Autonomous Satellite Servicing Using the Orbital Express Demonstration Manipulator System

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Abstract

The Orbital Express Demonstration System (OEDS) flight test, flown from March to July 2007, achieved all of its mission objectives, demonstrating a suite of capabilities required to autonomously service satellites on-orbit. Demonstrations were performed at varying levels of autonomy, from operations with pause points where approval from ground was required to continue, to fully autonomous operations where only a single command was sent to initiate the test scenario. The Orbital Express Demonstration Manipulator System (OEDMS), mounted on the ASTRO spacecraft (chaser), was used to service the NextSat spacecraft (client satellite). The OEDMS played a critical part in achieving two key goals of the OEDS flight test: autonomous capture of the free-flying NextSat and autonomous ORU (On-Orbit Replaceable Unit) transfer. This paper describes the OEDMS vision system and arm control visual servo capabilities, key enabling technologies for autonomous capture of the free-flying NextSat with a robotic manipulator. Features of the ORU transfer system, such as standardized non-proprietary interfaces for handling and attachment, are discussed. Finally, sample flight telemetry is presented.

1. Introduction

The purpose of DARPA's Orbital Express Demonstration System [1] was to demonstrate the operational utility and technical feasibility of autonomous techniques for on-orbit satellite servicing.

MDA's primary contribution to the OEDS mission was the Orbital Express Demonstration Manipulator System (OEDMS). The main components of the OEDMS were a 6-DOF rotary joint robotic arm and its Manipulator Control Unit (MCU). Mounted on the Autonomous Space Transfer & Robotic Orbital Servicer (ASTRO) spacecraft developed by Boeing, the arm was used to capture and service the NextSat, a client satellite provided by Ball Aerospace. A composite arm camera photo of the ASTRO/NextSat stack on-orbit is illustrated by Figure 1.

Using a robotic arm on-orbit, the Orbital Express mission demonstrated autonomous capture of a fully unconstrained free-flying client satellite, autonomous transfer of a functional battery ORU between two spacecraft, and autonomous transfer of a functional computer ORU. These operations were executed as part of mission scenarios that demonstrated complete sequences of autonomous rendezvous, capture, berthing and ORU transfer.

To support on-orbit commissioning of the satellites, the arm grappled NextSat (held de-rigidized by the ASTRO capture system) and positioned it to allow for the ejection of flight support equipment. On several occasions, the arm positioned the NextSat in front of ASTRO sensors for a sensor suite checkout. The last step of any operation where the arm grappled NextSat was to position NextSat within the capture envelope of the ASTRO capture system so that the two spacecraft could be re-mated. The arm also performed a global video survey of the two spacecraft early in the mission, using the camera mounted to its end-effector.

Photo Credit: DARPA/Boeing/MDA

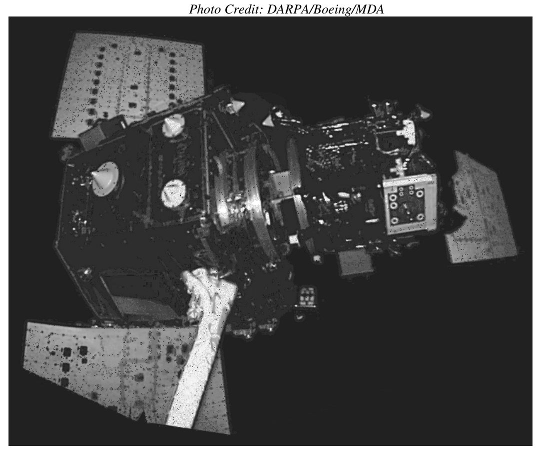

Figure 1. Composite photo of the mated ASTRO / NextSat stack on-orbit

MDA supplied two ORUs (On-Orbit Replaceable Unit) and their standard spacecraft mounting interfaces for the Orbital Express mission. One ORU contained a battery, while the other contained a computer. Both ORUs were latched to the ASTRO for launch. MDA also provided the OEDMS vision system target and grapple fixture mounted on the NextSat, as well as the Manipulator Ground Station used to receive OEDMS telemetry and upload files to the Manipulator Control Unit on ASTRO.

