TriDAR Test Results Onboard Final Shuttle Mission, Applications for Future of Non-Cooperative Autonomous Rendezvous & Docking

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This paper presents results from the final Space Shuttle test flight of the TriDAR vision system onboard Shuttle Atlantis on STS-135. The TriDAR (Triangulation + LIDAR) is a proximity operations 3D vision system for Autonomous Rendezvous and Docking (AR&D) missions to non-cooperative targets in space. The TriDAR has previously flown on STS-128 and STS-131 onboard Shuttle Discovery. The objectives of the TriDAR demonstrations were to demonstrate automatic acquisition and real-time embedded tracking of the International Space Station (ISS) without use of cooperative targets, detection and recovery from loss of tracking, and real-time navigation cues to crew. This paper details the enhancements made for this last demonstration mission to further improve performance and maturity of the technology.

1 INTRODUCTION

Traditionally, relative navigation vision systems for rendezvous and docking in space have relied on cooperative targets such as retro-reflectors installed on the spacecraft to capture [1][2]. While reliable, target based systems have operational limitations, as targets must be installed on the targeted payload. This is not always practical or even possible [3]. This approach is also inefficient, especially when active sensors are required to operate at long distances and require a wide field of view. Cooperative target based approaches typically need to acquire and process data over the entire field of view to find its targets but only use a few 3D coordinates to calculate the relative pose.

Neptec's TriDAR vision system was designed to provide full 6 degree of freedom (DOF) relative state vectors in real-time without requiring cooperative targets. To achieve this, the system uses two laser based 3D sensors and a thermal imager. TriDAR's software algorithms use geometric information contained in successive 3D point clouds to match against the known shape of the target object and calculate its position and orientation. These algorithms allow this process to be performed in real-time on TriDAR's onboard flight computer, while achieving the necessary robustness and reliability expected for mission critical operations [4]. TriDAR's onboard thermal imager is used to provide bearing and range information beyond the reach of the active 3D sensor.

Fast data acquisition has been achieved by implementing a smart scanning strategy referred to as "More Information Less Data" (MILD). Using this strategy, only the data that will be directly used to perform the pose estimation (~1000 3D measurements) is acquired by the sensor [5]. As opposed to reflector based solutions, all the data acquired by the sensor is used to compute the relative pose. This results in better sensor noise averaging and a more stable and accurate relative pose measurement. It also accommodates lower data acquisition speed and computational resources, such as processing speed, memory, and bandwidth, as more information is able to be extracted from less data.

Neptec has also developed the necessary tools and processes to configure, test and qualify the system for various targets and missions. Neptec's TriDAR simulator can produce highly accurate synthetic data that allow testing of the flight system using various characteristics that would be difficult to test on the ground. These include large targets, fly around and complex trajectories, long range, different material properties, and failed hardware states.

This paper details TriDAR's third and final test flight on STS-135. Section 2 introduces the TriDAR system. Section 3 summarizes the mission concept and objectives. Section 4 presents a summary of results obtained during ISS rendezvous and docking operations and Section 5 presents results from undocking and fly around operations. Section 6 details current and future work for TriDAR technology development.

2 TRIDAR RELATIVE NAVIGATION SYSTEM

Neptec's TriDAR (triangulation + LIDAR) sensor is a result of over 8 years of research and development funded by the Canadian Space Agency (CSA) and NASA. TriDAR provides the ability to automatically rendezvous and dock with vehicles that were not designed for servicing. The vision system combines an active 3D sensor, a thermal imager, and Neptec's model-based tracking software. Using only knowledge

