Proceeding of the 6th International Symposium on Artificial Intelligence and Robotics & Automation in Space: i-SAIRAS 2001, Canadian Space Agency, St-Hubert, Quebec, Canada, June 18-22, 2001.

# Target Tracking Object Pose Estimation, and Effects of the Sun on the NRC 3-D Laser Tracker*

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***Keywords***: *space vision system, object tracking, pose estimation, sun interference, laser scanner, photogrammetry.*

## Abstract

In this paper, we present a summary of the scientific and technical work that has been pursued in the development of sensing, dynamic tracking, and intelligent acquisition systems for space applications. The most up-to date experimental results will be presented with emphasis on immunity to sun interference and compatibility with Inconel and geometrical target tracking. The paper will conclude with an overview of the new space qualified laser scanner prototype developed by Neptec, to be tested onboard the Space Shuttle. This DTO mission is scheduled for summer 2001.

## 1. Introduction

Looking at the end results and comparing 3D acquisition systems with the more conventional 2D still and/or video cameras, more research is still needed to obtain the equivalent of ease of use of the 2D video and still cameras. 3D laser scanning is an emerging technology and does not have the same large consumer market and momentum that 2D still-imaging and video cameras enjoy. However the world is 3D and one key advantage of 3D vision systems that will never possess 2D video cameras is scale and rotation invariance of the acquired 3D data as opposed to the 2D perspective projection. And for space applications, there is one even bigger advantage: the very high tolerance of 3D laser scanners to ambient light and sun interferences.

During the late 80s, the 3D laser scanner systems developed at NRC were mostly limited to laboratory use and commercial systems were focused toward very specific applications such as the automobile industry. In the early 90s, a mobile (to differentiate with portable) version of the NRC auto-synchronized scanner was demonstrated for the acquisition of a scaled model of the cargo bay of the space shuttle [2]. In the mid-90s, the scanners are moved in the field, for example with experiments in Kennedy Space Center Florida, USA. With the development of the Biris portable sensor, cost effective experiments were made possible; a first in portable 3D equipment [2-3].

Advances in the sensing of dynamics and unstructured environments are still at the early research stage and require the development of intelligent systems, algorithms, and methods to minimize the human intervention. Because these intelligent systems are at the very early stage of development, cost justification of the research, prototypes, and the definition of the application, to narrow down the research objectives and expectations, are key questions. Space provides an initial impetus to reach this objective.

- Tracking and acquisition of dynamically moving objects.
- Study of the dynamics of the sensor and of the acquisition process.
- Smart intelligent acquisition systems for dynamic and unstructured environment.

## 2. Canada and Space

Canada plays a very important role in the Space Program and the National Research Council of Canada (NRC) has been a key player in Canada's contribution to the space initiatives. The robotic Canadarm, for example, is a technology whose origins are directly linked to NRC labs. Another key technology is the Space Vision System used on-board the Space Shuttle, developed and manufactured by Neptec Design Group [8].

In 1989, the Canadian Space Agency was created to supervise and coordinates Canada's efforts in space. For

* NRC-44876

the new International Space Station, one of Canada's main contribution is the Mobile Servicing System, which will support the assembly, maintenance, and servicing of the space station. Today, the Space Vision System is another key component for the assembly of the International Space Station.

In the early 90s, the Institute for Information Technology (IIT) of the National Research Council of Canada (NRC) successfully demonstrated major advances in the use of laser scanner technologies for space applications. The technique developed combines laser scanning technology, ranging, imaging, and tracking to compute in real-time the pose of objects [4]. This laser scanner was designed to be insensitive to background illumination such as the earth albedo and the sun and most of its reflections. To demonstrate the concept, retro-reflective targets were used and tracking was based on the intensity of the reflected laser light. In the mid 90s, the use of the laser scanner system for the acquisition of dense static 3D views and the integration of these multiple views in a single 3D object, using Polyworks™, were presented. During the late 90s, the focus of the 3D sensing research activities was shifted toward portability Biris, quality, and colour. All these combined advances also demonstrated the needs for more user-friendly acquisition systems, better adapted to the ever-changing conditions of dynamic environments.

