LASER SCANNING FOR CONSTRUCTION METROLOGY

by

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LASER SCANNING FOR CONSTRUCTION METROLOGY[1]

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ABSTRACT

This paper summarizes work at the National Institute of Standards and Technology (NIST) in the *Non-Intrusive Scanning Technologies for Construction Assessment Project*. The initial proof-of-concept phase of this project, the extension of the procedures and methods developed in the initial phase for an indoor environment to an outdoor, uncontrolled environment - a construction site, and future work planned are discussed.

1. INTRODUCTION

One of the more difficult items to track at a construction site is the geometry of objects which are not neatly classified as "components." The ability to capture such "amorphous" data becomes essential if one is to achieve true automation. Amorphous data include the state of excavation of terrain, progress of a concrete casting, highway alignment, paving operations, etc. To obtain such information, the current state-of-practice is to conduct surveys.

Equally important is the need to automatically capture the "as-built" condition of an existing structure, or to capture and clarify a complex construction operation as it happens and to provide real-time feedback to those conducting the operations. All of these present complex situations where traditional metrology techniques are ineffective, due to massive quantities of data needed to describe the environment. The research discussed herein focuses on the use of laser ranging technologies and three-dimensional analysis to automatically and non-intrusively scan a construction site, and to obtain useful information from those data for project planning and documentation purposes.

The National Institute of Standards and Technology's (NIST) project in *Non-Intrusive Scanning Technologies for Construction Status Assessment* builds on metrology and wireless communications. The objectives of the project are to utilize new scanning technologies to improve the critical construction status assessment needs by making those measurements faster and cheaper than traditional methods and to develop, in conjunction with industry, standard means for transmission and interpretation of such data.

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2. PROOF OF CONCEPT

The process of terrain tracking involves obtaining point cloud data with a laser scanner, and subsequently transferring, post-processing, and displaying the data. To demonstrate that this process could be accomplished in "real-time", a live demonstration was designed.

A laser scanner, a Riegl LPM98[3], was used to obtain the data. The laser scanner is a Class 1 (eyesafe) system that emits an infrared laser pulse with a wavelength of 905 nm ± 5 nm. The scanning field-of-view (FOV) is ±180° horizontally and ±150° vertically. The range of the laser scanner is up to 150 m. Distance measurements have a typical accuracy of ±20 mm, and ±50 mm in the worst case (e.g., due to dust and atmospheric effects). Beam divergence is approximately 3 mrad.

For purposes of the demonstration, a small sand pile was used to simulate terrain. The sand pile was located in a lab representing the construction site and the audience was located in separate building.

Before the demonstration, a graphical representation of the sand pile (initial state of terrain) was created by combining the point clouds obtained from four locations around the sand pile. Figure 1 shows the sand pile and the four point clouds obtained by the laser scanner from around the sand pile.

