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# AUTONOMOUS RPOD TECHNOLOGY CHALLENGES FOR THE COMING DECADE

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Rendezvous Proximity Operations and Docking (RPOD) technologies are important to a wide range of future space endeavors. This paper will review some of the recent and ongoing activities related to autonomous RPOD capabilities and summarize the current state of the art. Gaps are identified where future investments are necessary to successfully execute some of the missions likely to be conducted within the next ten years. A proposed RPOD technology roadmap that meets the broad needs of NASA's future missions will be outlined, and ongoing activities at GSFC in support of a future satellite servicing mission are presented. The case presented shows that an evolutionary, stair-step technology development program, including a robust campaign of coordinated ground tests and space-based system-level technology demonstration missions, will ultimately yield a multi-use mainstream autonomous RPOD capability suite with cross-cutting benefits across a wide range of future applications.

## INTRODUCTION

The ability of space assets to rendezvous and dock in orbits well beyond Low Earth Orbit (LEO) is important to a wide number of future National Aeronautics and Space Administration (NASA) applications including human exploration missions, large-scale science missions, as well as satellite servicing and rescue. These missions will require a range of cooperative and non-cooperative rendezvous, proximity operations, and capture techniques compatable with target objects spanning the spectrum from man-made space platforms and orbital debris to plantary or primitive bodies across the solar system. To meet these ambitious goals, investments in advanced technologies for relative navigation sensors, relative navigation and orbit/attitude control algorithms, as well as affordable and reliable actuators to provide precision vehicle and robotic control torques and forces will be required. One particularly challenging technology area in the coming decade will be the development and implementation of autonomously operating on-board systems capable of dynamically reacting to conditions sensed onboard. Developing sufficient confidence in these autonomous systems to entrust the success of future flagship-class missions to their successful operation will be equally challenging.

Unfortunately, a mainstream RPOD technology base for a wide spectrum of missions does not currently exist. New missions requiring autonomous RPOD capabilities continue to incur significant non-recurring engineering and development costs related to RPOD component sensors and integrated systems. To reduce these costs while ensuring mission success and crew safety it is imperative that NASA better coordinate any current and proposed RPOD technology development activities: such coordination will allow the developed technologies to be used in a much wider range of future applications.

In this paper we outline the current state of the art in RPOD technology by reviewing a wide range of recent and current missions requiring autonomous RPOD capabilities, looking for the needs of the

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future. Missions are grouped into five application classes in order to identify those areas in which the largest gaps exist between the current state of the art and future mission needs, and to highlight capabilities that cut across multiple RPOD applications. Recommendations are subsequently made regarding how NASA can advance autonomous RPOD capabilities through a robust campaign of co-ordinated ground tests and space-based system-level technology demonstration missions. Finally, the paper presents the status of the Argon Autonomous Rendezvous and Docking (AR&D) sensor ground test campaign currently underway at Goddard Space Flight Center (GSFC). Initiated to advance specific capabilities in support of a robotic satellite servicing mission, the Argon activity has the potential to provide benefits across a wide range of the applications discussed in this paper.

## MISSIONS AND TECHNOLOGIES

In this section we present important RPOD technologies required to conduct the near-term and likely future space missions requiring relative navigation, close proximity operations, and/or docking of spacecraft. Figure 1 shows selected RPOD flight missions or flight demonstrations recently conducted, in active development now (Near Term), or anticipated to be executed within the next decade or so (Future). These missions have been organized into five application classes, 1) robotic servicing and assembly; 2) human exploration; 3) Department of Defense (DoD) applications; 4) planetary and primitive body; and 5) precision formation flying, to distinguish different operating environments or varying applications of rendezvous, proximity operations, capture, or relative navigation capabilities.

Table 1 provides relevant references for the listed missions from the literature and information regarding specific RPOD technologies applicable to each. Again the missions are loosely organized by timeframe into recent, near-term, and future categories. While our focus is autonomous, onboard RPOD capabilities, there are many sensor, algorithm, and architecture parallels with these other mission types, so awareness and coordination between these categories is clearly beneficial.

*Robotic Servicing*[1] *and Assembly*[2] refer to the class of missions that make heavy use of robotic systems to modify or refurbish existing on-orbit assets, or build new assets on orbit that are too large to launch in one piece. These missions may require launch and corresponding RPOD of multiple elements. They also may require visual servoing of robot systems to perform autonomous robotic repair and construction tasks. Robotic capabilities such as these can be considered prerequisite to execute future human exploration missions which involve satellite servicing and assembly, as was explored in the recent joint "Manned GEO Study"[3] performed by NASA and Defense Advanced Research Projects Agency (DARPA). Various activities related to robotic servicing are currently underway within NASA, DARPA, commercial space,[4,5] and Europe.[6] .

*Human Exploration* activities have resulted in significant investments in RPOD technologies, particularly in the post-Columbia timeframe. NASA made significant investments in the RPOD sensors and systems to support the Orion Multi-Purpose Crew Vehicle (MPCV), including capabilities required to support lunar exploration. Numerous flight demonstrations have been conducted over the past five years to demonstrate and test sensors in support of Orion, Commercial Off-The-Shelf (COTS), and other International Space Station (ISS) applications. Outlining NASA's latest human spaceflight objectives, the Human Exploration Framework Team (HEFT) Report[7] clearly indicates that vehicle autonomous RPOD, as well as terrain-relative navigation for Near Earth Asteroid (NEA), planetary landing, and surface mobility remain extremely important to future human spaceflight objectives.

Many *Department of Defense* space applications require RPOD capabilities, and several recent demonstration missions or ground-based projects have contributed significantly to advancing sensors and systems that have overlapping applicability to robotic servicing, and human spaceflight

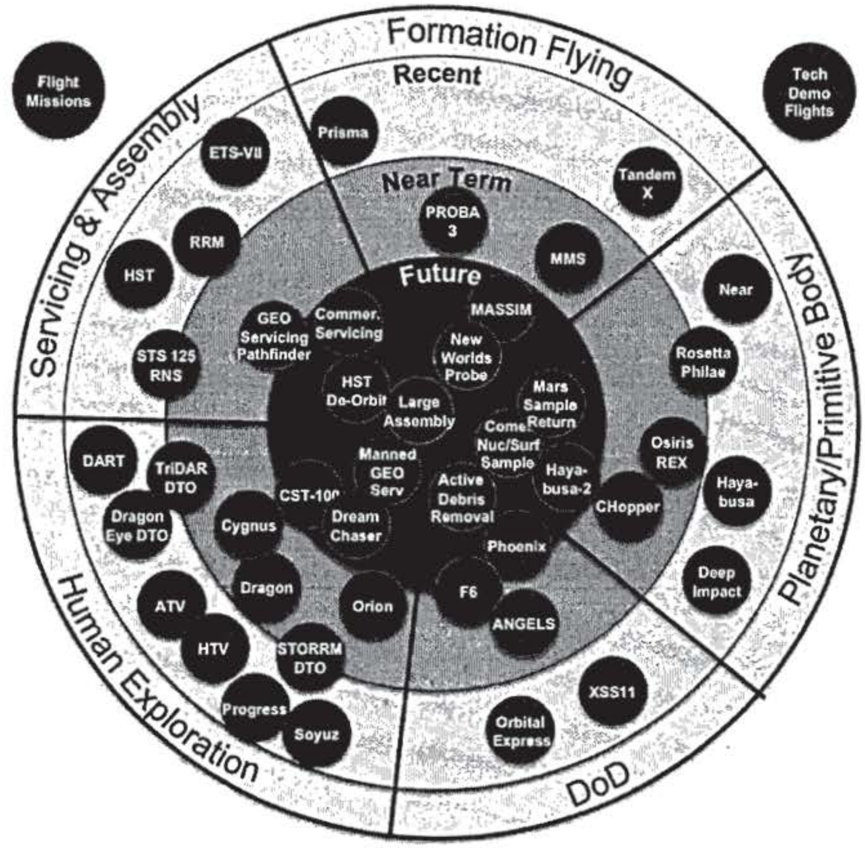


**Figure 1. Missions requiring technologies relevant to autonomous RPOD**

applicatons.[8–13] We present DoD missions only inasmuch as that information is available in the public domain.

*Planetary and primitive body* refers to the class of missions to planets, moons, asteroids, and comets. We have not included details on rovers, or atmospheric-entry landers, but technologies associated with those mission types are clearly relevant.

The term *precision* in *Precision Formation Flying (PFF)* refers to the class of formation flying missions that require extended onboard relative control of multiple vehicles to form the elements of a telescope aperture or other scientific instrument. These missions' main operating mode includes onboard control of inter-vehicle positioning, as well as short periods of formation reconfiguration similar to the proximity operations phase of RPOD. Most PFF missions will operate far from Earth, usually in Sun-Earth Lagrange point orbits, and may require advances in autonomy and fault detection capabilities to maintain formation control and prevent conjunctions.