Elements of the OEDMS design were derived from MDA's previous space-flight heritage with the SRMS and SSRMS manipulators on the Space Shuttle and Space Station, but with some significant differences. While SRMS and SSRMS operations are performed under direct human manual control, all OEDMS manipulator operations were pre-scripted and autonomous, with no manual mode of operation. This required the development of an OEDMS visual servo control mode and a target-based vision system to enable free-flyer capture, as well as the development of new non-proprietary interfaces for autonomous ORU exchange between spacecraft. This paper describes capabilities of the OEDMS and how it was used to demonstrate autonomous on-orbit satellite servicing techniques as part of the Orbital Express mission.

2. System Description

2.1. ASTRO

The ASTRO, developed by Boeing, was the servicer vehicle ([1], [2]). In a typical unmated scenario (operations where ASTRO undocked from NextSat), the autonomous rendezvous system flew the ASTRO without ground assistance while its sensors tracked the NextSat satellite. After station-keeping at near-range separation (e.g. 120 m [1]), ASTRO initiated proximity operations, such as executing a fly-around of the client satellite at a desired range. After a fly-around, the ASTRO performed station-keeping at a pre-defined range before entering the approach corridor. Final station-keeping was performed as the ASTRO arrived at close range (e.g. 10 m [1]) to NextSat. The ASTRO subsequently executed the final approach, maneuvering to position the NextSat within a desired capture envelope. The ASTRO then performed either a direct capture using its direct capture system, or a free-flyer capture using the OEDMS.

The ASTRO had two ORU bays, one for a battery ORU and the other for a computer ORU. Typically, the arm was used to transfer ORUs from the ASTRO to NextSat and back. The ORU Interface Assembly (OIA) provided the attachment point for an ORU on the spacecraft. An electrical connection at the centre of the interface allowed for the transfer of power and/or data between the ASTRO and the ORU.

2.2. NextSat

The NextSat, developed by Ball Aerospace, was the client satellite for the ASTRO servicer ([1], [2]). The NextSat could determine and control its attitude. The passive half of the ASTRO capture system was installed on NextSat to support direct capture, while an OEDMS vision system visual target and grapple fixture was installed on NextSat to support free-flyer capture with the robotic arm.

The NextSat had one ORU bay, which contained the attachment interface for an ORU. The battery ORU was transferred to NextSat prior to the execution of unmated operations, and it was incorporated into NextSat's electrical power and distribution system.

2.3. OEDMS

The OEDMS, developed by MDA, was a 6-DOF rotary joint manipulator system. Figure 2 shows the OEDMS in its Ground Support Equipment (GSE). The arm's physical layout consisted of a shoulder yaw joint, shoulder pitch joint, upper boom, elbow pitch joint, lower boom, wrist pitch joint, wrist yaw joint, wrist roll joint, force/moment sensor, end-effector, end-effector camera, and an externally routed cable harness. The arm had a large kinematic workspace. The joint angle travel limits were sized and the external cable harness was routed so that the arm could reach or obtain a camera view of almost every portion of the ASTRO and NextSat satellites when the two spacecraft were mated.

The OEDMS arm control software ran on the Manipulator Control Unit (MCU), an avionics box mounted inside the ASTRO near the base of the arm. The arm performed its various operations by executing pre-planned scripts resident on the MCU. The scripts were commanded to execute in sequences selected by the ASTRO Mission Manager software to perform mission scenarios.

The robotic arm had the following autonomous control modes: (1) Joint Angle Sequence – the arm joints were commanded to achieve a set of joint angle destinations; (2) Cartesian Position and Orientation Sequence – the Point of Resolution (POR) of the arm (its virtual tip) was commanded to achieve a 6-DOF pose with respect a fixed frame on the ASTRO spacecraft; (3) ORU Insertion/Extraction – the arm inserted/extracted an ORU to/from its mounting interface on the spacecraft; (4) ORU Latch/Unlatch – the arm latched/unlatched the ORU to/from its mounting interface on the spacecraft; (5) Limp – the arm lifted its joint brakes so that its joints could backdrive in the presence of externally applied torques; (6) Visual Servo – the tip of the arm was commanded to track and capture NextSat based on pose estimates from the vision system. The vision system sensor was a camera mounted on the arm end-effector.

