Satellite Servicing in GEO by Robotic Service Vehicle

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The geostationary orbit has a high commercial and strategic value, as do the satellite systems stationed there, for telecommunication, TV broadcasting, and weather forecasting. To safeguard the huge capital investments made as well as the usability of the orbit itself, it will soon be necessary to have adequate means of remote intervention for the servicing and repair of satellites. Since the physical, technical and economic constraints of such a mission make servicing by astronauts impossible, robotic service vehicles will have to do the work. ESA is now studying a robot-based Geostationary Service Vehicle, which would be similar to deep-sea and nuclear servicing robots.

Introduction

ESA is presently investigating the characteristics and potential of a Geostationary Service Vehicle (GSV) which could provide in-orbit inspection of geostationary satellites and intervention when necessary. So far, three types of services or 'interventions' have been identified:

- inspection of a satellite that has a severe malfunction and where a close-up view of the satellite could help to clarify the problem. This diagnostic data can be a basis for recovery actions from ground.
- mechanical assistance to a satellite in trouble, for example, with a non-deployed solar array or antenna, to restore operation.
- end-of-life re-orbiting of uncontrolled satellites into a graveyard orbit, an operation that will become more and more important in order to maintain the commercial exploitation potential of the geostationary orbit (GEO).

As was demonstrated recently with the successful repair of the Hubble Space Telescope, very good servicing results can be obtained if the subject satellite is built with the intention of being serviced later. However, because of the existing fleet of conventional satellites, a GSV must also be able to perform meaningful intervention tasks on commercial spacecraft that are not designed for in-orbit servicing.

GSV system overview

Concept feasibility

The baseline thinking is that a GSV should 'pay for itself', at least once it is in orbit. However, its capabilities and services must be sufficiently comprehensive to be attractive to satellite operators. This means that in order to be commercially viable both the development and operational costs must be kept within very tight bounds. Many of the enabling technologies for a GSV exist but still need to be adapted for use in space and to be proven in flight. A number of technological challenges also still need to be resolved, including the rendezvous, circumnavigation and approach to a non-cooperative spacecraft followed by its robotic capture and berthing.

Typical target spacecraft are spinning or three-axis stabilised telecommunication satellites positioned (or drifting) along the GEO arc. Examples of satellites with real problems for which a GSV could have been very useful are given in Table 1.

Table 1. Examples of satellites for which GSV services could have been very useful

Satellite	Problem	GSV action
Olympus	Satellite in unknown configuration and not controllable	Close-up inspection
Anik-E2	Only partial deployment of C-band reflector	Close-up inspection/mechanical intervention
TV Sat1	Non-deployment of solar panel	Mechanical intervention
Marecs-A	Solar array drive stuck	Mechanical intervention

Commercial potential

From an economic point of view, mechanical interventions are the type of GSV intervention with the greatest revenue potential. However, since spacecraft failures are unpredictable, it is difficult to base a commercial plan on the intervention missions alone. Re-orbiting missions, on the other hand, could provide a more steady income. If it was planned to move the spacecraft when depleted from its operational slot into a graveyard orbit using a GSV, a telecom satellite could continue operating until propellant depletion (roughly six months of extra exploitation). Additional revenues would be generated, and a reasonable share of this extra profit could be claimed by the GSV operator. Another potential GSV service is to re-orbit 'dead' satellites which could otherwise be a collision hazard to other satellites. For inspection tasks, revenues are expected to be low, although they could become considerable if the inspection leads to the recovery of the satellite.

It is estimated that a GSV could become economically viable if the design costs of the GSV can be kept in the range of two to three times the launch cost. This could be achieved by maturing the required technology via separate technology programmes to reduce the design risk. Here, ESA could play a key role in mobilising the available European expertise to provide a technical and commercial basis for a GSV.