The terms *cooperative* and *non-cooperative* imply important distinctions between some of the RPOD technologies in Table 1. The term *cooperative* is used when the satellite operating within proximity to each other cooperate to perform the rendezvous and docking functions. This could mean the client satellite was designed with sensor targets, active measurement systems–such as a radio frequency link for exchanging data, or with a docking system or grapple features. Nearly all of the human spaceflight missions involving rendezvous and docking have been designed as cooperative systems. The same can be said for extremely challenging precision formation flying missions.

The term *non-cooperative* refers to any target vehicle that does not have these features or can-

**Table 1. Capabilities required for autonomous Rendezvous Proximity Operations and Docking (RPOD) and similar mission types, and recent and future flight missions utilizing those capabilities**

| Mission | Flight system capabilities demonstrated (increasing complexity →) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 3DOF Nav | | | | | | | 6DOF Nav | | | | | | | | | System-Level Functions | | | | | | | | | | | | | | | | |
| | Sensor HW First Flight | Vis. Cam. Bearing | IR cam. Bearing | Active Illum 2D Image Range & Bearing | Laser Range & Bearing | Relative GPS | Coop RF Range, Bearing, Doppler | 3DOF Relnav Filter | Active Illum. 2D Image 6DOF pose | Coop Lidar 6DOF pose | Coop Vis. Cam. 6DOF pose | Coop. RF/Radar pose | Non-Coop. Vis. Cam. 6DOF pose | Non-Coop. IR Cam. 6DOF pose | Non-Coop. Lidar-based 6DOF pose | Non-Coop. RF-based 6DOF pose | 6DOF Relnav Filter | Supervised autonomy | Short Duration ProxOps | LEO Rendezvous/FF | GEO Rendezvous/FF | Cislunar Rendezvous/FF | Lunar Orbit Rendezvous/FF | Inter/Planetary Orbit Rendezvous/FF | Long Duration Prox Ops | Coop. autonomous capture | Primitive Body Open Loop Landing | cm-level precision formatoin flying | Terrain-relative Hazard Avoidance | Onboard Terrain-relative 6DOF pose | Robotic Vis. Servoeing | Non-cooperative capture | Fully Autonomous Activity | Primitive Body Precision Landing | Sub-arcsec Astrometric Alignment |
| Progress[14] | - | - | - | - | - | - | o | o | - | - | - | ● | - | - | - | - | o | * | ● | ● | - | - | - | - | - | ● | - | - | - | - | - | - | - | - | - |
| Near[15–17] | ● | ● | ● | - | ● | - | - | - | - | - | - | - | - | - | - | - | - | - | ● | - | - | - | - | ● | ● | - | ● | - | - | - | - | - | - | - | - |
| ETS-VII[18,19] | ● | - | - | - | ● | ● | - | ● | - | - | ● | - | - | - | - | - | o | ● | ● | ● | - | - | - | - | - | ● | - | - | - | - | ● | - | - | - | - |
| Hayabusa[20] | ● | ● | | ● | ● | - | - | o | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | ● | ● | - | ● | - | * | - | - | - | * | ● | - |
| Rosetta Philae[21,22] | | | | | | | | | | | | | | | | | | | | - | - | - | - | ● | | | o | | | | | | | - | - |
| Deep Impact[23] | | ● | ● | - | - | - | - | ● | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | ● | - | - | - | - | - | - | - | - | - | - | - |
| XSS-11[8] | o | ● | - | - | ● | - | - | ● | - | - | - | - | - | - | - | - | - | ● | ● | ● | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| DART[24,25] | ● | - | - | ● | - | ● | - | ● | ● | - | - | - | - | - | - | - | o | - | ● | ● | - | - | - | - | - | - | - | - | - | - | - | - | * | - | - |
| OE[9–12] | ● | ● | ● | ● | ● | - | - | ● | ● | - | ● | - | ● | ● | - | - | ● | ● | ● | ● | - | - | - | - | - | ● | - | - | - | - | ● | - | o | - | - |
| RNS[26] | ● | ● | - | - | - | - | - | - | - | - | - | - | ● | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| DragonEye[27] | ● | - | - | - | ● | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| TriDAR[28] | ● | - | o | - | ● | - | - | - | - | - | - | - | - | o | ● | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| PRISMA[29] | ● | ● | - | - | - | ● | ● | ● | ● | - | ● | - | - | - | - | - | o | ● | ● | ● | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Tandem-X[30] | o | - | - | - | - | ● | - | ● | - | - | - | - | - | - | - | - | - | ● | - | ● | - | - | - | - | ● | - | - | - | - | - | - | - | - | - | - |
| HTV[31,32] | | - | - | - | ● | ● | - | o | - | - | - | - | - | - | - | - | - | ● | ● | ● | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| ATV[33] | ● | - | - | ● | ● | - | - | ● | ● | - | - | ● | - | - | - | - | ● | ● | ● | ● | - | - | - | - | - | ● | - | - | - | - | - | - | - | - | - |
| STORRM[34] | ● | - | - | - | ● | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| GRAIL[35] | | | | | | | | | | | | | | | | | | | | | | - | ● | | | | | | | | | | | | |
| Dragon[36] | | | | | ● | o | o | ● | | | | | | | | | | ● | ● | ● | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Cygnus[36] | | | | | ● | o | o | ● | | | | | | | | | | ● | ● | ● | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| F6[37,38] | | | | | | ● | ● | ● | | | | | | | | | | o | ● | - | ● | - | - | - | ● | - | - | - | - | - | - | - | - | - | - |
| VivaSat[4] | | | | - | | - | - | o | - | - | - | - | | | | | o | o | o | - | ● | - | - | - | - | - | - | - | - | - | - | ● | - | - | - |
| MDA GEO Serv[5] | | ● | | | | | | o | | | | | | | | | | | | - | ● | - | - | - | - | - | - | - | - | - | - | ● | - | - | - |
| Phoenix[39] | | | | - | | - | - | o | - | - | - | - | | | | | o | o | o | - | ● | - | - | - | - | - | - | - | - | - | o | ● | - | - | - |
| CST-100[40] | | | | | | | | o | | | | | | | | | | | | ● | - | o | - | - | - | ● | - | - | - | - | - | - | - | - | - |
| Dream Chaser[41] | | | | | | | | o | | | | | | | | | | | | ● | - | - | - | - | | | | | | | - | | | - | - |
| Osiris REx[42] | | ● | ● | - | ● | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | ● | ● | - | ● | - | - | - | - | - | - | - | - |
| PROBA-3[43] | ● | ● | - | - | o | ● | o | ● | ● | - | - | - | - | - | - | - | ● | ● | - | - | o | - | - | - | ● | - | - | o | - | - | - | - | - | - | ● |
| Chopper[44] | - | o | o | - | | | | | | | | | | | | | | | | - | - | - | - | ● | | | ● | | | | | | | - | - |
| SSCO[1,45] | - | ● | ● | - | ● | - | - | ● | - | ● | ● | - | ● | ● | ● | - | ● | ● | ● | - | ● | - | - | - | - | ● | - | - | - | - | ● | ● | - | - | - |
| Orion[46] | - | ● | - | - | ● | - | o | ● | - | ● | - | - | - | - | - | - | ● | ● | ● | ● | - | - | ● | o | - | ● | - | - | - | | - | - | o | - | - |
| Angels[47] | | | | | | | | | | | | | | | | | | | | | ● | | | | | | | | | | | | | | |
| HST Deorbit | - | o | o | o | o | - | - | ● | o | o | o | - | o | o | o | o | ● | ● | ● | ● | - | - | - | - | - | ● | - | - | - | - | - | - | - | - | - |
| Debris Mitigation[48] | - | o | o | - | o | - | - | ● | - | - | - | - | o | o | o | o | ● | ● | ● | o | o | - | - | - | o | - | - | - | - | - | - | ● | - | - | - |
| Mars SR[49,50] | - | ● | - | o | ● | - | ● | ● | o | o | o | - | - | - | - | - | - | ● | ● | ● | - | - | - | ● | - | ● | ● | - | o | - | - | - | ● | - | - |
| Comet SR[51,52] | - | o | o | - | o | - | - | ● | - | - | - | - | o | o | o | o | o | ● | ● | ● | - | - | - | ● | o | - | o | - | o | o | - | - | o | ● | - |
| MASSIM[53] | o | o | - | o | o | - | o | ● | - | - | - | - | - | - | - | - | - | ● | ● | - | - | ● | - | - | - | - | - | - | - | - | - | - | - | - | ● |
| NWP[54] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ● |
| Hayabusa-2[55] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ● | - |

[● included onboard] [o unverified] [* resulted in anomaly] [ - not included] [blank cell unknown] not adjust its onboard modes (Attitude Control System (ACS), deployables, safe-mode, etc) in a favorable way for RPOD operations. For example, a potential servicing customer may not have any sensor targets or grapple features as the vehicle was never intended to be a target for rendezvous and docking. Applications in which a primitive body such as an asteroid or comet is the target body could also be considered non-cooperative from a navigation/sensing perspective. *Non-cooperative* sensors and sensor processing algorithms that can determine relative position and orientation based on observing natural features are very important in these applications.

