ULTOR® Passive Pose and Position Engine
For Spacecraft Relative Navigation

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ABSTRACT

The ULTOR® Passive Pose and Position Engine (P3E) technology, developed by Advanced Optical Systems, Inc (AOS), uses real-time image correlation to provide relative position and pose data for spacecraft guidance, navigation, and control. Potential data sources include a wide variety of sensors, including visible and infrared cameras. ULTOR® P3E has been demonstrated on a number of host processing platforms.

NASA is integrating ULTOR® P3E into its Relative Navigation System (RNS), which is being developed for the upcoming Hubble Space Telescope (HST) Servicing Mission 4 (SM4). During SM4 ULTOR® P3E will perform real-time pose and position measurements during both the approach and departure phases of the mission. This paper describes the RNS implementation of ULTOR® P3E, and presents results from NASA's hardware-in-the-loop simulation testing against the HST mockup.

Keywords: rendezvous and docking, correlator, space sensors, AR&D, pose estimation

1. INTRODUCTION

NASA Goddard Space Flight Center (GSFC) is currently working on a Relative Navigation System (RNS) for the upcoming Hubble Space Telescope (HST) Servicing Mission 4 (SM4). Testing for the RNS system was performed at the Marshall Space Flight Center (MSFC) Flight Robotics Lab (FRL). Systems such as the RNS are designed to support the development of sensor technologies that will be required for the next servicing mission to Hubble which will more than likely be fully robotic. In addition, the RNS experiment will help define the sensors needed for relative navigation and proximity ops needed for the next generation of NASA vehicles currently under design to support the NASA Vision for Space Exploration.

The technology behind RNS is applicable to more than just SM4. Applications such as automated rendezvous and docking (AR&D) require accurate, low-latency relative navigation measurements; sensors that can provide such measurements are also useful for crewed missions. Advanced Optical Systems, Inc. (AOS) has developed such sensors, one of which -- the ULTOR® Passive Pose and Position Engine (P3E) -- is part of RNS.

The RNS system consists of cameras, high capacity storage media and a high processing bandwidth hardware platform, and will be installed in the shuttle payload bay. The hardware platform will host algorithms including ULTOR® P3E that will process image data from the RNS cameras and perform real time measurements of the relative attitude and position between the shuttle and the HST.

AOS developed ULTOR® technology to support Department of Defense missile-based automatic target recognition (ATR) needs. ULTOR® for ATR has two key attributes that enabled AOS to extend ULTOR® to pose estimation for relative navigation applications. The first attribute is its ability to detect and locate targets in an image. The second is its ability to do so at real-time rates and with low latency. These characteristics allowed AOS to develop the ULTOR® P3E system to provide full six-degree-of-freedom (6DOF) information of a target. The ability of ULTOR® P3E to measure

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an object's attitude and position in real time is an enabling technology for Automated Rendezvous and Docking (AR&D), a needed capability to support NASA's Vision for Space Exploration.

This paper describes the results of two phases of testing performed at the MSFC FRL facility in 2007. During both phases, ULTOR® P3E successfully performed pose estimation on mockups of the HST. We present both the results and an overview of the preparations for the final flight build of ULTOR® P3E for RNS. We present data from both RNS Phase II testing in April 2007 and RNS Phase III testing from November/December 2007. Analysis of the testing at the FRL shows that ULTOR® P3E performed well within the specifications required for SM4 with a translation RMS error of less than 0.1 meters and a rotational RMS error of less than 1.6 degrees.

2. ULTOR® P3E SYSTEM FOR RNS

AOS designed ULTOR® P3E to be both reconfigurable and portable. It therefore can be hosted on a large number of hardware platforms. ULTOR® P3E combines a firmware (VHDL) based high speed image processing engine with real-time software algorithms that produce 6DOF information from the processed image data. To date, the ULTOR® P3E system has been successfully ported to five different processing platforms, including the SpaceCube platform for RNS. This flexibility in design allowed us to integrate several RNS external interfaces including:
- Integration of custom firmware to receive image data from the specific RNS camera
- Integration of command and control interfaces to other RNS flight subsystems
- RNS specific software algorithms for the HST target