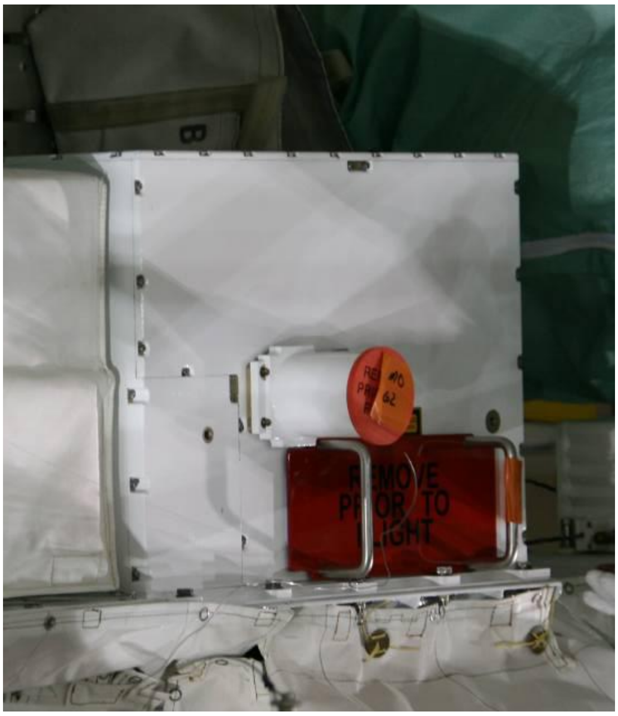

Figure 1: TriDAR sensor flight hardware

about the target spacecraft's geometry and 3D data acquired from the sensor, the system can automatically acquire and track an object in real-time. It outputs the 6 DOF relative pose directly. Optimized 3D computer vision algorithms allow this process to perform in real-time on TriDAR's embedded flight computer [4][5]. Initialization of the tracking process is performed by Neptec developed automatic target acquisition algorithms [6][7].

The TriDAR active three dimensional sensor (Fig. 1) is a hybrid scanner that combines auto-synchronous laser triangulation technology with Time of Flight ranging (LIDAR) in a single set of scanning optics. By combining the two ranging subsystem's optical paths, the TriDAR can provide the functionalities of two 3D sensors into a single package [8]. Both the triangulation and LIDAR ranging capabilities can be used during short range operations (<20m) thus providing an extra level of fault tolerance in the system for the last critical part of docking. The two subsystems share the same control and processing electronics thus providing further cost, power, weight, and computational savings compared to using two separate 3D sensors to cover the same operational range. A thermal imager is also included to allow the system to provide bearing and range information for operations well beyond LIDAR operating ranges.

Materials in space tend to be very dark, white or very shiny. Being able to image these surfaces over a wide operating range is critical for operations in space. The combination of auto-synchronous triangulation and LIDAR gives TriDAR a very wide dynamic range that allows the system to image such surfaces. This makes the TriDAR technology ideal for multiple space applications such as: rendezvous & docking, planetary navigation and landing, site inspection, material classification, and vehicle inspection.

3 MISSION OVERVIEW

TriDAR was installed in the Space Shuttle's payload bay on the Orbiter Docking System (ODS) next to the Trajectory Control System (TCS) rendezvous sensor (Fig. 2). The sensor was connected to a laptop computer on the flight deck inside Atlantis' crew cabin. The laptop was used to command the system, log the data and to display the tracking solution and other system statuses in real-time to the crew. All data processing and state vector calculations were performed locally on the sensor.

The specific configuration of the TriDAR laser hardware used for these Space Shuttle missions was selected to meet NASA eye safety requirements and ensure safe operations for both Shuttle and Station crews. This resulted in TriDAR configured with less than 10% of the laser power nominally available in the system. This significantly reduced the operational range of the system to be flight tested. This configuration was nevertheless sufficient to achieve mission objectives and demonstrate target-less tracking on-orbit.

