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SATELLITE SERVICING'S AUTONOMOUS RENDEZVOUS AND DOCKING TESTBED ON THE INTERNATIONAL SPACE STATION

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The Space Servicing Capabilities Project (SSCP) at NASA's Goddard Space Flight Center (GSFC) has been tasked with developing systems for servicing space assets. Starting in 2009, the SSCP completed a study documenting potential customers and the business case for servicing, as well as defining several notional missions and required technologies. In 2010, SSCP moved to the implementation stage by completing several ground demonstrations and commencing development of two International Space Station (ISS) payloads—the Robotic Refueling Mission (RRM) and the Dextre Pointing Package (DPP)—to mitigate new technology risks for a robotic mission to service existing assets in geosynchronous orbit. This paper introduces the DPP, scheduled to fly in July of 2012 on the third operational SpaceX Dragon mission, and its Autonomous Rendezvous and Docking (AR&D) instruments. The combination of sensors and advanced avionics provide valuable on-orbit demonstrations of essential technologies for servicing existing vehicles, both cooperative and non-cooperative.

INTRODUCTION

The Space Servicing Capabilities Project (SSCP) was created at NASA's Goddard Space Flight Center (GSFC) in late 2009 following completion of the Hubble Space Telescope (HST) Servicing Mission 4 (SM4) to assess the feasibility, practicality, and cost of servicing satellites using elements of currently planned and future NASA human spaceflight systems and/or robotic technologies. In 2010 the SSCP completed work on a Servicing Study[1] documenting potential customers, the business case, notional missions, and technologies required for robotic or manned servicing of space assets.

With the Servicing Study completed in 2010, SSCP moved on to development, fabrication, integration and test of two International Space Station (ISS) payloads that serve as risk mitigation demonstrations for an eventual servicing pathfinder mission. Ref. 2 introduced some details of that future mission (a robotic mission to refuel several US assets at Geosynchronous Earth Orbit (GEO)), including notional trajectories, multivehicle refueling rendezvous sequence optimization, and initial covariance analysis for Autonomous Rendezvous and Docking (AR&D) at GEO. The two risk mitigation payloads are the Robotic Refueling Mission (RRM) and the Dextre Pointing Package (DPP). SSCP is working towards launches of these two payloads in June of 2011 on STS-135, and July of 2012 on the third operational SpaceX Dragon mission, respectively.

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This paper introduces the Dextre Pointing Package (DPP), the second SSCP risk mitigation payload, and its AR&D Instrument. DPP, illustrated in Figure 1, is an ISS Payload which uses ISS robotics to enable flight testing of engineering and science enabling technologies. DPP avionics and sensors provide closed-loop control of the Special Purpose Dexterous Manipulator (SPDM), or Dextre, to point DPP instruments in a variety of pointing tasks including Earth-fixed, Local Vertical-Local Horizontal (LVLH)-fixed, Inertially-fixed, and ISS-proximate vehicle tracking.

Figure 1. Dextre Pointing Payload mounted to SPDM (background) tracking ATV (foreground)

Motivation for an ISS AR&D Testbed

Satellite Servicing and Orbit Debris mitigation, two topics currently of great interest to NASA and the DoD Aerospace community, provide unique new AR&D challenges, especially in the areas of sensing and capture. Combined effects of micro-gravity, radiation, lighting, target geometries, and target surface properties are virtually impossible to simulate on Earth. An experiment on-board ISS provides a unique opportunity to demonstrate this mission enabling technology. The DPP AR&D Instrument provides a testbed for these capabilities by installing and operating existing relative navigation sensors on the ISS as DPP payloads. The system performs vehicle relative navigation demonstrations to frequent ISS-proximate vehicles, and machine vision for robotic tasks (including autonomous capture). It will provide continued operation in space with the opportunity to track a variety of target vehicles. DPP will include on-board processing of sensor data, and reconfigurable software for on-orbit testing of multiple pose algorithms, and camera gain control algorithms.

Over the past several months the SSCP has worked with numerous organizations within NASA, the Canadian Space Agency (CSA), and industry to build a state-of-the-art AR&D system including the Ball Aerospace Technologies Corporation (BATC) Vision Navigation System (VNS), a flash Light Detection And Ranging (LiDAR) and Orion's primary relative navigation sensor; the Neptec Triangulation and Time-of-Flight Lidar (TriDAR), a scanning LiDAR which includes two 3D laser sensors and an Infrared Camera; two optical cameras built by MacDonald, Dettwiler and Associates (MDA) which also flew on the HST SM4 Relative Navigation Sensor (RNS) payload; and a powerful space processor called SpaceCube. Together this hardware makes the DPP an extremely valuable and affordable AR&D system demonstration.

The DPP AR&D Instrument will take advantage of the unique Space Station environment and capabilities to demonstrate passive and active relative navigation sensing and the associated vision processing, pose estimation, and filtering to combine these measurements into a relative navigation solution. The system will also close the loop around the filtered solution to point SPDM and DPP at ISS-proximate vehicles, tracking them as they approach and depart.

The US has made great progress on the relative navigation sensor front through several low cost missions and Demonstration Test Objectives (DTOs): the Demonstration of Autonomous Rendezvous Technology (DART),[3] Orbital Express (OE),[4–6] and Experimental Small Satellite-11 (XSS-11)[7] missions; the RNS[8] DTO on STS-125; TriDAR[9] DTOs on STS-128, 131, and potentially 135; the DragonEye DTO on STS-127; and the upcoming STORRM (VNS) DTO on STS-134. Recent changes in NASA's budget resulting in cancellation/postponement of four highly leveraged AR&D flight demonstrations (three Flagship missions and the Orion 1 Rendezvous Proximity Operations and Docking (RPOD) w/ ISS) make low cost flight demonstrations like DPP a key part of the AR&D technology roadmap.

DPP is the natural evolution of the work started with the DTOs, providing longer duration and dedicated support to AR&D activities. As shown in Figure 2, an AR&D testbed on ISS will continue the great progress from recent DTOs, and provide a valuable near term flight opportunity of new and existing technologies critical not only to SSCP, but NASA and other US agency objectives. Satellite Servicing–GSFC in particular–need not be the only customer for DPP. This is an AR&D platform that is very similar to the concept of an astrophysics observatory: researchers everywhere can request time to test their relative navigation algorithms, mission mode managers, and trajectory generation algorithms, that is, time to test their "science."