The term *astrometric alignment* refers to the use of sensors on one or more of the formation flying vehicles to precisely point the formation towards an inertial target, usually by using measurements from an optical sensor on one vehicle to determine and control the line of sight to another vehicle relative to stellar or other objects in the backfield of the image.

For each of the application classes, we consider the current state-of-the-art based on recently demonstrated capabilities, technologies actively under development now to meet the needs of near-term or future missions, and perceived gaps in which investments are needed to successfully execute future mission objectives.

**Human Spaceflight, DoD, Servicing and Assembly Missions**

*Recent and Near-Term Missions* - It has been nearly five years since the Orbital Express (OE) mission completed its objectives. Like Demonstration of Autonomous Rendezvous Technology (DART) and Experimental Small Satellite-11 (XSS-11) before it, OE made important contributions to US competencies for rendezvous and proximity operations in LEO. OE went further by also performing autonomous docking and autonomous capture demonstrations, and by demonstrating other satellite servicing tasks.[9–12]

In the last five years, the focus of US AR&D related flight activities has been on Space Shuttle-based demonstrations of relative navigation sensor hardware via the Sensor Test for Orion Rel-Nav Risk Mitigation (STORRM), DragonEye, Triangulation and Time-of-Flight Lidar (TriDAR), and Relative Navigation Sensor (RNS) flights. These demonstrations have helped to mature capabilities for long- and mid-range rendezvous using range and bearing measurements as the primary relative navigation source. Several different active and passive sensors capable of cooperative pose measurements during proximity operations with cooperative targets were demonstrated. Furthermore, the Space Shuttle demonstration payloads on STS-125 (RNS) and STS-128, 133, and 135 (TriDAR) demonstrated non-cooperative pose estimation and sensing during close proximity operations.

One needs only consider routine ISS operations to find many examples of operational (or soon to be operational) cooperative RPOD capabilities in LEO. ISS partner-nation vehicles including Soyuz, Progress, Automated Transfer Vehicle (ATV), and H-II Transfer Vehicle (HTV) routinely dock or berth with station to deliver crew and/or cargo. Within the US two companies, SpaceX (Dragon) and Orbital (Cygnus), are expected to demonstrate new vehicles capable of performing commercial cargo services for ISS within the next year. Meanwhile, in addition to NASA's Orion vehicle, several companies are working under NASA's Commercial Crew Development (CCDev) program to develop vehicles capable of providing crew launch and return capabilities for station in the near future. All of these new vehicles have required or will require the development of highly reliable cooperative RPOD capabilities for the LEO environment.

The upcoming, but little publicized, Autonomous Nanosatellite Guardian for Evaluating Local Space (ANGELS) mission, under development by the Air Force for launch in 2013, is also of interest. ANGELS provides the opportunity to demonstrate the operation of technologies relevant to future RPOD objectives at Geosynchronous Earth Orbit (GEO).

*Future Missions* - As a result of recent uncertainty regarding NASA's human spaceflight activities, near-term investments in RPOD capabilities for human spaceflight beyond LEO have stalled. Although the first test flights of the Orion spacecraft are not likely to involve RPOD activities, NASA's long-term human exploration goals to conduct missions to Near-Earth Asteroids, the moon's of Mars, or future crewed satellite servicing missions will require extension of current RPOD capabilities beyond LEO.

The applications of robotic servicing, "re-purposing" of on-orbit assets, and active orbital debris removal have emerged as high priority future applications of RPOD capabilities beyond LEO. NASA is aggressively pursuing a technology development program with the goal of conducting a geostationary robotic servicing mission in the near future. NASA conducted a comprehensive satellite servicing study in 2010,[1] launched a Robotic Refueling demonstration payload to the ISS in 2011, and is currently conducting a comprehensive ground test campaign to mature capabilities for non-cooperative proximity operations and capture that will be discussed in more detail later in the paper. DARPA's recently announced Phoenix program will require many of the same RPOD and robotics capabilities to demonstrate capabilities to rendezvous with "retired" spacecraft in geosynchronous disposal orbits. Furthermore, several nascent commercial satellite servicing initiatives have emerged recently.[4,5]

We anticipate this renewed interested in satellite servicing applications will lead to several significant firsts in the near future, including the first successful fully robotic capture of a non-cooperative (but still functional) spacecraft, and the first application of robotic satellite servicing to a non-cooperative target. A government-led GEO servicing demonstration mission could be followed by one or more commercial satellite servicing missions. These developments would bring a satellite-servicing capability within reach of a much wider range of applications, including one-off missions to service or repair high priority national spacecraft assets, perform active debris removal, and on-orbit assembly missions.[2] Performing RPOD with a non-cooperative target spacecraft in GEO presents some unique challenges;[45] however, most of the relative navigation sensor hardware technology applied to robotic servicing in GEO would have cross-cutting benefits to other applications discussed in this paper.

The future may also very likely see an increased emphasis on missions to Earth-Moon or Sun-Earth Lagrangian point orbits. Likely missions could include: 1) robotic missions involving two or more small spacecraft in Halo orbits for science observation data collection purposes; 2) human/robotic construction and/or servicing of large space telescopes designed to operate at in a Halo orbit; and 3) human exploration pre-cursor missions to safely test deep space human space flight technologies, such as flying human missions to Earth-Moon L1 or L2 in preparation for missions to near-Earth asteroids (NEAs) and eventually Mars and or its moons (Phobos and Deimos). In order to mature the technologies required for these types of missions, we will need to advance our current trajectory, targeting, and filtering algorithms in the near-term and possibly fly technology demonstration missions in the not-too-distant future.

**Precision Formation Flying Missions**

*Recent and Near-Term Missions* - Funding for formation flying research activities in the US has greatly decreased from a decade ago, but there continues to be notable activities outside of the US to applications in which very precise relative navigation and control will be required.

Gravity Recovery and Climate Experiment (GRACE), a NASA-led mission, includes twin satellites launched in March 2002 to make detailed measurements of Earth's gravity field by making accurate measurements of the distance between the two satellites, using Global Positioning System (GPS) and a microwave ranging system. Although the mission does not require precise control of the satellites relative to each other, the GRACE science is dependent on precise relative navigation using GPS and the inter-satellite ranging system. The Gravity Recovery and Interior Laboratory (GRAIL) mission, which consists of two satellites recently inserted into the same orbit around the moon, implements a gravity-measuring technique is essentially the same as that of the GRACE mission, but with the additional challenge of operating at the moon (and without the benefit of GPS.)

The Tandem-X vehicle recently joined its partner Terasar-X on orbit, flying in formation with an in-track separation of 1km.[30] This formation uses GPS and a cross-link device, in addition to a simple onboard relative navigation filter to maintain an onboard relative navigation accuracy of less than 3 meters. It also includes an onboard control mode called Tandem-X Autonomous Formation Flying (TAFF), which, when activated, will perform maneuvers every few orbits to maintain the formation in-track error to less than 10-20 meters (depending on the frequency of the maneuvers, and the solar activity.)

Prisma launched in June of 2010 on a mission to demonstrate autonomous formation flying, proximity operations, and rendezvous using three sensor systems: 1) a vision-based sensor which provides bearing measurements for angles-only navigation at long range, and uses LEDs on the target vehicle to perform cooperative pose estimation at closer range; 2) a GPS receiver plus cross-link for absolute and relative orbit determination within the range of the cross-link; and 3) a Formation Flying Radio Frequency (FFRF) sensor split between the two vehicles which operates in the S-band to provide inter-vehicle bearing and range to accuracy of 1° and 1m, respectively.

*Future Missions* - Table 1 lists only a subset of proposed PFF-class missions. The European Space Agency (ESA) PROBA-3 mission currently in the study phase, could launch as early as 2015 to demonstrate the PFF techniques required by a solar coronography mission. While details of the mission are not clear, it appears that PROBA-3 will perform the closest (150 m) long-term, 2-vehicle-formation-flying operations to date, and demonstrate astrometric alignment between a detector spacecraft and an external occulter. Potential measurement sensors for PROBA-3 include the Shadow Position Sensor, which determines astrometric alignment of the formation, and the Occulter Position Sensor, which measures detector orientation relative to the formation. The mission will likely be performed in Highly Eccentric Orbit (HEO).

Two future US missions of particular interest are Milli-Arc-Second Structure Imager (MASSIM)[53] and New Worlds Probe (NWP):[54] both missions require astrometric alignment on the order of 10 milli-arcsec. In the case of MASSIM, the formation would position an optics vehicle and a detector vehicle at 1000 km separation to enable ultra-high angular resolution astrophysics in the X-band. NWP would position a 50 m occulter in the field of view of James Webb Space Telesope (JWST) at 55,000 km range to enable, among other things, direct observation and characterization of extra-solar planets. NWP is unique because JWST is a *non-cooperative* formation flying partner.

