N93-11953

REQUIREMENTS AND APPLICATIONS FOR ROBOTIC SERVICING OF MILITARY SPACE SYSTEMS

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ABSTRACT

The utility of on-orbit servicing of spacecraft has been demonstrated by NASA several times using shuttle-based astronaut EVA. There has been interest in utilizing on-orbit servicing for military space systems as well. This interest has been driven by the increasing reliance of all branches of the military upon space-based assets, the growing numbers, complexity, and cost of those assets, and a desire to normalize support policies for space-based operations.

Many military satellites are placed in orbits which are unduly hostile for astronaut operations and/or cannot be reached by the shuttle. In addition, some of the projected tasks may involve hazardous operations. This has led to a focus on robotic systems, instead of astronauts, for the basis of projected servicing systems.

This paper describes studies and activities which will hopefully lead to on-orbit servicing being one of the tools available to military space systems designers and operators. The utility of various forms of servicing has been evaluated for present and projected systems, critical technologies have been identified, and strategies for the development and insertion of this technology into operational systems have been developed.

Many of the projected plans have been adversely affected by budgetary restrictions and evolving architectures, but the fundamental benefits and requirements are well understood. A method of introducing servicing capabilities in a manner which has a low impact on the system designer and does not require the prior development of an expensive infrastructure is discussed. This can potentially lead to an evolutionary implementation of the full technology.

1. HISTORY OF SPACE-BASED SERVICING

Space-based systems are very valuable for many diverse applications. They are also very expensive to build and to place into orbit. Although satellites are designed to high standards and extensively tested on the ground, they have suffered from the range and rate of anomalies to be expected fro such complex systems.

For the first 15 years of space activity, troubled systems could be salvaged only by creative reprogramming from the ground. For example, a Tracking and Data Relay Satellite (TDRSS) was raised into a useful orbit using its attitude control thrusters following a problem with the IUS. If such a work-around could not be achieved, there was no alternative but to launch a replacement system.

Once man began gaining regular access to space, the alternative of direct action on the problems became possible. There have been a number of space missions which have been saved by corrective actions taken by astronauts performing Extra Vehicular Activities (EVA). The first of these was on the initial deployment of Skylab in 1973 when repairs were made to the solar panels and thermal shield which had been damaged during launch. Had it not been for this manual improvisation, the vehicle would have been unusable.

In 1984, an EVA repair mission from the shuttle replaced a failed attitude control module on the Solar-Max satellite and restored that vehicle and its payload to full operational status. An additional 6 years of valuable data was obtained as a result of this repair. There were plans to revisit this satellite in 1990 for a second servicing mission to recover it before re-entry, but the only available flight opportunity was pre-empted by the recovery of the Long Duration Exposure Facility.

A pair of communication satellites, Palapa and Westar, were stranded in low earth orbit due to failures in their boost propulsion systems. Although these satellites were not originally designed with provisions for orbital handling, an on-orbit recovery mission was carried out from the shuttle in 1985. The spacecraft were recovered by astronaut EVA operations, refurbished, and later relaunched.

The most recent example of a space mission being saved by on-orbit action is the deployment of the Gamma Ray Observatory (GRO) on STS-37. After the high-gain antenna failed to deploy, the crew performed an EVA which successfully freed a stuck boom by using a crank designed for ground operations. Without this corrective action, the $650 million spacecraft would have been unable to return useful data to earth.

The Soviets have also salvaged several missions by on-orbit repairs of their Salyut/MIR space stations. Problems they have corrected by EVA range from the release of jammed mechanisms to the replacement of portions of a fluid system, which involved cutting and welding tubing.

2. MILITARY INTEREST IN SPACE SERVICING

These demonstrations created an interest within the Department of Defense in the benefits of space servicing operations. The use of space-based systems has become an integrated part of military doctrine, and the number, complexity, and expense of these systems is projected to increase in the future. This growing military reliance upon space requires that the systems meet the required operational availability and be fielded and operated within budgetary constraints. It was recognized that extending the service life of space-based assets by correcting conditions which would otherwise terminate the mission could reduce the life cycle costs and increase the operational utility of military systems.