Basic GSV configuration

The proposed configuration for a GSV (Fig. 1). synthesised during ESA's recent industrial study, is a satellite that would use the maximum upload capability of a dedicated Ariane-4

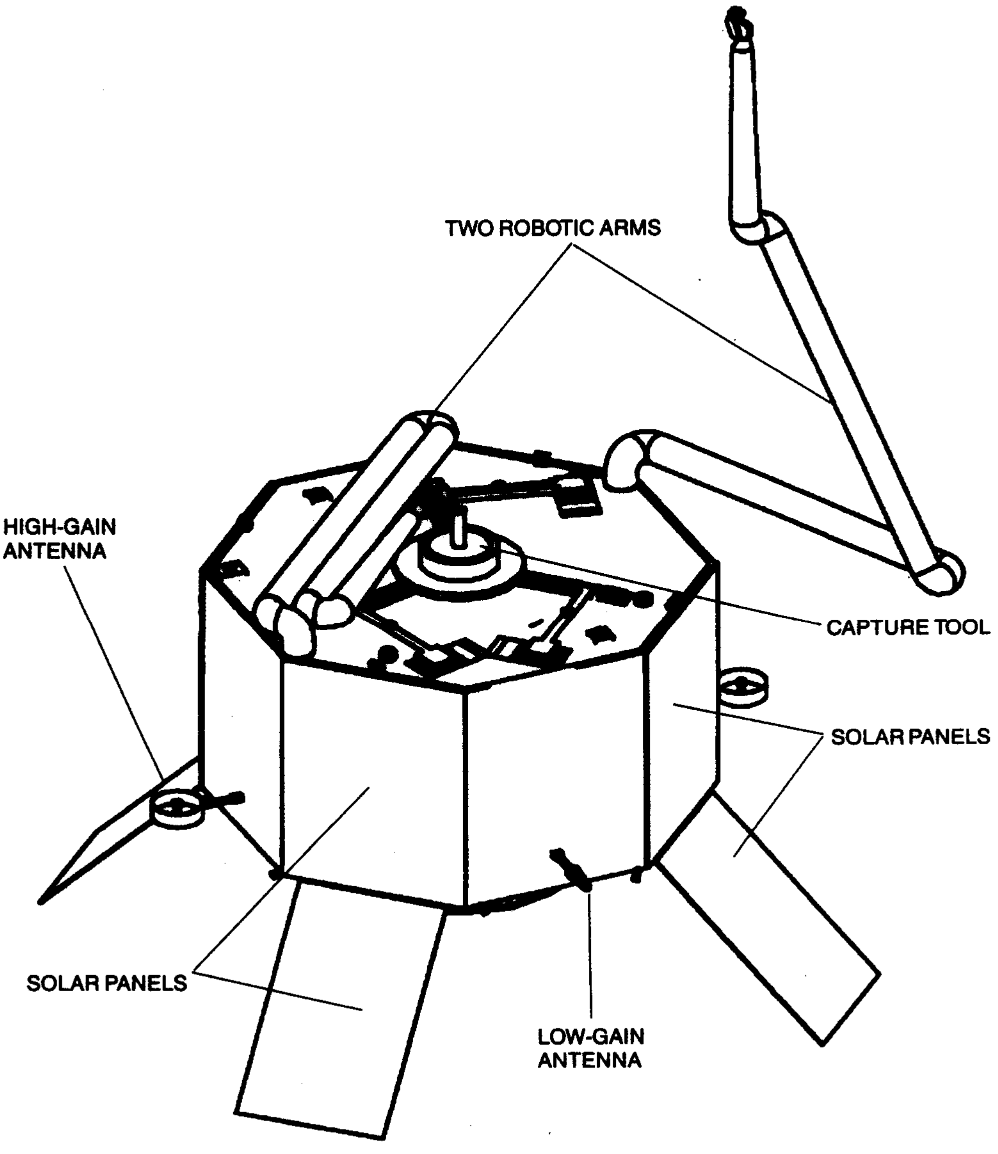


Fig. 1 A proposed GSV configuration

launch, thus a 4.2 ton spacecraft at launch. With a dry mass of approximately 1.2 tons, roughly 3 tons remain for fuel, which means a total delta-v of 3687 m/s (for a bi-propellant with a specific impulse of 300 seconds). The hexagonal configuration proposed uses the full fairing diameter of the launcher, and the height of the spacecraft is sized in proportion to the three tons of fuel. Solar panels would unfold from the outer surface of the hexagon, and the rendezvous sensors, the robot arm and its tools would be located on the top surface of the GSV. The bottom surface would be dedicated to the launcher interface ring and the GSV propulsion system.