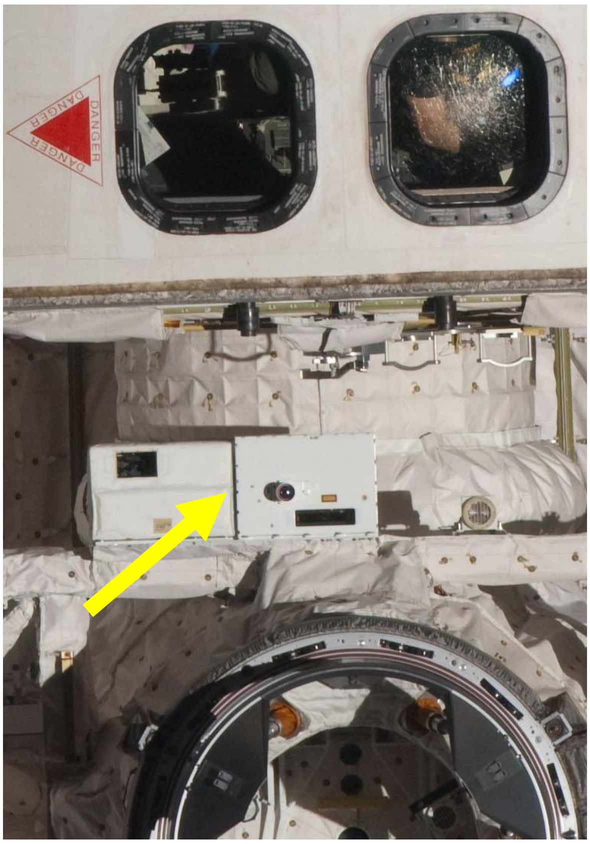

Figure 2: TriDAR flight unit installed in the Space Shuttle payload bay

The missions involved TriDAR operations during both the docking to the ISS and undocking/fly around phases. This allowed for two separate data collection opportunities. For docking operations, the system was activated during the final rendezvous corrections, when the Space Shuttle was a tens of kilometers away from the ISS. After initialization, TriDAR entered a search mode where 3D and thermal imager data was acquired until a lock on a signal was obtained. Once a signal was found, bearing and range information was provided until the target entered range for model based tracking. Once in range, the system automatically acquired the ISS and allowed full 6 DOF tracking to start. Automatic tracking restarts were also triggered periodically to demonstrate the automatic target acquisition capability of the vision system at various points during the operation.

TriDAR has been tested in this manner in space a total of three times. The first two flights were onboard Space Shuttle Discovery during the STS-128 and STS-131 missions to the ISS [9]. The final test flight was onboard Space Shuttle Atlantis during the historic final mission of STS-135. The objectives of all three flights were to demonstrate the capability of the system to autonomously acquire and track the ISS without using retro-reflectors or other cooperative targets. To reproduce the conditions of an unmanned docking, the system was configured to perform the entire mission autonomously, automatically acquiring the ISS and producing 6 DOF state vectors in real-time. The system was designed to self-monitor its tracking solution and was capable of automatically reacquiring the ISS if tracking was lost.

After two successful test flights, TriDAR mission objectives for its third and final flight were to further extended and evaluate improvements to the system's hardware and software. These included hardware upgrades for longer range target detection to improve the image quality from the thermal imager. Algorithms developed to allow real-time tracking from the thermal imager using template and feature tracking were also added. For the final Space Shuttle mission, the TriDAR also had the opportunity to document, in both 3D and thermal infrared, the last undocking and fly around the ISS, which was performed from a unique perspective, with the ISS yawed 90 degrees after Shuttle undock.

4 RENDEZVOUS AND DOCKING OPERATIONS

TriDAR was activated during rendezvous operations on Flight Day 3. Upon activation, the thermal imager was able to detect the ISS at a range of 34 km, respectively. This detection range was limited to the time the TriDAR was activated and initialized during flight, which was subject to openings in the crew rendezvous schedule, an extremely task filled portion of time. The thermal imager was able to detect the ISS in both night and day conditions. Fig. 3 presents sample images at both long and short range with color mapped to temperature.

TriDAR's Time of Flight (TOF) subsystem acquired the ISS at approximately 2.6 km. From initial acquisition onwards, TriDAR provided the crew with bearing, range and range rates to the ISS. Very good agreement with the other Shuttle cues (TCS, Radar and Hand Held LIDAR) was observed.

For the final flight, TriDAR entered into 6 DOF tracking from range and bearing mode at 200 m, as programmed into the system. This occurred right before the Shuttle performs its 360 degree back flip Rendezvous Pitch Maneuver (RPM) that allows the station crew to perform inspection photography of the Shuttle's thermal protection tiles. As expected, tracking was lost after the RPM thruster firing as the ISS left the TriDAR field of view. Tracking was automatically reacquired upon completion of the RPM when the ISS returned in the TriDAR FOV. The TriDAR then tracked the ISS into docking. No effects from ambient lighting conditions due to day/night transitions were observed for all three missions.