Military interest in space-servicing techniques was given a major stimulus by the Strategic Defense Initiative (SDI). The early SDI architectures featured large constellations of space-based weapons and surveillance systems. The potential supportability requirements associated with large numbers of complex and expensive satellites were identified as critical issues in the development of these systems.

3. DIVERGENCE OF DOD AND NASA REQUIREMENTS

Although DoD is following NASA's lead into orbital servicing and wishes to fully leverage NASA's experience and technology base in this area, there are significant differences between the needs and interests of the two agencies. NASA has developed a satellite servicing methodology and technology based upon astronauts performing EVA operations from the shuttle orbiter or, in future years, from the Space Station. As in the examples above, these operations take place in relatively low altitude earth orbits that can be reached by the shuttle orbiter.

Most of the prospective DoD candidates for servicing would be located in high altitude or high inclination orbits which could not be reached by the shuttle. In addition to military space assets being difficult to reach, many of them are located in environments are hazardous to astronaut operations, such as the radiation belts. It is also recognized that performing an EVA is inherently a high risk operation. If space-based servicing were to be incorporated as an operational tool, a potentially large number of remote operations might be required. It is prudent to reduce the potential risk to human life if a suitable alternative can be made available.

Another important difference between NASA and DoD requirements is the timeliness of response to problems. Most NASA systems are scientific satellites. The interruption of their data is an inconvenience that can generally be recovered from by later observation time. However, the critical defence missions of military satellites dictate that these systems be restored to full operational availability as quickly as possible after an anomaly. This may require timelines which are incompatible with the time required to schedule and launch a manned response but which can be met by a dedicated launch of a small unmanned system.

These requirements have led the DoD to emphasize a robotic approach utilizing expendable launch vehicles for the servicing of space assets rather than the astronaut EVA approach developed by NASA.

4. FAILURE MODES OF SPACE SYSTEMS

The requirements definition for a space-based servicing system begins with an examination of situations for which servicing might be an appropriate response. These failure modes can be classified into several broad categories. The first of these catagories is the failure of a component which results in the partial or complete loss of system functionality. These failures will almost always be of a random nature, since almost the entire mission life falls within the regime described by the flat or random failure region of a standard "bathtub shaped" reliability curve, as shown in Figure 1.

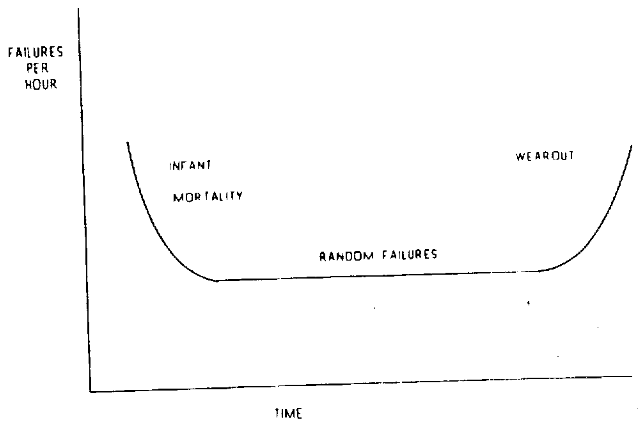

FIGURE 1. GENERIC RELIABILITY CURVE

There will be a relatively high rate of "infant mortality" early in the mission. With a few minor exceptions, the increase in failure rate associated with the wear out portion of the reliability curve is never reached.

Since these failures can occur at any time (although concentrated early in the mission) and often without warning, they are the most stressing in the time required for a response.

The second category is that of degradation in the performance of a component or subsystem. This type of failure has the effect of a gradual reduction in the performance margin of a system, sometimes reaching a threshold at which system functionality is lost. This usually gives ample time to plan a response, especially in cases where the rate of degradation can be well characterized. An example is degradation of solar cells due to radiation damage.