Photo Credit: MDA

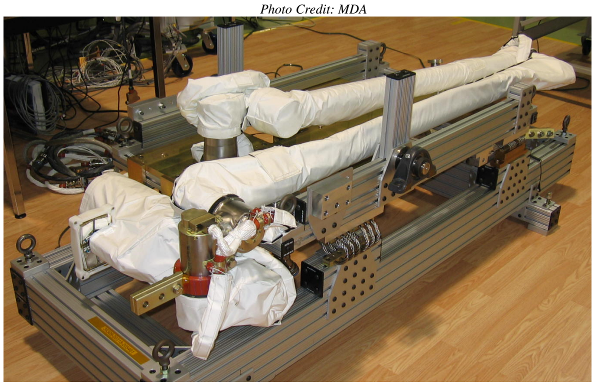

Figure 2. OEDMS

In the case of the Joint Angle Sequence mode, joint commands were calculated on an individual joint basis from the error to a joint's target destination. For all Cartesian modes of operation, the arm control resolved rate algorithm computed the joint rate commands required to achieve a specified arm tip linear and angular rate in desired linear and angular directions relative to the arm control base frame.

2.4. System Dynamics

The arm was mounted to the ASTRO spacecraft. When the arm was in motion, the ASTRO transitioned to a free-drift mode of operation. Operating a robotic arm on a free-floating base has been analyzed and discussed in the literature ([3], [4]).

The mass of the arm was roughly an order of magnitude lower than the mass of the ASTRO, but the rotational inertia of the arm about its base when outstretched was on the same order of magnitude as ASTRO's smallest principal inertia. ASTRO's attitude was perturbed when the arm was in motion, but maintaining ASTRO attitude while the arm was in motion was not a mission constraint. For a typical operational scenario, the ASTRO would correct its attitude using its reaction wheels after an arm motion script had completed. This approach was executed efficiently throughout the course of the mission.

3. Free-Flyer Capture

3.1. Technology Review

An overview of space robotics topics in the literature spanning nearly thirty years is presented in [4]. Free-flyer capture using a robotic arm on-orbit is a topic of considerable interest. The literature contains primarily analytical, simulation and laboratory test-bed results, as the acquisition of on-orbit experimental results is limited by the large investment of capital required to generate them.

The Space Shuttle's SRMS ([5], [6]) has captured many free-flying satellites, subsequently handling the captured payloads and berthing them in the Shuttle payload bay. A human operator controls the SRMS in a manual mode for on-orbit free-flyer capture and subsequent payload handling operations.

Operational autonomy is important for On-Orbit Servicing (OOS). The ETS-VII mission demonstrated a number of autonomous satellite servicing and space robotic manipulator techniques on-orbit ([7], [8]). On ETS-VII, a robotic arm released a client satellite to float freely. The motion of the client satellite was limited, however, by a docking mechanism that partially released for the experiment. After the client satellite had moved approximately 20 centimeters, the arm re-captured it using visual servo feedback with a 2 Hz sample period. The 2 Hz update rate imposed a direct constraint on the arm control closed-loop bandwidth, thereby limiting the dynamics that the arm could track.

On Orbital Express the OEDMS performed several visual servos to capture the NextSat. Four visual servo operations were performed where the NextSat was held de-rigidized by the ASTRO capture system. On two occasions, the OEDMS captured the NextSat while it was fully unconstrained and free-floating. OEDMS was capable of executing visual servos with a faster update rate than the ETS-VII robotic arm, increasing the range of dynamics and relative misalignments that the arm could track. The OEDMS vision system also maintained visual target tracking from target acquire, through approach and capture, all the way to full rigidization of NextSat to the end-effector. See [9] and [10] for results of the Orbital Express mission.

The ASTRO and NextSat were launched together for the Orbital Express mission. The ASTRO capture system released and separated from the NextSat to perform unmated operations such as autonomous rendezvous and capture. NextSat fully controlled its attitude until a short period before capture when it transitioned to a limited attitude control mode. The

ASTRO controlled its approach to the NextSat with its thrusters, so the relative rates between the two fell within controlled limits. For free-flyer capture using the OEDMS and direct capture using the ASTRO capture system, NextSat was equipped with an OEDMS Probe Fixture Assembly (including the target for arm visual servo) and the ASTRO capture system passive half, respectively. A robotic arm like the OEDMS could be equipped with an end-effector designed to interface with pre-existing features on a satellite, eliminating the need for a custom grapple fixture. Other projects have investigated the capture of a tumbling satellite or capturing a satellite without a pre-installed grapple fixture. The TEChnology SAtellite for demonstration and verification of Space systems (TECSAS) mission planned to launch a client and servicer satellite separately, to demonstrate autonomous rendezvous and capture of a tumbling satellite with a generic grapple fixture [11], but the project is currently on hold. The Front-end Robotics Enabling Near-term Demonstration (FREND) is developing a multi-robot system to autonomously grapple tumbling satellites without custom grapple fixtures ([12], [13]).

