THE ROAD TO OOS: ENABLING ARCHITECTURE

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1.0 Introduction

The enabling architecture for on-orbit servicing (OOS) using automation and robotics technology is the subject of this paper. We will focus on those aspects related to achieving orbit insertion and placement of servicing equipment, supplies and systems.

Many assumptions are needed prior to developing a working architecture. For the foreseeable future, we must assume the use of expendable launch systems used in dedicated or shared mode. Orbits of interest are well defined as medium-to-high inclination low-earth-orbits (LEO), medium-earth-orbits (MEO), and geostationary earth orbits (GEO). We must further restrict servicing missions to high-value spacecraft, such as space telescopes, large and complex spy satellite, large communications satellites, and certain other satellites that would be difficult and expensive to replace.

There is a great deal of interest in automated and robotic on-orbit servicing and several programs are actively engaged in developing technology and systems in order to provide rescue and repair services to satellites. For example, Orbital Recover Corp., a start up privately-funded company is developing spacecraft that can extend the on-orbit operational life of large GEO communications satellite. In another program, the U.S. Defense Advanced Research Projects Agency (DARPA) is funding Orbital Express, for which Boeing is under contract to develop an advanced technology demonstrator leading to routine on-orbit resupply and reconfiguration of satellites.

The fundamental idea of autonomous and robotic servicing of satellites appears to have many practical applications. Unfortunately, there are also many practical limitations associated with servicing operations, options and opportunities. There are technical constraints, financial considerations and political implications.

2.0 Limitations

There are many physical limitations associated with servicing satellites. The foremost constraint is related to energy needs to achieve orbit. In order to simply achieve LEO, the require energy, in terms of velocity change, is roughly 9,650 m/s. To achieve MEO this is in excess of 10,000 m/s. Finally, GEO requires at least 13,580 m/s. These figure assume launch from a ground-based launch facility with direct injection into the respective orbit. The next largest energy constraint is associated with on-orbit maneuvering. In those cases where orbit-raising, de-orbit, or life extension is involved, large amounts of propellant may be required to complete a mission. The space environment is also restricting in that systems must be protected from effects of hard vacuum, extreme temperature gradients and weightlessness.

Other limitations on the uses of on-orbit servicing arise from financial, political and security issues. A purely commercial endeavor, such as that being pursued by Orbital Recovery Corp., cannot succeed without realizing a profit from operations. This reality leads to pricing levels that reflect expenses, risks, investment amortization and profit. Government applications may be civil or military. Civil satellites or either scientific or utility-oriented, e.g., navigation, weather and data transfer. There are political implications associated with servicing navigation satellites. When it comes to military satellites, there are many security issues to be addressed.

3.0 History of Crew-Assisted Servicing

Our experience with on-orbit servicing has been limited almost exclusively to crew-assisted activities. While there have been a wide array of such activities, little has been accomplished using automation and robotics technology in terms of flight experiences. The following presents a representative list of crew-assisted program and events to illustrate the need for OOS.

Vehicle	Year(s)	Activities and Accomplishments
Voskhod	1965	First EVA
Gemini	1965-66	Ten EVAs
Soyuz	1969	Crew transfer
Apollo	1969-72	Crew transfer, repairs on lunar surface
Skylab	1973-74	Deployed sunshades and solar array, repaired science experiments
Space Shuttle	1983	Demonstrated MMU and hydrazine transfer
Mir	1987-00	Repaired various hardware
Space Shuttle	1992	Retrieved Intelsat VI, installed new PKM
Space Shuttle	1993-99	Serviced HST
ISS	1998-02	In orbit construction

4.0 OOS Mission Architecture

OOS mission architecture will consist of a set of required hardware elements, software programs, protocols, and operational procedures. A minimum set of hardware elements would include launch vehicles, ground preparation facilities, servicers and servicing supplies. Servicers may take a variety of shapes and sizes. Some will be launched as needed, while others will stationed in orbit and remain on call until needed. There may also be a series of on-orbit supply depots loaded with repair tools, replacement parts and propellant. The International Space Station may play an important part as a logistics and repair platform.

The final determination of architecture form will be influenced by the drivers, i.e., market demand, costs, reliability, complexity and availability. These drivers will evolve and adjust as the technology matures.

5.0 Drivers

Here we take another look at the OOS drivers. Practical and technical limitations are key to a successful OOS capability. Orbit constraints include altitude, inclination, as well as the launch site location. The servicer design must anticipate the number and types of servicing mission that it will be call on to support. The OOS market will be changing and evolving over a period of years, making a servicer rapidly obsolete. This invariably leads to large investments with little return during the early years.

A complete OOS operation needs to be ready for many kinds of operations, both planned and unplanned. In the early years, it appears that scheduled services would be the safest in terms of financial risks. Rescue and boost missions would present little risk, but are unpredictable events. High payoff missions would include life extension mission, such as those being proposed by Orbital Recovery Corp. Of course, one of the biggest drivers is the service mission value in comparison to satellite replacement costs.