During SM4, ULTOR® P3E will identify and locate a number of features in the field of view of the RNS camera(s). Using a digital correlation image processing technique, ULTOR® P3E will measure the position of specific HST features in the camera field of view. As shown in Figure 1, the feature positions are then input into an N-point perspective algorithm. This algorithm processes the measured spatial relationship between the features and compares them to the features' known location as defined by an accurate HST mechanical model. The output is a 6DOF solution for the target that will then be translated into quaternion data suitable for relative navigation and control applications.
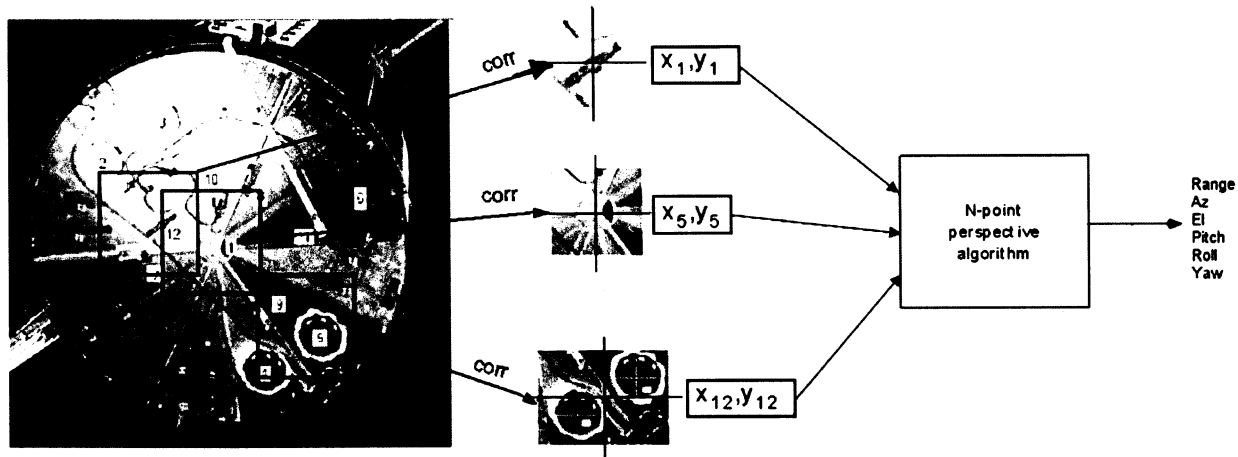

Figure 1. Feature based P3E overview.

For SM4, ULTOR® P3E will not be provided any *a priori* knowledge of the relative attitude and position between the shuttle and the HST. Therefore, ULTOR® P3E system will need to acquire, track and re-acquire the HST autonomously. ULTOR® P3E must be able to acquire the HST target from approximately 150m on approach and from approximately 5m on release. Acquisition will be accomplished by using an onboard library of HST reference filters produced from simulated imagery of the HST. ULTOR® P3E compares image data of HST features to a reference filter (or many reference filters) in real-time to determine the position of the feature. These filters are based on specific and unique features visible on the target. Such features may include handles, bundles of wires, and distinctive structural elements.[1] The filters are designed to support the full variance in the approach and release trajectories, referred to as trajectory

dispersion, expected during the SM4 mission. In acquisition mode, ULTOR® P3E will progress through a matrix of filters stored in onboard memory until the initial position and attitude of the HST are determined.

Once the HST has been acquired, ULTOR® P3E transitions into a target tracking mode and progresses through a matrix of filters associated with the measured range. For the most part, the filters are arranged in range bins or gates meaning that a set of filters is designed to perform over a certain range between the shuttle and the HST. For every range gate, the filters associated with the HST features are robust enough to measure the feature's location at any anticipated angle or position. As the Shuttle's range relative to the HST changes, ULTOR® P3E software will progress to the next appropriate range gate. This continues until the HST is no longer in the field of view--near dock and shortly after release, the HST will not be in the RNS camera field of view--or until the filters associated with a particular range gate do not provide sufficient accuracy in the measurement. In this case, ULTOR® P3E will transition into re-acquire mode.

For re-acquire, the ULTOR® P3E software will process filters in adjacent range gates to try to re-acquire the HST target. If after several tries the HST is not re-acquired, then ULTOR® P3E software will transition to full acquire mode. The usual event that would precipitate a re-acquire would be if the HST were to appear significantly different than expected or else if one of the RNS cameras stops functioning.

For RNS, the algorithms we have developed rely on high quality simulated imagery of the HST to produce robust filters. The simulated imagery must cover not only the nominal approach and release trajectories but also the expected dispersion. AOS has developed an approach to specifying, processing and testing filters generated from simulated imagery to verify accuracy, performance and insensitivity to lighting changes. These filters were tested during Phase II and Phase III testing at the FRL.

Table 1: RNS pose accuracy goals

Target Range	Lateral	Range	Roll	Yaw/Pitch
150 meters	1.0m	1.0m	15 deg	15 deg
30 meters	0.3m	0.5m	5 deg	5 deg
5 meters	0.1m	0.1m	1 deg	5 deg

The target accuracy goals for the pose algorithms to be flown on SM4 are listed in Table 1. The objective of the testing at the FRL was to measure the progress of the pose algorithms in meeting these goals. The next sections describe RNS testing and present the results from these tests.