GSV operation

It is proposed to operate the GSV through a dedicated, portable ground station. The S-band would be used for communication and the dedicated station would be co-located with the customer's main ground station. A key driver in the design of the antenna arrangement on board the GSV, will be the continuity of the communication link during all proximity operations. Low gain S-band antennas with wide lobes are proposed, especially for approach operations when the target spacecraft may obstruct the GSV antenna visibility.

GSV orbital manoeuvring

Fuel consumption and GSV lifetime

The primary requirement for a commercial GSV is its capability to reach as many target spacecraft as possible during its operational life. Once launched and positioned at its 'home' location, the GSV's ability to reach a troubled satellite is directly related to the amount of fuel the GSV operator is prepared to expend. The main fuel consumption parameters are the speed at which the GSV moves along the orbit, the phasing and inclination differences for which correction is needed, and the number of re-orbiting operations. Based on a scenario consisting of 25 re-orbiting missions, 10 inspections, 3 mechanical interventions, and 2 dead satellite removals, the proposed GSV configuration would have an operational lifetime of five years.

Rendezvous

The basic phases of a rendezvous are illustrated in Figure 2. After a call for assistance, the GSV begins the transfer to the troubled satellite by moving from its home position toward the target spacecraft, with a drift orbit a few hundred kilometres below the geostationary orbit. When it arrives within 10 km of the target spacecraft, the GSV is transferred back to the geostationary orbit (points S1 to S2). The GSV then approaches the target carefully (S2 to S4) and circumflies it to obtain status information (S4 to S5). The GSV then makes its final approach in preparation for capturing the target.

The rendezvous is performed with the help of ground tracking, radar tracking or angular measurement with a star-tracker, and eventually TV-camera tracking.

Final approach

When the GSV is within 50 metres of the target spacecraft, it begins its final approach and, using its robotic arm, captures the target (S6 to S7). The target is docked to the GSV itself and later they are 'rigidised' so that both spacecraft form one rigid compound. The robotic servicing intervention can then begin.

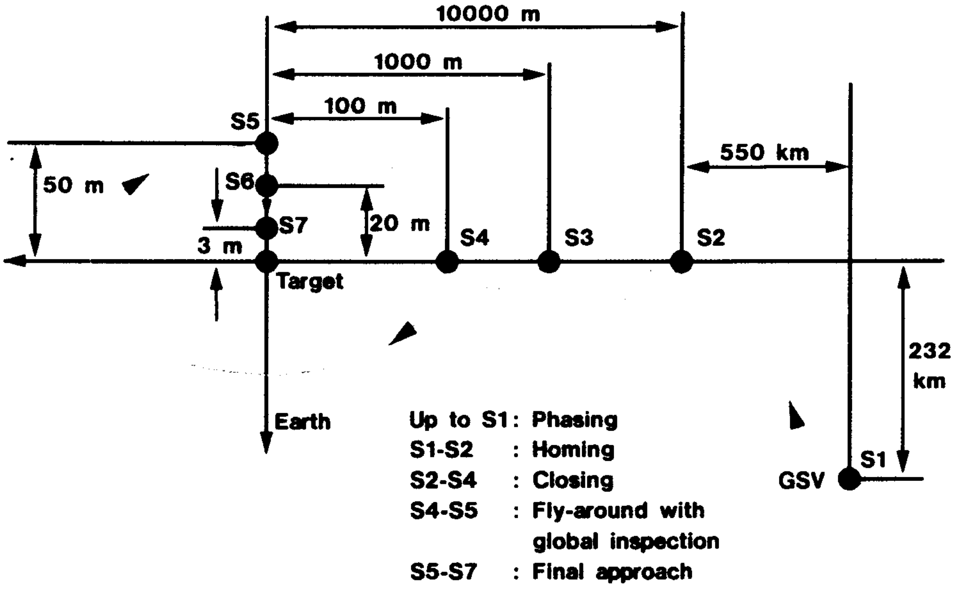


Fig. 2 The basic phases of the GSV's rendezvous with a target satellite

The GSV approaches a controlled satellite stabilised in its nominal Earth-pointing position from behind, along the Earth direction. In the case of an uncontrolled satellite, the target is expected to spin slowly around its main axis of inertia; for most satellites, this axis is perpendicular to the solar-array plane. The GSV then makes its final approach along the spin axis of the target satellite. At the very last moment, the GSV (or possibly its robotic capture tool) will be spun up to synchronise with the target.

