

Satellite capture and service appears to be a high-value mission. Our preliminary work suggests that use of robotic systems is a feasible solution to the dangers posed by capturing spinning, uncontrolled satellites. However, until satellites are designed for robotic repair, it is likely that this precision work will need to be done back on Earth, or by astronauts.

3. Mitigation of space debris

3.1 Motivation

The US Air Force Space Command is currently tracking approximately 9000 objects in orbit that are more than 10 cm in size. Some of these objects are satellites, and over 6000 are pieces of space junk [7][8]. Most of these objects are in low Earth orbit (LEO) and typically move at very high speeds with respect to satellites and other spacecraft (about 10 km/s on average). At such relative speeds, collision between a piece of space debris and a structure or craft such as the space shuttle or space station would be catastrophic. Table 2 summarizes the flux of debris (the number of pieces passing through a given area in a year) of different sizes, and the space station's strategies for dealing with potential collisions.

3.2 Background

For space operations in LEO involving large manned structures and spacecraft, space debris is a major concern. NASA is alerted if there is a possible collision involving a manned flight within the next 3 days. The space station is reorbited to avoid a potential collision if it is determined that there is a 1/10,000 chance of impact, and the space shuttle if there is a 1/100,000 chance. Although the flux through a square meter cross-section is low for objects in the trackable size range (Table 2), NASA's volume of concern for a spacecraft is several kilometers on a side, so has a cross-section on the order of 106 m. Collision with a trackable object is thus a concern every few years. Consequently, the space shuttle has changed orbit several times to avoid the possibility of collision, and the space station was moved in October 1999 to avoid the remainder of a Pegasus rocket and was transferred in December 2001 by the connected Space Shuttle to avoid Russian rocket remains. Moving the space station results in expenditure of fuel and disruption to the operation of the station and scientific experiments.

Debris diameter (cm)	Cross-sectional flux (#/m^2-year)	Space station safety strategy
10^{-4}	10,000	Deflection by bumper
10^{-3}	1000	
0.01	10	
0.1	0.01	
1	10^{-6}	Redundancy
10-100	10^{-7}	Change orbit

Table 2: Debris flux verses size, and corresponding space station protection strategies [7]

Methods for mitigating the danger of collision without requiring a change in orbit are thus highly desirable. Using a robot or team of robots to intercept debris is thus a potentially valuable mission being considered in this study. Space debris mitigation is very different from rescuing satellites. Satellite capture involves grasping a relatively large, well known object without damaging it, so that it may be serviced in orbit or transferred elsewhere for repair. In debris removal, the target's mass properties and size will be largely unknown, and damage to the target of less importance. Physical capture of the debris may not be necessary if its orbit can be sufficiently altered without a secure grasp.

3.3 Mission Concept

One possible concept (Figure 6) for such a mission to dispose of debris for protection of a spacecraft is presented here. First, a possible collision is detected and a decision is made to send robots to dispose of the debris. A transfer vehicle moves the robots to an orbit to intercept the debris, and the robots scan the volume in which the debris is expected to appear to determine its actual position and motion. Once the debris is located, the robots track and capture it at the intercept point. Finally, the debris is removed or deflected.

Collision alert and rendezvous. Based on current Earth-based tracking capabilities, it can be assumed that warning of potential collision with an object of greater than 10 cm would be made several days in advance. In many cases, the origin of the debris would be known, and thus at least a rough (and sometimes a precise) estimate could be made of the size, shape, material composition, and mass of the debris. In other cases, however, the exact size and shape of the debris would not be known until observed from space. Potentially dangerous elements, such as stray cables would need to be identified and considered. Here human capabilities (i.e., through telepresence) would be especially valuable.

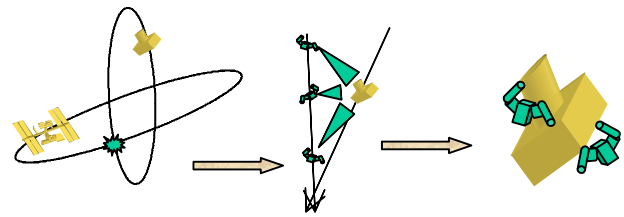

Figure 6: Debris mitigation mission: potential collision, tracking, intercept, and disposal.

It is then assumed that an orbital transfer vehicle would transfer the robots to an appropriate orbit for intercepting the debris. This intercept orbit would be selected so that the relative speed between the debris and the robots is sufficiently small to allow the robots to track and catch the debris. The debris' orbit will be known from ground observation, but the position within the orbit may be uncertain due to drag at the edge of the Earth's atmosphere. Hence the robots may have to search some volume of space for the debris before they can intercept it.