3.2. Initial Conditions for Free-Flyer Capture

To execute a free-flyer capture using the robotic arm, ASTRO approached and station-kept with NextSat so that the OEDMS vision system target and grapple probe on NextSat came within a specified capture envelope. In a typical scenario, the arm was commanded autonomously to the Ready for Free-Flyer Capture (RFFC) configuration prior to entering the NextSat approach corridor. The RFFC configuration positioned the arm end-effector at a pre-determined position and orientation with respect to a fixed frame on ASTRO.

The capture envelope position and orientation were fixed with respect to the base of the arm, specifying the initial position and orientation of the NextSat relative to the tip of the arm with linear and angular position tolerances (see Figure 3 for an artist's rendition of free-flyer capture initial conditions).

The maximum relative linear and angular velocities between the tip of the arm and the grapple fixture on the NextSat prior to the initiation of arm motion for free-flyer capture were controlled within specified limits. When these conditions were satisfied, the visual target and grapple fixture on the NextSat were within the field of view of the camera mounted on the arm end-effector.

Image Credit: DARPA/Boeing/MDA

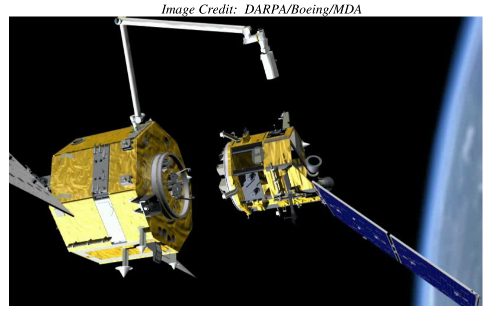

Figure 3. Free-flyer capture initial conditions

3.3. Visual Target Acquisition and Tracking

The arm was commanded to acquire the visual target using the OEDMS vision system while the ASTRO station-kept to maintain the NextSat in the capture envelope. Once the arm signaled the ASTRO mission manager that it had acquired the target, the ASTRO transitioned to free drift and the arm performed a visual servo operation to track and capture the NextSat. The NextSat was freely floating in a limited attitude control mode for the capture operation.

The OEDMS vision system primarily consisted of a camera, a frame-grabber and a pose estimate algorithm. The vision system first acquired the visual target and then transitioned to a tracking mode. After acquiring the visual target, the OEDMS vision system provided a 6-DOF estimate of the position and orientation of the target on NextSat relative to the tip of the arm. The arm visual servo control mode operated on this real-time sensor input to command the tip of the arm towards the grapple fixture on NextSat.

The arm visual servo control mode implemented an algorithm to command the tip of the arm towards the target based on pose estimate feedback from the vision system. The primary goal of the arm control law was to keep the visual target centered in the camera field of view (if the target exited the field of view the vision system would lose target-lock and abort the visual servo operation). The control law also attempted to satisfy the goals of reducing the range, lateral and angular offsets to the target, and to achieve a relative speed between the tip of the arm and the target larger than a minimum threshold for capture. The final output of the control law was a commanded speed for the tip of the arm in a desired direction relative to the arm base frame. The arm control resolved rate algorithm then computed the joint rate commands required to achieve the commanded arm tip speed and direction.

3.4. Client Satellite Capture

The NextSat was equipped with a grapple fixture called the Probe Fixture Assembly (PFA). The PFA consisted of a main cylindrical body with geometry and alignment features that allowed it to seat into the arm end-effector, a flexible probe that extended up from the centre of the grapple fixture, and the vision system visual target plate.

To capture the PFA, the arm commanded its end-effector towards the centre of the grapple fixture in a visual servo mode. The required accuracy of the visual servo mode was driven by the need to impact the tip of the grapple fixture probe within a certain lateral and angular misalignment tolerance, while simultaneously achieving a relative velocity between the tip of the end-effector and the tip of the probe larger than a minimum threshold. As contact was made between the end-effector and the tip of the grapple fixture probe, the probe deflected about compliance at its base. As the probe deflected, it was directed to strike a plunger at the centre of the end-effector. Impact on the plunger triggered an over-center mechanism that soft captured the probe, and sent a signal to software indicating that capture had been achieved. The control software then commanded the arm to halt its motion and retract the end-effector carriage to rigidly secure the NextSat to the tip of the arm via its grapple fixture. Once rigidization completed, the arm changed parameter sets to compensate for the new inertial loading condition, and brought the payload to rest relative to its base.