For both controlled and uncontrolled satellites, it seems realistic to assume that the GSV can maintain a relative position and attitude accuracy of ±5 cm and ±2 degrees with respect to the target. This does not apply for the roll axis of a spin-stabilised target since the roll-motion synchronisation will be done by a rotating capture tool. Possible nutations around the spin axis could be compensated by the robot holding the capture tool. After capture, the GSV will slow down the rotation of the target until both spacecraft attain the same rate. The 'rigidisation' between the two can then take place: the single point attachment between the two spacecraft is replaced by a more stable, multi-point fixation structure to strengthen and stiffen the bond between the GSV and the target satellite and to free the robot arm for other uses.

GSV robotic system

Why robots?

A GSV will be uncrewed, and the broad variety of tasks to be done, in combination with the unpredictable nature of the servicing tasks, calls for a flexible and multi-functional flight segment. Robotic systems are the only means available today to fulfil these needs. In addition, a robot can be controlled in a telemanipulation mode by a remote ground operator. In the case of a GEO-stationed spacecraft, the direct telecommunication link enables a good bandwidth. Because of the short time delay between ground control and the flight segment, the GSV robot can be operated in a telemanipulation mode of very good quality. This means that the motion of a ground master arm manipulated by a skilled operator, can be 'slaved' by the GSV robot and, in that way, quasi-human repair capabilities can be obtained.

As far as the robotic interaction with a conventional satellite is concerned, two major problems appear: 1) the limited options for capture/berthing and docking, and 2) the accessibility of the repair area for the GSV robotic system.

Robotic capture, berthing and docking

The robot arm must capture the target satellite, berth it to the GSV to align the axes of the two spacecraft, and dock it firmly. On a satellite that is fully covered with thermal insulation, there are few possibilities for proper mechanical interfacing with the GSV. However, two 'hard points' that are available on virtually all GEO satellites are the nozzle of the apogee boost motor and the launcher interface ring. The nozzle may not provide sufficient stiffness for use as the final docking interface but could serve as a first 'hook' for capture and temporary attachment. Rigidisation between the GSV and the launcher interface ring can then be performed. Due to a lack of standardisation in nozzles and interface rings, the capture and rigidisation mechanisms of the GSV must be highly adaptive.

An example of a nominal GSV manoeuvre with a stabilised target is illustrated in Figure 3. The GSV will service the Anik-E2 satellite, whose C-band reflector had only partially deployed. The GSV robot first prepares the spacecraft by erecting the docking/rigidisation structure (Fig. 3a). The GSV then approaches Anik-E2 from behind (Fig. 3b) and captures it by its main engine nozzle (Fig. 3c). The robot will do this using a dedicated capture tool. In the case of a spinning spacecraft, the GSV will be spun up to the same speed along the same axis. The capture tool's 'stinger' is inserted via the nozzle in the combustion chamber and expanded to prevent the target from escaping. Then the capture tool clamps to the outer ring of the nozzle to achieve a greater stiffness. The robot arm berths the spacecraft to the GSV (Fig. 3d) by latching the other end of the capture tool into its fixed position. The robot arm is now released and picks up a gripper from its toolbox (Fig. 3e). The robot then performs the intervention: it reaches for the stuck antenna, releases it and deploys it into its operational position (Fig. 3f).