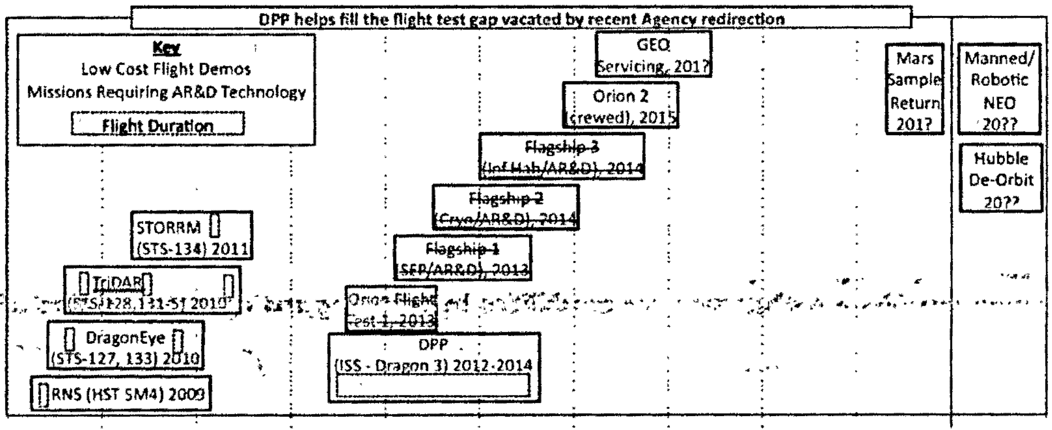


Figure 2. Notional schedule of NASA AR&D Flight Activities

ISS Visiting Vehicles

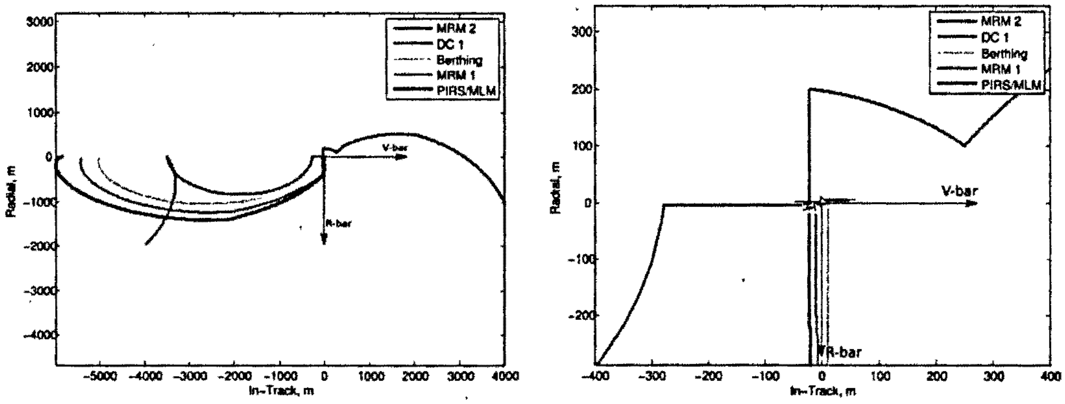
One aspect of the ISS which makes it an attractive testbed for AR&D sensors is the regular arrivals and departures of visiting vehicles including the European Automated Transfer Vehicle (ATV), the

Japanese H-II Transfer Vehicle (HTV), the Russian vehicles Progress and Soyuz, and planned US commercial vehicles such as Dragon (SpaceX) and Cygnus (Orbital Sciences Corporation). Using DPP to monitor and collect relative navigation data on these vehicles as they approach and depart the ISS will provide invaluable data for refining AR&D sensor technology and navigation algorithms. This is crucial for developing the robust AR&D capability required during spacecraft servicing missions. Moreover, the relative navigation data that DPP will provide during ISS visiting vehicle operations could augment existing monitoring capabilities, improving situational awareness, safety, and operational efficiency.

Figure 3. Nominal ISS Approach Corridors

Figure 3 presents a rendering of the ISS, the nominal approach corridors to each of the available docking locations, and the nominal approach corridor to the berthing box from which certain visiting vehicles (HTV, Dragon, and Cygnus) are captured by the ISS robotic arm (SSRMS) and berthed to the nadir port of the Node 2 module ("Harmony"). In addition to the Pressurized Mating Adapter (PMA)-2 docking port and the nadir berthing port of Harmony on the US side of ISS, the Russian side docking locations include DC 1, MRM 1, MRM 2, and PIRS/MLM. The ATV only docks at DC 1, while Progress and Soyuz can dock at any of the ports on the Russian side. The nominal approach corridors consist of cones whose axes extend out and away in a straight line from the centers of those docking ports.

Figure 4(a) shows exemplary nominal rendezvous trajectories (in the ISS Radial-InTrack-CrossTrack (RIC) frame) flown by vehicles bound for the various ISS docking locations or the berthing box. Due to the orientations of the docking ports (and the location of the berthing box) these trajectories are typically either along the local velocity direction (V-bar) or the local radial direction (R-bar) in which the final several hundred meters are essentially slow, straight-line forced motion trajectories accomplished by continuous control. Figure 4(b) provides a closer view in which the relationship between the approach trajectories and the ISS structure is becoming visible. Figure 5 provides an even closer view that shows each final approach trajectory terminating at the specified docking location (or berthing box location).



(a) Nominal Rendezvous Trajectories to Available ISS Docking Ports (b) Close-In View of Nominal Rendezvous Trajectories to Available ISS Docking Ports

Figure 4. Nominal ISS Rendezvous Trajectories

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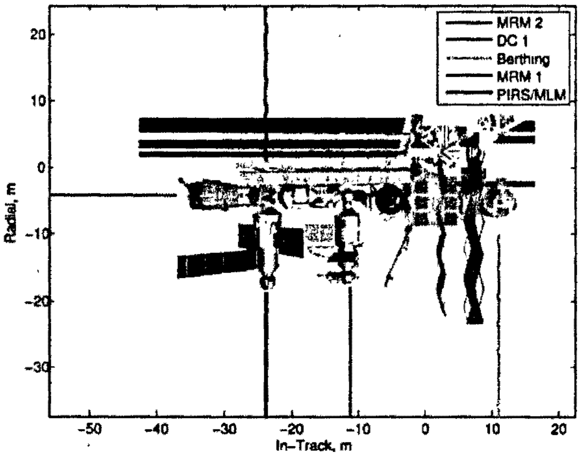


Figure 5. Nominal Final Approach Trajectories to Available ISS Docking Ports

Together, these different rendezvous and approach trajectories, combined with the various visiting vehicles that fly them, provide DPP with a diverse set of vehicles and approach geometries to observe. This ensures that the AR&D sensors and algorithms are exercised extensively, leading to robust advances in relative navigation capabilities.

DEXTRE POINTING PACKAGE (DPP)

Dextre Pointing Package (DPP), the second SSCP ISS risk mitigation payload, takes advantage of ISS resources to provide a unique new capability on ISS. In particular, the DPP utilizes the ISS Mobile Servicing System (MSS),[10] which consists of two robots and a mobile base that allows these robots to operate in various locations on ISS.

Many intricate science instruments – especially earth-scanning and climate-monitoring instruments – require a stable, motionless platform to perform their missions. Mounted at the end of the ISS SPDM robotic arm, the DPP is able to detect pointing disturbances from ISS motion and then command SPDM motion to compensate for and stabilize the pointing error, thereby providing a stable platform for science payloads that require "motionless" precision pointing. DPP allows NASA to push the technological frontiers of avionics and sensors – the first DPP instrument is an AR&D test-bed including sensors from SSCP, CSA, and Orion, and a Wireless Experiment Box. Using DPP, instruments can look and lock into specific spots in the Universe and on Earth with accuracy and confidence. DPP will be delivered to ISS no earlier than July 2012 as unpressurized cargo aboard a SpaceX Dragon capsule and installed on Express Logistics Carrier (ELC) #4 in a wake, inboard payload location.

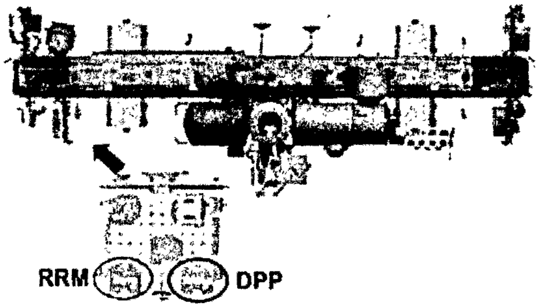


Figure 6. DPP mounting location on ELC 4

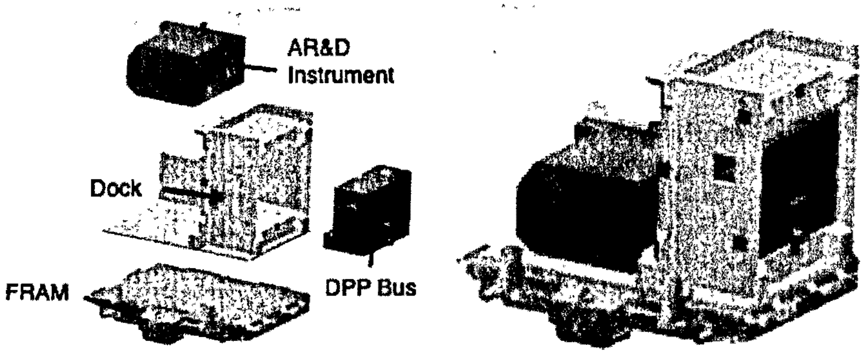
DPP includes three major components: the DPP Bus, a small enclosure with avionics, sensors, and software to support DPP Payload operations; the DPP Dock, an ELC Flight Releasable Attachment Mechanism (FRAM)-mounted structure for DPP storage, checkout, and fixed-pointing (ELC) operations; the DPP Instrument, where new technologies packaged as Instruments may be launched separately, or co-manifested with the DPP, such as the DPP AR&D Instrument. Depictions of these components in various configurations are shown in Figure 7.