For fuel usage examples shown in Figure 7, the transfer vehicle to send the robot to debris' orbit from the station's. The relative velocity between the debris and robot after transfer is assumed to be zero. It is clear that if inclination and the right ascension of ascending node become far from the station's orbit, substantial fuels are needed for transfer vehicle to match the orbit. Figure 8 shows fuel usages when relative velocity is remained. If certain relative velocity to catch or push the debris is allowed, it has potential to greatly reduce the usage of fuels.

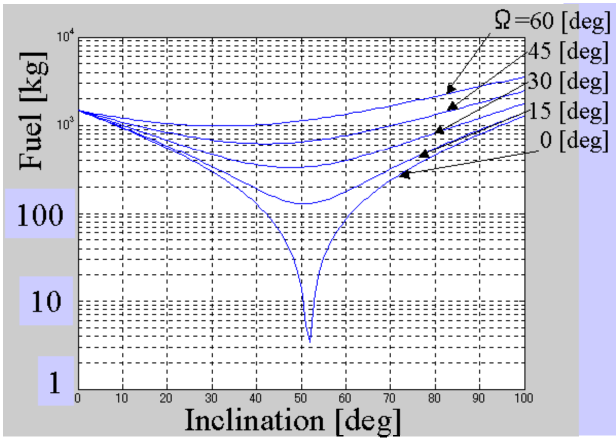

Figure 7: Fuel usage for orbital transfer: From station's orbit (altitude 400km, inclination 51.6deg, RAAN 0 deg) to debris' orbit (altitude 400km, Ω is RAAN). RAAN stands for right ascension of ascending node.

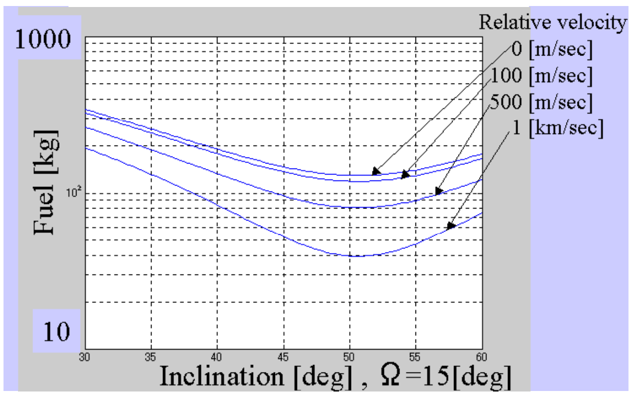

Figure 8: Fuel usage for orbital transfer: To debris' orbit (altitude 400km, RAAN 15deg). Relative velocity is difference between robot and debris.

Debris disposal. In some cases, actually catching the debris might be appropriate. If the debris is small but moving quickly relative to the robot, a device for catching the object might be specially designed. For instance, a catching mechanism resembling a baseball catcher's mitt might be used. For larger objects, one or more robots will need to grasp the object. The catching process may be more difficult than the satellite capture due to the fact that proper hard points for the catch, mass, and inertial properties may not be known, and there may be unknown damage to the object. However, plume impingement from the control jets will be less of a concern during the catch, because contamination is not a problem. It might also be acceptable to apply large forces, because damage to the debris is acceptable. For very large debris, it may be better to simply push or deflect the object to change its orbit to one that is not an immediate hazard. Due to the uncertainties involved, human judgment will be necessary for choosing the method for debris mitigation, and especially for determining any strategy for actually catching debris.

Once the debris has been captured, there are a number of ways it might be dealt with. For multiple small objects, it might be best to place them in a container and return it to Earth. It might be possible to attach a rocket-pack to de-orbit a larger object. If the fuel necessary for de-orbiting the object is too expensive, it might be sufficient to simply change its orbit enough that it is no longer an immediate danger.

3.4 Conclusion

Again, because of the dangers associated with this mission, it is attractive for robotic solutions. However it is more unstructured than the satellite capture problem. The shape and properties of the debris may be complex and unknown prior to rendezvous. Combined with the relatively short time available on orbit to plan the mission, it can be concluded that the superior decision-making capabilities of humans would be required to precisely plan the various phases of the mission.

4. Summary and conclusion

This paper has presented two orbital missions potentially suited for robots: capture of uncontrolled satellites and collection and removal of space debris. These missions are motivated by current and future challenges in the productive use of orbital space. Capture of satellites present realistic near-term challenges, and the use of robots to mitigate danger from space debris is an interesting potential solution to a problem that will become increasingly important for future work in space. In each case it is clear that robots can play important roles, especially for addressing the issues of mission cost and astronaut safety. However, in each mission it is found that the capabilities of humans would be essential for the complete mission. This human assistance may take the form of teleoperation or telepresence.

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