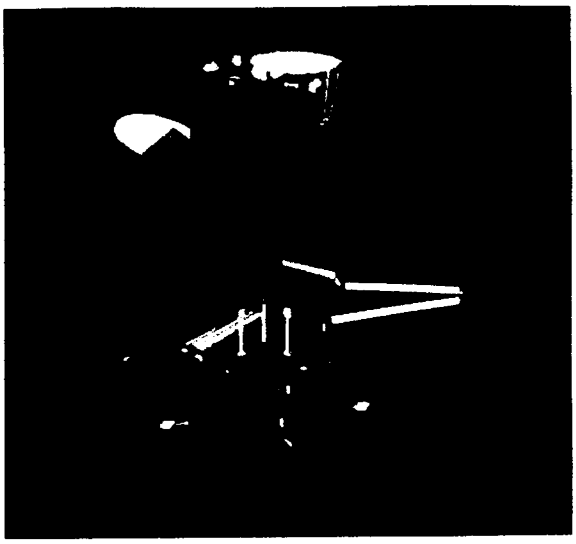
In the case of an uncontrolled tumbling target (Fig. 4), the capture tool will be spun up in synchronisation with the rotation of the nozzle. The robot arm also compensates for part of the orbital motion by keeping the capture tool aligned with the nozzle. It is expected that the images provided by the rendezvous camera on the main body of the GSV will give sufficiently accurate information so that the robot arm can safely insert the stinger of the capture tool in the combustion chamber. During insertion, the robot will continuously adjust its motion based upon distance and contact force measurements. After latching, the robot arm and the capture tool will gradually eliminate the tumbling motions, and the berthing and docking of the two spacecraft will then follow.

Robotic mechanical intervention

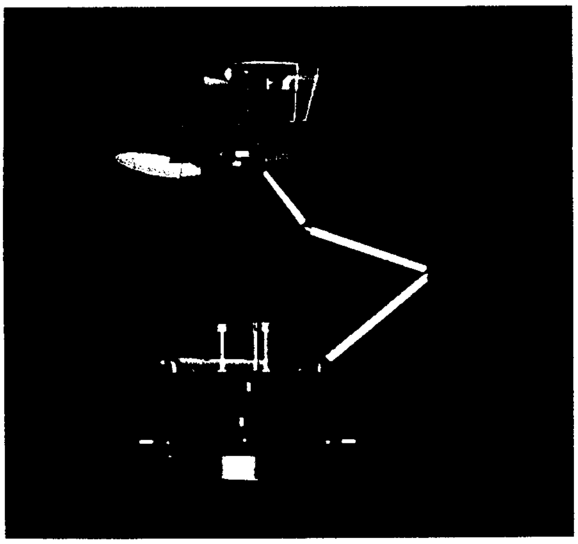
The intervention for servicing can be divided into three sub-phases:

- reaching the repair zone
- close inspection of the repair zone
- intervention using tools, e.g. removing and replacing sections of the thermal blanket, severing restraint cables that prevent deployment of the antenna or solar array, or hinging/removing deployable mechanisms that are stuck.

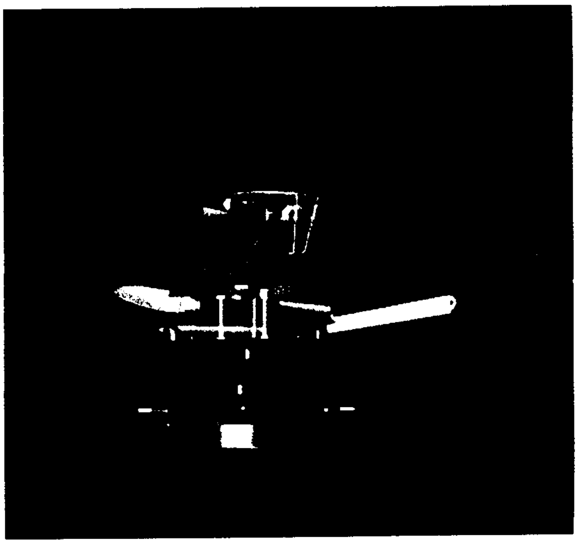
3a. GSV prepares the docking interface by folding out the three satellite supports