This system architecture takes advantage of the existing ISS communications structure that is currently in place for ISS operations. Additionally, the communications paths between DPP, SPDM, and ELC all currently exist on-orbit. As mentioned previously, DPP utilizes the SPDM robot to point its Instrument, effectively closing the loop around the AR&D sensor measurements. This capability will require an MSS software change to allow SPDM to receive pointing commands from DPP to reorient the robotic arm.

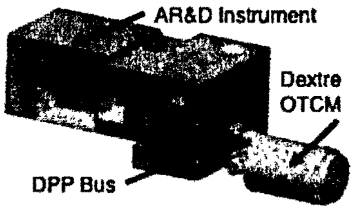
The following subsections will detail the Guidance, Navigation, and Control (GN&C) hardware on the DPP bus with the AR&D hardware described in a later section. Following the hardware section will be a brief description of the DPP GN&C software, followed by a section detailing the DPP Operations Plan.

GN&C Hardware

With the exception of independent power generation and vehicle control subsystems, the DPP houses all the same subsystems that would be found in a typical earth- or space-observing spacecraft. DPP implements its own command and data handling, centralized flight computer, power conditioning, inertial navigation, flight data recording, and thermal maintenance, as well as mission-specific instruments. Of particular interest are those mission-critical subsystems that are also technology



(a) DPP Main Assemblies (b) DPP launch configuration



(c) DPP on OTCM

Figure 7. DPP Configurations

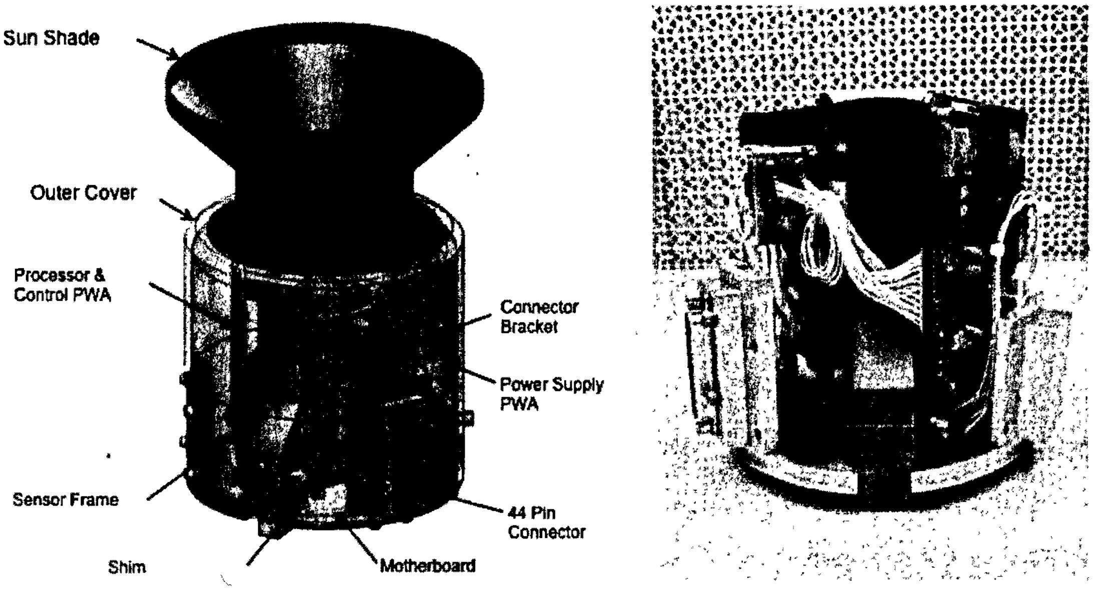
demonstrations in the areas of inertial navigation, such as a new star tracker, a six degree of freedom inertial measurement unit, and the GSFC-designed and -built flight data computer, SpaceCube.

BATC Star Tracker Officially designated as the FT-701, the star tracker flown on DPP was a joint development venture between the DPP project and BATC. The star tracker, shown in Figure 8, is a unique mix of old and new using a mechanical enclosure and optical assembly from Ball's CT-600 series trackers to surround new electronics that incorporate state-of-the-art parts and processes. The balance between heritage and new development is key in making the tracker available in the short time frame allowed by the project: where new tracker development would take 18–24 months, the Ball group did so in ten.

The centerpiece of the FT-701 is the Active Pixel Sensor (APS)—a CMOS-based image sensor that provides the tracker's detecting capability. While the recent trend of moving away from Charged-Coupled Device (CCD)-based star trackers has its roots in power, and therefore mass, savings, other users will find the APS's ability to randomly access pixels provides enough flexibility to perform advanced processing on the raw measurement while keeping, or even increasing, the output measurement update rate.

The initial build of the star tracker, with all its bumps and bruises from being the first, shows performance results comparable to those of Sodern, Galileo, and DTU. The short development cycle did require that some space-rated parts be substituted for available commercial equivalents, however, the electrical design does have a direct path to a fully space-qualified version given a more reasonable schedule for obtaining parts.

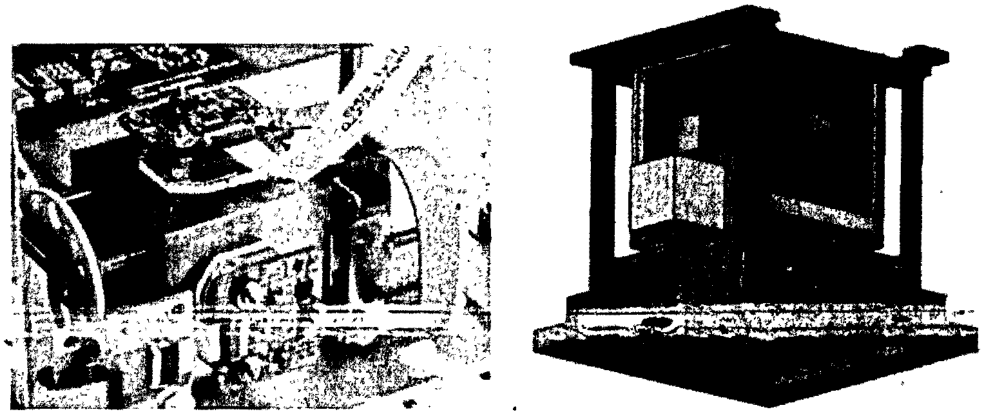
Draper Inertial Measurement Unit (IMU) The IMU is another advanced-technology sensor onboard DPP. Designed by the Charles Stark Draper Laboratory, the DPP IMU uses Micro-Electro-Mechanical System (MEMS) technology to significantly lower the volume, power, and mass al-



(a) As-designed CAD model (b) As-built flight unit (cover removed)

Figure 8. BATC FT-701 Star Tracker

located to traditional IMU devices. This device measures linear accelerations and inertial angular rates. The linear acceleration measurements will be used to measure the on-orbit vibration environment of the SPDM to refine ground based flexibility models and enable disturbance reduction on-orbit. The inertial angular rate measurements will enable dead reckoning of the filtered attitude estimate during star tracker outages. Figure 9 shows the benchtop prototype as well as a CAD rendering of the as-designed unit.



(a) Benchtop Prototype (b) Flight Design (outer cover removed)

Figure 9. Draper IMU Hardware and Design

The project originally planned to use a Honeywell Miniature Inertial Measurement Unit (MIMU) to provide these measurements. As the design progressed, the project realized that the MIMU took a significant portion of the DPP Bus' power budget—about 20%—so they looked for a state-of-the-art but already-in-progress solution that reduced the physical allocations while maintaining performance. Draper Labs was already building a similar unit for a ground-based military application, so, the project worked with them to update the electrical and mechanical design for space. The final design beat the MIMU by 2.5× in mass, 5.5× in volume, and 3× in power, while only giving up 2× the performance.

