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A DOCKING SOLUTION FOR ON-ORBIT SATELLITE SERVICING: PART OF THE RESPONSIVE SPACE EQUATION

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ABSTRACT

The ability to service satellites on orbit (i.e., refuel or replenish consumables, re-boost, repair, or upgrade) would increase both their lifetime and utility. In the case of tactical space assets, there is an ever-growing need to maneuver satellites to new orbits on a regular basis. The ability of a satellite to change orbits allows it to be repositioned to observe new crisis areas, reduces the need for multiple-satellite constellations to provide global coverage, and also makes it less vulnerable to attack. Michigan Aerospace Corporation has developed a mechanism that enables autonomous docking and servicing of space assets. Based on the probe/cone concept, the docking mechanism provides a soft-docking capability and can be used with any size asset, from nanosats to full-size spacecraft. A prototype of the mechanism has been successfully tested at Marshall Space Flight Center's flat floor facility and on NASA's KC-135 microgravity aircraft. The simplicity of the concept has resulted in a low-cost design that minimizes size, weight, and power, while maximizing tolerance to misalignment, which means that it can be integrated with a minimal effect on the spacecraft. This paper will discuss the benefits of the docking mechanism as an enabling technology for military, scientific and commercial autonomous spacecraft applications and as one of the elements in a responsive space architecture.

INTRODUCTION

Responsiveness, in any industry, is a valuable commodity. In the commercial space sector, it can mean the difference between profit and loss. In the military space sector, the ramifications can be much higher.

The need for launch or deployment on demand has been well documented. Programs such as DARPA's Responsive Access, Small Cargo, Affordable Launch (RASCAL) are gearing up to address this demand. But part of the equation in providing on-orbit services in a timely manner involves the ability to extend the useful life of assets already there.

DARPA's Orbital Express program will demonstrate one such concept for refueling, repairing or upgrading satellites using a dedicated on-orbit servicing satellite. Another aspect of that program will demonstrate the ability to observe and thereby protect geo-stationary assets using a micro-satellite escort (SPAWN – Space Awareness program).

An on-orbit satellite servicing capability, however, requires a fundamental change in the approach to satellite design. In its final form, this change in philosophy ultimately demands a new architecture. If this new architecture is to be accepted by both the user community and satellite providers, those changes must be minimized.

One of the key technologies required to enable these capabilities is the docking system. A light-weight, compact, compliant and cost-effective docking system is essential to minimizing the impact on satellite customers and providers.

Michigan Aerospace Corporation has developed a docking system that meets those requirements, with the added benefit that it is applicable to a wide range of satellite sizes, from nano- and micro-satellites to multi-ton spacecraft. This paper provides a brief description of the history behind this development, an overview of the operational concept, status of the current prototypes, including testing, and applicability to a responsive space architecture.

BACKGROUND

The flexible extending probe concept was first implemented in the Autonomous Rendezvous and Docking (ARD) program over 12 years ago by researchers at the Environmental Research Institute of Michigan (ERIM). That program would have resulted in the first on-orbit demonstration of autonomous rendezvous and docking by the United States. ARD was originally scheduled to fly as part of the Commercial Experiment Transporter (COMET) satellite on the maiden flight of Deke Slayton's Conestoga rocket in 1991. The ARD payload was removed from the manifest, however, due to uncertainties in the launch vehicle's insertion altitude capability. This proved to be fortunate, as the rocket developed a problem shortly after launch from Wallops Island and had to be destroyed by range safety.

In 1999, Michigan Aerospace Corporation revisited the soft-dock cable concept under the Autonomous Satellite Docking System (ASDS) project. The Defense Advanced Research Projects Agency (DARPA), under an independent SBIR, funded the concept development.

Under the SBIR and Orbital Express, the ASDS mechanism was developed to prototype phase and was fabricated for testing at Marshall Space Flight Center in Huntsville, Alabama. The mechanism's chaser and target components were mounted on free-floating air-bearing mobility bases to simulate a micro-gravity condition in two dimensions. Extensive testing was done on the mechanism, which performed very well.

ASDS was originally designed to handle docking of larger satellites, on the order of thousands of pounds each. Because of growing interest in the field of micro-satellite servicing and refueling, the Air Force funded Michigan Aerospace in a joint effort with Microcosm, Inc. to develop the Autonomous Micro-satellite Docking System for test flight on the KC-135. The larger ASDS system was modified to optimize it for smaller satellite servicing applications. This mechanism was extensively modeled with dynamic computer simulation software and test-flown in a microgravity environment on the KC-135. Again, the device proved suitable for docking and berthing of small spacecraft as well as larger vehicles.