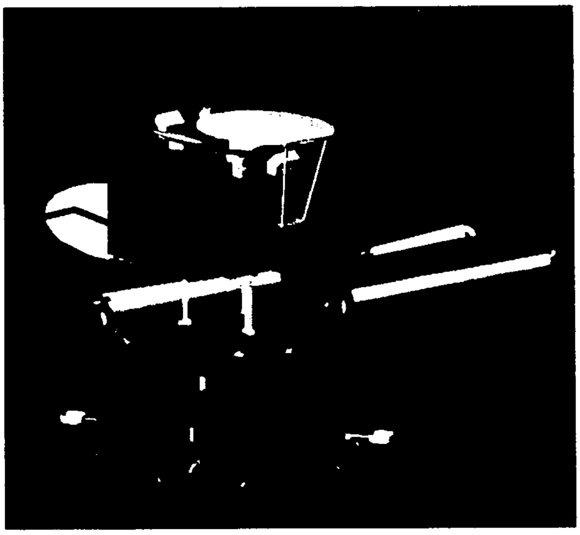
3b. GSV approaches the target satellite and is ready to capture it



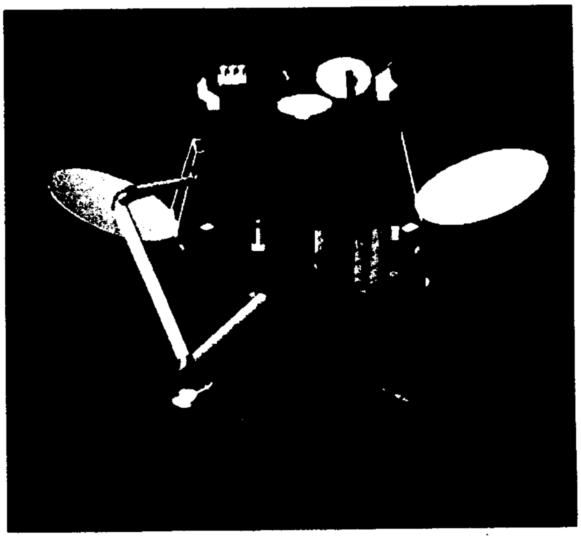
3c. The robot inserts its capture tool into the satellite's apogee motor nozzle



3d. It places the captured satellite on the supports and docks it

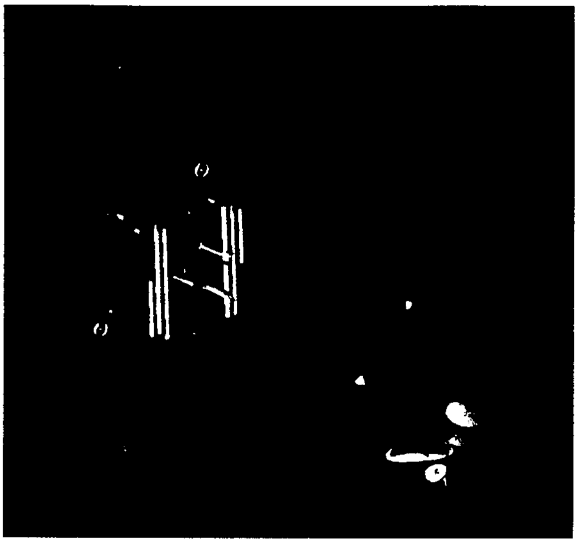


3e. The arm takes the gripper tool from the toolbox and grasps the jammed reflector (white disc on Anik's top face)

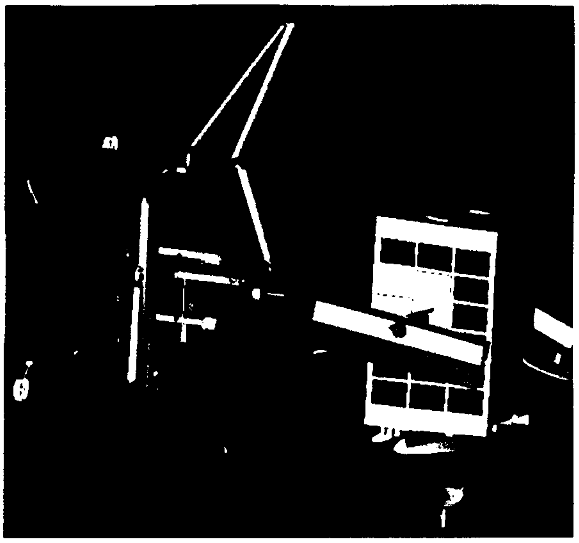


3f. It folds the jammed reflector out into its nominal position. The repaired satellite will then be released.