In the summer of 1999, in close collaboration with Neptec Design Group engineers, the laser scanner prototype was successfully interfaced to the Space Vision System [5] with major advances in both software and hardware technology. The prototype automatically searches and tracks in 3D retro-targets attached to the object. Stability of the photo-solution was advantageously compared to results obtained using existing video cameras but with the added feature of generating robust solutions in the presence of strong background illumination. With this success Neptec Design Group, the National Research Council of Canada and the Canadian Space Agency, are currently working on a space-qualified version of the Laser Scanner prototype, to be flown on board mission STS 105 during summer 2001.

More recent research work has also demonstrated the capabilities of the laser technology to track the existing Inconel Black/White targets making the system compatible with existing NASA equipment, a key feature for acceptance. This research has also demonstrated the first successful results of dynamic controls of 3D scanning, real "real-time" (msec range) geometrical (3D) processing, tracking, and relative pose evaluation of moving object/sensors.

## 3. Space a Harsh Environment

Experience gained in ground simulation and on orbit during space shuttle missions has proved the importance of vision for space applications. As mentioned previously, a key component, currently used by NASA for the assembly of the International Space Station is the Space Vision System. This vision system uses video cameras and photogrammetry-based methods to compute in real-time the pose (position and orientation) of an object [6,7].

**Figure 1.** The existing Space Vision System (SVS) uses the known locations of the B/W targets to compute the pose of objects. Effects of sun illumination and earth albedo on video images that affect accuracy and reliability are wide dynamic range, poor signal, saturation, and shadows. (Courtesy of NASA)

Video camera based systems are attractive because of their ease of use, low maintenance, and simplicity of integration to existing equipment. Unfortunately, the presence of the sun or any other strong sources of light adversely affect the quality of the conventional methods that rely on standard video images, e.g. the camera on-board the Space Shuttle. Poor contrast between features on the object and background makes these conventional video images difficult to analyze. Figure 1 shows a typical example of video images obtained on orbit that illustrates potential problems a vision system will encounter during normal operation.

**Figure 2:** Inspection in orbit, a key task for 3D systems. Fine surface details can be accurately monitored and inspected using the 3D geometry. (Courtesy NASA)

Camera saturation, insufficient light and shadows are very serious problems that limit the normal operation of conventional video-based vision systems. A special case for automated machine vision system is concerned with lighting gradients (cast shadows), which requires both extended dynamic range for the video camera and sophisticated image processing algorithms. Although this seems a-priori a straightforward problem for the human eye (brain), it is not as simple for limited dynamic range camera systems. It is therefore very important that any complementary systems like a laser scanner be robust to operational conditions such as sun interference, saturation, shadows, or simply insufficient light.

The laser-based range scanner approach presented here offers the advantage of being close to 100% operational throughout the changing illumination conditions in orbit. The technique is designed to be insensitive to background illumination such as the sun and most of its reflections. The laser scanner uses two principal modes of operation:

- **Imaging** produces a dense raster type 3D (range) image of the object.
- **Real-time tracking** of multiple targets on object(s): to compute the orientation and position of the object in 3D space.

One of the unique features of this laser system is its potential to combine in a single unit different ranging and object pose estimation methods:

- Triangulation-based method for short to medium distance measurements (<5-10 m)
- Photogrammetry-based technique (spatial resection) and target tracking, compatible with current Space Vision System (SVS) used by NASA.

Using the **imaging** mode, the main applications include inspection and maintenance; where as, assembly, docking, and any tele-operations are solved using the **tracking mode**. In **tracking mode**, the variable resolution laser scanner of Figure 3 tracks in real time targets and/or geometrical features of an object as shown in Figures 4 and 9. The scanner uses two high-speed galvanometers and a collimated laser beam to address individual targets on the object. Very high resolution and excellent tracking accuracy are obtained using Lissajous scanning patterns [8]. Laser wavelengths at 1.5 μm (eye-safe), 820 nm (infrared), and 523 nm (green) have been tested.

The Space Vision System [9] tracks the small black dot targets visible in Figure 1. Because the exact locations of these features on the object are known, object position is computed from their relative positions in the video images using photogrammetry-based techniques. Obviously tracking compatibility with these B/W targets is a key aspect for the laser scanner and system sensitivity becomes mostly a question of minimum laser signal power relative to the background light rather than the minimum signal detected and detector electrical noise.

