Orbital Express Space Operations Architecture Program

James Shoemaker

Defense Advanced Research Projects Agency, 3701 N Fairfax Drive, Arlington, VA, USA 22203
jshoemaker@darpa.mil, 703-696-2368

Melissa Wright, Sanjivan Sivapiragasam

SRS Technologies, 4001 N Fairfax Drive, Arlington, VA, USA 22203
Melissa.wright@wg.srs.com, 703-284-7782; sanj@wg.srs.com, 703-284-7788

ABSTRACT

The goal of the Orbital Express Space Operations Architecture program is to validate the technical feasibility of robotic, autonomous on-orbit refueling and reconfiguration of satellites to support a broad range of future U.S. national security and commercial space programs. Refueling satellites will enable frequent maneuvers to improve coverage, change arrival times to counter denial and deception, and improve survivability, as well as extend satellite lifetime. Electronics upgrades on-orbit can provide performance improvements and dramatically reduce the time to deploy new technology.

The Orbital Express advanced technology demonstration will design, develop, and test on orbit a prototype servicing satellite (ASTRO), a surrogate next generation serviceable satellite (NEXTSat). The elements of the Orbital Express demonstration will be tied together by non-proprietary satellite servicing interfaces (mechanical, electrical, etc.) that will facilitate the development of an industry wide on-orbit servicing infrastructure. NASA will apply the sensors and software developed for autonomous rendezvous and proximity operations to enable future commercial resupply of the International Space Station.

Keywords: satellite servicing, autonomous rendezvous

1. Introduction

The Orbital Express program is envisioned to set the stage for the establishment of an on-orbit satellite servicing infrastructure for routine, cost-effective, autonomous capability for resupply and reconfiguration of on-orbit spacecraft in the post-2010 timeframe. An Orbital Express-derived satellite servicing architecture will usher in a revolution in space operations, enabling new and enhanced satellite capabilities supporting not only national security missions, but civil and commercial space activities as well.

Routine, autonomous satellite servicing will provide spacecraft with unprecedented freedom of maneuver, allowing satellite coverage to be adjusted or optimized at will, or enabling spacecraft to employ unpredictable maneuvers to counter possible threats or adversary activity scheduling. Routine, autonomous, preplanned upgrades or reconfiguration of spacecraft components will dramatically reduce the "time to market" of new technology into operational satellites, increasing

mission performance more efficiently than through block replacements of satellite constellations.

DARPA's vision of post-2010 space operations foresees satellites designed and equipped with Orbital Express-derived standard mechanical and electrical interfaces enabling automated receipt of fluid consumables (fuel and cryogenics) and upgraded electronic components via an unmanned servicing spacecraft (Autonomous Space Transfer and Robotic Orbiter vehicle, or ASTRO). ASTRO will also be capable of refueling microsatellites.

In order to take advantage of an on-orbit servicing infrastructure, the next generation of satellites (NEXTSats) will have to be designed to enable routine, autonomous on-orbit servicing. A non-proprietary, "open" industry standard for satellite-to-satellite servicing interfaces must be adopted to ensure on-orbit servicing compatibility among ASTROs and NEXTSats

Approved for Public Release, Distribution Unlimited – DARPA Case #43484

designed and produced by different manufacturers. NEXTSats must also be designed such that fluid transfer interfaces and Orbital Replacement Unit (ORU) installation ports are unobstructed and readily accessible by an autonomous servicing spacecraft.

The Orbital Express Advanced Technology Demonstration (ATD) program will facilitate the realization of this vision of routine, autonomous on-orbit satellite servicing, and in so doing will prompt a

revolution in both system acquisition and in the flexibility with which national security, civil and commercial space systems are employed. The demonstration will develop and validate technologies which are critical to the establishment of an operational satellite servicing system, convincingly showing that the Orbital Express vision is technically feasible, sufficiently mature, and will provide the mission utility and operational value that future customers will require.