DOCKING MECHANISM OVERVIEW

The docking mechanism shown here was originally designed for DARPA's Orbital Express program. This design and its predecessors utilize a soft-dock flexible cable for first contact between spacecraft, making it ideally suited for autonomous docking with minimal disturbance force imparted to either spacecraft.

Figure 1 and Figure 2 show the primary elements of the docking system. The mechanism consists of an active half, (probe side) located on the chase vehicle; and a passive half (cone side), located on the target vehicle. The active half of the mechanism is composed of a load-bearing superstructure that attaches to the spacecraft bus, a spring-loaded conical hard-dock contact head, and an internal soft-dock cable with an automatic latching end effector. The target half of the mechanism consists of a target receptacle for the latching end effector located at the bottom of a concave alignment cone, which is fixed to the target spacecraft bus.

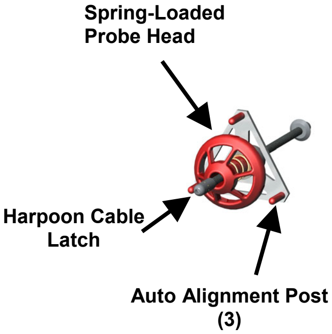

Figure 1 Docking Mechanism – Probe Side

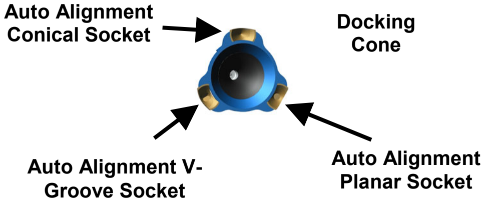

Figure 2 Docking Mechanism – Cone Side

When the halves are docked, five degrees of freedom (translation in three Cartesian dimensions and pitch and yaw rotations) are constrained by the hard-dock contact head, cable actuator system, and main target cone receptacle. The remaining degree of freedom (roll) is constrained by a trio of cylindrical posts on the chase vehicle, which engage with a matching trio of target receptacles (planar, conical, and v-groove sockets) on the target vehicle.

The docking sequence is illustrated in Figure 3. In the initial state, the soft-dock cable is fully retracted and the latching end effector is configured in its ready-to-capture state (armed). While the target vehicle maintains its attitude, the guidance, navigation, and control system of the chase vehicle controls the rendezvous, resulting in a relative position and orientation of the two vehicles that is within the docking mechanism's capture envelope.

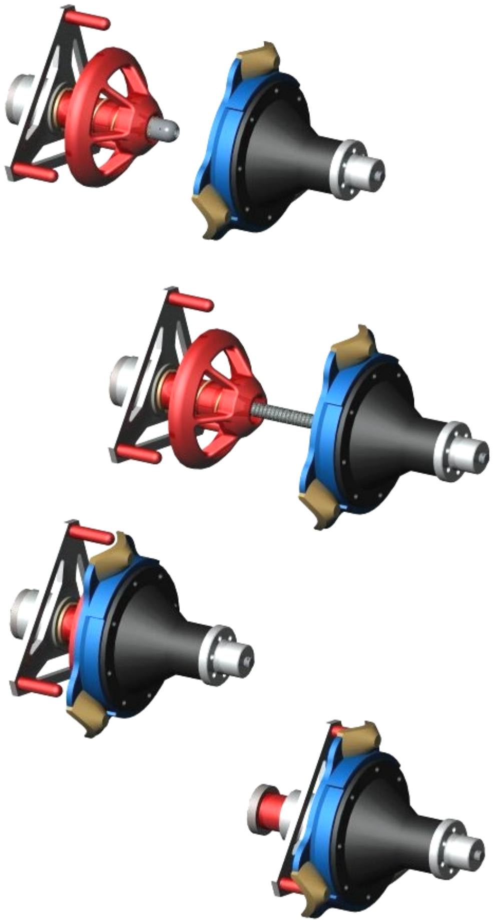

Figure 3 Docking Sequence

Then, with the target vehicle in free drift, the soft-dock cable is extended from the chase vehicle to engage the alignment cone, which guides the latching end effector into the target receptacle as the cable is extended further. The flexibility of the soft-dock cable and the relatively small mass of the latching end effector minimize the disturbance forces on the vehicles during this operation. When the end effector reaches the bottom of the target receptacle, the latching mechanism is triggered and the vehicles are soft docked. Next, the soft-dock cable is retracted into the chaser structure, pulling the two spacecraft together. This causes the conical hard-dock head to mate with the target receptacle cone, providing alignment and constraining relative vehicle motion in most axes. As the cable is retracted further, the hard-dock head is compressed against its spring, bringing the auto-alignment posts into engagement with their corresponding receptacles on the target structure. The load is now borne by the three alignment posts and receptacles, providing a well-defined load path and positive alignment between the vehicles for all degrees of freedom.