The most recent works use the geometry of simple 3D features such as holes or circular protuberances, sphere. Although this is still limited, it opens the door to fully track the detailed geometry of an object.

**Table 1:** Conditions for ambient illumination and their effect on the Laser Scanner System.

| **Illumination conditions** | **Possible effect on laser scanner** |
|---|---|
| Normal conditions | None – normal conditions |
| Partial target shadowing | None – outside instantaneous field of view of camera |
| Full target shadowing | Reduced accuracy – Distortion on signal or saturation |
| Saturation (Field of view) | Minimal – normally outside instantaneous FOV of camera |
| No Light (Dark) | None - Ideal for laser scanner |

**Estimated percentage of "conditions" of operation in orbit**

| | | | |
|---|---|---|---|
| 60% | Normal conditions | 35% | Shadow conditions |
| <5% | Saturation & poor illumination | <1% | Back illumination |


**Figure 3:** Prototype of the laser scanner system, a conventional video camera is "temporarily" mounted on the laser scanner for monitoring and comparison with conventional video methods.

**Table 2:** Typical acquisition time for the 3D Laser Scanner System used in raster and tracking modes; acquisition speed is 20,000 voxels/sec.

| **Raster Mode (3-D Image Size)** | **Refresh Rate** (sec) |
|---|---|
| 128 × 128 | 0.8 |
| 256 × 256 | 3.3 |
| 512 ×512 | 13.1 |

| **Tracking mode** | **Tracking Speed** |
|---|---|
| Single target | 6.6 msec |
| Multiple targets | 10 msec × Targets |

Raster imaging can then be used to obtain very dense images while simultaneously tracking the relative motion of the moving objects or the camera.

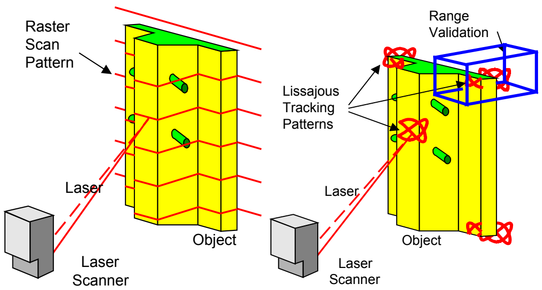


**Figure 4:** (Left) Conventional raster type imaging mode. The whole object is scanned line by line and a raster type image is created. (Right) Illustration of real-time tracking of geometrical features using Lissajous patterns. Range information is used to discriminate between the object and its background.

## 4. Imaging vs Real-time Tracking

Because of the inertia and limited speed of galvanometers, a 3D laser scanner used in the conventional raster-imaging mode of operation will be very slow. As shown in Figure 4, raster imaging consists of scanning the scene line-by-line, emulating the video reading mechanism of conventional CCD/CMOS cameras. Although video 3D range imaging has been demonstrated [10] using very fast rotating mirrors, maximum range and accuracy measurements are limited and insufficient for tracking. Table 2 shows the speed of acquiring a 3D-range image assuming an acquisition speed of 20,000 voxels/sec. It is clear that refresh rates will be prohibitively slow with conventional raster type images.

Real-time tracking of targets or geometrical features on an object is implemented using Lissajous figures, to obtain good scanning speed and accuracy. Driving the two axis galvanometers with sine waves of different frequencies creates a Lissajous pattern [4,5]. Figure 4 also illustrates the geometrical tracking principle using the 3D range information on the Lissajous pattern, to (a) identify targets on the object or any useful geometrical feature and (b) to discriminate the target from its background as illustrated by the bounding box. Lissajous patterns are used to efficiently scan objects at refresh rates exceeding the bandwidth of the mechanical deflection system. The natural inertia of the galvanometer-mirror structure smoothes the scanning pattern and hence increases the pointing accuracy of the tracking system.

Section 7 will describe the principle associated with position tracking of a single target using Lissajous patterns (Figure 11). Range and intensity data are measured for each of the N points on the scanning pattern. Both range and intensity data can be used to discriminate targets and background.