2. Operational System Vision

Orbital Express will establish a revolutionary approach to new space architectures, providing a cost-effective method for autonomous satellite servicing, using a standard industry-wide interface.

DARPA envisions an operational Orbital Express satellite servicing system which will revolutionize space operations by providing a routine, cost-effective, autonomous capability to resupply satellites in the post-2010 timeframe. The capability to refuel satellites will enable more frequent maneuvering, allowing coverage to be adjusted as needed. The capability to replace electronics will reduce the “time to market” for new technology by allowing spacecraft to be upgraded as the new parts become available, not waiting for the next block upgrade. This will increase spacecraft mission performance, and will enable new satellite capabilities

for national security, civil and commercial space activities.

Future systems that make use of this servicing capability will have many advantages over traditional spacecraft architectures. Satellites will be able to maneuver on demand to improve coverage, avoid threats, or surprise adversaries with unpredictable fly-over times. Earlier operational capability will be possible with a partially deployed constellation. Fully functional satellites will be able to be rescued from delivery to the wrong orbital location. Failed or degraded satellites will be repaired or refueled to restore full or partial capability. Satellites will be repositioned or reconfigured to address changing market needs. Larger and more sophisticated satellites will be launched with minimum propellant onboard.

Figure 1: Operational System ASTRO
Approved for Public Release, Distribution Unlimited – DARPA Case #43484

As shown in Figure 1, the operational ASTRO servicer consists of a spacecraft bus with several servicing elements: rendezvous and prox ops (RPO) sensors to determine the location and attitude of the target satellite; a capture system module which contains the docking mechanism as well as fluid couplers and electrical connectors; a robotic arm to transfer ORUs and/or to grapple the target spacecraft from a larger stand-off distance; a cargo section to house the fluid and ORUs being transferred from the commodities spacecraft (CSC) to the client spacecraft.

The concept of operations (CONOPS) for a servicing architecture is based on a standard set of mission procedures and servicing elements for all missions, but each mission/client will have an optimum combination of steps and elements. Notionally, a given ASTRO would reside on orbit for years, ferrying supplies back and forth between disposable commodities depots and multiple client spacecraft in a constellation, but the architecture can easily be modified to accommodate a wide range of servicing scenarios. The CONOPS is depicted in Figure 2, with a representative client spacecraft (NEXTSat) and commodities depot (CSC), and consists of the following elements:

1. **Pre-launch / Mission Planning:**
Determine the CONOPS for that particular mission/client, including the type of servicing desired, the frequency of servicing required, the optimum number and placement of servicers, etc
2. **Launch:**
ASTRO is launched into an orbit near the NEXTSat, fully loaded with fluid and/or ORUs. As needed, commodities depots are launched into a lower, but compatible, orbit.
3. **Far Field Rendezvous:**
ASTRO uses a ground-provided estimate of NEXTSat's position to rendezvous to within sensor range. Long range sensors track NEXTSat's position as ASTRO approaches.
4. **Near Field Rendezvous:**
ASTRO transitions to short range sensors as it nears the target, allowing higher fidelity estimation of NEXTSat's position and attitude.
5. **Prox Ops & Capture:**
ASTRO begins its final approach, aligning its

docking face to NEXTSat's, and matching rotational rates. An optional crosslink allows ASTRO to notify NEXTSat of its approach, and to confirm that NEXTSat is ready for servicing. At this point, ASTRO can either "direct capture" by flying close to the client spacecraft and engaging the capture mechanism, or it can stand off a distance from the client and engage the robotic arm to "grapple" the client spacecraft, then drawing it close to engage the capture mechanism.