3.5. Payload Handling and Berthing

After the transient dynamics of the capture event were nulled out, the ASTRO Mission Manager commanded the arm to move the NextSat to a pre-determined position and orientation relative to the active half of the ASTRO direct capture system on the ASTRO spacecraft. The arm presented the NextSat to the ASTRO capture system, where the ASTRO would soft-capture the NextSat. Finally, the arm released and backed away from the NextSat grapple fixture, and the ASTRO capture system re-mated the NextSat to ASTRO. The arm was then stowed in a parked configuration. The entire free-flyer capture sequence was executed autonomously by the ASTRO Mission Manager.

The inertia of the arm about its base when holding the NextSat was considerable, and larger than the principal inertias of the two spacecraft. Both the ASTRO and NextSat were in a free-drift mode when the arm was in motion between them, which would perturb the attitude of the spacecraft stack. The induced attitude error would be corrected by the ASTRO after arm operations had been completed.

3.6. Summary of Visual Servo Operations

The OEDMS performed a total of 7 visual servo operations on-orbit. There were three different categories of visual servo operations: (1) Visual Servo Checkout (once), (2) Static NextSat Capture (four times), and (3) Free-Flying NextSat Capture (twice).

The first visual servo operation performed on-orbit was the visual servo checkout. The checkout involved NextSat target acquire, track and approach, with the tip of the arm coming to rest at a pre-determined distance from the NextSat grapple fixture. The next four visual servo operations involved target acquire, track, approach, capture and rigidize, with the NextSat being held in a de-rigidized state by the ASTRO capture system. Arm visual servo trajectory tracking performance was found to be as predicted by simulation and very repeatable. The misalignments between the end-effector and the tip of the NextSat grapple fixture at the time of initial contact were well within the required end-effector capture envelope.

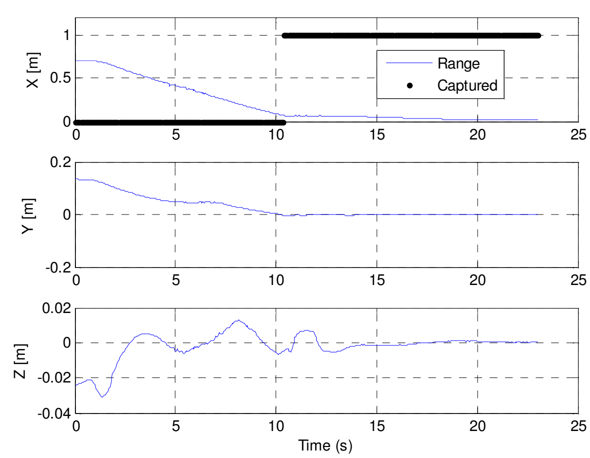

Figure 4. Vector from arm tip to target from target track to capture and rigidize

For the final two visual servo operations, the OEDMS captured the fully free floating NextSat, as part of Orbital Express Mission Scenarios 7-1 and 8-2. In both cases, the arm acquired the target and performed a visual servo, making contact with the NextSat grapple fixture probe well within the capture envelope of the end-effector. In both cases the arm subsequently captured the NextSat PFA and ultimately rigidized it to the arm end-effector. OEDMS vision system data from the free-flyer capture operation in

Scenario 7-1 is presented in Figure 4. This figure illustrates the vector from the tip of the arm to the NextSat grapple fixture, from initiation of target tracking to payload rigidization to the arm end-effector. The x-axis component of this vector is the range to the target from the tip of the arm. The payload captured flag is superimposed on the x-axis plot. Capture of the NextSat grapple fixture probe by the end-effector is indicated when this flag transitions from 0 to 1.

4. ORU Transfer

The Orbital Express ORU transfer architecture is based upon standardized, non-proprietary interfaces, designed for robotic compatibility. Each spacecraft was equipped with one or more ORU Interface Adapters (OIA), to which the ORU Container Assemblies (OCA) were latched during an ORU transfer operation. The OCA provides a standardized package into which many different ORU variations can be placed. The OCA and the ORU it contains are collectively referred to as an ORU (Figure 5).

