HANDLING TECHNOLOGY
FOR
ON-ORBIT SERVICING

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Abstract

Introduction

On-orbit servicing provides fundamental infrastructure support to Earth-orbiting space assets through increasing their availability. Operational availability – a measure of system performance - relates the concepts of reliability, maintainability and resource supply and may be defined as:

$$A=\left(\frac{MTBF}{MTBF+MTTR+MTFS}\right)$$

where MTBF=mean time between failures (a reliability metric)
MTTR=mean time to repair (a maintainability metric)
MTFS=mean time for supply (a logistics metric)

Clearly, it is desirable to increase availability within cost constraints. Currently, almost all spacecraft are designed to maximise availability through reliability by incorporating redundancy. Redundancy is extremely costly in diminishing the mass available for payload – it is important to remember that the payload is the *raison d'etre* of the mission. The reason for this approach is that there is currently no alternative means for maximising availability – until now. On-orbit servicing (OOS) offers the means to reduce MTTR by increasing maintainability. MTFS must also be reduced by providing the logistics required to supply (of resources) for maintainability. OOS is thus a push-technology – it provides the means for reduced reliance on a single, expensive design philosophy based on high reliability. High component reliability pushes up costs, and redundancy pushes up costs by launching mass that performs no function other than to alleviate risk. The increased deisgn options for OOS are likely to yield considerable cost reductions in space asset development.

There are a number of hindrances to OOS development in space. Spacecraft manufacturers have a vested interest in maximising the number of spacecraft launched. Space agencies are in the business of technology development with little real interest in space commercialisation. Commercial satellite operators are forced to track new technological advances (eg. greater transponder capacity) and so develop new, bigger satellite platforms. Space insurers lack interest as they are not interested in technology development – they often regard technology advance as the greatest risk of all. Yet robotic OOS offers great utility in providing an infrastructure to maximise the cost-effectiveness of space satellites. There are few industries which would willing spend ~$\$10^8$ on highly designed hardware with short lifetimes and without the provision for repair or upgrade. In terms of economics, the most appropriate customer for OOS appears to be the private sector such as geostationary satellite purchasers. However, another important sector are science platforms – uninsured, expensive, one-off government-funded platforms flying state-of-the-art instruments with typically short lifecycles, eg. Earth observation and astronomy missions. An obvious example of this type of mission are the infrared satellites IRAS and ISO which were limited in operational lifetime by the boil-off of helium cryogens. These types of spacecraft will become increasingly important to the astronomy community – the infrared/submm spectrum, hitherto inaccessible to astronomers on the ground, offers as rich a source of data as optical wavelengths which have been recorded by astronomers for 3000 years. The science community is likely to gain much from extending science satellite lifetimes in terms of data return over longer and more significant timescales without the need for cross-correlating data from different instruments on new platforms. An example where OOS was of critical importance was the Hubble Space Telescope which was designed for servicing – fortunately. The science community appear to be pushing the boundaries and explicitly requiring longer lifetimes for their satellites and are embracing OOS as the means to achieve this, eg. XEUS platform to be regularly serviced by ISS.

Current State of OOS

A typical servicing profile is generally associated with beginning-of-life failures (infant mortality - BOL) where projected revenues are threatened, or with end-of-life failures (senility - EOL) where expected revenues have been achieved. The commonest BOL failure is inadequate orbit injection such as the failure of a GEO satellite apogee kick motor to circularise in the operational orbit. Most OOS activities are associated with this tyoe of failure, eg. Solar Maximum Repair Mission (1984), 1st Hubble Space Telescope Repair Mission (1993), etc. Although they have been highly effective demonstrators of OOS, the use of astronauts as “cable repairmen” does not represent an effective mode of deployment of highly trained humans who would be better served in being deployed for activities beyond state-of-the-art robotics. Furthermore, the use of astronauts is extremely expensive and they are limited to LEO operations only. The technological corrolary of this is the development of ROBONAUT, a robotic astronaut prototype which is designed to aid astronauts for external servicing on ISS. The most common mode of satellite “repair” is through the uploading of software workarounds – this can often be highly effective, eg. ExoSat. However, it can lead to sub-optimal performance and reduced mission return (eg. Galileo), or worse, be wholly inadequate (eg. Palapa B2/Westar 6 in 1984 which required recovery and refurbishment on Earth).

The commonest EOL failures are depletion of fuel/power/cryogens – replenishment of such consumables can extend the life of a spacecraft considerably. Such retro-fit or upgrades can considerably extend the revenue phase of a mission, and spread the overhead cost over a longer time period. The repair of dysfunctional satellites be it through failure or senility offers a strategy for debris mitigation by tackling the problem at source, ie. reducing the number of dead spacecraft. This debris issue cannot be over-emphasised – it provides a strong political reason for supporting robotic OOS as one of the few strategic means for tackling the debris problem. All other solutions (such as debris clearance robots) are essentially *ad hoc* without dealing with the fundamental issue that satellite manufacturers and operators are defecating in their own backyard – more satellites inevitably means more in-orbit junk.