6. **Mated Operations:**
Once mated, ASTRO initiates delivery of the required fluid and/or ORUs, coordinating activities with NEXTSat via a hardline electrical connection. Typically, the NEXTSat attitude control will be disabled and ASTRO will provide attitude control for the mated stack.
7. **Release & Separation:**
After servicing is completed, ASTRO releases NEXTSat from the capture mechanism and backs away, maintaining sensor lock to preclude recontact between the two spacecraft.
8. **Loiter Orbit:**
While not actively engaged in servicing operations, ASTRO resides in a loiter orbit somewhere below the NEXTSat.
9. **Deploy / Retrieve Microsat:**
As required, ASTRO can deploy, refuel, or retrieve microsats. These microsats can be launched berthed in ASTRO, attached to a CSC, or by some other method.
10. **Rendezvous & Capture CSC:**
ASTRO performs the same steps used to rendezvous with NEXTSat to rendezvous with the CSC.
11. **Mated Ops at CSC:**
ASTRO transfers the fluid and ORUs from the CSC, maintaining attitude control of the mated stack. ASTRO refuels itself from the CSC as well.
12. **Disposal:**
After ASTRO has completed all required servicing operations, or has exceeded its useful lifetime, it is put into a rapidly decaying disposal orbit. The CSC reenters passively due to atmospheric drag at the lower altitude.

Figure 2: Operational CONOPS Overview

Each of these elements can be performed autonomously, with as much supervision as needed to make the client feel comfortable. Orbital Express has

defined four levels of supervised autonomy, shown in Figure 3.

<u>Level</u>	<u>Supervision</u>
1	Require ground approval or data uplink before execution
2	Allow ample time for ground override before the system automatically carries out a command
3	Run autonomously, sending commands to the ground for occasional verification
4	Fully automated operations, with ground analysis only when a problem occurs

Figure 3: Four Levels of Supervised Autonomy

3. Advanced Technology Demonstration

The ATD will demonstrate critical technologies to enable an on-orbit satellite servicing system, including: standard satellite servicing interfaces; autonomous GN&C system; autonomous rendezvous, proximity operations, and docking; fluid and ORU transfers. During the course of the demonstration, the team will continue to refine conceptual operational missions, and will continue to perform mission utility analysis and life cycle cost estimates, along with a plan for transitioning from a demonstration to an operational system. The demo spacecraft and test plan are designed to provide maximum traceability to an operational system, in order to build confidence within the customer community that the system is flight-proven and ready to deploy.

The Orbital Express ATD program will design, build, and fly a prototype servicer and a representative serviceable spacecraft, to successfully demonstrate all aspects of autonomous servicing and to cultivate a client base for a future operational system. The ATD is a \$100M baseline program, awarded in March 2002 to a contractor team led by Boeing Phantom Works, and including Ball Aerospace, Draper Laboratory, Northrop Grumman, Starsys Research, and MD Robotics.

3.1. Demonstration test plan

The demonstration consists of the ASTRO and NEXTSat spacecraft, which will repeatedly perform rendezvous, servicing & separation under a wide variety of conditions, to demonstrate the reliability and

robustness of the Orbital Express system design. The two satellites will be launched mated and will perform the initial fluid and ORU transfers before ever separating, in an effort to achieve as many test objectives as possible early in the mission. Figure 4 shows the demonstration test plan, including the type of

rendezvous to be performed, the method of capture, any simulated failures, time and fuel used, and number of fluid and ORU transfers to be performed. This test plan is frequently revised as system capabilities and customer requirements become better understood.