## 5. Raster Imaging Demonstration

Results demonstrating the accuracy of a 3-D Laser Camera build at the NRC for the creation of models and measurements were presented with a test case that was performed in collaboration with the Canadian Space Agency (CSA) and NASA [2,11]. The goal of this test was to evaluate the technology in tasks that will ease the documentation, assembly, and inspection of the international space station.

After acquiring many 3D images all around the Orbital Docking Station (ODS), interfacing the MIR station and the Space Shuttle, these images were merged to create a complex 3D model of the ODS at different level of complexity depending on the application.

Figures 6 and 7 show the experiment and the results obtained. There are still several unresolved issues such as the evaluation and selection of the proper views for image registration and object occlusions, however it is worth mentioning that object model creation has considerably evolved since then and powerful commercial software, such as Polyworks™ from Innovmetric Software, are now readily available.

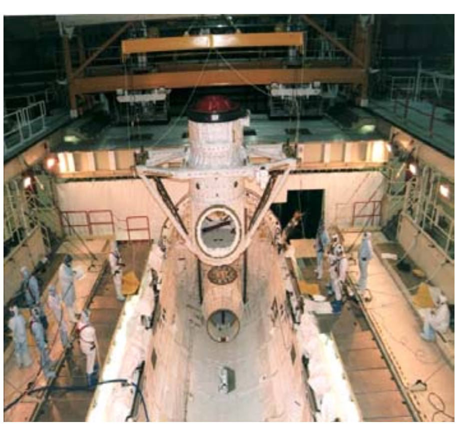

**Figure 5:** The ODS module at KSC. (Courtesy of NASA)

**Figure 6:** Scanning the ODS.

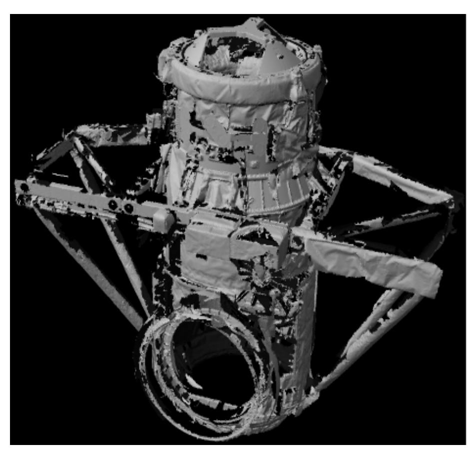

**Figure 7:** Creation of a 3D model of the ODS module.

## 6. Integration of Laser Camera System with the Space Vision System

The demonstration of real-time cooperative targets was the next logical step in the demonstration of intelligent systems. Accuracy and ruggedness to harsh lighting conditions and environments were therefore some of the key questions to answer. The Laser Camera System – SVS demonstration project had two main objectives [5]:

- To demonstrate that the Space Vision System (SVS) accuracy performance, with the Laser Tracking System used as a sensor, is equivalent to the performance of the system using an orbiter quality video camera as a sensor.
- To demonstrate that the LCS provides greater robustness to adverse lighting conditions than is provided by a video camera.

Figure 9 shows the multiple targets tracking process in action where the laser scanner is programmed to sequentially scan different sections of the object. One of the targets is here in the search mode and the scanner uses a larger Lissajous pattern to locate it. When found, the scanner automatically switches from the search mode to the track mode using a smaller Lissajous pattern to increase target centroid accuracy. Using this method, errors introduced by the measurement process are always optimal because the scanner automatically centers and optimizes the size of the tracking patterns based on the measured target to object distance, for each target individually. The laser scanner sequentially scans different sections or targets on one or multiple objects.

The locations of the centroid of the detected targets are fed directly into the existing photosolution and attitude control modules of the Space Vision System (SVS). The SVS uses real-time photogrammetry techniques to compute the poses (position and orientation) of multiple objects. For the SVS system, the Laser Scanner appears like a conventional video camera.