The already difficult task of designing a flight-rated IMU was made more complex by the expected operating environment for DPP. In this case, the main challenge was isolating the temperature-sensitive MEMS components from the large temperature swings that can be seen on the end of SPDM. The final design has each of the six sensor boards—three for each gyro and three for each accelerometer—embedded in a beryllium block, which is mounted on top of a titanium flexure. The flexure provides thermal isolation from the power-conditioning boards located below it, and the flexure design provides vibration isolation for frequencies higher than 560 Hz, beyond which lies the drive frequencies for the MEMS tuning fork gyro.

GSFC Space Cube The DPP SpaceCube is the flight box from the HST SM4 RNS flight,[8,11] with several minor changes including addition of 1553 and ethernet interfaces (2 each), and with a new Video Control Module (VCM) slice. SpaceCube is composed of five "slices": two Power Slices; two Processor Slices; and one VCM Slice. A CAD model and photographs of SpaceCube are shown in Figure 10. The two SpaceCube processor slices, also referred to as "SCμPs" (pronounced "scups") host the DPP user applications, including pose algorithms (Goddard Natural Feature Image Recognition (GNFIR) and flash LiDAR pose), a Relative Navigation Filter (RNF), and Automatic Gain Control (AGC) on SCμP-1, and Command and Data Handling (C&DH) and the GN&C functions (attitude guidance, estimation, and pointing control) on SCμP-2. The VCM is an upgraded version of the RNS Video Interface Module (VIM) slice. In addition to the video compression the VIM provided, the VCM provides 16 Gb of flash memory, new data paths and software, and a Data Over Video (DOV) interface to the MSS analog video interface.

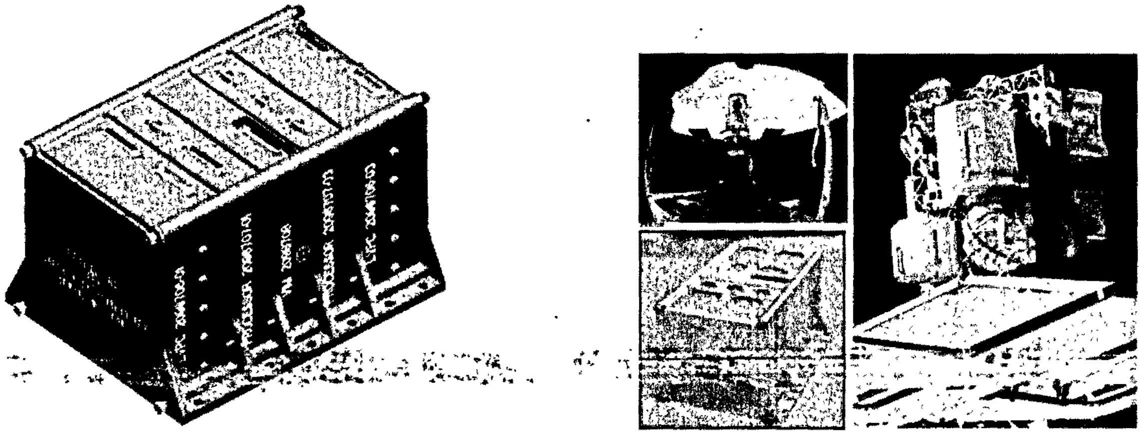


Figure 10. SpaceCube CAD model and photograph of flight unit and its two flights to date (HST SM4 and MISSE7 on ISS)

The SpaceCube processor slice is a miniaturized C&DH system on a single 4 x 4 inch board. Processing power is provided by four Virtex 4 FPGAs, each with two PowerPC 405 processors, which can be run in parallel, giving added processor cycles. Whereas RNS utilized three of the Virtex 4s, and only three of the eight processors, DPP uses all four FPGAs, and at least seven of the eight processors. It also process data from nine sensors (five cameras, two LiDARs, a star tracker, and an IMU), compared to just three cameras on RNS.

GN&C Software

The DPP GNC software is tasked with synthesizing the star tracker and IMU measurements into a coherent inertial attitude and rate estimate, processing relative navigation sensor data, and executing control routines for target pointing. While the first step is knowing where you are located in space (navigation), the next goal is to determine where your target is in space (guidance), and the final goal, for DPP, is to point at the target (control).

To address the navigation step requires development of a filter to combine the different inertial measurement sources of the star tracker and the IMU. The navigation system has a required accuracy of inertial attitude knowledge to [20,20,30] arc-seconds in the DPP body frame. Less accuracy is placed on the Z-axis as this is the boresight of the star tracker, about which knowledge is less than cross-boresight. To achieve these requirements, a Multiplicative Extended Kalman Filter (MEKF) based on Ref 12 has been designed to estimate the inertial attitude and rate of DPP. A MEMS gyroscope suffers from thermal dependencies more than traditional gyroscopes due to the electro-mechanical design. As such the MEKF has been augmented to estimate and mitigate the temperature sensitive bias in the IMU.

A simulation of the DPP mission has been developed that includes an implementation of the MEKF. An attitude error plot from the simulation is shown in Figure 11. Note that most of the filter error remains within the 3σ covariance bounds, as expected. The variations in the covariance, clearly shown in the Z-axis, result from maneuvers to different targets in this Earth pointing scenario.

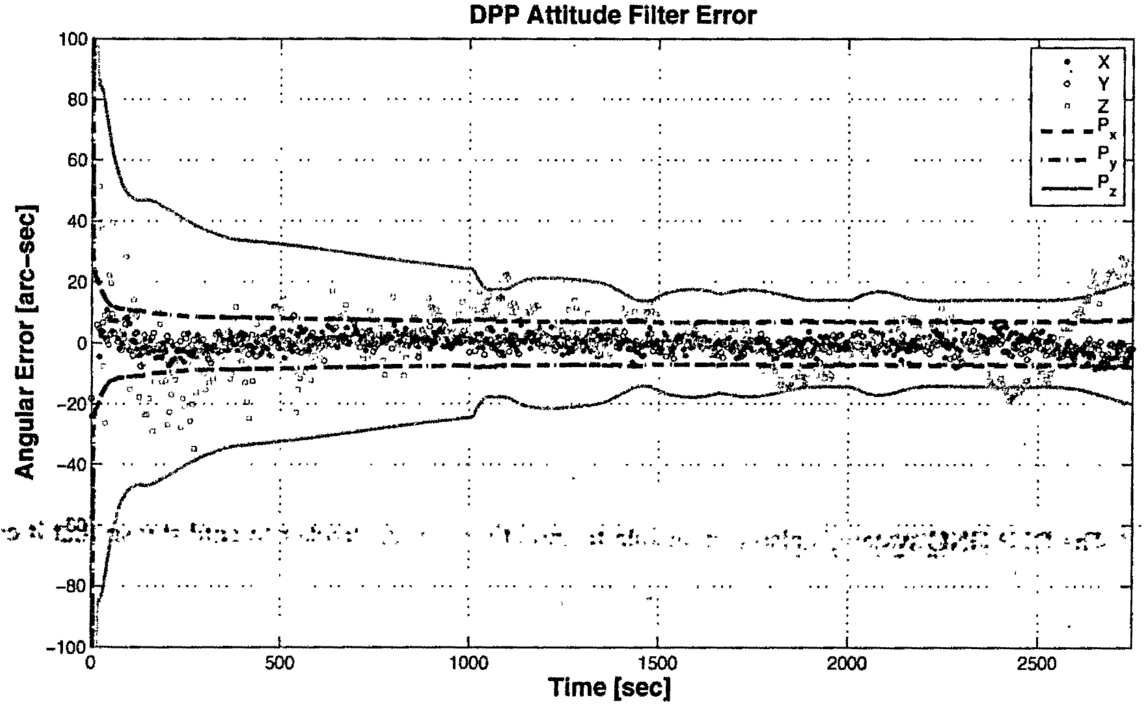


Figure 11. DPP Attitude Estimation Error for Earth Pointing Scenario

Once the inertial attitude and rate have been estimated, the system must now determine the target pointing direction. DPP will have several types of targets, Earth fixed targets, Inertially fixed targets, ISS Proximate vehicle targets, ISS body fixed targets, and Earth/Inertial scanning modes to scan the Earth surface or the dark sky. Each of these targeting modes, save the ISS proximate vehicle and ISS body fixed targets, do not require additional sensor measurements to accurately track the target. DPP ground operations will determine which Earth targets, Inertial targets or which type of scanning mode is available given the operational window. Therefore, for these modes, a list of target parameters will be sent to DPP via command from the DPP Ground Terminal, and DPP will determine the target location in an appropriate reference frame that will enable the control to track the target. In the case of the ISS Proximate vehicle tracking and ISS body fixed target modes, DPP will use the pose measurements to determine an appropriate target input to the DPP control software.