6.0 Definition of Services

I have attempted to identify the types of service that should be available. Additionally, for each type of service, I have tried to anticipate required logistical support along with needed equipment and supplies. The following table lists the three service classes with details on the kind of service in each class. In addition, associated top-level logistical support and supplies for each service are listed.

SERVICE CLASS	KIND OF SERVICE	LOGISTICAL SUPPORT	EQUIPMENT/SUPPLIES
Moving a satellite	Orbit re-boost	Servicer with attach device	Propellants
	De-orbit	Servicer with attach device	Propellants
	Salvage	Servicer with attach and stroage devices	Stowage restraints
Satellite manipulation	Scheduled maintenance	Servicer with attach device	Inspection and repair kit
	Repair	Servicer with attach device	Inspection and repair equipment
	Retrofit	Servicer with attach device	Inspection and retrofit kit
	Docked inspection	Servicer with attach device	Inspection and test kit
Observation	Remote inspection	Servicer with special sensors	Remote sensing devices

7.0 Technology, Design and Engineering Requirements

Although the many needed OOS technologies already exist, there is a great deal of work required to implement an operational system. One must take the technology and apply the rules of design and engineering to make OOS a reality. I have attempted to identify most of the key technologies and how to fit them into a working system.

There are no less than 50 different launch systems around the world. While we can eliminate the smaller ones from the OOS support list, almost any of the remaining vehicle could become an OOS system launcher. Selection depends on orbit access, payload capacity, payload flexibility, cost, availability and reliability. The servicer to be launched must have a design that is compatible with the vehicle restrictions, including mass and volumetric constraints.

The servicer must carry software for maneuvering, target evaluation and health monitoring, as well as the normal spacecraft algorithms. Almost every servicer design must incorporate a propulsion system for maneuvering and control. Inspection and interrogation techniques and devices have to be developed for the various servicing missions. If the mission requires docking with a target vehicle, rendezvous and docking techniques and devices also have to be developed. Once docked, the servicer has to carry out preprogrammed repair and replacement scenarios. Some of these will require adaptive strategies to address unanticipated repair problems.

Of course, most satellites to be serviced will have to designed for servicing, i.e., incorporate serviceability. While these mission are proceeding continuous orbital-to-Earth communications links via TDRS relay will be a necessity.

All servicing spacecraft will be complete in terms of having satellite subsystems such as structures, control, propulsion, telemetry and command, power and thermal control. However, the nature of servicing mission will require special considerations. For example, low-orbit operations lead to high energy storage needs, and high-power generation leads to large solar arrays that act as sources of dynamic instability and obstacles for simple communications and vision. Since earth shadowing is significant at low altitude, large energy storage device will be needed.

All this adds to the weight and complexity of the servicer. This, in turn, leads to more expensive servicing missions and made a commercial operation more difficult to justify. There is more than sufficient motivation to apply innovative spacecraft and mission design techniques. As with most new and complex programs, there will be a significant early investment in bringing the many technologies together in order to create an efficient OOS system.

8.0 Mission Options and Operations

Mission must be cleverly designed in order to achieve efficient OOS operations at an affordable cost for customers. As the cost go up, the number of justifiable servicing missions goes down. Thus, there is a cost-benefit balance between servicing and replacement. It is clear that early OOS mission must be focused on high-value spacecraft, such the Hubble Space Telescope, ISS, and GEO communications satellites. Here, we address mission options and related operational choices. It is the balance of the mission options that must be determined early in the evolution of OOS systems to insure a high probability of financial and operational success. The selection of OOS mission options includes such scenarios as launch-on-demand, repair-on-demand, and replace-on-demand. The last of these may or may not require a servicer vehicle.

Launch-on-demand requires the continuous commitment of one or more dedicated launch vehicles to be ready to launch with minimal notice. Repair-on-demand mission may make use of dedicated launchers and/or in-orbit tenders. In either case, mission might take advantage of in-orbit supply depots. Prior to establishing a full in-orbit network of support station, servicers will probably be complex, maneuverable, multifunction servicing machines.

9.0 Conclusions

Many conclusions can be drawn from a consideration of the enabling architecture. To begin, complete OOS systems will likely require a large variety of complex missions and hardware. To reach full operability launch vehicles, servicers, in-orbit depots and ground support equipment and personnel must be in place.

The economics of servicing compared to replacing satellites effectively limits OOS applications, i.e., only a few applications can be justified, because servicing costs appear comparable or greater than replacement costs in many cases. As OOS matures and demand grows, more missions will be able to take advantage of servicing. In addition, increasing a permanent presence in space will lead to servicing as a commonly used technique to maintain the space infrastructure, i.e., as space is colonized, servicing will be commonplace.

Satellites will evolve toward serviceability and servicers will become more uniform and less complex. Standardization of interfaces and modules would reduce servicing costs. Minimum repair costs will be realized when in-orbit repair is limited to assembly/disassembly of modules.

If in-orbit manufacturing is to become practical, we will need in-orbit servicing. Finally, colonization of space will only be possible with the full capabilities of OOS systems.