Another mission that probably best fits into this category is DARPA's System F6, a technology demonstrator that will use not PFF, but "cluster flight" to demonstrate the concept of fractionated spacecraft.[37] Some tasks to be demonstrated by F6 are: "1) formation-keeping over long time domains while allowing additional assets to join or leave the formation; 2) sharing information across the formation in a real-time fashion; 3) adapting the formation shape to maintain system functionality when faced with poor network links or component failure; and 4) scattering and reforming the cluster in a semi-autonomous fashion to handle possible collisions with on-orbit debris."

**Planetary and Primitive Body Missions**

*Recent and Near-Term Missions* - Near Earth Asteroid Rendezvous - Shoemaker (NEAR) performed ground commanded rendezvous and extended proximity operations with the asteroid Eros, as well as a heroic end-of-mission open-loop landing on the asteroid (the first soft-landing on an asteroid). Asteroid-relative navigation functions were performed via ground processing of data from NEAR's Multispectral Imager, Laser Rangefinder, and Near-Infrared Spectrometer. Maneuver sequences were then uploaded to the vehicle to perform proximity operations and landing sequences.

On July 4, 2005, NASA's Deep Impact vehicle executed an intercept and intentional collision with the comet Temple 1 using an onboard autonomous navigation system to position the impactor in the path of the comet. The Deep Impact Autonomous Navigation (AutoNav) software was originally developed and demonstrated during the Deep Space 1 (DS1) mission and was subsequently used on the Stardust mission; in both cases the objective was to keep the target body in the field of view of the sensors.[56,57] Deep Impact took the high speed encounter to a new level and required new algorithms to target a particular location on the comet nucleus, synchronize the timing of imaging sequences on the two spacecraft, and capture the impact event, by processing navigation images.[23]

The Hayabusa mission is of particular interest due not only to its significant achievement - closed-loop, onboard control during the final descent to land on an asteroid in November 2005, but also for lessons learned from the mission. Hayabusa performed precision descent to Itokawa by placing a target marker on the surface, making Itokawa a *cooperative* target. Hayabusa then used an onboard camera and a laser rangefinder to descend to the surface twice. The first descent experienced a fault from the Fan Beam Sensor (an obstacle detector that was subsequently disabled) which resulted in failure to engage the sample collection once the craft landed. The second descent was completed without incident, although once again the collection mechanism failed to execute. Hayabusa's hopper lander, called MIcro/Nano Experimental Robot Vehicle for Asteroid (MINERVA), failed to reach the surface after a LIDAR error (or improper response to the error) released the lander not in the intended open-loop descent to the surface, but on an escape trajectory.

Three other missions of interest in this class include: 1) the Rosetta mission, and it's lander, Philae, which will land after a ballistic transfer on Comet 67P/Churyumov-Gerasimenko and use harpoons to attach itself to the surface and perform in-situ measurements; 2) Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx), which will perform rendezvous, extended proximity operations, and open-loop Touch and Go (TAG) maneuver to collect samples at the asteroid 1999 RQ36 and return them to Earth; and 3) Comet Hopper (CHopper), which will land several times on Comet Wirtanen and perform several small "hops" to better understand the heterogeneity of the comet.

*Future Missions* - Planetary and Primitive Body Missions still in the planning phase and relevant to this paper include Mars Sample Return, Hayabusa-2, the Comet Nucleus Sample Return, as well as future human exploration missions.

Mars Sample Return is actually an autonomous RPOD application - it is a mission that will rendezvous with and capture a sample canister ejected from the Martian surface by a previous lander mission, and return it to Earth. This is an extremely challenging scenario for 3 main reasons: 1) latency in the data transfer from Mars requires this to be a fully autonomous rendezvous; 2) the canister and its launch vehicle must be extremely simple, meaning the initial dispersion may be large, and the canister will be minimally cooperative; 3) since the entire operation must occur at Mars, the vehicle performing the RPOD will be extremely mass limited, and therefor the sensing and capture hardware must be minimal.

Hayabusa-2 is currently in the study phase, and is listed here in hopes that it will continue to push the boundaries of autonomy in primitive body landing. The mission will likely include another separate lander (like MINERVA on the first Hayabusa mission).

Comet Nucleus Sample Return[51,52] is one of the missions in the National Academy of Sciences (NAS) Planetary Decadal Survey, and a mission that could take great benefit from onboard control to reduce the terrain-relative navigation error during sample collection. Consider that comet material is not uniform, and that samples near small outgassing jets may be of more scientific interest, than samples taken at random within say a 50 m ellipse. In such a case, an onboard capability to perform terrain-relative guidance, navigation, and control would provide far greater science return. Of course, like in the Mars Sample Return example, such a system would have to be very simple (low weight and power), and very robust to ensure safe autonomous operations.

## TECHNOLOGY GAP

As shown in Table 1, recent flight activities have accomplished many of the key stepping stones towards enabling a widespread US capability for autonomous RPOD and other similar applications. This section will discuss current technology gaps, real and percieved, in meeting the needs of future missions.

### Real Technology Gaps

*Non-Cooperative Vehicle RPOD: Especially Pose Estimation and Capture* - Studying Table 1 it is immediately apparent that while several missions have performed autonomous RPOD in the recent years, only one of those missions included non-cooperative pose estimation (OE's Vision-based Software for Track, Attitude, and Ranging (Vis-STAR) included a non-cooperative silhouette tracking mode that returned pose estimates from both the visible and Infrared (IR) cameras). Only two other flight missions demonstrated this measurement type (TriDAR and RNS), and neither of those demonstrated use of the measurement to control the host vehicle.

Figure 2 shows a potential relative navigation sensor suite appropriate for autonomous RPOD with a non-cooperative vehicle. The shaded region between separations of approximately 100 m and capture represents the portion of non-cooperative RPOD that is quite new and requires risk mitigation activities. Note that while many of the sensors required to perform these measurement types have been previously demonstrated, the measurement processing and system-level use of these sensor for non-cooperative RPOD is quite unproven.

While autonomous capture of a grapple feature or cooperative docking mechanism have been demonstrated,[9,18] no mission has demonstrated autonomous capture of a non-cooperative vehicle. Figure 3 shows a technology tree for sensors, onboard pose estimation, and autonomous capture. The "Onboard Pose Estimation" tree shows branches for algorithms compatible with cooperative and non-cooperative target types, and 2D and 3D sensor types. The "Autonomous Capture" tree shows 5 possible capture features (2 cooperative and 3 non-cooperative). While the left-side (sensor hardware) of this figure appears to be well sampled, the right-hand side, and in particular the "non-cooperative" branches of the right-hand side require additional attention.

*Terrain-Relative Navigation and Autonomous Precision Landing* - In the case of primitive body lander missions, autonomous operations will one day provide greatly improved science returns by enabling collection of the most interesting samples by placing vehicles within much smaller landing ellipses. Unfortunately, at least for the moment, incorporation of such autonomy into operations appears to be more risky than using deterministic techniques with waive off criteria or other built in safeguards. The perceived risk of autonomous operations on an expensive primitive body science mission is just too high. Furthermore, terrain-relative Six Degrees of Freedom (6-DOF) pose estimation has yet to be proven in space. Mass, power, and processing power will certainly be highly constrained on this type of vehicle. This combination of high-reliability, and low mass, power, and processing requirements will be a considerable challenge.

*Autonomous Systems* - Clearly some of the future missions discussed in this paper call for increased levels of autonomy, or would benefit from the continued trend of increasingly capable onboard navigation capabilities reducing the role of ground operators in conducting real time navigation operations. While Deep Impact succeeded in performing onboard autonomous navigation to

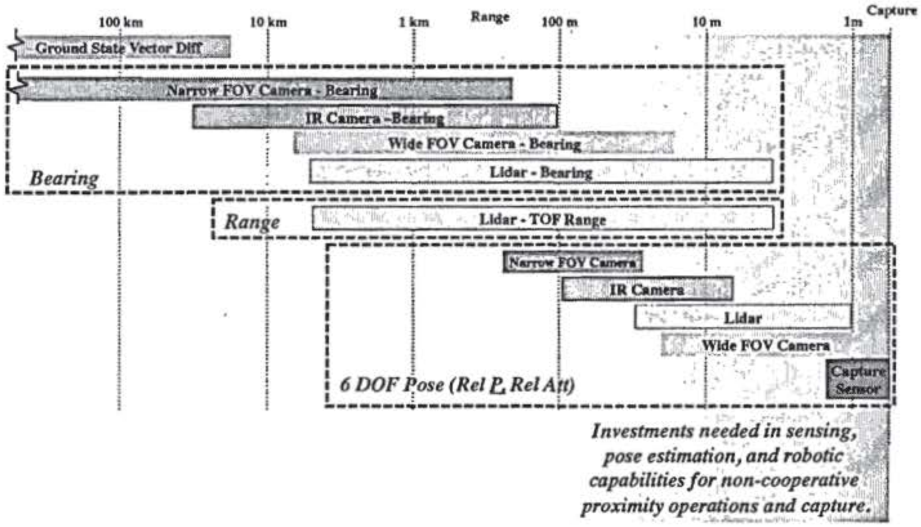


**Figure 2. Notional sensor regimes for a non-cooperative, autonomous RPOD mission.**

target the impact with Tempel 1, other missions such as Hayabusa, DART, OE, and Progress (to name a few) experienced anomalies do to improper system-level autonomous response to component-level issues. The problem is not in our access to Autonomous Software Systems–these are actually quite simple. Rather, the difficulty is in the testing autonomous vehicle control systems thoroughly on the ground, where 6-DOF dynamics, lighting, full range of motion, and space environment effects are often impossible to test simultaneously.