3. RNS PHASE II TESTING

In April of 2007, the RNS system was taken to the MSFC FRL lab. A high fidelity mockup of the HST aft bulkhead was mounted on the Dynamic Overhead Target Simulator (DOTS) system at the FRL.
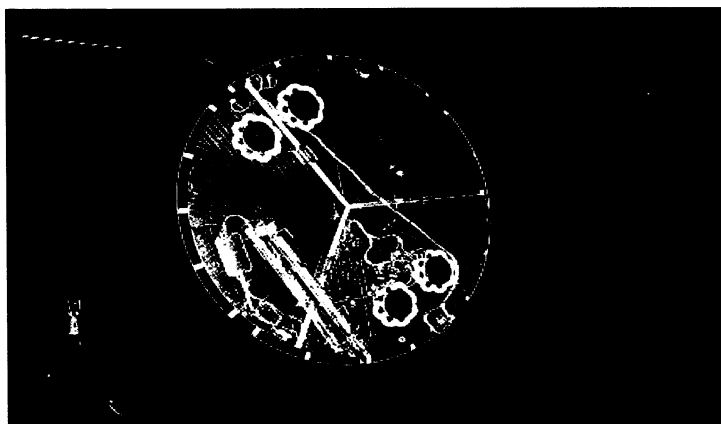

Figure 2: HST mockup mounted on DOTS at the FRL

DOTS was programmed to move the HST mockup through simulated shuttle trajectories during SM4. In addition to the HST mockup, the RNS cameras were mounted to a tower and an adjacent mockup of the shuttle payload bay lights to simulate the shuttle payload bay. The FRL also provided a solar simulator that was used to simulate the angle and intensity of the sun expected during the SM4 mission.
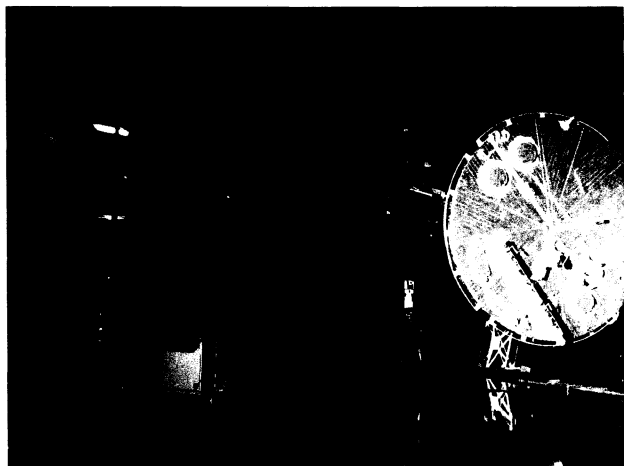

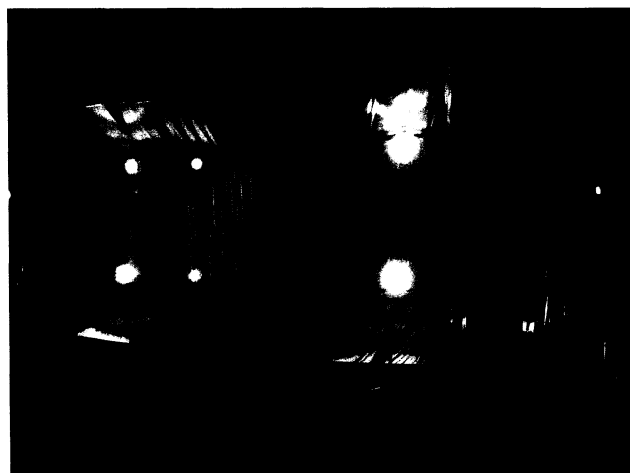Figure 3a: Solar simulator with HST mockup
tower to the right

Figure 3b: Payload bay simulator. RNS cameras on

Due to limitations in the size of the FRL, only a subset of the full SM4 approach could be simulated. Also due to space restrictions, the approach trajectory was divided up into two pieces, labeled "RBar-To-Grapple" and "Grapple-To-Berth". On SM4 the shuttle is properly aligned to the RBar axis at a range of approximately 30m from the HST. The grapple position occurs at roughly 10m. In addition to approach, two departure trajectories were planned.

ULTOR® P3E was configured to acquire and track the HST for every trajectory. Specific filters were created for each trajectory to save upload time to the SpaceCube. In flight, the filters will be uploaded from internal memory, though this capability was not available for Phase II testing. Quaternion outputs from ULTOR® P3E were sent to other SpaceCube processes for logging. In addition, a debug port for ULTOR® P3E was available and several debug parameters were displayed in real-time. The debug data was logged for later analysis.

4. RESULTS OF PHASE II TESTING

The ULTOR® P3E data was compared to truth data collected during each trajectory at the FRL. An analysis of ULTOR® P3E against specification was also performed for every trajectory. In nearly all of the trajectories, ULTOR® P3E pose measurements exhibited a constant bias error in range and the pose angles, as shown in Figures 4 and 5.