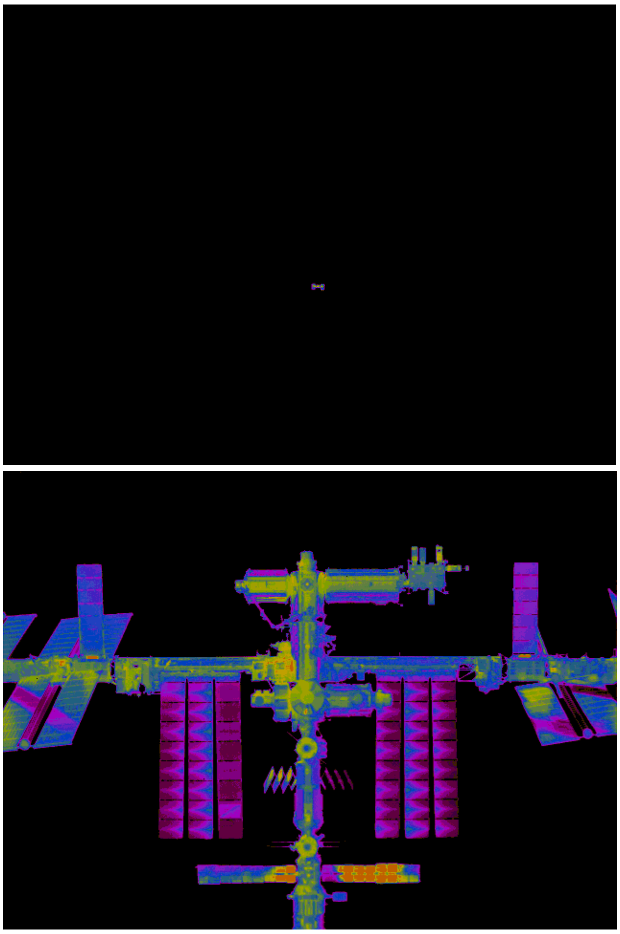

Figure 3: Thermal imagery of the ISS at 34 km (top) and 200 m (bottom)