A third life-limiting category is depletion of consumables. It is somewhat similar to degradation in that it is a time- or cycle-dependent phenomena, but fundamentally different on that the performance of the system is not affected until the consumable is depleted, at which time functionality is lost. Consumption of fuel in a propulsion system is a typical example.

Another category where servicing might be beneficial is that of a system which has not failed, but has become outmoded. A capability of inserting upgraded technology into the basic system could extend the spacecraft's useful life,enhance its mission capabilities and lower life cycle cost.

5. RESPONSES TO FAILURE MODES

There are three general types of responses available to life limiting issues or failure modes. The first of these is to change the design. If a mission is limited by depletion of a consumable, adding a larger amount of that consumable to the original design is more efficient than supplying more once the system is on station, provided that the additional mass is within the available launch capacity. Additional margin can be built into systems which suffer from degradation, with the same proviso on weight limitations. Reliability of complex systems can be improved by providing both component level and subsystem level redundancy. However, there is a limit to the level of redundancy which can be provided before the potential failures arising from the increased complexity outweigh the benefits. Launch weight limitations can be a factor here as well.

A more sophisticated design change would be to change the function. Failure modes such as those associated with mechanical mechanisms can be designed out of the system or alternative approaches can be used for the overall system architecture. A subtle variant is to reconfigure the system by telemetry to "work around" anomalies.

These design approaches are normally used to maximize service life, and will continue to be the most appropriate first response for failure modes which can be clearly identified.

However, experience has shown that good design practice alone cannot eliminate on-orbit failures. The classical response to such failures is to abandon and replace the failed, degraded, or obsolete asset. This will continue to be the most appropriate response in some cases.

The emerging alternative to abandonment of failed assets is on-orbit servicing. This response has been demonstrated on an ad-hoc basis on systems which were not originally designed for servicing, but offers the greatest promise if it is a basic design feature of the system. Servicing is not a universal panacea, but merely another tool which the system designer can exploit to achieve the most responsive concept. The economic viability of servicing is dependent upon the cost, weight, and inherent reliability of the satellite, launch costs, and the nature of the failure. It must be recognized that designing for servicing is an additional requirement which can conflict with other design requirements and may entail cost and mass penalties. However, these penalties may be offset by producibility and testing benefits as well the benefits gained by servicing.

In each case, the choice of whether the potentially mission limiting feature should be responded to by design changes or by operational servicing is a question to be decided on the basis of lowest cost, with the answer tempered by technical capabilities. For military systems, operational needs and availability will also be a strong consideration and may outweigh other factors. In many cases the optimum solution will utilize both approaches, with the system designed to provide the maximum possible life and servicing providing an extension in capability beyond that constrained by engineering or initial launch weight.

6. KEY SERVICING TECHNOLOGIES

Our examination of the specific operations required to perform on-orbit servicing identified the technologies which must be developed to achieve this capability. We found these to be relatively few and well within current engineering practice. The most critical issue appears to be that of designing the systems for servicing.

As we evaluated the details of how to perform servicing of failed or degraded components it became apparent that current military design practice is not compatible with robotic on-orbit servicing. Systems are assembled by building outward from a tightly packed interior. Components are integrated on equipment platforms and are thus largely inaccessible. It is pointless to debate the levels of robotic technology required when these tasks could not be performed even by an astronaut with a complete tool kit.

The full benefits of on-orbit servicing can be achieved only if the spacecraft to be serviced is designed from its very inception with a large percentage of its systems modular and accessible. Robotic removal of these modules should also be a design consideration. This goal is best implemented by a spacecraft architecture featuring standard fittings, interfaces, and docking locations with the orbital replacement units (ORUs) located on an external frame where they are accessible.

An important consequence of this modular architecture is that it implies a radically new manufacturing, test, and assembly flow. Modules can be built up in parallel and tested independently by plugging into spacecraft bus simulators. Errors could be detected and corrected at a lower level with less impact than in the traditional buildup of equipment platforms into spacecraft.