The final step is to utilize a control algorithm to achieve target pointing or tracking. DPP relies on the SPDM robotic system to point its cameras appropriately. Specifically, DPP is required to create position and attitude rate commands and communicate these to the Robotic WorkStation (RWS) on ISS that will in turn actuate the SPDM robotic arm. In this manner, any motion requested by DPP is inherently checked by the RWS system and ISS ground operations to ensure that the SPDM robot is obeying safety constraints and pre-existing hazard controls. The goal then of the DPP control software is to reduce the error between the navigation and guidance solutions to achieve target tracking. The left portion of Figure 12 shows a still image of DPP tracking the Hawaiian Island chain, while the right portion of Figure 12 shows the control error for a particular Earth pointing scenario.

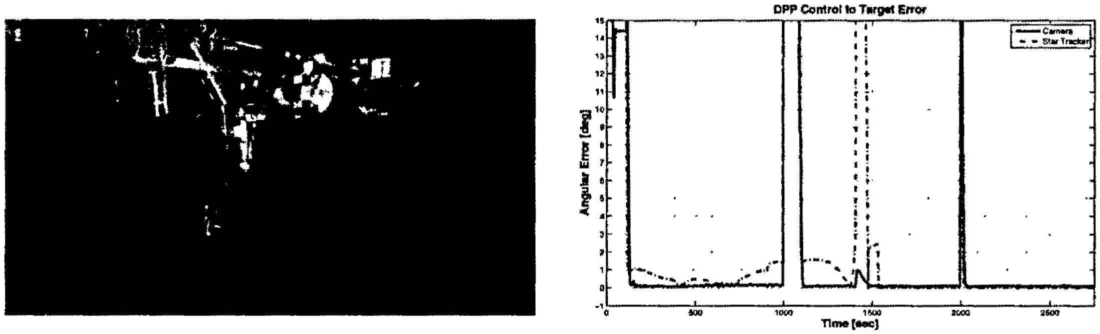


Figure 12. DPP Earth Pointing Mode (left), DPP Pointing Control Error (right)

In this simulated observation sequence, the target to be tracked is changed, first at 1000 seconds, and then again at 2000 seconds, which explains the instantaneous large angular error in Figure 12 for the Camera pointing error. The error is initially quite large but converges to within the 1° requirement within 130 seconds. Upon reorientation of the camera boresight to different targets at 1000 and 2000 seconds, the Camera pointing error converges within 105 and 20 seconds, respectively.

The DPP GNC system is also responsible for pointing the star tracker to cold sky so that it can provide an attitude estimate. The Star Tracker Error plot in Figure 12 represents the error between the optimal cold sky pointing direction and the current pointing direction of the star tracker. As long as the star tracker angular error to cold sky does not exceed 9°, or half of its field-of-view, then it is not occluded. From the Star Tracker pointing error plot in Figure 12, this requirement is satisfied, save the pointing error rise at 1400 seconds. This increased error demonstrates the difficulty of satisfying all of the constraints of DPP when attempting to point at the Earth. The ISS blocks a lot of cold sky above DPP, and the Earth takes up much more beneath DPP. At 1400 seconds in the simulation, the DPP motion to track its target results in an object nearing the FOV of the star tracker, causing a large reorientation to point to cold sky. The change in Star Tracker pointing requires a large reorientation of DPP, but note that the Camera pointing error never exceeds the 1° requirement, and the Star Tracker pointing error is reduced within 100 seconds.

The ability of DPP to accurately point at the desired target is enabled by the Constraint Control algorithms in the GN&C system. These algorithms utilize not only the attitudinal degrees of freedom of the SPDM robot arm, but also the translational degrees of freedom to manage the additional constraints of pointing the star tracker to cold sky. These Constraint Control algorithms enable the DPP GNC system to maintain accurate target tracking and the synthesis of an accurate attitude solution through the entire scenario, in simulation.

The DPP GNC system will have the ability to synthesize the star tracker and IMU measurements into an accurate attitude solution, determine targets to be tracked by either ground command (Earth targets, Inertial targets, ISS fixed targets) or by actively closing the loop around the pose sensor measurements (Rendezvousing/Departing Vehicle Tracking). For all of these scenarios, it is critical to have the ability to reorient the DPP experiment in real-time, and to increase the field of regard of the experiment by using the Space Station Remote Manipulator System (SSRMS) to move clear of ISS structure.

Operations

DPP operations will encompass a flight test of AR&D sensors and algorithms including visible and infrared cameras, scanning and flash laser radars, and associated pose estimation and 6-DOF relative navigation filters. DPP will also demonstrate closed-loop Earth-fixed and inertial pointing operations for future ISS utilization payloads. This, with the hardware, software and operations in place, will provide interfaces for new payloads to be integrated later.

The Dextre Pointing operations team will be located at the GSFC Satellite Servicing Control Center in Greenbelt, MD. Flight operations will fall under five general categories: checkout operations, reconfiguration operations, pre-sortie preparation, sorties, post-sortie data downlink.

Checkout Operations Includes simple checkout operations on the ELC-based DPP Dock, and more complicated checkout of DPP sensors and SPDM control interface when first mounted to the SPDM OTCM. Operations include commanding of DPP via either ELC or Mobile Servicing System (MSS) 1553, and data downlink via ISS external wireless, SPDM analog video, and/or ELC Ethernet.

Reconfiguration Operations Robotic activity to reconfigure the DPP system and ISS robotics, including moving the DPP Bus to one of three locations (Dock Garage, Dock Porch, SPDM); moving the DPP AR&D Instrument to one of three locations (DPP Bus, Dock Instrument Site 1 or 2); and installation of a new DPP Instrument. DPP-specific commanding to include DPP and ELC commands to power DPP internal heaters.

Pre-Sortie Preparation Uplink of sortie-specific details including timelines, recording scripts, target details, with infrequent (months) updates to the DPP software via ISS file transfer

Sortie Operations Performed only on SPDM, usually involving tracking of an ISS proximate vehicle during rendezvous or deploy, but also tracking of Earth/Inertial and ISS-fixed targets. Sorties will consist of some upfront commanding, followed by a period of autonomous activity in which DPP points its instrument at the specified target and transmits telemetry (1553) and high speed data (wireless/analog video as available).

Post-Sortie Data Downlink Downlink of DPP data after a sortie using ISS external wireless (primary), SPDM analog video (secondary), or ELC Ethernet (if Dextre Pointing Bus is on its Dock on

ELC). Operations consist of commands sent from the GSFC Satellite Servicing Control Center to the DPP Bus via either ELC or the MSS 1553.

The DPP operations team intends to operate during as many rendezvous and deploy events as possible. A notional timeline based on current ISS rendezvous and deploy information is provided in Figure 13. It is clear that there are ample opportunities to observe vehicles rendezvousing and departing ISS to meet DPP goals. The DPP AR&D sensor suite is experimental, and the more iterations it is given to take data, have that data be analyzed on the ground, and then have improvements made to the on-board algorithms, the more mature the system will become for future AR&D missions.