The demonstration setup utilized the 3A-Z1 install task simulation in the Neptec Vision System Certification Lab (VSCL), shown in Figure 8. This simulation consisted of half-scale models of the Unity and Z1 truss models with Inconel targets applied in flight locations and closely located retro-reflective targets. The model set-up simulated an orbiter orientation with the starboard wing into the floor of the lab with the nose toward the east wall and the payload bay toward the north wall. For demonstration purposes a good quality JVC video camera and the LCS had been set up in a location that roughly approximates the center of the payload bay on a GAS bridge in the aft section of the payload bay.

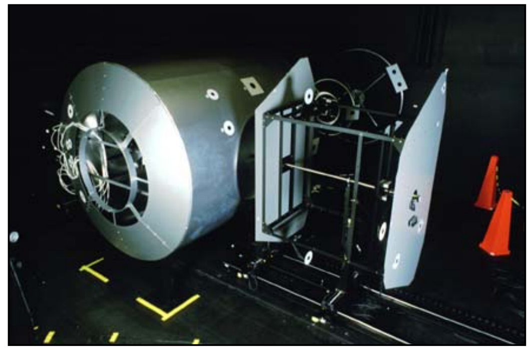

**Figure 8**: The Node and Z1 modules experimental setup (1/2 scale).

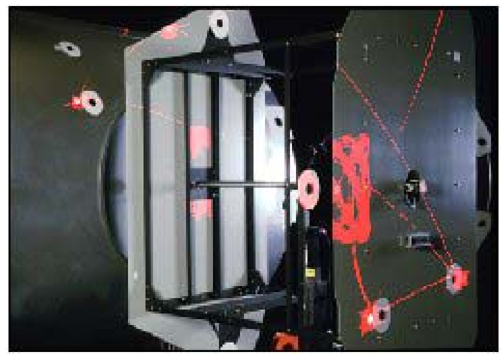

**Figure 9.** Real-time tracking of targets on the simulated Node and Z1 modules. Two types of target are visible, Inconel B/W and retro-reflective targets. The system tracks each retro-target sequentially. In this example, one of the targets is in "search mode" (larger Lissajous pattern).

This configuration demonstrated the LCS performance in a flight like task geometry; the relationship between sensor, targets and payloads is representative of on-orbit operations. The results indicated that, under the correctly chosen conditions, the agreement between the camera and LCS solution was within 6 mm (0.25") and 0.25 degrees (worst case).

#### Lighting Robustness Testing

To demonstrate the robustness of the LCS to adverse lighting conditions, different specific lighting configurations were used.

- Light was placed to create a sharp shadow in the vicinity of a target. By raising and lowering the light the shadow could be made to move across the face of the target such as illustrated in Figure 10.
- Shining a very directional 1000-Watt light source directly at the LCS and camera. This situation was intended to simulate the condition of the sun shining directly into the camera.
- Measurements done outside under clear sunny day.

Testing showed that when using the video camera, the SVS would not continue to generate a solution. When the same test was performed with the LCS there was no loss of solution. In [9] a more complete sensitivity analysis of the tracking system to sun interferences is presented.

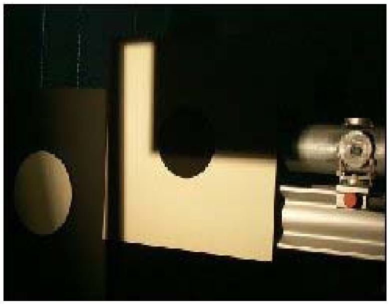

**Figure 10:** Effect of light shadows on a target. There was no loss of photo-solution using the Laser Scanner System.

**System Dynamic Range**

The geometrical tracking principle uses both the 3D range and intensity information on the scanning pattern to (a) identify targets on the object or any useful geometrical feature, and (b) to discriminate the target from its background. Although it seems a-priori that intensity reflectance should be sufficient, in practice this is far from reality since target reflectivity is highly dependant on surface material, angle of incidence on the surface, specular reflections, and ambient illumination. Tracking brings very interesting and practical challenges for automated detection:

- illumination and poor contrast between the targets and/or geometrical features and their surrounding background,
- specular reflections created by metallic structures,
- defects and non-uniformity of the targeted surfaces,
- variations in the material reflectivity, surface incident angles,
- ambient intensity variations and shadows introduced by sunlight,
- occlusions.