Test Scen	Rendezvous		Prox Ops					Capture		Unmated				Mated			
	Direction	Max Rng	Flyrnd	Max Rng	Apprch	Contin Mnvr	Cmd	Type	Lite	Hr	Min	m/s	kg	ORUs	Fluid	Days	kg
C/O	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	4	0.5
0	-	-	-	-	-	-	-	-	-	-	-	-	-	3	17	14	0.0
1	-	-	-	-	-	-	-	-	-	23	40	0.0	0.0	2	8	10	4.0
2	-	-	-	10 m	Sol Inrl	-	Grd	Direct	D	1	50	1.0	0.6	2	2	4	0.0
3	-	-	-	10 m	Sol Inrl	-	XL	Fr-Flr	N	1	50	1.0	0.6	2	2	4	0.0
4	-	-	-	30 m	Sol Inrl	-	XL	Fr-Flr	N	1	50	1.7	0.9	0	2	4	0.0
5	-	-	-	30 m	Sol Inrl	Bkout 20-30	Grd	Direct	N	1	50	1.7	0.9	0	2	4	0.0
6	-	-	-	60 m	Sol Inrl	-	Grd	Direct	D	1	50	2.6	1.4	2	0	4	0.0
7	-	-	-	60 m	Sol Inrl	-	XL	Direct	D	1	50	2.6	1.4	0	0	4	0.0
8	-	-	Flyrd 1x	120 x 60 m	Sol Inrl	30 m Hold	Grd	Direct	D	3	30	3.5	1.9	0	0	4	0.0
9	-	-	Flyrd 1x	100 x 100 m	Sol Inrl	-	XL	Direct	D	3	30	3.9	2.1	2	2	4	0.0
10	Behind	1 km	Direct	120 to 60 m	Sol Inrl	-	Grd	Direct	D	23	40	5.2	2.9	0	0	4	0.0
11	In Front	1 km	Flyrd 2x	100 x 100 m	Sol Inrl	Brkout 8-30	Grd	Direct	N	23	40	5.6	3.1	0	0	4	0.0
12	Behind	7 km	Flyrd 1x	120 x 60 m	Sol Inrl	-	XL	Fr-Flr	N	23	40	7.0	3.8	0	0	4	0.0
13	In Front	7 km	Flyrd 3x	100 x 100 m	+V-Bar	-	XL	Fr-Flr	N	23	40	7.4	4.0	0	0	4	0.3
14	Behind	200 km	Direct	120 to 60 m	Sol Inrl	4 km Hold	XL	Direct	D	47	5	22.0	11.9	2	2	4	0.0
15	In Front	200 km	Direct	120 to 60 m	-R-Bar	-	Grd	Direct	D	47	0	24.0	12.8	0	0	4	0.3
16	Behind	1000 km	Direct	120 to 60 m	Sol Inrl	-	XL	Fr-Flr	N	240	0	32.0	16.8	2	2	4	0.0
17	Reserved for Scenario Repeat (Duration and Fuel Based on Scenario 7)									1	50	2.6	1.4	0	0	4	0.0
18	Reserved for Scenario Repeat (Duration and Fuel Based on Scenario 8)									3	30	3.5	1.8	0	0	4	0.0
19	Reserved for Scenario Repeat (Duration and Fuel Based on Scenario 9)									3	30	3.9	2.0	0	0	4	0.0
20	Reserved for Scenario Repeat (Duration and Fuel Based on Scenario 10)									23	40	5.2	2.7	2	2	4	0.0
-	Mated Reboost									-	-	-	-	0	0	1	0.0
All	Engine Canting, Dispersions, Uncertainties (30%)									150	52	40.9	21.9	0	0	0	1.5
-	Total Defined:		132 Days		102 kg Fuel		27		5	47	177.3	95.1	19	41	105	6.6	
-	Total Undefined:		233 Days		42 kg Fuel		-		-	-	-	-	-	-	-	-	
-	Total:		365 Days		144 kg Fuel (FTAPS Usable)		27		5	47	177.3	95.1	19	41	105	6.6	

Figure 4: Demonstration Test Plan Summary (Delta IV - Rev I)

The difficulty of the scenarios increases with time, building up from short range to long range rendezvous and adding in simulated failures to test the system's autonomous fault response capability. At least one scenario will take ASTRO beyond sensor range, to demonstrate a "cold acquisition" of NEXTSat using only ground-provided position information.

Similarly, the system will gradually increase the level of autonomy, reducing the number of ground authorizations required until at least one scenario is conducted with full "trusted autonomy."