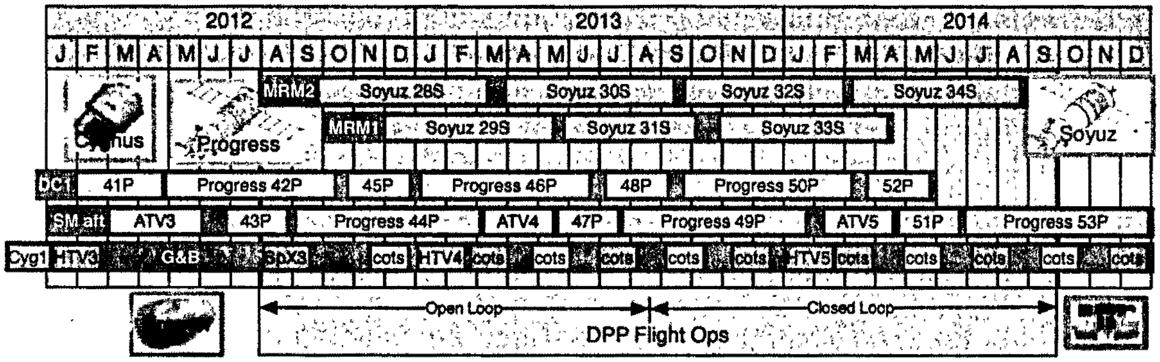


Figure 13. **Notional rendezvous and deploy events during DPP operations (boxes represent notional, not official, docking and undocking events)**

AUTONOMOUS RENDEZVOUS & DOCKING (AR&D) INSTRUMENTS

As described in the *Dextre Pointing Package* section of this paper, DPP has been designed to support interchangeable instruments, and will be launched with an Autonomous Rendezvous and Docking (AR&D) payload as its first instrument. The DPP AR&D Instrument consists of several active and passive sensors, including wide and narrow field of view cameras (2), an Infrared (IR) camera, a scanning LiDAR, and a flash LiDAR. Additionally, several AR&D algorithms will be hosted on DPP's Xilinx Virtex-4 based SpaceCube processor, including optical and LiDAR pose algorithms and a 6-DOF relative navigation filter. The AR&D Instrument will also contain a wireless box to augment communications between DPP and the ISS for increased data downlink capability.

As previously mentioned, the ISS provides a superb environment for testing and refining AR&D sensors and algorithms. The most challenging aspects of AR&D sensing and pose estimation (and also the most challenging to test on the ground) include, in particular: 1) full 6-DOF motion; 2) high-dynamic-range lighting and the effects of target geometries and surface properties on sensor and algorithm performance; 3) full performance in the relevant vacuum and thermal environment; and 4) implementation of the algorithms on a sufficiently radiation-tolerant processor (and execution in the radiation environment).

To test an AR&D sensor at the full extent of the motion, we require 6-DOF motion over several kilometers range, and nearly 4π steradians attitude variation. If we can limit the attitude variation for close range (less than about 25 meters) testing, we can make testing in a lab feasible (for example with a target model mounted to a robot arm). Testing at longer ranges is clearly more challenging due to the physical limits of typical lab spaces. To increase available space, we can push our testing outdoors and replace robot-manipulated targets with aircraft-carried targets, but clearly several other problems present themselves.

Whether our required trajectory fits into a lab space or not, lighting is an even more significant challenge (especially for adequate testing of camera AGC algorithms). While expensive lighting apparatus can do a fair job of simulating light from the Sun,[11] proper simulation of reflected light (including Earth albedo or light reflected off the servicing vehicle) is prohibitive enough to drive the system design away from its intended goal of "test-as-you-fly". Furthermore, while lab walls and floors are often painted with non-reflective black paint, direct reflection of light from a solar simulator or active illuminator off of these surfaces provides a substantial noise source for both 2D (optical) and 3D (time-of-flight) detectors.

Fortunately the ISS provides an excellent environment for testing the relative navigation sensor systems *with all of the challenging physical phenomena occurring simultaneously.* As shown in the notional schedule in Figure 13, nearly 50 rendezvous and deploy events will occur during DPP orbital operations. These events will provide relevant targets in full 6-DOF motion in a variety of on-orbit lighting conditions, for six different types of vehicles. DPP operations will also take advantage of ISS structure and DPP Dock hardware as targets of opportunity to test pose and filtering algorithms. This will further expand the variety of lighting, surface property, and background clutter while demonstrating the full system operation in the relevant thermal, vacuum, and radiation environment. For these reasons, the DPP AR&D Instrument is clearly a valuable near-term flight test of the critical Servicing AR&D System.[1]

Recent (and upcoming) sensor DTOs,[8,9] including the DragonEye DTO on STS-127 and the upcoming STORRM DTO on STS-134, are extremely important but suffer from one or more of the following issues: 1) short operational times and reduced exposure to a relevant environment; 2) not directly applicable to AR&D with a non-cooperative target; 3) no on-board processing of vision data; 4) no on-board updates in response to lessons learned. The following paragraphs expand on each of these issues.

1. Each prior DTO has one rendezvous and one deploy sequence (two of each for the VNS STORRM DTO), for a total of only a few hours of operating time in the space environment. Obviously this is better than no time in the space environment, but severely limits exposure to several critical effects, including effects of micro-gravity, radiation, lighting, and target geometries and surface properties. The combination of these effects are virtually impossible to simulate on Earth. DPP provides hundreds of hours of operating time by operating during many of the approximately 50 rendezvous and deploy events (at least six different vehicles) in its 2 year life, and a wide variety of other ISS-fixed targets of opportunity.

2. The VNS DTO (STORRM) takes full advantage of the fact that ISS is a cooperative target: the VNS will image reflectors on PMA2. Non-cooperative vehicles are the primary near-term customer of Satellite Servicing. Experience imaging ISS visiting vehicles (a wide variety of targets) as surrogates for non-cooperative servicing client satellites will be extremely advantageous.

3. DPP is not just a sensor DTO , it is an AR&D system DTO including sensors, pose algorithms, relative navigation filters, and closed-loop control. Unlike Orion, which performs

close-in relative navigation by imaging a single, known, reflective target array, DPP, and future servicing vehicles, will need to perform pose relative to skin features of a new target every few weeks. An on-board testbed on DPP provides an excellent environment to develop and test the following critical process: 1) model target using ground imagery and models; 2) train pose algorithms on target; 3) perform real-time, on-board pose estimation, and get it right the first time.

4. With the exception of TriDAR, which will have had three flights to ISS (STS-128, -131, -135), there will be little or no opportunity to apply lessons learned on the DTOs or re-test in the space environment. The DPP testbed will be reconfigurable on orbit for testing of multiple pose, robotic machine vision, camera and LiDAR gain control and windowing algorithms, and will allow update of these algorithms, sensor software and firmware in response to lessons learned.

Sensor Hardware

As mentioned earlier, the AR&D payload consists of many relative navigation sensors, each using a different sensing technology. Such a diverse group of sensors allows DPP to contrast and compare the output of each against the different phases of the approach trajectory.

Triangulation and Time-of-Flight Lidar (TriDAR) Having roots in the Laser Camera System (LCS) used to perform on-orbit inspections of Orbiter heat tiles, the Neptec TriDAR is one of the most mature relative navigation sensors available. The TriDAR is a scanning LiDAR that uses two different lasers for its measurements: a short-range triangulation unit and a long-range time-of-flight unit. Having this dual-sensing capability, the TriDAR is able to independently optimize over both near- and far-field operations. Additionally, Neptec incorporates a Commercial Off-The-Shelf (COTS) IR camera into the TriDAR system, allowing for three independent and simultaneous measurements. Funding to include TriDAR in the DPP was provided by CSA.

In 3D mode, using either the triangulation or time-of-flight technique, the TriDAR is able to scan the scene in a variety of *waveforms*—optimized scan patterns of the field-of-regard—that allow the unit to cover a representative portion of the scene as fast as possible. The waveform point cloud is then autonomously fit to an on-board model of the target in order to determine the relative pose. While varying TriDAR's scan patterns allow it to vastly increase its measurement rate over a subset of it's field-of-regard, the TriDAR does provide a mode to scan the scene in a rectilinear pattern to produce a more visually appealing, i.e. pixelated, 3D image. Figure 14 contains such an image collected from the STS-128 DTO,[9] which is the same unit that will fly on DPP.