The OEDS mission demonstrated two of these variations. The first was a battery ORU (Batt) transfer, removing and replacing a component of the client satellite's power subsystem, and re-integrating it into the power distribution network. The second was a computer (AC3) ORU transfer, demonstrating the ability to perform remove/replace operations on a major component of the client satellite's GN&C subsystem. Eight autonomous ORU transfers (seven Batt transfers and one AC3 transfer) were completed during the OEDS mission.

4.1. Technology Review

ORU transfer architectures are primarily found on the International Space Station (ISS), where there is a range of ORUs and ORU attachment interfaces, with different alignment features and stiffness properties. Given the variety of ORU designs, an active Force/Moment Accommodation (FMA) feature was implemented in the Special Purpose Dexterous Manipulator (SPDM) for the performance of contact operations such as ORU grasping and ORU insertion. The FMA feature of the SPDM and its applicability to ORU insertion operations is described in [14] and [15].

ETS-VII demonstrated interfaces and robotic capabilities that could be incorporated into ORU transfer architectures for spacecraft servicing. The chaser satellite's robotic arm extracted a small sample cartridge from the client satellite, inserted the cartridge on the chaser and then moved it back to the client. The arm mated/demated electrical connectors on a task board, performed peg-in-hole experiments, and had the ability to change its end-effector. Performing contact tasks with the robotic arm required various sensor inputs and calibration techniques.

Photo Credit: MDA

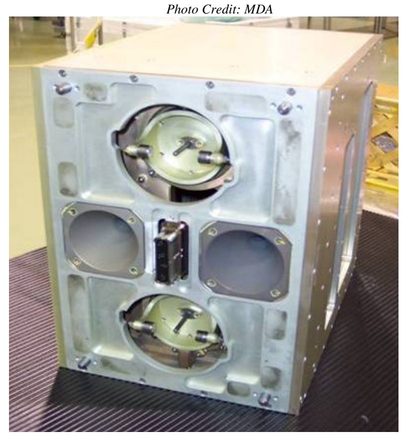

Figure 5. Cam followers, guide cones, and electrical connector on ORU underside

Orbital Express demonstrated a complete ORU transfer architecture that differed from the approaches taken on Space Station and ETS-VII. For Orbital Express, a single ORU interface was designed for robotic compatibility, which enabled fully autonomous ORU transfer operations without the use of an FMA feature or arm tip position calibration on-orbit. This "blind tip-accuracy" method was enabled by an ORU insertion interface with generous lead-in geometry, knowledge of arm tip force capability, tip accuracy and tip stiffness properties, as well as knowledge of the interface geometry and as-built spacecraft dimensions. The advantage on Orbital Express was the arm designers also had control of the ORU interface designs. For an operational satellite servicing system, where this is less likely to be the case, additional arm capabilities, such as Force/Moment Accommodation, could be included in the arm control design that mission planners could elect to use where appropriate.

4.2. ORU Extraction

To perform a transfer, the OEDMS extracted the ORU from its initial location. To achieve this, the arm first moved to a high-hover position above a grapple fixture on the ORU (the design of an ORU grapple fixture was essentially the same as the design of the grapple fixture provided for NextSat). The arm then descended to a low hover position, drove into contact with the grapple fixture probe and subsequently captured it. The connection was then rigidized in preparation for ORU extraction.

The arm unlatched the ORU by rotating the wrist roll and the end-effector 90 degrees, driving cam-followers on the OCA through channels in the barrel cams on the OIA. A change of state in micro-switches located on the OIA provided indication that the ORU was no longer latched to the spacecraft. It was at this point that the ORU was considered "out-of-bay", as the spacecraft could no longer provide services (e.g. keep-alive power) to the ORU. The ORU was then extracted to the high-hover position above the source OIA. Figure 6 presents an image captured by the arm camera during the execution of an ORU transfer operation.