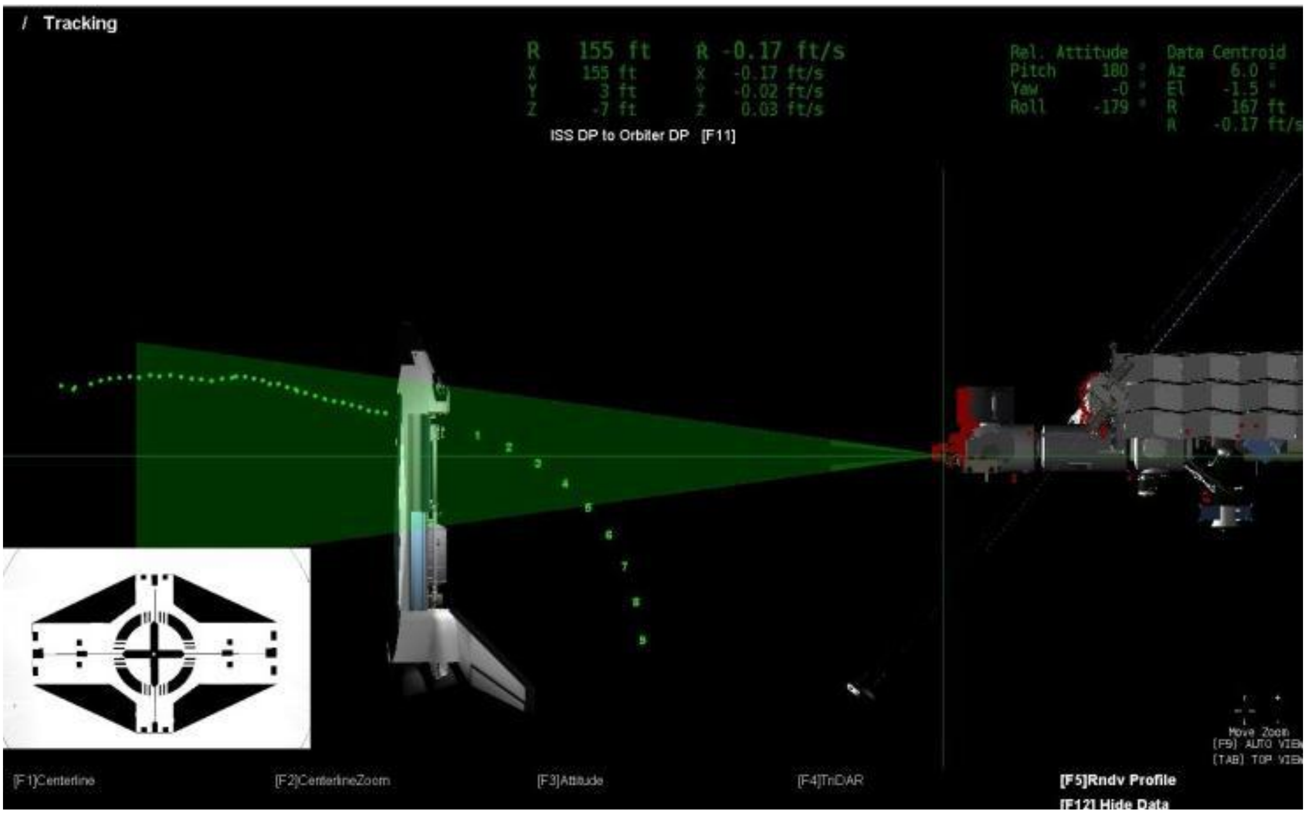

Figure 4: Crew display of TRiDAR real-time 6DOF tracking

Target acquisition and tracking was performed without the use of cooperative targets (visible, retro-reflector, or otherwise), and without any human intervention. TriDAR tracked the ISS in real-time the continuously up to docking except for the planned periodic automatic restarts which were used to exercise automatic target acquisition capability.

The tracking solution was displayed to the crew in real-time. Fig. 4 shows the crew display. In addition to the 6 DOF tracking solution displayed numerically on the top, the tracking pose solution is also shown graphically via the shuttle position and orientation shown with respect to the ISS, along with the docking corridor in translucent green. The 3D laser data points acquired by the TriDAR are shown in red, previous poses are displayed as green dots, and predicted position of the Shuttle, as calculated by its orbital dynamics, is shown in green numbers. All these display features were developed to mimic the crew onboard displays, to aid in training and simplify on-orbit operation.

Finally, as shown on the bottom left of the figure, the docking target of the ISS was shown to the crew as a visual docking aid. At 30 m from docking, the crew are instructed to visually inspect the docking target on the ISS to determine the Shuttle's orientation with respect to the ISS. This is a difficult task to do visually, as translations away from the center of the docking target introduce parallax effects to its appearance to the observer. Lighting conditions can also make this task challenging. This real-time display provides the crew with a clear indication of relative attitude that compensates for the perspective issue and is immune to lighting conditions.

Fig. 5 represents the tracking solution (Shuttle to ISS relative pose) generated for the final portion of the rendezvous and docking by TriDAR in real-time during STS-135, after the RPM. Displayed beside the tracking

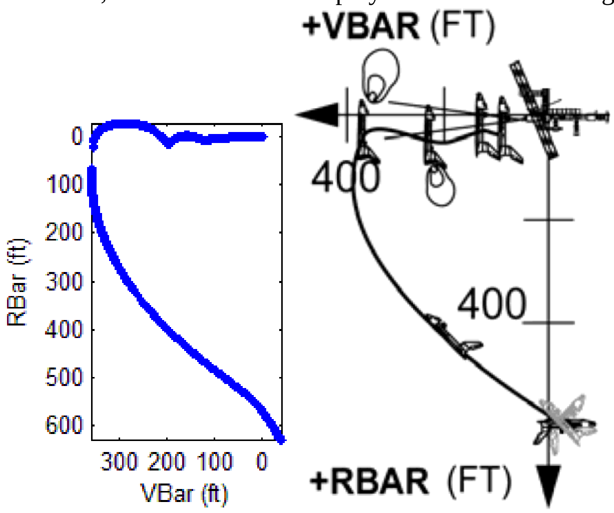

Figure 5: TriDAR tracking profile compared to nominal rendezvous handbook trajectory