Current Status of Capabilities

Despite its utility, there exists no OOS infrastructure. The key to this is robotics which provides the means for the projection of human capabilities into space. A number of research groups have been examining the technological issues involved in OOS, robotics in particular. NASA has been involved with a number of robotic servicing programmes. The most obvious are the Remote Manipulator System (designed by MD Robotics of Canada) carried by the Space Shuttle which provides the basis for the ISS manipulators. Fokker similarly have developed the European Robotic Arm (ERA) for adoption on ISS. These are large cargo-handling manipulators. Often, automation and robotics programmes have been “tagged on” to larger programmes with the inevitability of being the first casualties in being slashed under budget over-runs. This was the case of the Flight Telerobotic Servicer (FTS) and Orbital Maneouvring Vehicle (OMV) which were considered essential in early space station designs. In the case of NASA, the greatest threat to space robotics activity is the ill-perceived notion that robotics represents a threat to manned space activities. Regrettably this perception is endemic despite its falsity even amongst engineers who should know better. Of particular relevance to OOS is the US Ranger programme administered by the University of Maryland which has culminated in a Neutral Bouyancy Vehicle and Shuttle Pallet Experiment – it is unclear the current status of this programme. DLR in Germany are almost certainly the world-leaders in this application of space robotics – their early experience with ROTEX on the Spacelab D2 mission has led to their involvement in the Japanese ETS-VII programme which demonstrated basic servicing maneouvres between a target and chaser satellite. A number of other groups in m,any nations have had some involvement of a lesser nature, including the UK. The corollary of this is that robotic OOS activities have been uncoordinated and fragmented, often leading to replicated work, and worse, lacking any common purpose or goal. This is in stark contrast to the great success and focus of astronaut-mediated OOS. Indeed, astronaut OOS has been so successful that NASA, for a time, justified its manned programme on just that basis.

There are two polarised views on OOS: protagonists (often technologists) who have generally exhibited over-enthusiasm in stating the economic case for OOS versus detractors (often bureaucrats) who have lacked the vision to push the space frontier. Clearly, both are incorrect – there is a middle ground which mixes vision tempered with practicality. The most important message is that OOS is essential for the future development of a space-based infrastructure. Space stations and moon landings are not the keys to space – infrastructure is. Space development will always be prohibitively expensive as long as expensive assets are discarded before their time. Although there are trends towards lengthening GEO satellite liftimes to 15 years, this comes at a cost – increased reliability requirements imply greater stress on redundancy, and increased resources implies increased fuel and design power. These all impact on the spacecraft mass detracting from payload capacity. Furthermore, reliance on reliability for high availability implies the need for high reliability components which are costly. OOS provides additional design options for reducing satellite costs and increased payload.

Types of OOS Missions

Due to the large delta-v requirements for maneouvring between orbital regimes (such as between near-equatorial low earth orbit, medium earth orbit, equatorial geosynchronous orbit, and ploar orbits), it is not practical to design a multi-orbital servicer for all orbital regimes. The simplest OOS task is remote inspection – AERCam is an example of this capability. It requires only sensory instrumentation such as cameras for vision, X-ray for non-destructive testing, and/or chemical sensors for vapour leakage detection. There is no requirement for direct manipulation of objects but there is a requirement for propulsive maneouvres for proximity operations. Such servicing aids the diagnosis of problems but does not contribute directly to the solution. Remote observation can significantly aid in rapid diagnosis for software workaround solutions. Remote observation provides the basic technology demonstration of high accuracy maneouvring that is a pre-requisite for rendezvous-and-docking (RVD) required for more complex servicing tasks. The next level of complexity in OOS – target motion/movement – requires RVD and latching. Target capture is the minimum actuation requirement for OOS beyond remote inspection. This represents an order of magnitude increase in OOS complexity but introduces OOS in the provision of solutions to problems. RVD requires high accuracy maneouvring. Furthermore, RVD requires knowledge of the physical properties of the target – such is likely to exist from CAD/CAM models which offer the opportunity for extended planning in servicing. Re-orbit/de-orbit requires a high delta-v capability (electric propulsion may be an option but the high power requirements translate as high power system mass). Re-orbit/de-orbit is the most straight-forward servicing task beyond inspection and it requires latching to the target. Latching to the target and performing orbit maneouvres requires mass-to-mass matching – handling of 250 kg requires different OOS characteristics to handling of 5 kg. Engine module plug-in requires a servicer of fairly high mass – it is generally easier to attach a propulsion module through well-defined mechanical latch than other options. Change-out of a replacement module requires consideration of mechanical/electrical/optical/thermal interfaces – all connectors must be reversinbly breakable. This is the first step in "design for servicing" spacecraft – there is some opportunity for adapting current design practice in connectors (with maintained connector logs) and the need for module/component accessibility during assembly testing. Refuelling through a "petrol cap" which requires the handling of flexible, fuel-filled objects. Targets may be passive (which require all actuation to be performed by the servicer) or active (which may enable co-operative RVD). Targets may be of constant attitude in which minimal motion tracking is required, spinning which requires acquisition of the tareget along the spin vector, or tumbling which requires de-tumbling of the target with sophisticated motion tracking capability. Acquisition of GEO spacecraft with apogee engines may be through the thruster nozzle. Target acquistion requires servo-control, the frequency of the control loop depending on the motion of the target and the damping characteristics of both target and servicer.