For example, the reflected signal ratio between the white surface and its darker background may vary between 2:1 and 1.5:1 depending on the incident angle of the laser beam (10:1 for Inconel material). Other interesting dynamic signal ratios are non-uniform signal response of the "dark" background and vignetting (3:1), variations of reflectivity versus surface incident angle (4:1), specularity of non-diffusing surfaces (>20:1), ambient light and shadows (3:1), variation of target reflectivity with range (>100:1). The laser scanner must therefore exhibit an equivalent SNR of more than $10^4$ to $10^5$ of dynamic range, far exceeding the 256:1 ratio of conventional frame grabbers and the 20:1 of electronic shutters. With the laser technology, this is accomplished by dynamically varying the laser power and the sensitivity of the laser spot position sensor on a per target basis, and by automatic compensation of the non-linear dynamics of the scanning system. Because of the constraints of signal dynamic range ($10^4$ to $10^5$ and Figure 10) geometrical range processing is the only truly reliable method to differentiate the target from its environment.

## 7. Geometrical Tracking

To simplify the discussion, we are here assuming that most geometrical objects can be modeled using planar surfaces (or meshes). Because the laser scanner provides range information, the equation of a surface can be defined using $0=ax+by+cz+d$. Target discrimination is obtained by removing measurements that do not belong to the plane of the target. Because most objects can be defined using planes, meshes, or simple geometries, best fit of surfaces (or simple geometries) is a robust method for target detection and tracking as seen in Figures 11 to 13. Although the extension of the method to other geometries such as spheres will not be presented here, it is obviously possible as seen in Figure 12.

Real-time geometrical target processing and tracking in the laser scanner inverse spherical coordinate system is used. This corresponds to the angles of measurements and the inverse of the range $u=x/z$, $v=y/z$, and $w=1/z$ [12]. Using the homogenous $UVW$ coordinates system, the high correlation normally obtained using the three axes $x$-$y$-$z$ in the Cartesian coordinate system relative to the object distance $R$, is minimized. The $UVW$ coordinate system also eliminates the $z^2$ dependency of range error, linearizing the error equations, and more important, eliminating the possibility of ill-conditioned systems of equations. Of primary interest is the direct relationship between the sensor raw measurements and the equation of a plane $z=ax+by+c$, becoming $w=\alpha u+\beta v+\chi$. Linear minimization techniques can then be efficiently used since the errors are constant for the whole volume. Furthermore, because $u$ and $v$ are mostly correlated with only the angles $\varphi$ and $\theta$, of the scanner, quadratic error minimization will never be ill conditioned, of primary importance for real-time computation. Several techniques can be used for plane extraction; the method we selected combines split and merge and outlier removal (robust fitting).

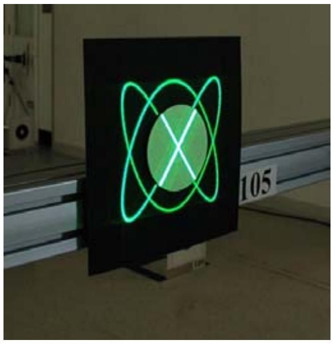


**Figure 11.** Tracking using the Lissajous pattern and a planar circular target.

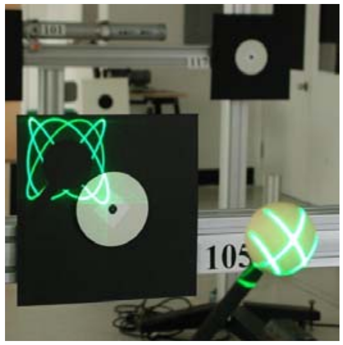


**Figure 12.** Geometrical tracking of a sphere illustrating the discrimination of similar colour/shape targets at different range.