In 2D mode, the TriDAR relies on images captured by the IR camera. Results from the recent DTOs show that the IR camera can acquire the ISS from 2 km and further. As a result, the TriDAR will provide long-range bearing (range and bearing) information to the user, as well as use the IR data to seed the 3D calculations outlined above. Neptec is also working on algorithms to calculate 3D relative pose using the IR images only. Figure 14 also contains an example IR image taken from the same DTO.

Even though it has many operational hours in space, the TriDAR was not designed for long-duration space operations. The normal time-span of a TriDAR DTO is on the order of 14 days with the unit powered for 2-3 hours during rendezvous and departure. For DPP, the TriDAR will be on-orbit for two years and be operational for stretches of five hours at a time. The DPP team will need to be aware of these constraints when using the unit. Some of these limitations were removed when

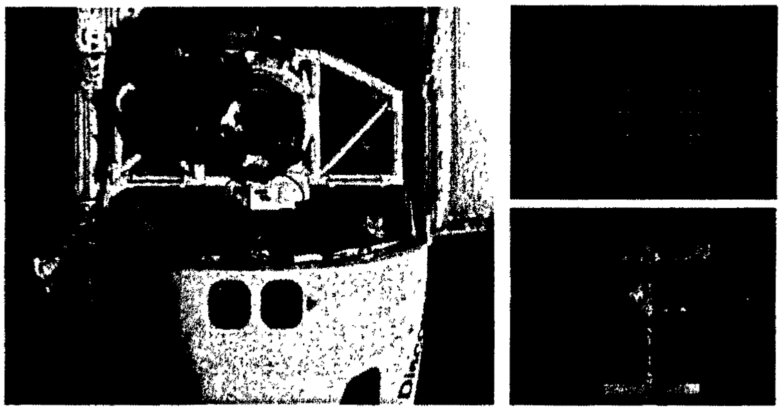


Figure 14. TriDAR on STS-128 (left) and range (top right) and IR (bottom right) imagery from that mission

Neptec performed hardware and software modifications to the STS-128 unit. The primary changes were done to allow the unit to operate longer in the challenging thermal environment. In addition, the DPP unit will have upgraded software to allow on-orbit software and firmware uploads to the unit using the bandwidth-limited ISS infrastructure.

Vision Navigation System (VNS) The VNS, shown in Figure 15, was designed and built to be the primary relative navigation sensor for the Orion Crew Exploration Vehicle. Instead of scanning the scene with a single beam, the VNS flashes the scene once and then collects multiple returns via a pixelated detector. The raw data collected from each pixel of the 256 × 256 detector includes both time-of-flight and return intensity, which allows algorithm developers to utilize both 2D and 3D methods in computing a relative pose. Like the TriDAR, the VNS will take part in on-orbit testing as part of the Sensor Test for Orion Rel-Nav Risk Mitigation (STORRM) DTO on STS-134.

As designed, the VNS operates in a cooperative environment, that is, the vehicle targets have sensor targets which are specifically designed to work with the VNS wavelengths. Specifically, the sensor target is a black-and-white rhombus-like panel with 1-inch diameter retro-reflectors attached. The returns of each retro-reflector appear in the raw image as bright range and bearing centroids. An embedded processor autonomously scans the raw image, acquires these centroids, and computes the relative pose using an on-board model of the retroreflector pattern. If the pattern is asymmetrical, then the returned pose solution is unique. For the VNS target, a retroreflector on a 12-inch tower extending from the middle of the panel gives the necessary measurement in the third dimension.

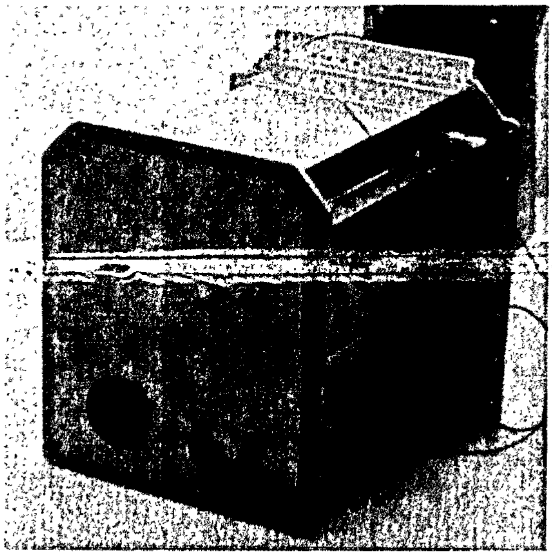


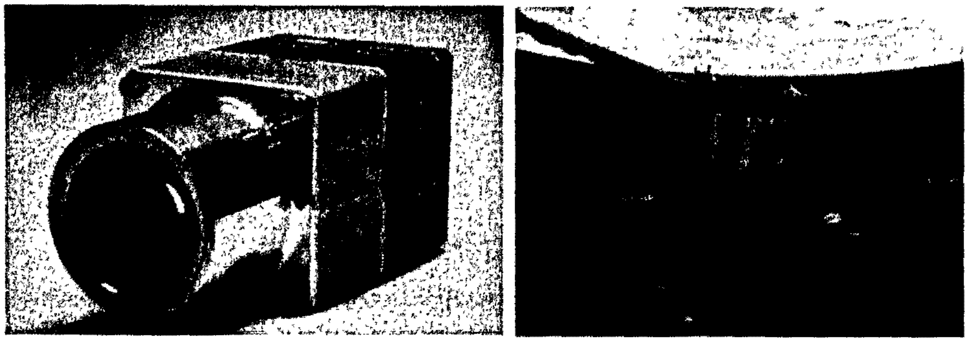
Figure 15. Photo of the STORRM VNS unit

The operational plan for DPP, however, does not assume that any target vehicle will have a

VNS target attached. In fact, only while imaging a visiting Orion Module, or in the special case where DPP is imaging the PMA2 docking port during a simulated Orion rendezvous, will VNS be used cooperatively. Instead DPP developers are writing new, non-cooperative, skin-based pose algorithms which are briefly discussed in the following sections.

Unlike the TriDAR, the VNS was designed for long-duration missions from the onset. The electrical design is fully compatible with the space environment including radiation effects. The mechanical design is in compliance with all the manned space flight requirements levied by the Agency. The specific unit to be flown was funded through a multi-party arrangement that includes the Orion Project, Lockheed Martin, Ball Aerospace, the Constellation Program, and the NASA Engineering and Safety Center (NESC).

MDA Cameras Built by MDA, the optical cameras in DPP provide additional, passive measurements. The 1 MPixel cameras, shown in Figure 16, are hardware from the HST SM4 RNS experiment where they successfully captured the images used to compute a real-time, on-board pose solution to HST.[8] One camera is included in the DPP bus, and one is included in the AR&D instrument. Being built specifically for the RNS experiment, the MDA cameras are fully qualified and rated for space.



(a) Flight MDA Camera (b) On the MULE during STS-125 (SM4)

Figure 16. Photos of the MDA Cameras as used on HST SM4

In a similar fashion to the RNS experiment, the DPP cameras will have fixed-focus lenses. The bus-side camera, with an 11°field-of-view and a depth of focus of 28–260 m, provides the narrow field-of-view ideal for long-range operations. In contrast, the instrument-side camera has a wider field-of-view of 56.5°and a wider depth-of-field of 1–inf m that DPP will use as a *target search* camera. Both cameras, along with the LiDARs above, will be co-boresighted.

Algorithms

Pose The intent of the DPP mission is not only to demonstrate AR&D sensor measurements, but to also demonstrate AR&D algorithms that process those measurements. Of the three sensor types, the visual cameras and scanning LiDAR have mature algorithms to return 6-DOF pose measurements. The flash LiDAR sensor processing is the least developed as the sensor has not had a DTO, nor has any pose algorithm been tested on-orbit that utilizes flash LiDAR measurements.

To process the visual camera data, the GNFIR algorithm that flew on HST SM4 will be utilized to return a pose measurement. The results from the HST SM4 mission, documented in Ref. 8, show success in tracking HST during the rendezvous and deploy sequences, but the quantification of success was difficult due to the lack of an accurate truth estimate of the relative position.