We performed a thorough study of the ULTOR® P3E data and the truth data to determine the source of the errors. The range error was due to an inaccurate focal length parameter for one of the RNS cameras. Since ULTOR® P3E produced pose by measuring the spatial relationships between features, not using the correct focal length produces a scale error in range. The source of the roll and yaw error was determined to be misinterpretation of a transform between the ULTOR® P3E pose data's coordinate frame and that of the FRL truth data. Once this was corrected, the image data was re-processed through ULTOR® P3E in SpaceCube hardware. These results are shown in Figures 4 and 5.
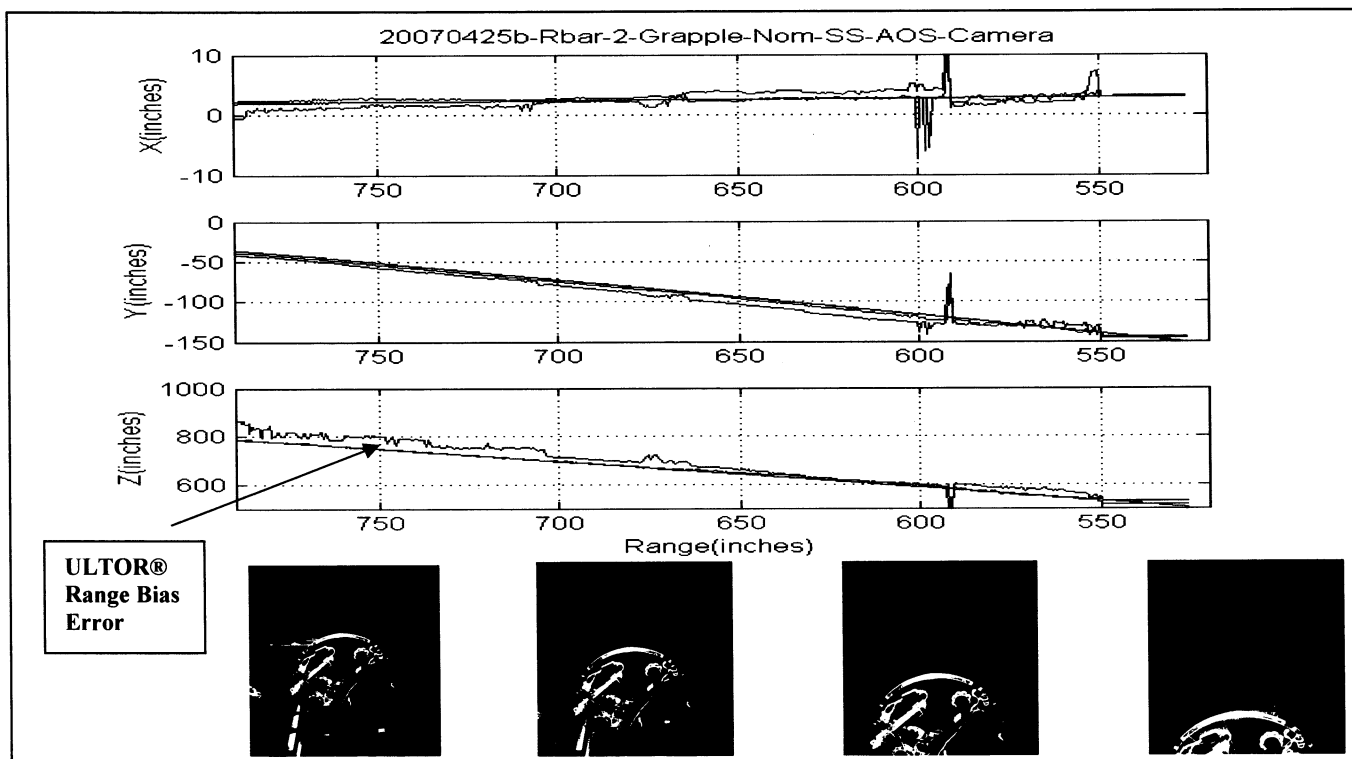
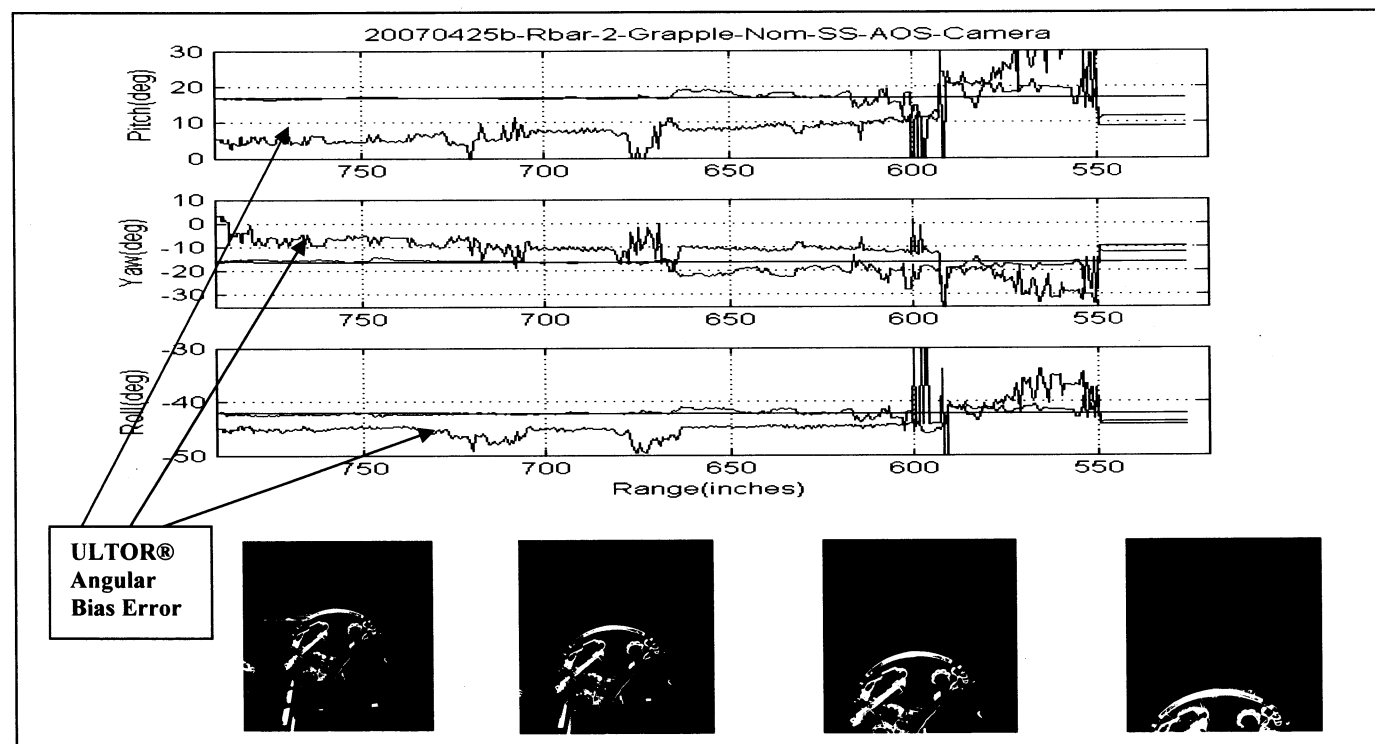Figure 4: Results from RBar-To-Grapple trajectory of x, y and z