For each scenario, the system starts in a mated configuration (Figure 5), maneuvers to the desired separation attitude, then ASTRO separates and performs back-away maneuvers, maintaining sensor lock on NEXTSat. When it reaches the desired separation distance for that scenario, ASTRO reverses direction and performs the prescribed rendezvous, prox ops & capture operations.

Figure 5: Orbital Express Demo Spacecraft (Mated)

Using its ability to detect NEXTSat's attitude, ASTRO has the capability to approach along any axis (assuming spacecraft rotation rates are not excessive). The default orientation for each spacecraft as well as for the mated stack is solar inertial, so many of the scenarios demonstrate a solar inertial approach corridor, as shown

in Figure 6. In this figure, ASTRO locks onto the short range targets on NEXTSat's docking face at 60m and maintains that relative orientation throughout the remainder of the approach and capture sequence. To do so, ASTRO has to spiral in, matching the NEXTSat's rotation rate as it follows the sun.

Figure 6: Proximity Operations - Typical Body Approach Profile
Approved for Public Release, Distribution Unlimited – DARPA Case #43484

3.2. ASTRO spacecraft

ASTRO is the prototype servicing spacecraft, containing the active elements of the servicing interface, the rendezvous sensors, and the autonomous GN&C software. The demo ASTRO is built by Boeing

Phantom Works, and is a new development spacecraft. Figure 7 shows the ASTRO spacecraft, with its key elements.

Figure 7: Demonstration ASTRO

3.3. NEXTSat spacecraft

NEXTSat is required to emulate a future client spacecraft as well as a future CSC, meaning that transfers will be demonstrated in both directions to simulate receipt as well as delivery of commodities.

The demo NEXTSat is built by Ball Aerospace, and is based on their commercial RS-300 spacecraft bus, as shown in Figure 8.

Figure 8: Demonstration NEXTSat / CSC

4. Transition Plan

In order to transition the Orbital Express vision of autonomous on-orbit satellite servicing from a technology demonstration to a ready-to-field operational system, additional technologies will need to be developed and validated. During the demonstration phase, the Orbital Express team is actively soliciting input from potential future customers to ensure that their needs are addressed.

The fluid transfer system will need to demonstrate compatibility with fluids other than hydrazine. NTO is a challenge due to issues with material incompatibility – metal bellows tanks or an NTO-compatible pump would be required. High pressure and cryogenic fluids also pose a challenge – it may be preferable to transfer an entire tank (similar to ORU transfer) rather than try to flow high pressure or cryogenic fluids across the interface.

The rendezvous and prox ops system would benefit from additional sensor development, some of which is already underway at MSFC, JPL & Boeing. Also, additional efficiency would be achieved with increased rendezvous autonomy, particularly full-scale fault management and contingency operations software. The transition plan can leverage ongoing autonomy work at Draper, JPL & Boeing.

The ORU transfer system will likely require an increase in complexity, accompanied by increased dexterity in the robotic arm. The arm will be scaled from 3m to 6m, and ASTRO may carry a “toolkit” of end effectors for the arm, interchangeable depending on the particular task at hand. Development of modular focal plane array and propellant tank ORUs will be another challenge that may be posed by future clients.

Lifetime issues will need to be addressed as well. The demonstration mission duration is one year, but an

Approved for Public Release, Distribution Unlimited – DARPA Case #43484

operational ASTRO could well be expected to operate for ten or fifteen years. This will necessitate additional redundancy and radiation hardening, among other things. Protective covers may be required for electrical

connectors, fluid couplers, capture mechanisms and/or sensors, to prevent contamination buildup.

5. Conclusion

The concept of on-orbit servicing has been around for many years, but it has taken until now for the technology to catch up to the concept. DARPA's Orbital Express program will develop the critical

technologies and provide a convincing demonstration that autonomous satellite servicing is technically feasible, cost effective, and operationally invaluable.