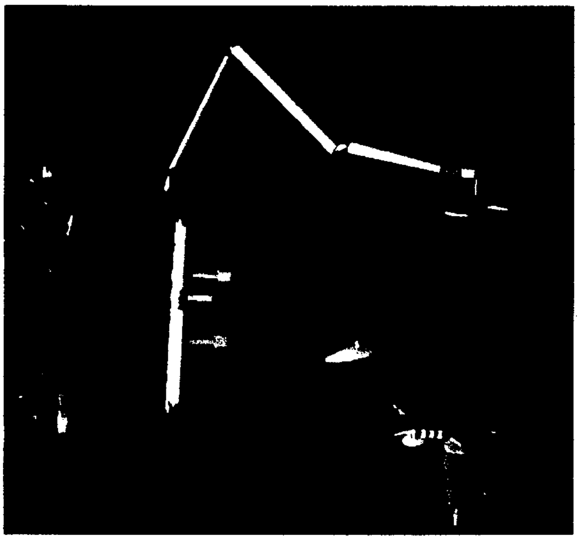
Fig. 3 A nominal GSV manoeuvre with a stabilised target, the Anik-E2 satellite whose C-band reflector only partially deployed



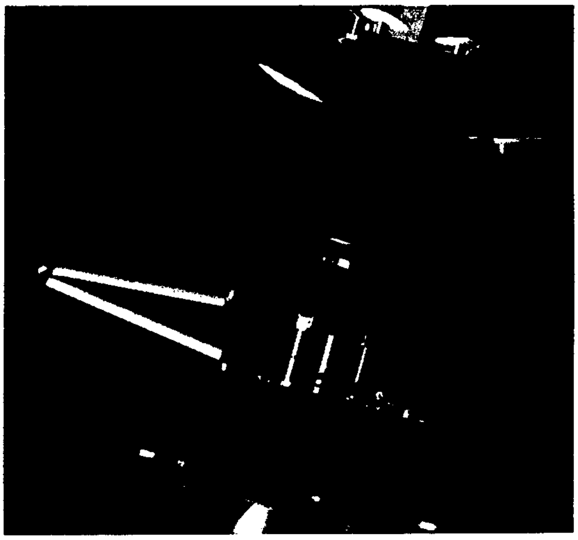
4a. The GSV approaches the target satellite and starts spinning along the same axis



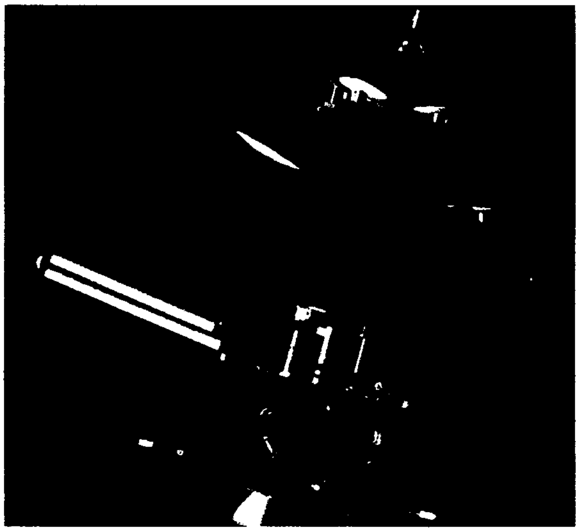
4b. One robot picks up the capture tool and moves toward the satellite (spinning synchronously)



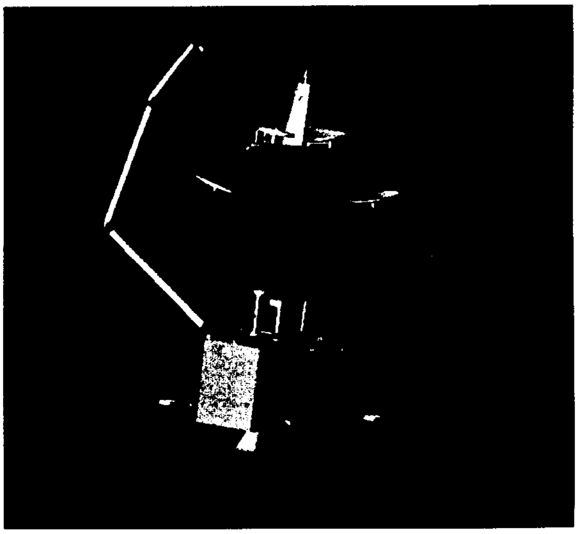
4c. The robot inserts the capture tool's 'stinger' in the nozzle and locks it