**Perceived Technology Gaps**

Often a perceived technology gap is worse than a true one. Here we list some technologies that, while critically important, are well understood and should not be feared because of their critical nature. These are technology elements that require non-recurring engineering, but are in reality very mature and waiting only for sufficient mission demand to make the final small maturity steps required for full mission readiness.

*Relative navigation sensor hardware* - Sensors for vehicle-relative and terrain-relative navigation (especially cameras and Light Detection and Ranging (LIDAR) sensors), while not rapidly available "off-the-shelf", have matured greatly and are no longer a major risk area provided that adequate demand prevents the "history of obsolescence" that has plagued this field in the past.[58] Figure 3 shows a sensor hardware technology tree (left), with branches including passive 2D imagers (visible and IR), and active laser and Radio Frequency (RF) sensors, linked to their associated flight mission (center).

*Guidance and Control Algorithms* - While implementation of vehicle onboard guidance and control software will require significant non-recurring engineering for any new implementer, these systems are well understood for cooperative RPOD targets, and differ only slightly for non-cooperative targets.

*Onboard Navigation Filters* - Numerous examples of successful utilization of the Extended Kalman Filter for onboard navigation exist.[59–61] This software, as well as the guidance and control software above, should be prime candidates for a collaborative open-source RPOD capability. The gap (or opportunity) is in the area of collaboration to avoid continually re-inventing the wheel by performing re-work when existing solutions may exist that could be adapted for future applications.

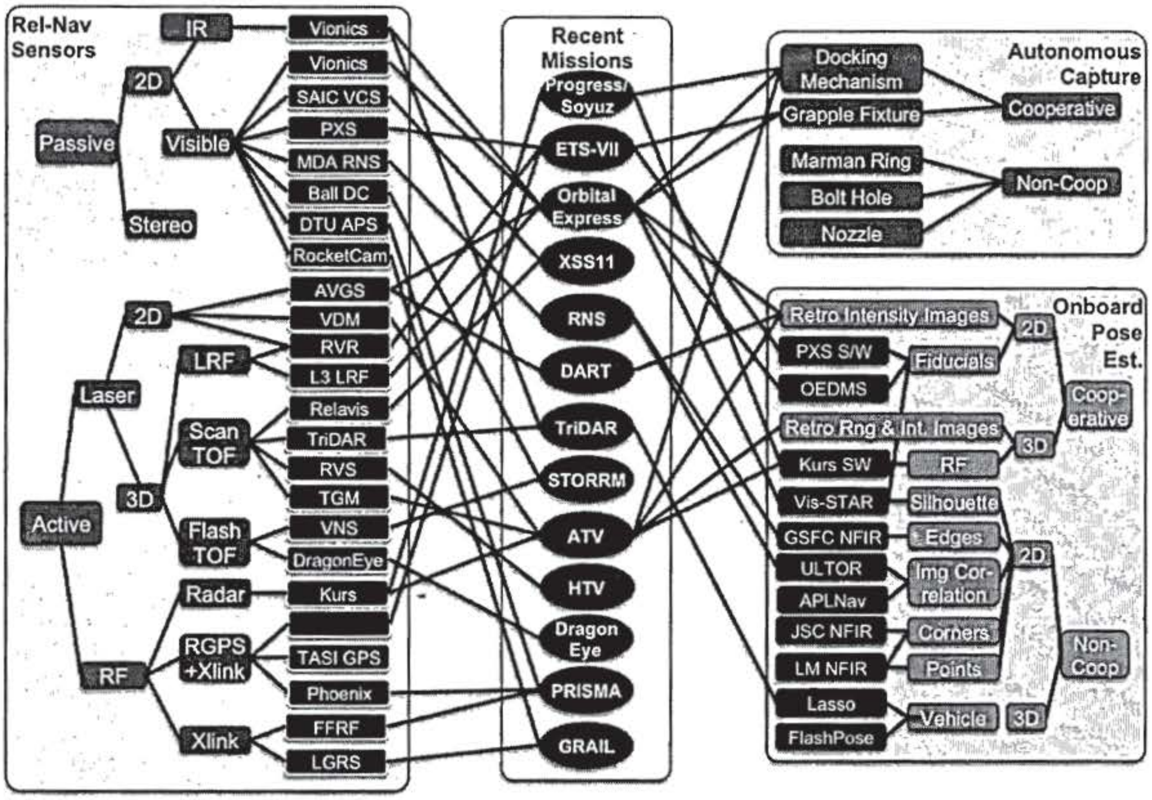


**Figure 3. Sensor and pose technology tree**

## CLOSING THE TECHNOLOGICAL GAP

To close the technology gaps presented above, one can rely on the traditional approach for developing spacecraft technology: 1) component and system level ground development and extensive ground test; 2) component and system level flight demonstration (where funds permit); 3) operational flight mission. Since these technology systems are quite sensitive to the orbit environment, and quite difficult to test thoroughly on the ground, the need for system level flight demonstration (item 2 above) is quite high. We also examine steps that could be taken to increase opportunities to perform critical system level flight demonstrations in the future.

### Ground Demos

Ground-based demonstrations can be extremely valuable to perform system-level demonstration of RPOD capabilities, for significantly less cost than a full-up flight demonstration. In particular, ground based testing can be used to evaluate multiple candidate sensors, provide realistic data and insight into system interactions useful for developing and then perfecting algorithms. In particular for RPOD system testing; however, some conditions such as lighting remain extremely challenging to realistically reproduce on the ground. It can also be extremely difficult to realistically test the performance of sensors at large separations, or the critical transitions between the operational ranges or settings of sensors and algorithms. For this reason flight demonstration of RPOD system performance is still extremely valuable.

### Flight Demos

Nearly every sensor or system ever developed for RPOD had some kind of failure on its maiden voyage to space that either caused, or would have caused, an operational system to fail. Whether this is due to insufficient ground test funds, lack of understanding of the system, or just bad luck, the fact remains that ground test campaigns of these complicated systems have always failed to uncover issues, some of them quite simple and quite devastating.[25] For this reason, we stress using flight demonstrations *at the system level* wherever possible to test these systems. Unfortunately, system-level demonstrations of these technologies are costly and seldom selected for funding. Furthermore, if they are funded, they are not usually performed with enough accessibility and transparency to the community at large to result in real, useable advances. Two system-level flight demonstration concepts that sidestep both the cost and accessibility issues are ISS utilization and extended missions.

*International Space Station (ISS) Utilization* - With the completion of the ISS, standard external payload interfaces provided by the Express Logistics Carriers and the Japanese Experimental Module–External Facility provide the opportunity to conduct rapid, low-cost flight demonstrations relative to the cost and schedule required to develop a free-flying spacecraft. Examples of this type of flight demo are Dextre Pointing Package (DPP)[62] and Robotic Refueling Mission (RRM).[63] Another benefit of ISS utilization is the widespread accessibility and public awareness associated with operations there. Technologists should keep in mind that both the ISS, and the many visiting vehicles provide a great opportunity for secondary payloads, much like Space Shuttle Demonstration Test Objectives (DTOs) of the past.

*Extended Missions* - An underutilized method of demonstrating technology is the concept of the extended mission. Case in point: RPOD technologists continue to lament the collective failure to identify resources to fund an extension of the OE mission. There were a number of high payoff activities OE was quite capable of completing (for instance, a visible-camera-only non-cooperative capture, or a PFF demonstration); however, the value of this opportunity was not identified early enough. There have been great success stories from extended missions and forward thinking Program-level architecting: the Themis vehicles demonstrated Earth-Moon Lagrange point maneuvers, and are now orbiting the moon; the Mars rovers use existing orbital assets which were wisely scarred for that use; NEAR demonstrated a risky landing on an asteroid to close out it's highly successful mission. The issue with these types of demonstration is not that they are costly, but that they require vision. At this point we ask ourselves, what vision should we have now to scar current or near term missions for similar daring and game-changing mission extensions?