Photo Credit: DARPA/Boeing/MDA

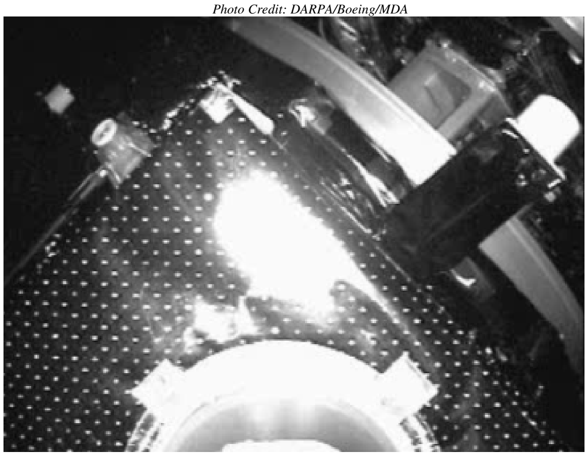

Figure 6. End-effector ORU transfer image

4.3. ORU Transfer to Destination

The arm translated the ORU through a series of scripted motions to the high-hover position above the destination OIA. There were no requirements for tight position tolerances on these free-space trajectories. The motions could be performed quickly and coarsely to minimize ORU "out-of-bay" time.

4.4. ORU Insertion

From the high-hover position, the arm moved to a low-hover position above the destination OIA. This motion was performed at low speed, to a tight end-point positional tolerance. At the low-hover position, guide cones in the base of the ORU were approximately level with the tip of the guide pins on the OIA. The arm entered the ORU Insertion control mode, driving the ORU to contact with the destination OIA. The arm force/moment sensor was used to monitor the tip force as a safety check, stopping the insertion if the forces grew beyond expected values. Ready-to-Latch micro-switches on the OIA provided confirmation that the ORU could be latched to the spacecraft. A 90 degree roll of the wrist roll and end-effector drove the cam-followers down the barrel cams, latching the ORU to the spacecraft.

4.5. Repeatability

The seven Batt ORU transfers on Orbital Express showed repeatability well within the allowable tolerances of the ORU interface, and no appreciable differences in the measured force profile during insertion. Timelines for the Batt transfer operations were repeatable to within approximately 2%. Figure 7 illustrates the lateral and angular trajectory of the arm POR (virtual tip) relative to the OIA plate for three successful ORU insertion operations.

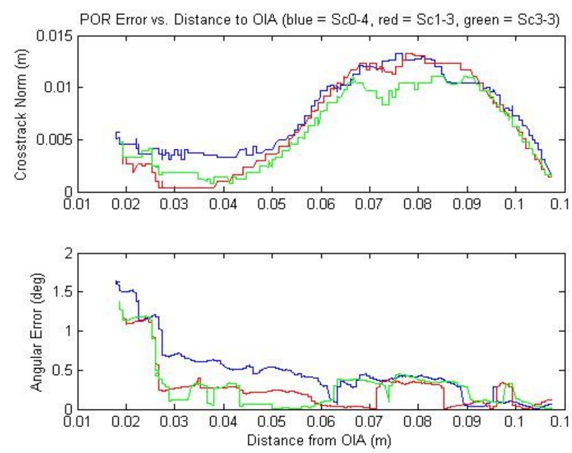

Figure 7. ORU insertion trajectory repeatability

4.6. Workspace Constraints

The ORU bays on ASTRO were recessed into the spacecraft body. These recesses created narrow corridors that the arm had to drive the ORU into before it could engage the OIA lead-in features. Various effects (e.g. joint friction) typically cause the tip of a robotic manipulator to deviate from its ideally commanded tip trajectory to some extent. Trajectory tracking control compensation was employed to maintain OEDMS tip deviations within acceptable limits while handling a payload. This allowed for effective use of manipulator-based ORU transfer even in very tightly constrained workspaces.

4.7. Autonomy

Transfers were performed at increasing levels of autonomy, with the first requiring ATP (Authorization to Proceed) from mission control after every manipulator arm script. The transfers culminated in a compound scenario, kicked off by a single ground command, which performed two consecutive ORU transfers in a fully autonomous mode. For operations of this type, the ground control team simply monitored the available telemetry.

5. Conclusions

DARPA's Orbital Express mission successfully demonstrated the technologies required for autonomous on-orbit satellite servicing: rendezvous, capture, berthing, refueling, and component transfer.

A small, lightweight servicing arm plays a critical role for ORU transfer, and can act as a primary or backup method for free-flyer capture and docking. Arm end-effector tools could be provided for the actuation of various interfaces on a client satellite. An arm can also perform spacecraft inspections with a camera mounted on its end-effector.

The operations conducted for Orbital Express demonstrate that autonomous satellite servicing is technically feasible, a technology that may find its place as the importance of maintaining and expanding the capabilities of commercial or military satellite fleets increases.

6. Acknowledgments

MDA congratulates DARPA, Boeing, Ball and the rest of the Orbital Express team on their successful accomplishment of the OEDS mission.

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