4d. The captured satellite is slowly rotated and moved to the docking interface



4e. Finally, the satellite is docked to the GSV



4f. One arm, with a camera on its tip, provides ground control with close-up images of the repair zone

Fig. 4. A GSV manoeuvre with an uncontrolled, tumbling satellite which is spinning about an axis orthogonal to the apogee moto

A major disadvantage of the capture and docking concept described, is the distance (roughly 5 metres) between the repair area and the GSV. Indeed, most of the defects are expected to be at the other extreme of the satellite where the payloads and subsystems, such as antenna reflectors, are located. It will require innovative robotic systems that can easily access the servicing area and at the same time provide good local precision, dexterity and stiffness to enable a good repair.

Robotic concepts

An obvious solution is to have one or two large robot arms that operate from the top face of the GSV and which can access the service zone directly. This straightforward solution can adequately solve the accessibility problem but a severe limitation is that these big crane-type robots have limited manipulation capabilities. First, the precision is in the order of centimetres or even decimetres which is often insufficient for repair work. Secondly, the local dexterity, i.e. the freedom of motion available at the robot tip, in this stretched position, is generally quite poor. This necessitates a very specific tool set to compensate for these limitations, implying less universality and thus less possibilities to cope with unforeseen defects.

Another candidate concept is a micro-macro manipulator. This is a cascade configuration of a large manipulator carrying a small, instrumental robot. Technically, this is a very attractive solution since both robots complement each other well. The large one acts like a cherrypicker-crane that carries a small, dextrous robot (often with two arms) to the repair zone to do the precise part of the work. This concept is popular on ground and in LEO, but the equipment tends to be heavy and the concept is therefore less effective in GEO where every kilogram counts. It is also a more expensive solution which jeopardises the potential commercial future of a GSV.

At the research level, new robotic concepts are being developed which could be very useful for later versions of a GSV. For instance, there are already testbeds of a small robot which is able to build a lightweight structure (e.g. a truss) on its own, and over which it can move easily. Such a scaffold could provide a universal structure used to bring a small instrumental robot to where it is needed.

Robotic tool set

In the same way as a human worker needs a comprehensive tool set for repair tasks, a GSV robot cannot perform all the tasks mentioned with one universal end-effector. A number of tools that are required were identified in the industrial study:

- — a satellite-capture tool
- — a docking/rigidisation tool
- — a satellite close-up inspection tool
- — a two-finger gripper
- — a cable/pin cutter
- — a self-reacted lever-force tool.

Some tools, such as inspection cameras, can be permanently mounted on the robot arm. Others must be detachable end-effectors, preferably designed as a modular family to minimise mass and volume.

Control concept

The GSV proximity and robotic operations normally require complex control systems. However, due to the availability of a continuous and direct communication link, the general control concept for a GSV is to have only the bare minimum of control functions implemented on board. For rendezvous, these necessary on-board functions are to ensure attitude and position stability, and back-up procedures to ensure the integrity and health of both the GSV and target satellite, in case ground control is lost. For robotics, the control functions on board are to ensure robot arm motion stability and accuracy, and to perform guidance for time critical motions such as the capture of a target satellite.

Spin-off potential

The similarity between robotic servicing in GEO and deep-sea exploration and exploitation and nuclear-reactor servicing is striking. Remote intervention in hostile environments is expected to become increasingly important in the future, with new applications such as in the clean-up of radioactive or toxic waste, firefighting, demining, the handling of explosives or inflammable material, security and police work, telemedecine, and in many other areas. A technology programme for the development of a GSV could act as a precursor to robotic servicing in the other environments, offering promising potential spin-off benefits to those terrestrial applications.

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