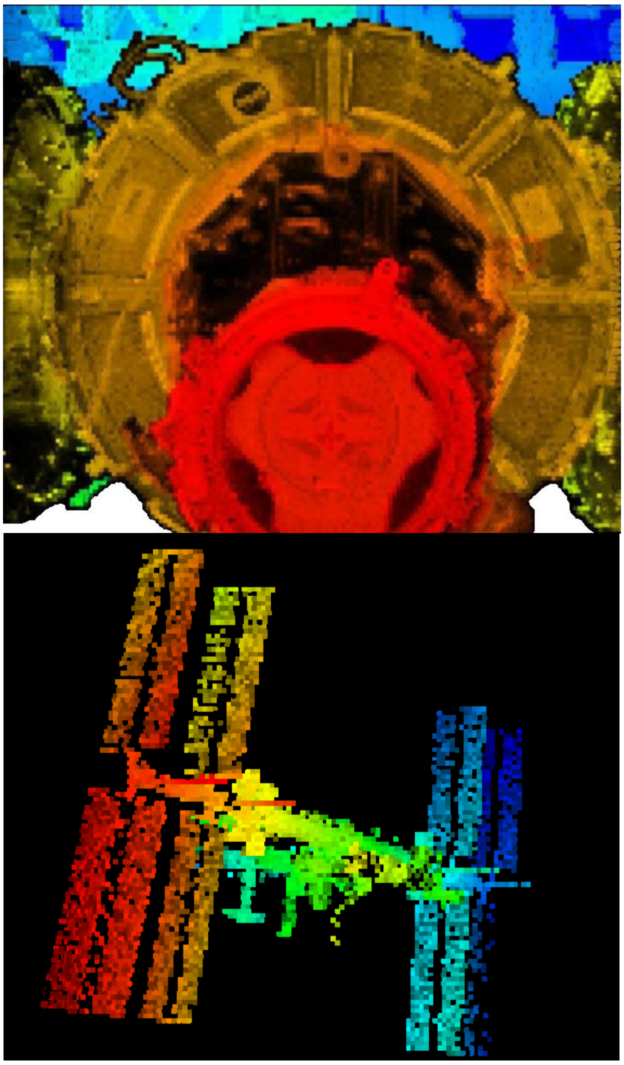

Figure 6: 3D imaging data of ISS, soon after undocking (top), and after ISS yaw initiated (bottom), color coded to range

plot is the reference rendezvous and docking trajectory as shown in the rendezvous plan.

5 UNDOCKING AND FLY AROUND

Real-time tracking of the undock and fly around was successfully performed on STS-131 by TriDAR, marking the first time a 3D based vision system performed real-time 6 DOF tracking of a non-cooperative tumbling target [9]. With this accomplishment, there was less urgency to repeat this operation on STS-135. However, the opportunity to image the historic final fly around in 3D was compelling, especially given the unique nature of its trajectory. For this occasion the completed ISS was yawed 90 degrees after Shuttle undock, so that the Shuttle fly around was performed at an unprecedented orientation around the ISS. This allowed the Shuttle a unique vantage point around the ISS as it flew around the ISS about its stack axis, rather than its truss axis as it had been performed until now. Therefore, during undocking and fly around, TriDAR imaged the ISS in 3D and IR. An example of the data is shown in Fig. 6 and 7.

6 CURRENT AND FUTURE DEVELOPMENT

6.1 Hardware Development

With its testing phase now over, TriDAR has entered into production as an operational relative navigation sensor. TriDAR has been selected by Orbital Sciences to be a primary proximity operations sensor on board its Cygnus