The use of standard subsystem ORUs across several programs would enable an economy of scale to be achieve which could substantially reduce unit costs. The greater experience base for each hardware item would also allow the ultimate reliability rates to be improved over what they would be if a specific item were developed for each application. This module standardization and mass production also enhances the availability of production line spares. These spares and the ease of repair on the ORU level will reduce production delays on the system level.

The synergistic relationship between modularity and serviceability recalls the experience of the Solar Max. The on-orbit repair which returned it to service was possible not because the MMS spacecraft had been designed to be serviceable but because it was designed to achieve the production and assembly benefits of modularity. The repair was an unanticipated benefit of the resultant accessibility.

Our implementation analysis identified several technologies which are either enabling or enhancing to remote servicing missions. Three of these were judged to be key in that they must be demonstrated in order for on-orbit to be fully accepted as an operational concept. These are autonomous rendezvous and docking, robotic ORU replacement, and fluid transfer.

It is possible to fly a rendezvous and docking mission entirely under remote piloted control. However, an autonomous system would significantly reduce operational support requirements and costs as well as provide higher reliability and more efficient propellant usage. This technique is regularly used by the USSR in supplying their space station but has not yet been demonstrated by the US.

The location of many DoD assets in orbits with high radiation fluxes or other hazards makes it desirable to perform servicing robotically. Robotic replacement of ORUs by simple, well defined motion can be enabled by a standardization of docking locations and fittings. This can eliminate the requirement for highly capable robots with advanced sensing, manipulative, and cognitive capabilities. The man-in-the loop requirements will be minimized by the definition of the locations and motions to be executed. This autonomy reduces the criticality of the time delay in the feedback loop which has been seen as a limit to tele-operations.

There is a trade-off between the degree of structure provided in the environment and the level of robotic technology required. It appears best to begin with a simple, structured system which has a growth path to higher complexity. The servicing robot would operate in the supervised autonomy mode, carrying out a series of pre-programmed "macro" instructions, pausing between each operation for verification and authority to proceed. Manual override and tele-robotic operation would be available for dealing with unanticipated situations. It is important to design the robot to fail in a safe and recoverable mode and not induce failures on either the servicer or the spacecraft being serviced.

The reduction of robotic operations to simple, well defined motions allows the robotic servicing subsystem to be very simple. This is a very important concept because this simplicity allows the robotic device to achieve a high level of reliability. On-orbit servicing can be economically viable only if the failure rates of the support system are extremely low. This simplicity also allows the robotic servicer to be developed with near-term technologies.

The connectors and procedures for on-orbit fluid transfer comprise the third key technology which must be demonstrated. The replenishment of propellants or other fluids was identified as one of the prime candidates for on-orbit servicing. DoD has a near term interest in hydrazine for refuelling a variety of spacecraft in both low and high altitude orbits, with a longer term interest in liquid cryogens for propulsion or space-based weapons. NASA is interest is in supplying superfluid helium to scientific satellites such as the Space Infrared Telescope Facility (SERTF).

Since refuelling can be implemented with minimal impact upon the spacecraft architecture, its potential benefits have been examined in several government sponsored studies. The most recent of these was performed for Air Force Space Systems Division Long Range Planning and Development Office. The study found two classes of satellites which could benefit from on-orbit refuelling. These were satellites in low earth orbit which had a basic propulsion requirement for drag makeup, and those in geo-synchronous orbit which have a base requirement for station-keeping. In both cases, the benefits of refuelling were derived more from the operational flexibility of greater maneuver capability than by addressing the basic propulsion requirement.

Analysis usually shows that the most cost-effective method of extending propulsion lifetime of satellites is to increase the size of the original fuel tanks, up to the limit imposed by booster capacity. If the remainder of the payload is of sufficiently high reliability and value, it can even pay to move to the next larger class of booster.