What will happen to Prisma at the end of its mission? What about OSIRIS-REx and CHopper? As previously stated, the perceived risk of autonomous operations on an expensive primitive body science mission is just too high. Can we find a way to enable an OSIRIS-REx or CHopper extended Mission to demonstrate autonomous operations at a comet or asteroid? Such an extended mission concept would require the onboard instruments to be accessible by the Guidance, Navigation, and Control (GN&C) system while not significantly impacting the cost or risk associated with mission.

### Coordination and Collaboration

Given the limited availability of resources to complete challenging new missions, one of the most important steps we can take to address the technology gaps discussed in the paper is to improve coordination within NASA and across the government. In spite of recent, successful RPOD demonstration missions such as XSS-11 and Orbital Express, these activities have not resulted in a significant reduction in the development time or cost to implement AR&D capabilities on new missions. In many cases, the sensors or capabilities developed for these missions are essentially obsolete and not available to support current missions without additional non-recurring engineering costs. Limited resources require a strong emphasis towards working together as a community to further capabilities. *A Proposed Strategy for the U.S. to Develop and Maintain a Mainstream Capability Suite (Warehouse) for Automated/Autonomous Rendezvous and Docking in Low Earth Orbit and Beyond,* authored by the NASA-wide AR&D Community of Practice spells out this history of obsolescence and outlines steps NASA could take to significantly reduce the cost and development time associated with implementing the RPOD capabilities required for future NASA missions.[58] If successful, this strategy would directly benefit the other RPOD applications discussed in this paper.

The whitepaper proposes two steps are needed to achieve these benefits. First, NASA must develop a clear strategy or roadmap to guide required investments in RPOD technologies, and provide incentives and resources for funded programs to take the additional steps that will allow the investments they are making to have the broadest possible application to future missions. Second, the concept of an AR&D *warehouse* or library is introduced. The warehouse enables sharing of key elements of the AR&D solution, specifically in the areas of 1) Relative Navigation Sensors and Integrated Communications, 2) Robust AR&D GN&C and Real-Time Flight Software, 3) Docking/Capture Mechanisms/Interfaces, and 4) Mission/System Managers for Autonomy/Automation. The warehouse provides a capability to foster standards for interfaces between sensors and hardware, to share software and algorithms, and ultimately provide a library of capabilities that future projects can leverage when implementing a new RPOD solution in a way that has not been possible in the past.

The whitepaper goes on to summarize that, through these steps, NASA could implement a cohesive cross-Agency strategic direction for AR&D. Advances in capabilities will be achieved through an evolutionary stair-step development using a coordinated campaign of ground tests and space-based system demonstrations. Furthermore a mainstream AR&D technology base applicable to a wide spectrum of missions can be developed that is ready-to-fly, low-risk, reliable, versatile, architecture and destination-independent, and extremely cost-effective. Beyond enabling future NASA missions, this capability would benefit the DoD and the commercial spaceflight sector, and would re-establish U.S. leadership in the AR&D community.

## SATELLITE SERVICING TECHNOLOGY DEVELOPMENT ACTIVITIES

This section summarizes ongoing RPOD technology development activities being performed at GSFC in support of a future robotic satellite servicing missions. The Space Servicing Capabilities Office (SSCO) at GSFC was established to continue NASA's 30-year legacy of satellite servicing and repair by

- Advancing the state of robotic servicing technology to the point where America can routinely service satellites never designed to be serviced,
- Positioning America to be a global leader in on-orbit repair, maintenance and satellite disposal, and
- Supporting the development of a U.S. industry for spacecraft servicing

To apply these tenets, the SSCO is designing a notional robotic servicing mission which will offer refueling, repair, and repositioning services to satellites in geosynchronous orbit. Furthermore, the SSCO has two active projects to advance and demonstrate key technologies required to conduct a GEO servicing mission: RRM and Argon.

Launched on STS-135 and installed on the ISS in July 2011, RRM is an ISS experiment to test robotic refueling technology, tools, and techniques.[63] The RRM demonstration consists of the "RRM module," ISS's twin-armed Canadian "Dextre" robot, and four RRM Tools. Dextre acts as the skilled spacecraft refueling and servicing technician. Remote-controlled by Mission Operators on Earth, Dextre will interact with the RRM module, which is covered with servicing-related activity boards and other components. Using four unique RRM tools, Dextre will cut and peel back protective thermal blankets, unscrew caps, access valves, and transfer fluid demonstrating that a robot can do the tasks needed to service a satellite in orbit.

The Argon Project is a ground-based test campaign to mature autonomous rendezvous and docking capabilities required to service a non-cooperative target spacecraft; the target spacecraft are assumed to have no cooperative retro reflectors or sensors, they do not have docking or grapple features; and some form of robotic manipulator is required to capture a suitable feature such as a marmon ring on the satellite. Some of the high-level objectives of the Argon test campaign include:

- Advancing sensor and algorithm technologies needed to perform rendezvous, proximity operations, and capture of *non-cooperative* satellite targets,
- Evaluating performance of specific candidate sensors and algorithms,
- Performing side-by-side performance comparisons of selected sensors,
- Fostering collaboration with NASA, Naval Research Laboratory (NRL), and other U.S. Government stakeholders participating in the Argon test campaign, and
- Furthering objectives of the NASA AR&D Community of Practice towards developing an *AR&D Warehouse* for future US Government AR&D missions

Practically, Argon is focused on testing relative navigation sensors and algorithms that can be used with non-cooperative spacecraft at separation distances from approximately 100 meters to the point of capture, which is about 2 meters. During this period, 6-DOF pose (relative position and relative attitude) information is required, and a critical transition must be made between the AR&D system and the autonomous robotic capture system to execute the actual capture of the target. These capabilities have generally not been the focus of most recent AR&D activities.

**Argon System Description**

Originally formulated as an ISS flight payload,[62] the Argon system, shown in Figure 4, includes all of the major component elements that would be part of the AR&D subsystem on a servicing spacecraft. Argon includes two, one mega-pixel optical cameras built by MacDonald, Dettwiler and Associates (MDA) that provide passive visible wavelength images for processing by the Goddard Natural Feature Image Recognition (GNFIR) algorithm. The two Argon cameras were flown previously on the Hubble Space Telescope (HST) Servicing Mission 4 (SM4) RNS experiment, where they successfully captured images used to compute a real-time, on-board pose solution to HST.[26] One camera has a 57 deg FOV, the other with 11 deg Field of View (FOV)—each tuned to a specific depth of field chosen to optimize near- and far-field viewing.

Argon has been designed to accommodate multiple sensors to allow performance benchmarking and collection of parallel data sets. These sensors include the Vision Navigation System (VNS) flash LIDAR, a COTS IR camera, the TriDAR scanning LIDAR, and the RNS cameras. It also includes a full Engineering Development Unit (EDU) version of the DPP SpaceCube. These hardware are described in detail in Ref. 26.

Argon also includes a power control unit designed to support the ISS FRAM-based cargo electrical interfaces and provide control of the supply of power to each device. Although not include in the ground system, a wireless experiment box and antennas, which were developed to interface with the ISS external wireless network, are also available for Argon.

Because the Argon system was originally developed as an ISS payload, a comprehensive ground system has been developed and implemented via ASIST workstations to send commands to and receive telemetry from Argon. During every test, Argon sensors record images of the spacecraft target