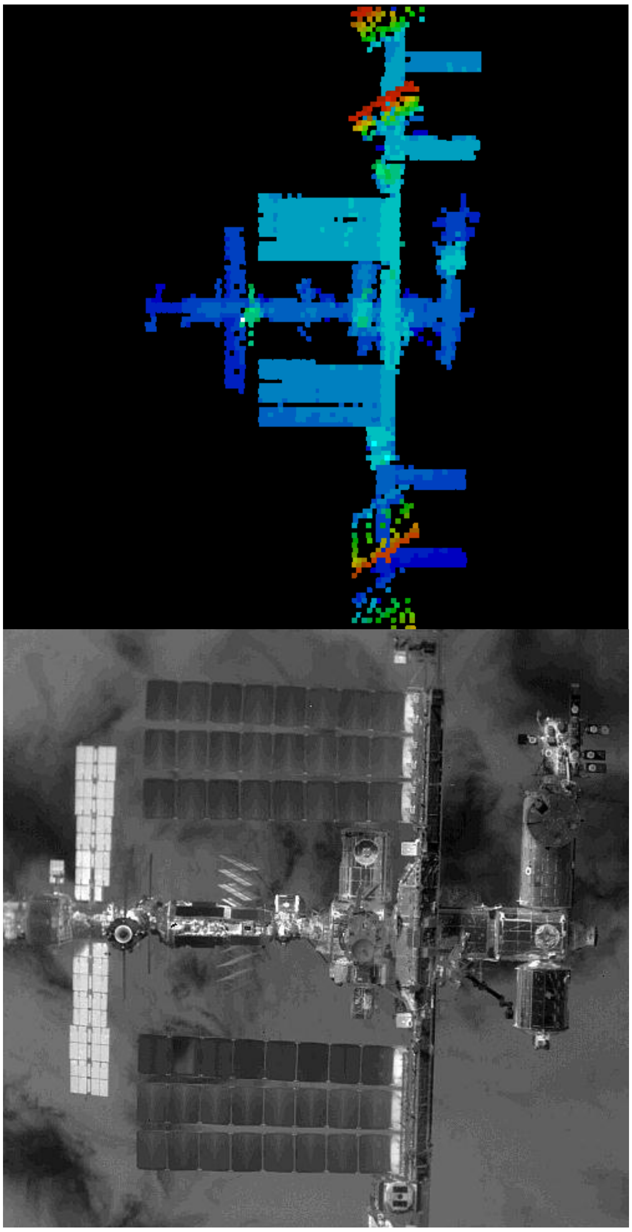

Figure 7: 3D (top) and IR (bottom) imagery of ISS during final Shuttle fly around

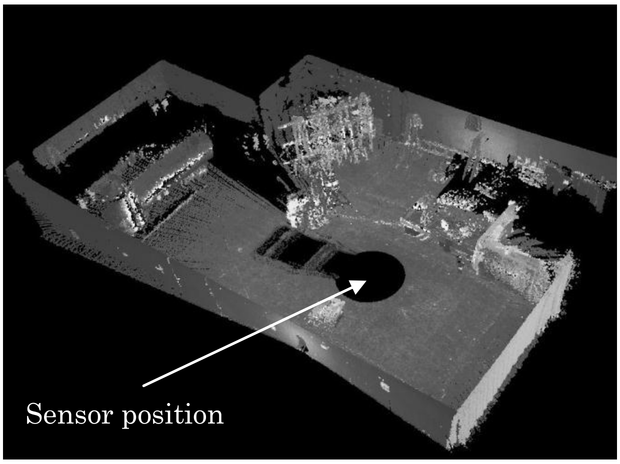

Figure 8: 3D dataset of 360 scanning LIDAR

unmanned ISS resupply spacecraft. The Cygnus is scheduled to begin operations in 2012 under NASA's Commercial Orbital Transport Services (COTS) and Commercial Resupply Services (CRS) programs. For these resupply missions, TriDAR will provide 6 DOF tracking to the Cygnus for rendezvous and berthing to the ISS along its R-Bar, and then grappled using the Canadarm2 to be docked to the ISS Node 2 Harmony module.

The evolution of TriDAR technology also continues. In addition to the software development being performed on the 3D and 2D thermal tracking algorithms, several hardware upgrades are also in development. This includes a significant reduction in TriDAR's size, mass, and power consumption, as well as an increase in its field of view. Coupled with its non-cooperative relative navigation vision system, these upgrades will contribute to make TriDAR a prime technology enabler for a host of applications that cannot rely on cooperative targets. These applications include providing 6 DOF tracking solutions for the servicing of non-cooperative satellites, orbital debris removal, and as a relative navigation sensor onboard the ISS to validate the approach and rendezvous of the many unmanned autonomous vehicles servicing the ISS, all without the need for any design changes on the vehicle.

TriDAR technology is also being applied to a new 360x45 degree scanning LIDAR. While scanning at a high rotational frequency in azimuth, phase shifting the elevation axis allows for a high density 360 degree 3D dataset to be gathered in a short amount of time. This sensor is being developed for planetary rover applications, and, due to its high speed and 360x45 degree FOV, it is well suited for situational awareness, mapping and hazard avoidance. A sample dataset of the LIDAR sensor is shown in Fig. 8. This 2 million measurement 3D pointcloud of Neptec's Vision System Certification Laboratory was acquired in 10 seconds.