The problem of matching the fuel capacity to the rest of the system lies in the nature of the failure rates of the rest of the system. The design life of the system, which is normally used for sizing of subsystems, is not a hard limit unless it is set by exhaustion of a consumable. It is not even marked by a cluster of expected failures unless system lifetime is dominated by wearout failures. System lifetime is usually determined by random failures which occur at an even rate once the infant mortality period is passed. Thus the design life is a statistical concept denoting the point at which the predicted availability falls below the system allocation.

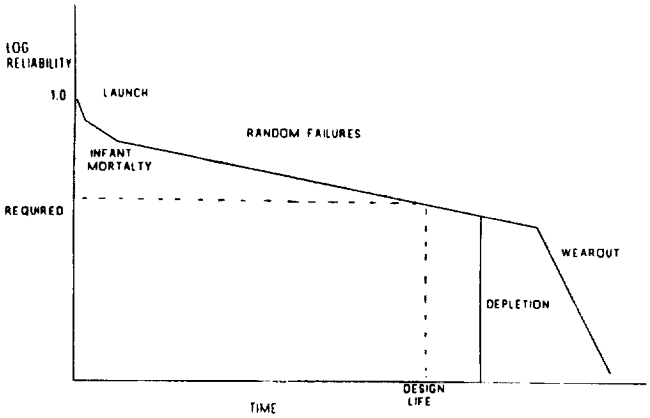

FIGURE 2. SYSTEM RELIABILITY OR AVAILABILITY

The probability that a space system will be operating satisfactorily follows the pattern shown in Figure 2. There is an immediate drop in reliability due to the chance of failure during launch and deployment. The availability then decreases with time during the early infant mortality period, with the rate of failure decreasing as the random failure region is reached. The failure rate increases again if the wearout region is reached. However, depletion of a consumable such as fuel will usually terminate system operation before wearout is reached. A nominal design life point is shown.

It is this statistical basis of the random failures that provides an economic incentive for refuelling. There will be systems which will reach the nominal design life without failure. If they are sufficiently far from a wearout mode limit they will be no more likely to fail during the next x years than they were during the first x years. Therefore, there is additional useful life which could be obtained by refuelling. The statistical chance that there might also be an unrecoverable failure early in the mission makes it unprofitable to oversize the fuel tanks to the point of requiring a larger booster.

The economics and utility of refuelling can thus be seen to be justified primarily on a contingency basis. It is those off-nominal cases where the system is required to make unanticipated maneuvers, or when the system continues to operate successfully beyond the nominal design lifetime that benefit from the capability to provide additional fluids in orbit. These benefits can be potentially large in relation to the costs required to achieve them.

7. REQUIRED TECHNOLOGY DEMONSTRATIONS

Spacecraft fluids can be classified by physical properties and hardware technology requirements into five general categories.

Gases
Monopropellants (includes water)
Bipropellants
Superfluid Helium
All Other Cryogens

There is nothing unique to the space environment which affects gas transfer, so its technology is well in hand. Supply and handling systems for the other four categories have each been given some development attention, and vary to the degree of technical maturity.

The on-orbit transfer of hydrazine was demonstrated by an experiment in the shuttle payload bay in 1984. Hydrazine was transferred from one tank to another after a valve was opened by an astronaut. This resolved many of the issues associated with low-gravity fluid transfer, including adiabatic recompression. The Storable Fluid Management Experiment further resolved micro-gravity fluid handling issues by observing the behavior of water in a transparent tank in the shuttle mid-deck in 1985. There are still some issues to further explored, such as mass gauging and robotic operation of "zero-leak" connectors under micro-gravity conditions. However, the physics is well understood and only a demonstration is required.

NASA is current developing an on-orbit demonstration of superfluid helium transfer in the SHOOT (Superfluid Helium On Orbit Transfer) experiment. This will resolve many of the additional technical issues peculiar to this fluid such as the fluid transfer process and mechanisms, tank chill-down and venting operations in micro-gravity, and verification of thermal models for heat transfer within the tank due to mixing.