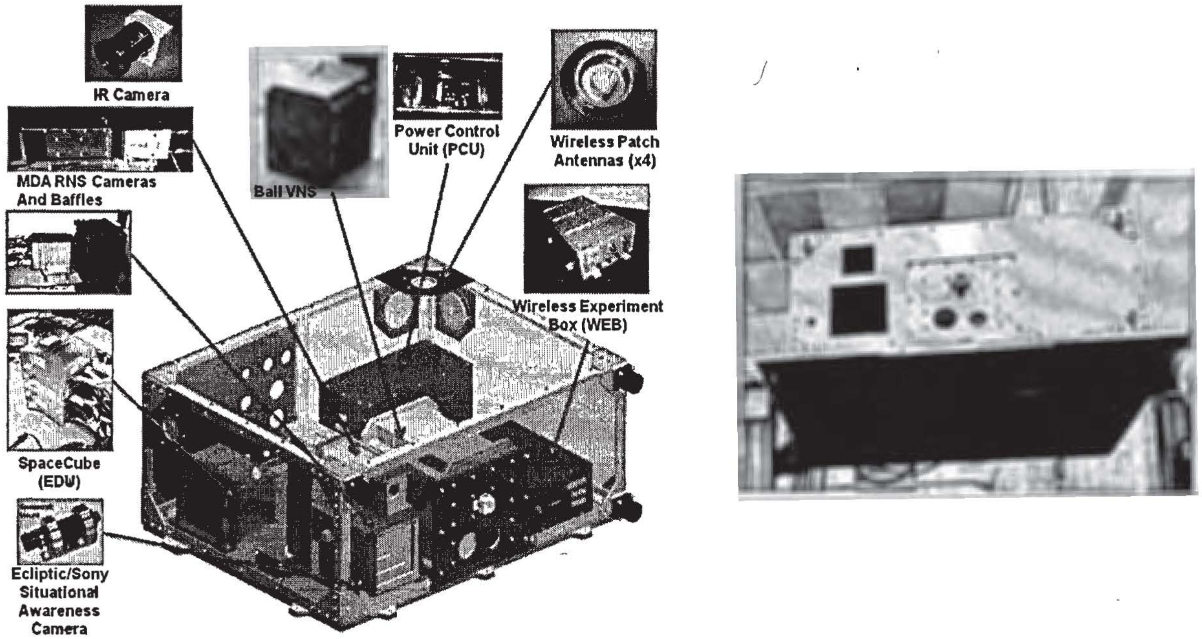


Figure 4. Argon Components

as it moves through some pre-determined motion. Argon can be configured to run multiple versions of the GNFIR algorithm onboard to simultaneously process data from each camera, while also running the FlashPose algorithm on VNS range images. In parallel, compressed images and onboard pose solutions are telemetered to the ground system in real-time to ground based workstations running independent GNFIR and FlashPose algorithms: such functionality allows the operations team to monitor onboard algorithm performance. Commands are issued from the ground system to configure sensor settings, command changes in Automatic Gain Control (AGC) settings, reconfigure telemetry, or re-initialize the onboard solutions. This system architecture allows Argon operations to be conducted in a manner similar to that of an actual RPOD flight mission.

## Argon Algorithms

***Goddard Natural Feature Image Recognition*** - To process the visual camera data, Argon utilizes the GNFIR algorithm to return a pose measurement.[26] The algorithm uses the visual information to extract features from the data. The features are then matched to a model (formulated as a set of edges) as shown in Figure 5. GSFC has made significant investments in the capability to simulate ground models of imagery of various potential targets for use in development of pose algorithms. Figure 5 (left image) shows the GNFIR algorithm processing and image of HST from the STS-125 SM4 mission. Figure 5 (right image) shows a screen shot of the GNFIR algorithm tracking a full-scale model of the GOES-12 spacecraft aft-bulkhead during Argon testing. Argon will test many advancements to GNFIR over what flew on STS-125 including general acquisition strategies for multiple targets, range-assisted acquisition, FPGA acceleration of looped processes, and GNFIR-commanded windowing in the AGC algorithm.

***GSFC FlashPose*** - Argon also hosts the GSFC FlashPose algorithm, which processes real-time flash LIDAR frames to produce a 6-DOF pose estimate. The algorithm processes range images as a point cloud, subsamples the cloud based on certain quality metrics, and uses a custom Iterative Closest Point (ICP) algorithm to determine an optimal estimate of the relative position and attitude. Figure 6 shows a screen shot of the FlashPose algorithm running during Argon testing. Demonstra-

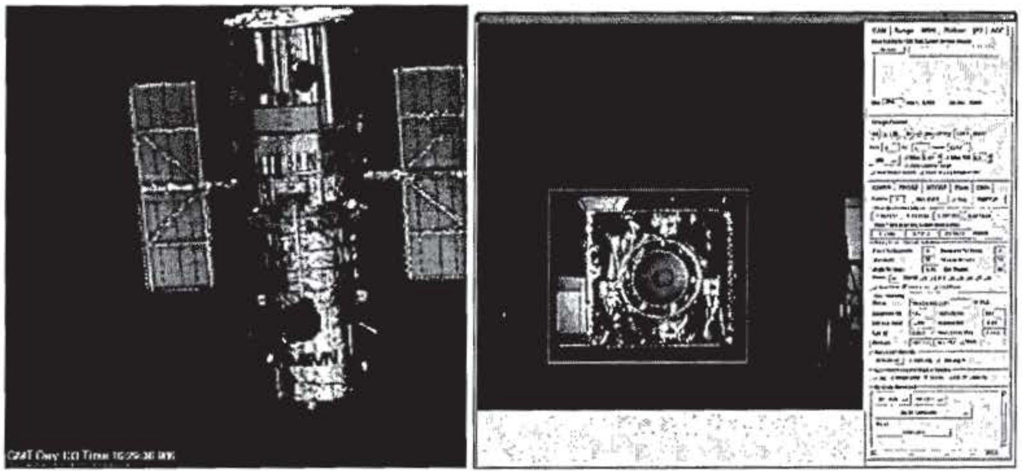

**Figure 5. GNFIR algorithm processing image of HST from STS-125 SM4(left) and GOES-12 mockup during Argon testing (right)**

tion of this FlashPose capability with range images from non-cooperative target vehicles is a major objective of Argon.

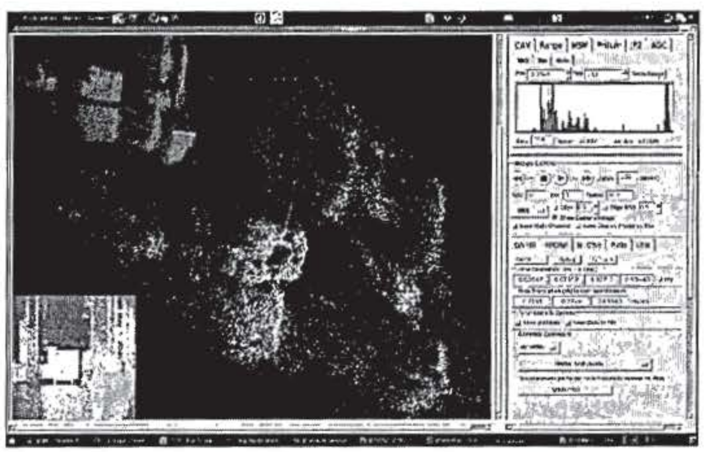

**Figure 6. Flashpose algorithm processing VNS range image (inset lower left) of GOES-12 mockup during Argon testing**

***JSC Cooperative 3D Pose* -** The Argon team collaborated with Johnson Space Center (JSC) to port Orion cooperative navigation algorithms to the SpaceCube. These algorithms take centroid measurements of target retro-reflectors computed from VNS range and intensity images and matches them to an internal model of the retro-reflector target pattern to compute the pose of the docking target. Figure 7 shows the stand-off cross docking target provided by JSC, a VNS intensity image, and red x-marks indicating the successful identification of the reflector locations.

**Argon Test Plans and Results**

The Argon Project completed integration in November 2011 and began a ground test campaign that will culminate in an end-to-end simulation of proximity operations, approach, and capture of a non-cooperative spacecraft target in the Fall of 2012. This campaign builds on the series of four successful demonstrations conducted as part of the SUMO/FREND program.[13] The Argon team will conduct a series of increasingly sophisticated demonstrations leading up to the end-to-end test. Two different models for the GOES-12 spacecraft; a geostationary satellite that is a potential candidate

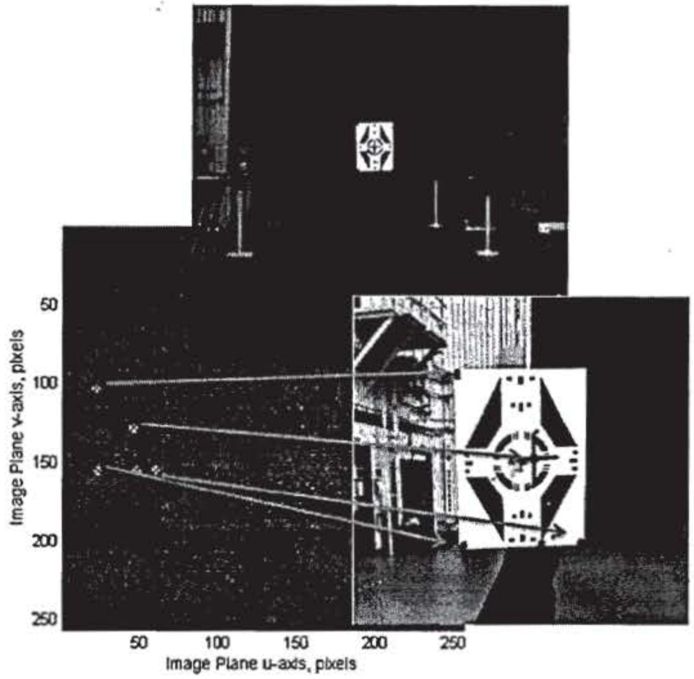


**Figure 7. VNS intensity image, reflectors identified by the JSC algorithm annotated with red "x"**

for a refueling mission, have been used. One of the models is a 1/10th scale model of the spacecraft, the other is a full scale model of the GOES-12 aft bulkhead, including the marmon ring that will be the likely capture feature.