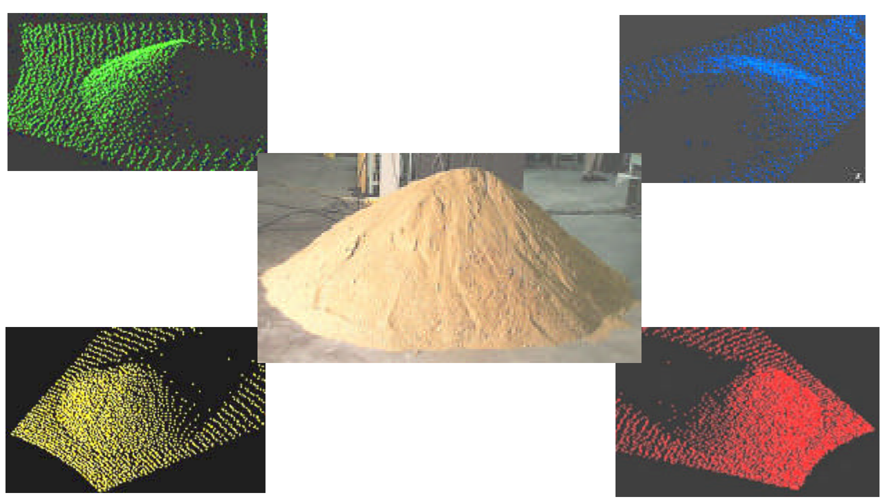
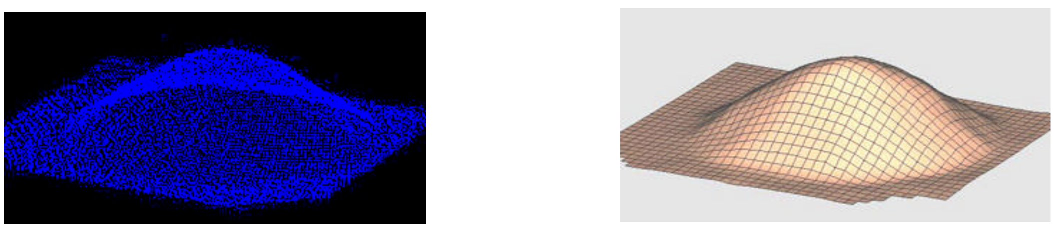


Figure 1. Sand Pile and 4 Point Clouds from Around the Sand Pile.

[3] Certain trade names or company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

By obtaining views from different locations, a true 3-D representation of the sand pile is possible since any features occluded from one location are captured from the other locations. Prior to combining the point clouds, the corresponding data from the four locations have to be registered (rotational and translational transformation to a common reference frame) to a common reference frame. For this demonstration, all transformations (translations and rotations) were done manually.

Figure 2 shows the point cloud resulting form registering and combining of four scans and the 3-D surface of the sand pile created from the point cloud.



a. Combined Point Cloud from 4 Scans

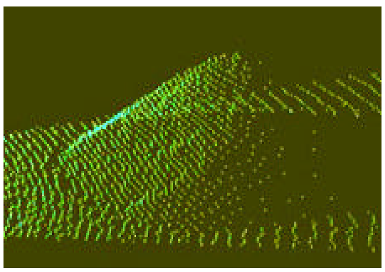
b. 3-D Surface

Figure 2. 3-D Surface of Sand Pile.

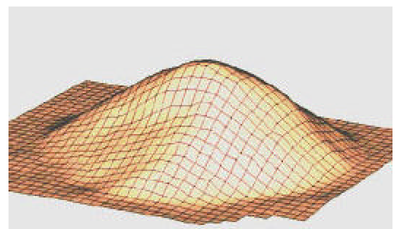
To simulate a change in the terrain, some sand was removed from the sand pile and the volume removed was automatically calculated as shown in Fig. 3. The sand pile was re-scanned from only one location, in the interest of time, as the demonstration was live. If all changes to the sand pile could not have been captured from one scan location, the sand pile would have had to be rescanned from two or more locations and the point clouds would have had be registered requiring more time than was available for the demonstration.

a. Sand removal.

b. “Changed Terrain.



c. Rescan from one location.



V = 1.770: removed 0.168 (m^3)

d. Combined new scan with the three previous scans to regenerate the 3-D face.

Figure 3. Sand Removal Simulating “Changed” Terrain.

Once the data were acquired, the data file was sent via FTP to a computer lab where the volume calculations were performed and the new surface was regenerated and displayed. Data transmission, volume calculation, and surface regeneration were accomplished in a matter of seconds.

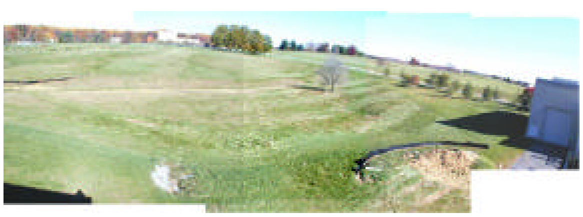
3. FIELD DEMONSTRATION

To test the procedures and methods developed in a more realistic environment, terrain tracking at a construction site located on the NIST campus was undertaken (Cheok et al. 2000b). The construction project involved earthmoving and the assembly of an emissions control system for a fire testing facility.