Figure 5: Results from RBar-To-Grapple trajectory of roll, pitch and yaw

During Phase II testing, a NASA Automatic Gain Control (AGC) algorithm was tested in SpaceCube. It was intended to continuously modify the RNS camera's exposure and gain to provide reasonable illumination of the HST target. This meant that the AGC would try to keep image pixels from the RNS camera out of saturation and out of total darkness. A study of the AGC performance during Phase II testing revealed that the AGC was too reactive to saturated pixels with the end result being loss of dynamic range as pixel values were being driven to darker gray levels. Figure 6 contains an image from Phase II testing and its associated histogram.

Count: 389372   Min: 0
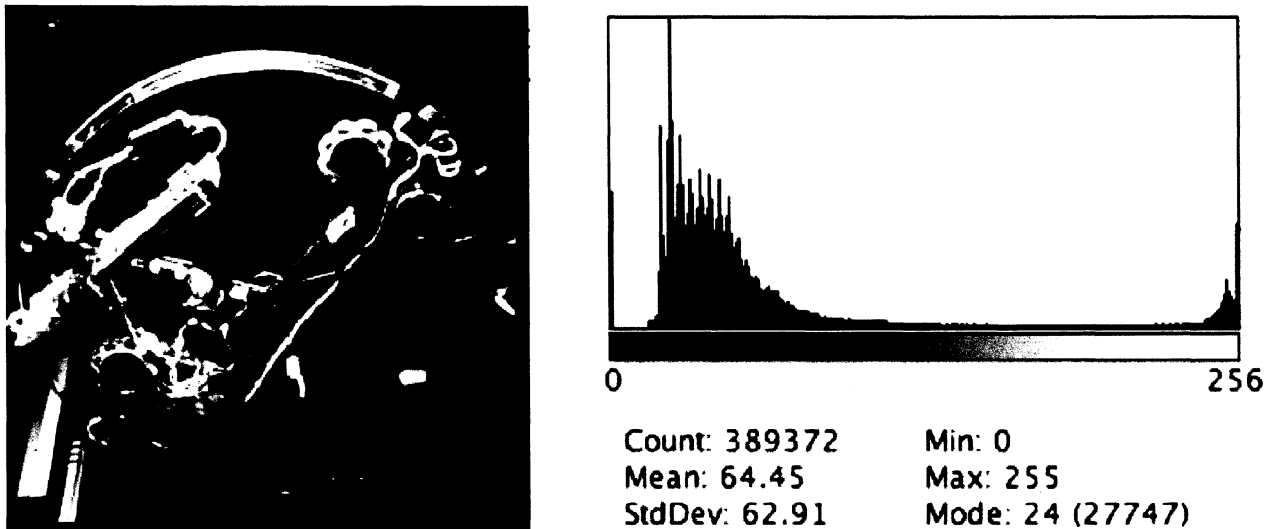Mean: 64.45   Max: 255
StdDev: 62.91   Mode: 24 (27747)