Generally, the introduction of physical handling of objects represents a further increase in robotic complexity. The adoption of manipulators reduces the accuracy requirements for RVD. Any robotic maneouvre is a series of "controlled" collisions which introduces the problem of repeatability in a complex world characterised by uncertainty and unpredictability. On acquisition of the target, passivation of the target may be required. Both target acquisition and passivation will require force control. Tactile sensing will be required for maintenance, repair and retrofit servicing tasks, though simple orbit replacement unit (ORU) changeout (ie. design for servicing) will be achievable using force control algorithms. The parallel jaw gripper will be sufficient for ORU-exchange (a generalisation of the bolt-in-hole robotic task) but specialised tooling (similar to those developed for astronaut EVAs) will be required in addition and will be peculiar to the specific servicing task. Torque extertion of ~kNm has considerable implications for actuator requirements and sizing. Compliance is essential – the remote centred linkage offers passive compliance. Cutting, pinning and re-taping of thermal blankets will be an especially challenging task. Actuation and handling introduces the problem of logistic supply. This may involve on-demand piggyback launches of servicer fuel tanks, replacement parts and specialised tooling of mass <100 kg. This imposes a limitation on OOS reactivity. Alternatively, ISS could potentially be used for warehousing purposes but this is likely to be expensive.

Technological OOS Issues

Latching is a critical technology area – robust, positive latching with self-locking is required for RVD. Ready reversibility of latching is an important requirement and guide rails should provide self-alignment. Translation along a single axis – preferably without a rotational component. The ESA latch is a good model of a mechanical latch – it requires a target capture pin. Careful consideration of electrical connectors is required – the BNC-type pin connector involces rotation mating but the RJ-45 connector is pish-pull but is fragile. A combination of push-pull mating with high robustness and robustness to alignment errors is required. Thermal interfacing is an important consideration – breaking and repinning of thermal blankets requires considerable advances in robotics in the area of tactile sensing.

There are a number of supporting technologies required – ground station computational facilities, the development of human-machine interfaces, the ground-orbital communications link, predictive graphical displays, automated manipulation subroutines, stereoscopic vision systems, automated visual recognition, onboard computing power, spacecraft power generation and storage, etc. Many if the traditional problems associated with OOS have been solved, eg. the manipulator-spacecraft dynamic interaction problem. Many of these issues have been addressed in the author's book "An Introduction to Space Robotics" through an OOS spacecraft design called ATLAS.

Conclusions

The principal problems for OOS have been described. A more general problem is that the servicer must be designed as part of a single system – the servicer plus target, the latter being highly variable and unknown. The servicer, unlike most other Earth-oriented space missions, is required to survive a variable environment rather than operate from a single orbit. The servicer must react to external events in real-time in an unpredictable and varied environment. Interfacing issues are paramount implying the need for co-operative satellite design. Design for servicing has been achieved in the 1980s for some space platforms – modular spacecraft such as Solar Maximum and spacecraft to be serviced by astronauts such as Hubble Space Telescope. One-off, high cost science platforms are pushing the boundaries in OOS such as XEUS which will be designed to be serviced by the European Robotic Arm (ERA) on ISS. The technology for inspection missions are in place as these missions are modest in comparison with RVD and manipulation missions. The technology for RVD maneouvres is essentially in place. The technology for latching of grapple pins is in place and has been demonstrated with the Shuttle RMS. The technology for robotic manipulation is under development – simple operations are achievable in the near-term (up to ORU exchange). The basis for much of co-operative design can be achieved in new satellites and has been adopted on some current and previous platforms. There is no doubt that from a technology point of view, parallel advances in robotics on the servicer and cooperative satellite design will yield technological reality in OOS for increasingly advanced servicing tasks – an evolutionary approach. The technology for OOS is probably less of an issue than political and/or economic issues.