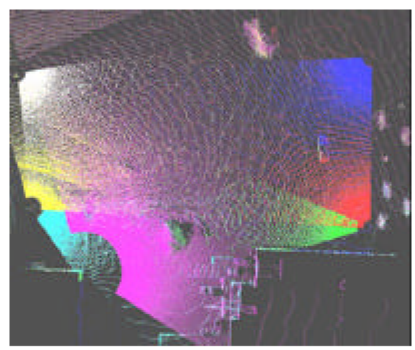
To track the terrain changes, the scanned data were obtained from two fixed locations around the construction site at the end of those work days which involved new excavation: on the roof of a building adjacent to the construction site and from a steel pole located within the construction site just beyond the construction boundary. The rooftop location was selected because it allowed for the least obstructed view and was out of the way of construction equipment. When the scan was completed, the data were stored in a laptop and were later transferred via FTP (file transfer protocol) to a remote computer for post-processing.

Post-processing involved initial registration of the two scans based on the known positions of the scanner, fine tuning the registration visually, determining the regions of interest, cropping the scanned data set to the regions of interest, creating a surface model from the scanned data, and computing a volume. Measurement of volume changes is needed to track the construction progress, amount of materials delivered, and for determining payment of tasks completed.

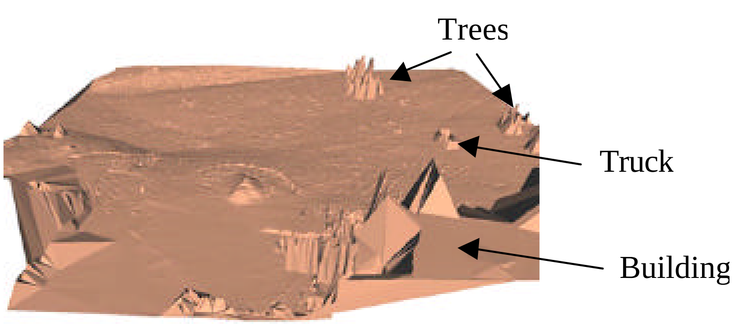
Prior to the commencement of any construction work, the terrain was scanned from 5 positions around the site to obtain an initial reference surface. The surface was created from the combined point cloud data from seven scans (at two positions, two scans were obtained from each position). A truck was parked in the scanned area to aid in the registration of the seven scans as shown in Fig. 4. Care was taken to ensure that the truck would not be in an area where volume calculations would subsequently be important. This was because the points defining the truck would not be distinguishable from the points defining the terrain. Therefore, the surface generated from the combined point cloud would include the truck data and yield a "false" differential volume.



a. Construction Site



b. Combined Point Cloud



c. Surface Model of Terrain

Figure 4. Initial Terrain

Figure 4c shows the surface model of the initial terrain. As seen in the figure, the buildings, trees and truck are not easily recognizable as such and prior knowledge or other visual aids are needed to identify them.

3.1 Post-Processing Data

Data registration presented a challenge when post-processing the data. Initial transformations were performed using the known position of the scanner locations with further adjustments made using an interactive graphics program. This visual alignment of the scans works well for adjusting the X- and Y-translations and rotations about the Z–axis. Adjustments about the remaining degrees-of-freedom were not possible due to the inability to visually differentiate the points in the foreground and the background. To adjust the rotations about the X- and Y-axes and the Z-translations, surface models of the scans were used to aid in visual detection of any misalignments which show up as ridges along the scan path in the model. Making these manual adjustments for each data set was very time consuming.