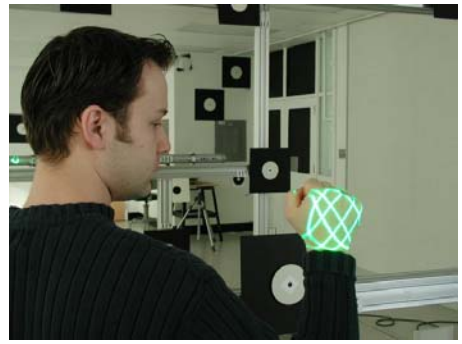

**Figure 13:** Tracking of natural geometrical features.

Figures 11 to 13 demonstrate the tracking method using the plane of the target to discriminate the target from the surrounding environment and ambient light. The intensity gradient of the target is used to discriminate the target itself. Figure 12 shows geometrical tracking. If we compare the method with a 2D video camera, the background target and the sphere will be identical (same color) and impossible to differentiate using conventional video methods. Finally, Figure 13, shows an extension of the technique tracking natural object features.

## 8. Object Pose Evaluation

Object pose evaluation is a complex subject by itself and an in depth analysis is beyond the scope of this paper. We will rather provide here a qualitative analysis of the method from a mathematical point of view based on similar concepts.

Assuming a set of known coordinates ($x_o$,$y_o$,$z_o$) on a rigid object, the expected location of these targets in the laser scanner 3D space $(\hat{x}, \hat{y}, \hat{z})$ is given using $\hat{\mathbf{X}} = \mathbf{M} \cdot \mathbf{X}_o$ where **M** is a 4x4 rigid transformation matrix (|**M**|=1) that maps the object target coordinates $X_o = [x_o \quad y_o \quad z_o \quad 1]^T$ in the laser scanner space $\hat{X} = [\hat{x} \quad \hat{y} \quad \hat{z} \quad 1]^T$. The matrix **M** has 6 unknowns, 3 translations and 3 rotations (yaw-pitch-roll). Object pose estimation consists of evaluating the transformation matrix that will minimize a set of error equations. The most commonly used method minimizes the quadratic error between the expected position computed from the previous equation and the laser scanner measurements $\mathbf{X} = [x \quad y \quad z \quad 1]^T$. Different techniques are available to minimize this set of equations such as based on least-squares adjustment, and quaternion. However, for medium to long range, the error vector $\mathbf{E} = \mathbf{X} - \hat{\mathbf{X}}$ will be highly dependent on the range measurement $\Delta\mathbf{E} \approx R^2 \Delta p$.

Using the camera pinhole model and photogrammetry methods, pose estimation requires the minimization of the error vector $\mathbf{E} = \mathbf{U} - \hat{\mathbf{U}}$ of the projected vector **U**=[u v 1]$^T$ and the dependence of the error vector **E** on range *R* is minimized compared to the previous approach. Accuracy of the photogrammetric method should then be much better than direct range data minimization for medium to long range *R*.

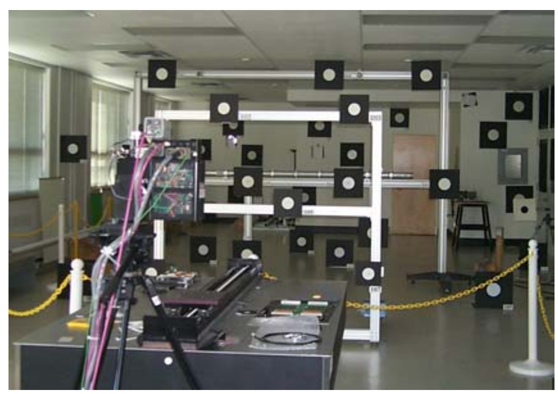

**Figure 14.** Experimental setup used to verify the accuracy of the tracking system. The blinds were shut to prevent saturation in this photograph.

In order to compare the two methods, the targets on the structure shown in Figure 14 were divided in three groups and the targets acquired over a period of twelve hours. Standard deviation of the pointing stability for the targets was 40 μrad. Figure 15 shows the results of the object pose model (simulation) using the previous methods for a 1 m × 1 m array and for the targets of Figure 14. Increased stability/resolution using the photogrammetric model *UV*, compared to *XYZ* data is important.