AIR-BEARING FLAT FLOOR TESTING

The Autonomous Satellite Docking System was prototyped and tested in the Flight Robotics Lab's flat floor facility at the George C. Marshall Space Flight Center (MSFC) in Huntsville, Alabama. This test was designed to simulate the dynamic interactions of the passive and active docking mechanism halves in a frictionless two-dimensional representation of micro-gravity. The prototype active chaser mechanism was mounted to one spacecraft simulator and the prototype passive target mechanism was mounted to the other spacecraft simulator. A series of docking tests were conducted using these simulated spacecraft, complete with guidance, navigation, and control algorithms that positioned the chaser simulator relative to the target simulator.

After a prototype mechanism was constructed, the testing was performed on the facility's two Air-Bearing

Mobility Simulators (ABMS), which consisted of structural frameworks that floated on air bearing pads above a poured-epoxy resin floor space and were maneuvered by simple pneumatic thrusters. Each mobility simulator was self-contained, including all power, air supply, movement control, and data collection equipment, and was connected to a ground station via a short-range wireless radio network connection.

Figure 4 shows the docking mechanism test setup on the air bearing mobility bases. The probe is mounted to the Small Mobility Base (SMB) and the cone is mounted to the Large Mobility Base (LMB). The following results were obtained:

- Demonstrated successful docking and un-docking between the two air-bearing mobility bases, starting from the station-keeping phase of operations.
- Measured the docking forces with a force torque sensor mounted at the cone interface
- Validated many elements of the dynamic model of the docking system.

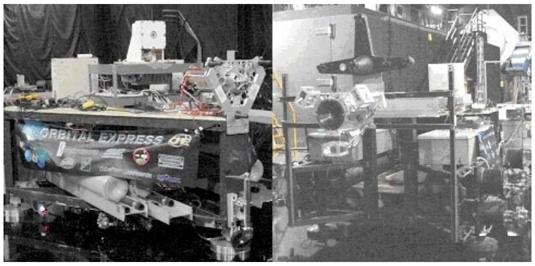

Figure 4 MSFC Flat Floor Facility, Air-Bearing Mobility Simulators; Probe Side of Docking Mechanism on Small Mobility Base (Left), Cone Side on Large Mobility Base (Right)

A micro-satellite version of the docking mechanism has also been tested on the NASA KC-135 zero-g aircraft. The results were very successful and will be described in two upcoming SPIE papers.[2] [3] Details cannot be provided here because they have not been cleared for publication at the time of this writing.

APPLICABILITY TO RESPONSIVE SPACE

The development of autonomous satellite servicing systems has a wide range of applications in the military, commercial, and scientific communities. Tactical applications that are particularly relevant involve increasing the useful lifetime and utilization of on-orbit surveillance assets. The capability of providing on-orbit refueling, repairing and upgrading of these critical space assets will likely play a role in the responsive space architecture of the future.

In the commercial space sector, a similar justification may exist for operational systems whose data is essential and where the cost of replacement is very high, both in terms of building the asset

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[2] “KC-135 Zero-G Testing of a Micro-Satellite Docking Mechanism,” J. Pavlich, P. Tchoryk, Jr., A. Hays, G. Wassick, SPIE AeroSense Symposium, Space Systems Technology and Operations Conference, Orlando, FL, April 24, 2003.

[3] “Dynamic Simulation and Validation of a Satellite Docking System,” A. Hays, P. Tchoryk, Jr., J. Pavlich, G. Wassick, SPIE AeroSense Symposium, Space Systems Technology and Operations Conference, Orlando, FL, April 24, 2003.

and a potential lost opportunity if the asset cannot be replaced in a timely fashion.

The infrastructure that would allow serviceable satellites, however, must be demonstrated first. DARPA's Orbital Express, NASA's Demonstration of Autonomous Rendezvous Technology (DART) program and AFRL's XSS-11 program are all working toward demonstrating critical elements of this infrastructure. In the commercial sector, it may be the insurance underwriters, since they cover the cost of failures or lost revenue, that drive the user community to make satellites serviceable on orbit. It goes without saying that in order to be marketable, the cost and physical impact on the satellite will have to be minimal.

To meet this need, Michigan Aerospace Corporation is continuing its development of a light-weight, cost-effective, compact, and compliant docking mechanism that has been successfully demonstrated in flat floor tests as well as on KC-135 microgravity flights. The mechanism can be used with many different platforms, ranging from nano- and micro-satellite to large space structures. It is anticipated that this technology will provide one more link in the responsive space architecture of the future.

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