Figure 6: HST mockup image and histogram from Phase II testing

The results of Phase II data analysis revealed that ULTOR® P3E needed several improvements including more accurate camera parameters, a better understanding of the coordinate transform process and robustness to lighting changes. Table 2 shows the RMS error for RBar-To-Grapple trajectory data collected during Phase II testing.

Table 2: ULTOR® P3E RMS error from RBar-To-Grapple trajectory during Phase II testing

	RBar-To-Grapple Trajectory
X Error	0.08m RMS
Y Error	0.10m RMS
Z Error	0.51m RMS
Roll Error	10 deg RMS
Pitch Error	4 deg RMS
Yaw Error	15 deg RMS

5. RNS PHASE III TESTING

A thorough characterization of the RNS cameras provided more accurate measurements of key camera parameters such as focal length, dynamic range and sensitivity. AOS provided input to the RNS group developing the improved AGC algorithm for Phase III and for flight. It was determined the AGC algorithm would be re-designed to maximize the information content in the imagery. It was anticipated that the extreme reaction to saturated pixels would be lessened, thus producing images with better contrast.

In addition, we integrated new image pre-processing algorithms into the ULTOR® P3E firmware to improve the effective dynamic range of the image data. This included both a contrast stretching algorithm and a common photographic edge enhancement technique called un-sharp mask. The contrast stretching algorithm allows for a specified number of pixels above a high pixel value threshold and a low pixel value threshold. Then all remaining pixel values are re-binned into values between 0 and 256 since the RNS camera image data has 8 bits per pixel. This in effect stretches

the contrast. As long as the new AGC would not eliminate the dynamic range by suppressing lower grey scale pixel values, the ULTOR® P3E pre-processing algorithms design would maximize the contrast and enhance the edges of the imagery, which in turn would improve the system's performance. Both techniques have been successfully implemented in earlier versions of the ULTOR® system.

As in Phase II testing, the HST mockup was mounted to DOTS, the payload bay light simulator was re-constructed and the solar simulator was used to provide the lighting anticipated on SM4. Since Phase III testing was the last chance for extensive testing before the SM4 flight, it included many more trajectories including a 1/10th scale mockup of the HST to simulate long range trajectories (out to 200 meters).

6. RESULTS OF PHASE III TESTING

Since Phase III was the most extensive test to be performed prior to flight, ULTOR® P3E software and firmware were configured for flight in many respects. The Phase III ULTOR® P3E build included the ability to support auto-loading of filters from flash memory using an external processor. We also developed a single compressed filter set to cover the full approach trajectories. In Phase II testing, we had a single uncompressed filter set for each trajectory. The filters for Phase III testing were designed to perform over a wider dispersion. Phase III testing included several different trajectories including:

- RBar-To-Grapple
- Grapple-To-Berth
- 1/10 Scale Initial Approach
- 1/10 Scale Near RBar Approach
- Full Scale Near RBar Approach
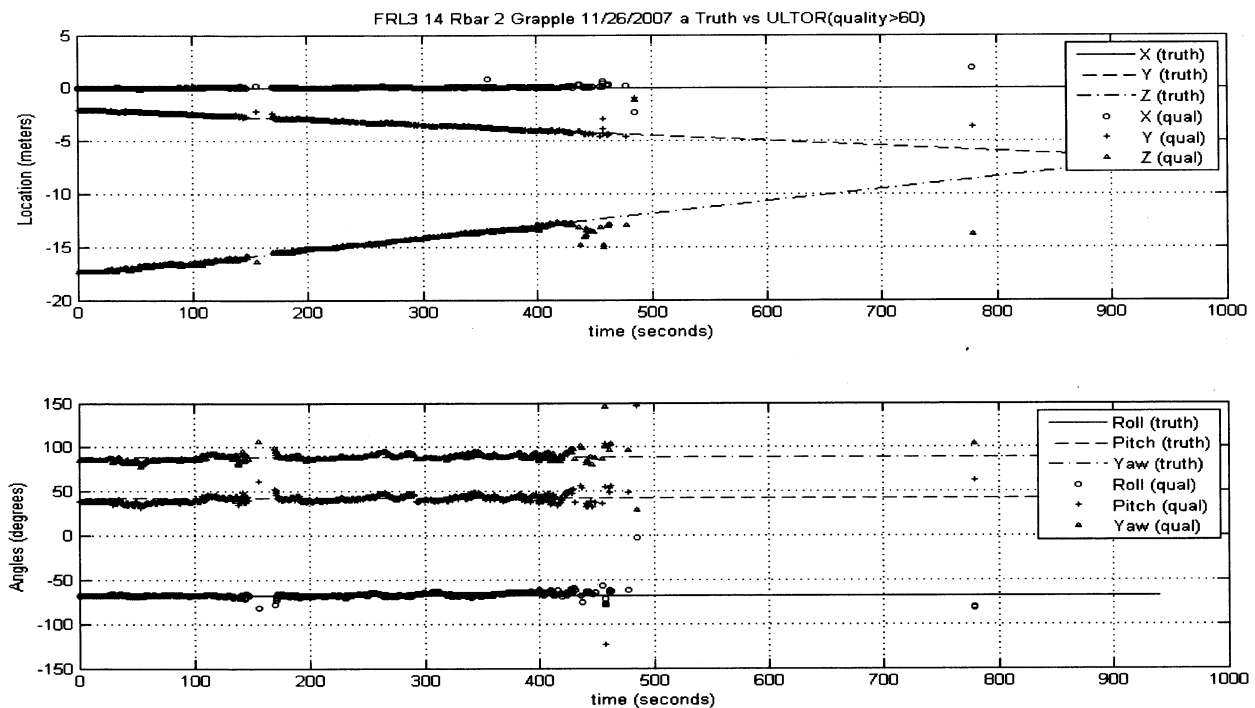- HST Release
- Simulated "SM5" approach trajectories

Figure 7: ULTOR® P3E results versus truth for one run during Phase III testing. HST leaves field of view after 450 sec.

The contrast stretching and un-sharp mask algorithms consistently provided quality imagery to the ULTOR® P3E processing imagery and the accuracy of the system improved over Phase II. In addition, the new AGC algorithm provided images with much improved range as compared to those in Phase II. Several of the trajectories were run multiple times to tweak the AGC parameters as well as to compare runs with and without the solar simulator. ULTOR® P3E was able to successfully perform pose estimation regardless of the lighting conditions.
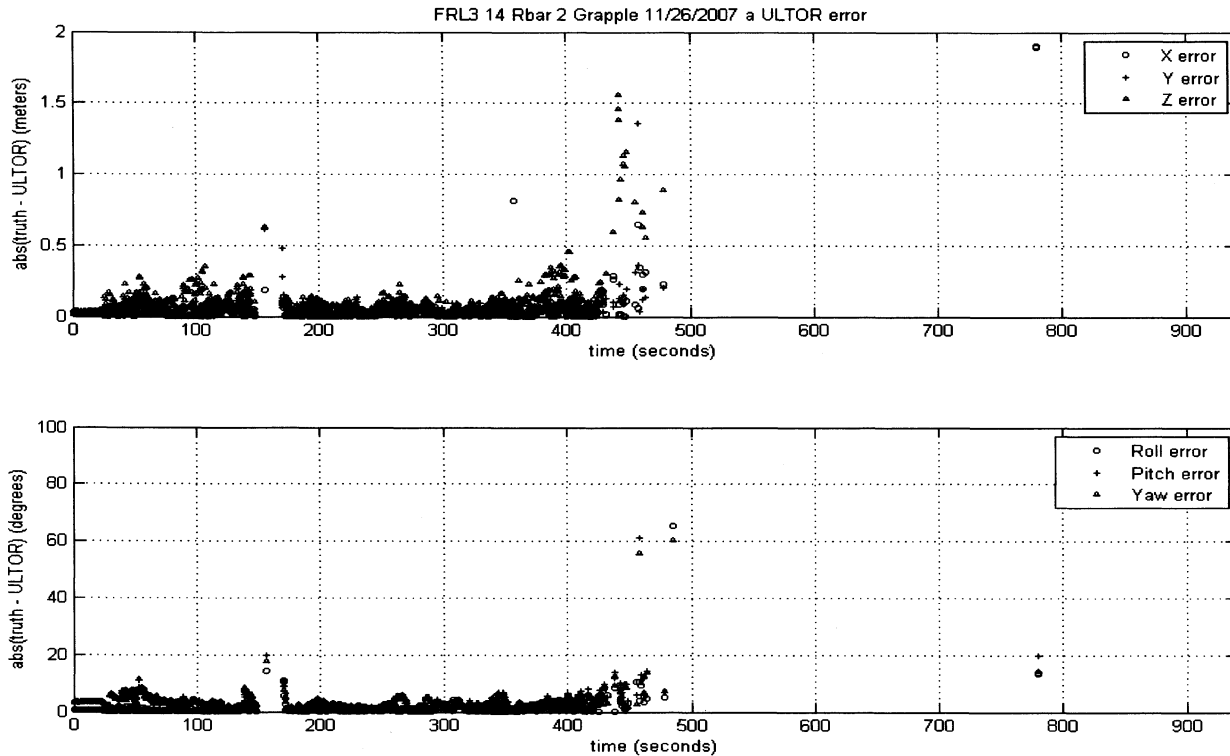