A substantial amount of hardware supportive of on-orbit fluid transfer has been built and tested on the ground. Several prototype valves and connectors suitable for robotic operation have been developed under contract to NASA-JSC. An automatic fluid interface system (AFIS) which could hold these valves and act as a coupler between the servicer and target spacecraft has been built under contract to NASA-MSFC.

Much of the remaining technical development required for an on-orbit fluid transfer system can be performed as part of an experiment within the shuttle payload bay. However, true confidence on the part of potential users will not be obtained until mating and fluid transfer is demonstrated on free-flying satellites.

There is very little technology work required for an autonomous rendezvous and docking system, as all the requisite technologies exist as components. What remains to be done is the system integration and demonstration. The control system operation can be partially verified by a test and evaluation program which begins with software simulation and evolves into hardware-in-the-loop simulations on air-bearing tables. However, the final full-up demonstration of responses in all six dynamic dimensions must be achieved as a free-flying space experiment. Although preliminary development of the sensor systems can be done on ground test ranges, a space flight experiment will be required to verify performance at operational ranges against realistic backgrounds.

The development and demonstration requirements for the robotic manipulator system parallel those for the docking control system. The control loops and end effector operation can largely be demonstrated on the ground in all aspects except those affected by micro-gravity. Manipulator arm dynamic response in a micro-gravity environment is important only for large, light assemblies such as those being developed for the Flight Telerobotic Servicer (FTS). A simpler, more compact manipulator as described above might have enough stiffness to be verified in ground tests. The arm dynamics can be assessed as part of an attached shuttle payload experiment.

The major dynamics issue which can be resolved only through a free-flight experiment is the cross-coupling between the manipulator dynamics and the control systems of the servicer and target spacecraft.

In addition to the extensive component development which has been carried out in each of the core enabling technology areas, there have been several attempts to integrate them into a full system demonstration. The most ambitious was the Satellite Servicer System Flight Demonstration which was jointly sponsored by NASA and DoD. This program was to have drawn upon the hardware base described above as well as the Orbital Maneuvering Vehicle (OMV) and FTS programs to produce a free flying orbital demonstration of the three critical servicing technologies. Budgetary constraints at the sponsoring agencies led to its cancellation just as the contractors were about to begin design definition work.

Air Force Space Systems Division recently sponsored a concept study addressing rendezvous, docking, and refuelling on a smaller scale using an expendable vehicle. This study was carried out by NASA-Jet Propulsion Laboratory. Various means of carrying this concept forth to a flight demonstration are under consideration. One promising approach might be to use the SPAS hardware owned by SDIO which has already flown twice and will be reused for several additional experiment payloads.

We cannot ignore the fact that other nations have been active in this area, and the first flight demonstration may be performed by either the Japanese or Europeans. In particular, the Japanese ETS-7 spacecraft appears to have this as its goal. The ETS-7 will demonstrate the 3 key technologies described earlier.

8. IMPLEMENTATION OF SERVICING

One of the problems which must be addressed in order to obtain the benefits of on-orbit servicing is how this technology might be inserted into operational systems. There is a very long lead time in the development of new series of spacecraft and there is an understandable reluctance to make provisions for a capability which has not been fully integrated and demonstrated. Likewise, it is difficult to develop a support infrastructure in the absence of established users.

An effective way to work out of this chicken and egg impasse might be to introduce servicing capabilities on a contingency basis. For example, a grappling fixture could be incorporated into a spacecraft design at minimal cost and mass penalty. There may not be plans to use this in the original operational concept, but it might enable some corrective action to be taken later in the case of unanticipated events, as has occurred so often in the past.

Likewise, the capability for on-orbit refuelling could be provided at relatively low cost to the user. A fill valve is normally provided in spacecraft propulsion systems to allow the satellite to be fuelled shortly before launch. Making this valve compatible with robotic operations and allowing accessibility to it would enable on-orbit refuelling to take place at some future time, should the need arise and a servicing system be developed.

These contingency provisions can be justified by the extremely high ratio of the benefits which might be achieved, if they were ever to be needed, to the relatively modest costs of incorporating them as standard spacecraft design features.