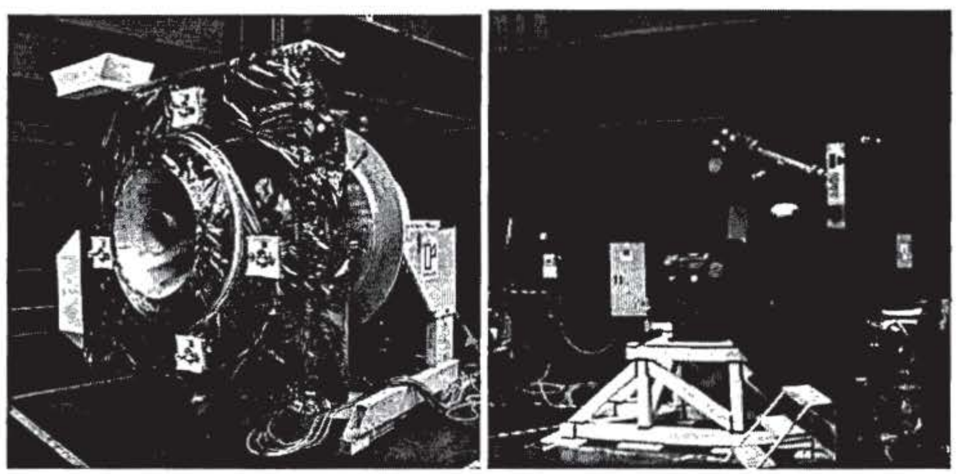

**Figure 8. Argon system and GOES 12 Aft Bulkhead model in SSCO robotic test facility**

Tests were conducted in late 2011 that simulated separation distances between approximately 90 meters and 1 meter, with the targets positioned statically or with relative motion simulated by an overhead crane. Current testing underway in the SSCO facility at GSFC where the relative motion between Argon and the target is simulated using robotic motion platforms (Figure 8). These tests involve both open- and closed-loop motion to demonstrate relative navigation solutions produced from Argon can be used to control the motion of the Argon platform and match the dynamics of the target. The facility allows separation distances between approximately 13 to 1 meter, appropriate to simulate the final approach to the target spacecraft and insertion into a "capture box" at approximately 2 meters separation. In March 2012, the Argon system will be tested in the Proximity Operations Testbed (POTS) at the Naval Research Laboratory. This facility has dual 6-DOF motion platforms that will allow closed-loop system test from separations of 20 meters or more to the point of capture. Additional long-range sensor testing (separation ranges from 100 m to 1 km or more) is planned during the April timeframe.

In parallel with the Argon test campaign, the SSCO is conducting a development and test program to integrate robot arm technology with a marman ring capture tool that can be used to reach out and grab on to the target spacecraft at the point of capture. This development is ongoing in the SSCO facility and will come together with the Argon system in late 2012 to conduct the end-to-end non-cooperative proximity operations and capture demonstration for a potential servicing mission.

In addition to furthering non-cooperative sensing and estimation capabilities in support of satellite servicing objectives, the Argon Project has a number of cross-cutting benefits to other application areas. The VNS flash lidar in the Argon system is available only because the Orion Project donated EDU components and the NASA Engineering and Safety Center (NESC) provided funding to integrate and deliver this system to GSFC. Collaboration with JSC has resulting in team members gaining experience implementing JSC developed algorithms on the Argon system, and future collaborations are planned, which could include using the Argon VNS to conduct testing of interest to human spaceflight objectives. GSFC is actively working within the NASA AR&D Community of Practive (COP) to explore ways to contribute capabilities matured under Argon into the AR&D warehouse concept discussed in the COP Whitepaper.

## CONCLUSION

Technologies for autonomous RPOD are important to NASA's future in many ways. Some high priority areas for future work include: 1) extending previously demonstrated capabilities to GEO and to applications beyond Earth orbit; 2) advancing capabilities to perform proximity operations with non-cooperative spacecraft and primitive planetary bodies; and 3) developing the necessary autonomy to successfully execute the aspects of future missions that can not rely ground (or crew) involvement. Although some objectives for human spaceflight have been scaled back or delayed, interest in satellite servicing, refueling, and/or re-purposing applications has increased with NASA, DoD, and even some commercial entities, who are working on a range of applicable technology development activities. GSFC is conducting a ground test campaign called Argon focused on advancing sensors and algorithms for non-cooperative proximity operations and capture of a target satellite with a robotic arm.

More than ever, it is necessary to carefully leverage the limited resources available for NASA activities in a manner that has the widest possible benefit across NASA's many exploration objectives. The NASA AR&D Community of Practice has recommended how, through increased collaboration, NASA can improve the chances that investments in sensor development, new algorithms, test or flight demonstration activities can be utilized or leveraged by other missions in the future. Some of the ways improvements can be acheived are through collaboration on software and/or algorithm repositories, or in some cases working in a fully open source environment; by working more closely together on sensor development and procurements; and by fostering more opportunities for critically important flight demonstrations via secondary payloads or extended mission opportunities. Such coordination and collaboration will help to reduce the non-recurring engineering costs for future RPOD applications which will have wide benefits within NASA and other US space activities.

## ACKNOWLEDGEMENTS

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| **6-DOF** | Six Degrees of Freedom |
| **2D** | Two Dimensional |
| **3D** | Three DImensional |
| **ACS** | Attitude Control System |
| **AGC** | Automatic Gain Control |
| **ANGELS** | Autonomous Nanosatellite Guardian for Evaluating Local Space |
| **AR&D** | Autonomous Rendezvous and Docking |
| **ATV** | Automated Transfer Vehicle |
| **CCDev** | Commercial Crew Development |
| **CHopper** | Comet Hopper |
| **COP** | Community of Practive |
| **COTS** | Commercial Off-The-Shelf |
| **DARPA** | Defense Advanced Research Projects Agency |
| **DART** | Demonstration of Autonomous Rendezvous Technology |
| **DoD** | Department of Defense |
| **DPP** | Dextre Pointing Package |
| **DS1** | Deep Space 1 |
| **DTO** | Demonstration Test Objective |
| **EDU** | Engineering Development Unit |
| **ESA** | European Space Agency |
| **FFRF** | Formation Flying Radio Frequency |

| | |
|---|---|
| **FOV** | Field of View |
| **FPGA** | Field Programmable Gate Array |
| **FRAM** | Flight Releasable Attachment Mechanism |
| **FREND** | Front-end Robotics Enabling Near-term Demonstration |
| **GEO** | Geosynchronous Earth Orbit |
| **GN&C** | Guidance, Navigation, and Control |
| **GNFIR** | Goddard Natural Feature Image Recognition |
| **GOES** | Geostationary Operational Environmental Satellites |
| **GPS** | Global Positioning System |
| **GRACE** | Gravity Recovery and Climate Experiment |
| **GRAIL** | Gravity Recovery and Interior Laboratory |
| **GSFC** | Goddard Space Flight Center |
| **HEFT** | Human Exploration Framework Team |
| **HEO** | Highly Eccentric Orbit |
| **HST** | Hubble Space Telescope |
| **HTV** | H-II Transfer Vehicle |
| **ICP** | Iterative Closest Point |
| **IR** | Infrared |
| **ISS** | International Space Station |
| **JWST** | James Webb Space Telesope |
| **JSC** | Johnson Space Center |
| **LEO** | Low Earth Orbit |
| **LIDAR** | Light Detection and Ranging |
| **MASSIM** | Milli-Arc-Second Structure Imager |
| **MDA** | MacDonald, Dettwiler and Associates |
| **MINERVA** | MIcro/Nano Experimental Robot Vehicle for Asteroid |
| **MPCV** | Multi-Purpose Crew Vehicle |
| **NAS** | National Academy of Sciences |
| **NASA** | National Aeronautics and Space Administration |
| **NEA** | Near Earth Asteroid |
| **NEAR** | Near Earth Asteroid Rendezvous - Shoemaker |
| **NESC** | NASA Engineering and Safety Center |
| **NRL** | Naval Research Laboratory |
| **NWP** | New Worlds Probe |
| **OE** | Orbital Express |
| **OSIRIS-REx** | Origins Spectral Interpretation Resource Identification Security Regolith Explorer |
| **PFF** | Precision Formation Flying |
| **POTS** | Proximity Operations Testbed |
| **PROBA-3** | PROBA-3 |
| **RF** | Radio Frequency |
| **RNS** | Relative Navigation Sensor |
| **RPOD** | Rendezvous Proximity Operations and Docking |
| **RRM** | Robotic Refueling Mission |
| **SM4** | Servicing Mission 4 |
| **SSCO** | Space Servicing Capabilities Office |
| **STORRM** | Sensor Test for Orion Rel-Nav Risk Mitigation |
| **SUMO** | Spacecraft for the Universal Modification of Orbits |
| **TAG** | Touch and Go |
| **TAFF** | Tandem-X Autonomous Formation Flying |
| **TriDAR** | Triangulation and Time-of-Flight Lidar |
| **Vis-STAR** | Vision-based Software for Track, Attitude, and Ranging |
| **VNS** | Vision Navigation System |
| **XSS-11** | Experimental Small Satellite-11 |