Figure 8: ULTOR® P3E position and angular error RBar-To-Grapple Trajectory. HST leaves field of view after 450 sec.

Figure 7 shows the data from a Phase III RBar-To-Grapple trajectory run. The plots compare ULTOR® P3E performance to FRL truth data. A pose quality factor was implemented in ULTOR® P3E software for Phase III testing. It was based on a number of parameters including the number of identified features, the "goodness" of correlation for each feature and the computational time required to derive a pose solution. Only data with a pose quality factor of 60 (out of 256) or higher is shown.

Table 3: ULTOR® P3E RMS error from RBar-To-Grapple trajectory during Phase III testing

	RBar-To-Grapple Trajectory
X Error	0.08m RMS
Y Error	0.08m RMS
Z Error	0.09m RMS
Roll Error	.42 deg RMS
Pitch Error	1.23deg RMS
Yaw Error	1.53 deg RMS

The error plot for ULTOR® P3E versus truth for the RBar-To-Grapple trajectory is shown in Figure 8. In both Figures 7 and 8, the measurement becomes less accurate around 450 seconds as the HST mockup leaves the field of view of the RNS camera. The plots also show that the "bias" errors due to focal length and transform errors were corrected in Phase III testing. Table 3 shows the RMS error for the RBar-To-Grapple trajectory. This data shows that ULTOR® P3E

performance has improved significantly since Phase II testing. The angular RMS error was reduced by nearly an order of magnitude. The Z (range) RMS error was reduced to just 20% of its Phase II value.

7. ULTOR® P3E PATH TO FLIGHT

With the completion of Phase III testing, focus was placed on making final changes to ULTOR® P3E to support the SM4 flight. These improvements will include filters that include additional features on the HST that were not present on the HST mockup during Phase II and Phase III testing.

New training imagery will be produced and processed into filter data to support the full dispersions for SM4 which are shown in Table 4. These wide dispersions were not required for Phase II or Phase III testing due to FRL and DOTS limitations of movement. In addition to new filters, several algorithm changes will be made to support the wider dispersion.

Table 4: Anticipated angular dispersion of trajectory during SM4

	Pre-Grapple	Post Grapple	Departure
Roll	+- 20 degrees	+/- 5 degrees	+/- 3 degrees
Pitch	+/- 20 degrees	+/- 5 degrees	+/- 3 degrees

A new acquisition algorithm will be developed to minimize the amount of time needed to identify the position and attitude of the HST target. With the increased number of filters due to the wide angular dispersion, an algorithm other than "brute force" will be required to acquire. A vector based search algorithm will be developed and integrated into ULTOR® P3E software that will reduce the time for acquisition.

8. CONCLUSIONS

ULTOR® P3E has consistently shown that it can provide real-time, low latency pose measurements that meet the system requirements for a number of Department Of Defense and space related hardware platforms. It has been tested in multiple hardware-in the-loop facilities including the FRL for RNS. The ability to perform pose estimation using passive optical sensors will be needed to support NASA's Vision for Space Exploration.

During RNS Phase II and Phase III testing, AOS has adapted ULTOR® P3E to meet the unique requirements of the SM4 mission and continuously improved its performance throughout the program. The ULTOR® P3E system has demonstrated flexibility in supporting the interfaces required for integration into the RNS hardware. Phase II and Phase III testing has confirmed that ULTOR® P3E can meet or exceed the specification for pose estimation on SM4.

With the completion of Phase III testing, focus will be placed on the flight ULTOR® P3E build that will provide for a successful SM4 and RNS mission in late 2008. The techniques and algorithms developed during RNS will position ULTOR® P3E to support the next generation of space vehicles, such as the ORION, with key relative navigation sensor technology.

ACKNOWLEDGEMENTS

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[1] Balch, M., Tandy D., "A pose and position measurement system for the Hubble Space Telescope servicing mission", *Proceedings of SPIE*, Howard, R.T. and Richards, R.D., vol. 6555, pp. 65550F-1 – 65550F-8, SPIE, Bellingham, WA, 2007.