6.2 IR Camera Algorithm Development

Since the time immediately following the final test flight of the TriDAR, algorithm development has been ongoing for the thermal IR imager. The results of the development include a means for robust, lighting immune, real-time bearing and ranging of the ISS target using the thermal imager. This is achieved via a novel application of a suite of computer vision techniques operating in tandem, to exploit their respective advantages while mitigating each of their weaknesses and optimizing for processing time on flight hardware.

Four computer vision techniques were used together in this tracking scheme. They include: basic blob centroiding, Oriented BRIEF (ORB) [10], template matching, and Speed Up Robust Features (SURF) [11]. Based on the processing time constraints on the flight hardware, a method of algorithm selection was developed to choose the best suited algorithm to the given input 2D imagery. By choosing the algorithm in real-time that was best suited to process a given input image, performance could be optimized as a best compromise of speed and accuracy for each individual image frame. Algorithms were also run in parallel at times to cross-check one another, in order to increase the robustness of the overall result. These tracking techniques, used together, were run using thermal imagery data acquired on STS-135. The tracking algorithm was able to provide bearing and range estimates that correlated well with estimates of the rendezvous approach.

6.3 Shape from Motion

In addition to being able to provide range/bearing tracking using the passive IR imager, the 2D imager is also capable of generating 3D data using a shape from motion technique [12]. By only registering matching pixels in successive frames, 3D data can be generated without an IMU or external localization source. The only limitation is that the data generated is determined up to scaling factor: while the 3D data points relative to themselves are accurate, there is no sense of scale, so the dataset is dimensionless which prevents absolute measurement. However, if the target size is known, as the ISS is, scale can be determined by correlating the expected size of the target to the dataset. This synthetic 3D data can be used as a cross-check to further improve robustness and reliability of other 3D navigation sensors. Fig. 9 shows the 3D data of the ISS generated from the 2D thermal imager during the undock and fly around, along with the self-located 3D positions of the camera views used to generate the pointcloud.

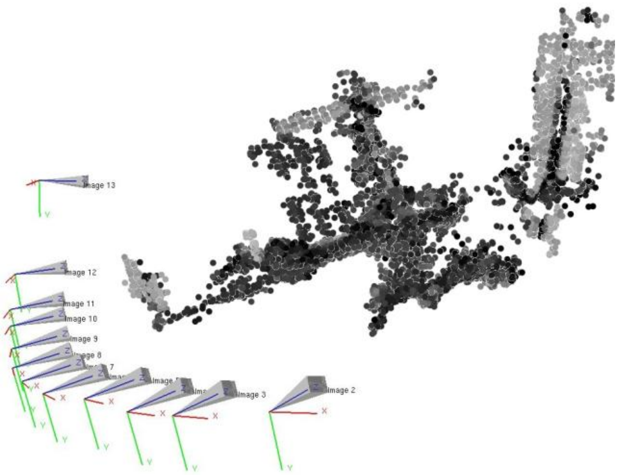

Figure 9: 3D Pointcloud generated from 2D Thermal Imager

7 CONCLUSION

Neptec's TriDAR vision system provides full 6 DOF relative state vectors for autonomous rendezvous and docking operations in space without requiring the use of cooperative targets. TriDAR uses knowledge about the shape of the target spacecraft along with successive 3D point clouds acquired from a hybrid 3D scanner to automatically acquire and track an object in real-time.

The vision system was tested for the third time on board Space Shuttle Atlantis during STS-135, the final Shuttle mission to the ISS. TriDAR has previously been tested on board Space Shuttle Discovery during STS-128 and STS-131. The objective of the missions were to demonstrate TriDAR's target-less tracking ability during ISS rendezvous, docking, undocking and fly around operations. Throughout the three test flights, TriDAR accomplished all its test objectives.

With its testing phase now over, TriDAR has emerged as a mature technology ready for production applications. TriDAR has been selected as an autonomous navigation sensor on board the unmanned Orbital Cygnus ISS resupply vehicle. The technology is also undergoing continuous development, in improving its performance specifications, and also spinning off a new sensor geared for planetary rover applications. While the Space Shuttle program is now over, TriDAR has used the opportunity to test on board the Shuttle to develop a relative navigation sensor technology that is ready to be used on the next generation of space vehicles.

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