Figure 17. GNFIR Algorithm of RNS Camera

The GNFIR 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 17. The GNFIR algorithm is built upon the foundation of feature tracking described in Ref. 13. The algorithm will be enhanced for DPP to include a more general acquisition strategy to support multiple targets, additional acceleration of the algorithm by moving processing to the FPGA, communication with the camera's active gain control algorithm to window a specific portion of the camera field-of-view, an increase of the frame rate to 6Hz, and the use of a range seed from the LiDAR sensors.

The scanning LiDAR, TriDAR, will utilize algorithms developed and matured from various DTOs,[9] with a slight modification to output range information to be used by GNFIR. The majority of its data will be compressed and telemetred to the DPP ground system for later analysis. The hardware and algorithms are provided by Neptec, Inc.

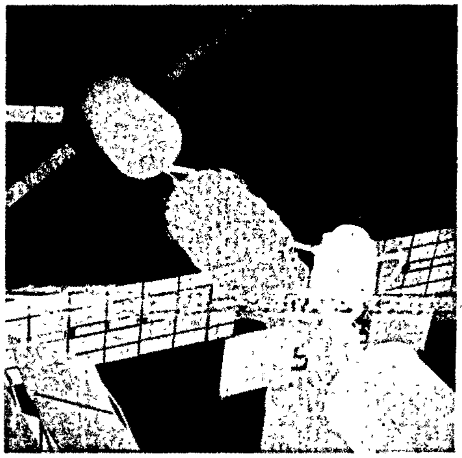


Figure 18. Flash Lidar Simulation

The flash LiDAR sensor, VNS ADRE, will have its data taken in by the SpaceCube, giving the DPP software the opportunity to process the data measurements in real-time, determine a pose measurement, and perhaps use the pose measurement in a control algorithm or filter. The algorithm will be processing range measurements, similar to that shown in Figure 18, which is of ATV docking at the DC1 port of ISS. This image does not account for laser measurements that never return to the sensor or material reflections, but these enhancements will be incorporated into the flash LiDAR measurement simulation. The algorithm to process flash LiDAR information can be as varied to matching points and minimizing error, to extracting features from the range and intensity information and matching those features to a model, similar to GNFIR.

Relative Navigation Filter (RNF) The filter currently under development for DPP produces estimates of the full 6-DOF relative states of approaching ISS visiting vehicles. An Extended Kalman Filter (EKF) will be employed for the relative position and velocity, while an MEKF will be used to estimate the relative attitude quaternion and attitude rates. At far distances, when neither range nor pose measurements are available, the filter will perform angles-only processing of bearing measurements from the cameras to estimate relative position and velocity, but relative attitude will not be estimated. When the vehicle is close enough for range measurements to be gathered, they will be processed along with the bearing angle measurements (though relative attitude will remain unavailable). Finally, once the vehicle is close enough for pose measurements to be collected ($\approx$ 300 m or less, according to current estimates), relative position, relative velocity, relative attitude, and relative attitude rates will all be estimated by the RNF using the pose measurements.

The output of the RNF will be the relative position and velocity of the visiting vehicle in the LVLH frame of the ISS, along with the attitude and attitude rates of the vehicle with respect to the J2000 inertial frame. Figure 19 depicts the kinematic chain which transforms the pose measurements for processing in the RNF. Internally, the filter utilizes the Clohessy-Wiltshire (CW) equations of relative spacecraft motion, which should provide sufficient accuracy at reduced computational cost due to the nearly circular orbit of the ISS and the small time steps taken by the RNF.

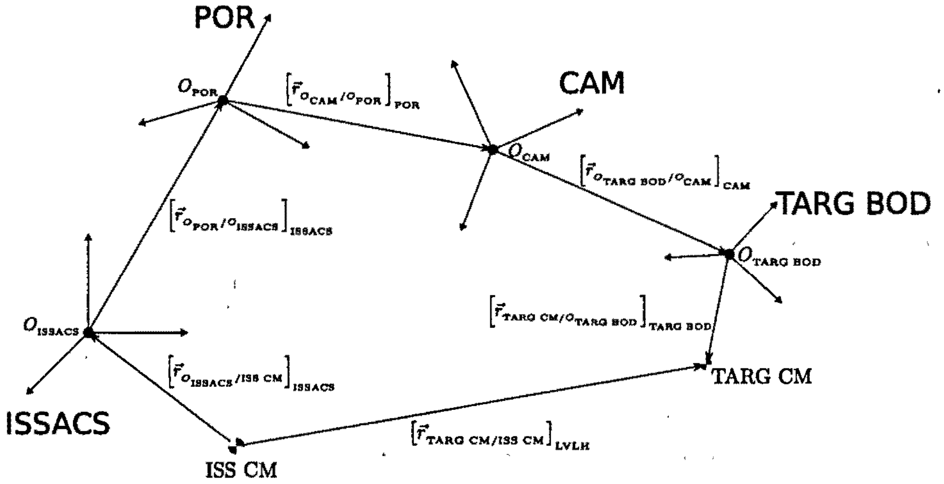


Figure 19. Kinematic Chain for Relative Navigation Measurements

In addition to estimating the relative position and velocity of the incoming vehicle, the RNF also estimates any thrust acceleration that the incoming vehicle may be experiencing due to maneuvers. This precludes the need to know the vehicle's maneuver plans in advance and makes DPP that much more robust by virtue of independence. In particular, this ability will be important during future AR&D activities for various servicing mission profiles in which information about the customer vehicle may be lacking. The RNF models incoming vehicle thruster acceleration as a first order Gauss-Markov process, and tuning the associated time constant is a current area of research.

Relative attitude and angular rate processing in the filter is completely separate and decoupled from the relative position and velocity processing. The relative attitude quaternion portions of the pose measurements are processed by the RNF using an MEKF formulation based on the mathematical specifications presented by Markley.[12] An MEKF formulation was chosen to allow for a nonlinear propagation of the attitude quaternion while computing a three-component attitude error estimate. The MEKF state is comprised of the relative attitude of the target vehicle body frame with respect to the inertial frame, the angular rate of the target vehicle body frame with respect to the inertial frame, and a constant pose attitude measurement bias. Rigid body dynamics are used to calculate the angular acceleration of the target vehicle. Assuming small filter step sizes, the state and process noise transition matrices are calculated using the angular acceleration and finite differencing.

Pose measurements provide the relative attitude quaternion of the target vehicle body frame with respect to the DPP camera frame. The relative attitude pose measurements are rotated into the inertial frame using information from the DPP attitude filter before processing in the relative attitude MEKF. As suggested by Markley,[12] the attitude error is parametrized using the Gibbs vector formulation. Depending on the filter mode of operation, measurements can be edited if the corresponding residual falls outside of a user-defined sigma-threshold. Following the state estimate and covariance measurement, the global target body attitude quaternion is updated and the MEKF state is reset to zero.

CONCLUSION

In the final analysis, the DPP mission is critical to moving forward the AR&D technology for the Agency. The suite of hardware DPP proposes to demonstrate, from the visual cameras, the TriDAR, the VNS, to the star tracker, IMU and SpaceCube, are all new technologies that will push the envelope of current sensor technology. In addition to demonstrating new sensors, the DPP aims to demonstrate closed-loop control using these sensor measurements refined with pose algorithms and Kalman filters to achieve the accuracy requirements of a servicing mission. The DPP hardware will support updates to flight software, which is a critical element in developing algorithms and sensor processing that can meet AR&D mission objectives. The modularity being built into the DPP hardware will allow for the inclusion and cooperation of many researchers, including those with AR&D interests, to those with Earth and Stellar observing interests.

Future/Ongoing Work

The future for DPP will include incorporating the TriDAR and VNS sensors into the AR&D instrument and developing the firmware that will read their telemetry streams, store their data for transmit to the ground, and use the measurements in pose algorithms executed in the Spacecube. These sensors are set to be delivered by April 2011, with the star tracker already having been delivered. SpaceCube hardware and software development has been ongoing under the DPP project since its inception. Development work continues on these fronts, as does the development of the architecture, robotics and sensor hardware for a future satellite servicing mission.

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