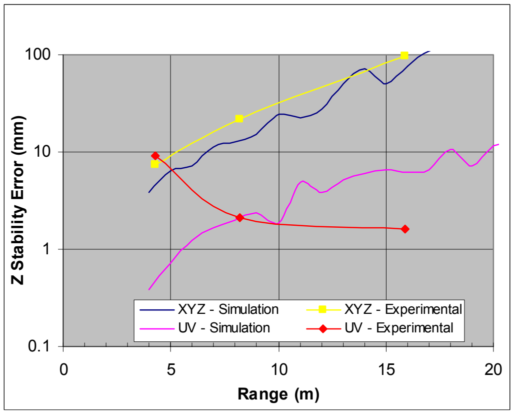


**Figure 15:** Model simulation and experimental results for analysis of the stability of the pose.

There are several key factors that must be considered when comparing the stability of the pose from the model data and these experimental results, the most important being the distribution of the target, the number, and their sustained angle (size). For the *UVW* method, the distribution of the targets on the structures of Figure 14 was definitely an advantage, providing a large triangulation base. The model used a regular target array of 1 m × 1 m, while the experimental data used targets distributed within the whole FOV of the laser scanner. This gain is important at longer range for the *UV* method and almost negligible for the *XYZ* method. In [13] the B/W targets were bigger than the targets used here and pointing accuracy has also been improved. From both the simulated model and experimental data, an increase in accuracy using resection methods is important.

## 9. Neptec Space Qualified Laser Camera

The previous concepts have been experimentally verified using the laboratory prototype of Figure 3. However this prototype was not designed to survive the high vibrations levels of the Space Shuttle launch, neither the high temperature fluctuations nor the vacuum of space.

Following the successful integration tests between the NRC Laser Tracking System and the Space Vision System, Neptec initiated the development of a space-qualified version of the laser scanner. Figure 16 shows the new Neptec Laser Scanner Camera undergoing vibration testing at Canadian Space Agency David Florida Laboratories. This camera head is fully contained and includes the entire electronics, optics, and laser source, and computers needed for real-time operation. At the time of writing the Laser Camera System was installed in the shuttle payload bay awaiting a scheduled 12 July launch date. The planned on-orbit testing program includes acquisition of both real time tracking data and high-resolution images of elements of the international space station.

Because this new laser scanner system design has been optimized and engineered with the latest state-of-the-art technologies, we are expecting better performances than the one presented in this paper. But experience dictates that the final conclusion will only be available after testing on board the Space Shuttle.

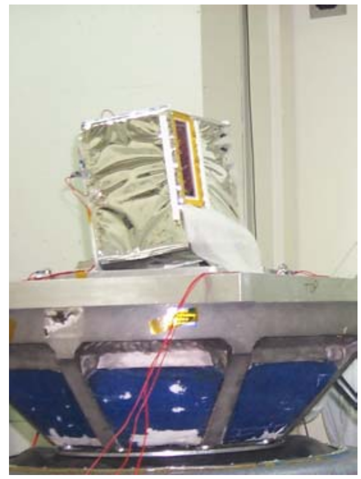

**Figure 16.** The Neptec Laser Camera Tracking System under vibration tests at the David Florida Laboratory. The camera head contains the entire electronics, optics, laser source, and processing computer.

## 10. Conclusion

This paper has presented some of the research performed toward reaching the objectives of 3D acquisition and tracking of objects in non-cooperative environments. Because most of current 3D acquisition systems still require static scenes and supervised operations, the dynamics of the 3D system is becoming very important for uncontrolled environments. Geometrical tracking and space applications provide an initial impetus to study this objective.

Because the dynamics of the acquisition process and space environments are extremely complex, this work has progressively solved several key questions:

- the acquisition of dense 3D images and the integration of multiple views for the creation of complex 3D objects to study the basic problems of acquisition and small volume calibration;
- the demonstration of large volume cooperative target tracking and immunity to sun illumination to analyse the problems of ambient light interferences;
- the understanding of the scanner and the acquisition process dynamics;

- a first demonstration of geometrical object features/target tracking and larger volume calibration;
- the evaluation of the dynamics of object/scanner relative position (moving objects);
- the development of a space qualified version of the laser scanner system.

Future research work should demonstrate the tracking of complex 3D geometrical features, the integration of simultaneous imaging and tracking (moving object/camera), and fully automated acquisition. In the mean time, the authors are patiently awaiting the analysis of the experimental results that will follow the real and ultimate tests onboard the Space Shuttle, this summer.

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