A first attempt was made to develop an algorithm for automatic registration of a point cloud to a surface by minimizing the deviations between the point cloud and the surface. The program assumes that the scans were already initially transformed to a global coordinate system, i.e., close to "truth". This attempt was hampered by data noise. This method also assumes that one scan represents ground truth which is incorrect. The inclusion of targets with known geometry and position in the scene may aid in data registration and will be investigated in future efforts in this project.

Volumes were calculated using two methods, triangulation and tetrahedralization, as described in Cheok *et al.* (2000a). The calculated volumes for selected dates are given in Table 1 where A2 and A3 regions cover areas of different sizes and where A3 is encompassed within A2. For example, the second row represents the volume change between Mar. 7, 2000 and Mar. 6, 2000 and these are fill volumes (positive values). No uncertainty values can be associated with these values for two reasons. First, it was not possible to measure the actual volumes of the material added or removed. Second, there do not exist any accepted or standard test protocols for instrument calibration. In addition to procedures for traditional instrument calibration (range and pointing accuracy), it is important to recognize that calibration also includes the ability to determine measures of performance for the algorithms used to generate the 3-D surface models that are subsequently used in volumetric calculations. Registration errors will also have to be included when determining the combined uncertainty for the volume calculations. For these reasons, it is not possible to determine which of the two values obtained for the A2 region for Mar. 9 / Mar. 7 (Table 1) is more accurate. NIST has current research programs working towards resolution of these calibration issues for LADAR-based terrain metrology.

Table 1. Computed Volume Changes‡‡ for Selected Dates

Selected Dates Second date / First date	A2§ Region (m^3)		A3§ Region (m^3)	
	Triangulation	Tetrahedralization	Triangulation	Tetrahedralization
Dec. 17 / Initial Terrain	+340.6	+339.7	+35.0	+35.2
Mar. 7 / Mar. 6	+287.1	+293.3	+111.5	+111.7
Mar. 9 / Mar. 7	-19.8	-43.0	-38.9	-39.0

§ A2 region comprises of the area (67 m x 50 m). A3 region comprises a region 31 m x 33 m.
‡‡ Volume change = Second date minus first date. A positive value indicates a fill volume and a negative value indicates a cut volume.

3.2 Issues in Field Scanning

Several challenges were encountered when obtaining field scans. One was to supply power to the scanner when it was on top of a roof and in a field where AC power was not readily available. A obvious solution was to use a battery for the power supply, and an auto battery would meet the necessary power requirements. A battery, however, is heavy and very cumbersome to carry up and down from buildings and around the construction site. The scanner, laptop, and accessories also had to be carried up to and down from the roof and to the field pole. A solution is to have multiple scanners and to leave the equipment in place inside weatherproof, auto-deploying poles which pop up several times daily, capture and transmit their data, then go into "sleep" mode and close their environmental enclosures. For eventual routine applications, it may well be necessary to have several scanners at fixed locations. This approach would eliminate re-registration, daily set-up, alignment and leveling of the scanner. However, the cost of purchasing multiple scanners (a factor that could be moderated by the development of low cost LADARs), the need to develop waterproof casings for the equipment, and the ability to secure the equipment from theft are major considerations in this approach.

As expected, the scanned data taken from the roof had fewer obstructed regions than similar data obtained from the pole in the field. Besides scanning from a much lower height, the situation in the field was further aggravated when a large pile of dirt was placed in front of the pole which further obstructed the scene. Also, access to the pole in the field was at times blocked by construction materials and machinery, and the scanning equipment and accessories had to be hand-carried to the pole.

Since it was a relatively small construction project, it was possible to make arrangements with the contractor to have most of the machinery parked beyond the areas of interest at the end of the day. This allowed the scanned areas to have fewer occluded regions and to be relatively free of obstructions. However, such arrangements may not be possible in larger construction projects. Here, the ability for object identification would be required when post-processing the scanned data in order to remove any objects that are not part of the terrain.

4. DISCUSSION

Based on the field demonstration, three areas in need of further research are identified: data registration, sensor calibration, and object identification. Testing protocols are needed to assess the uncertainties caused by the registration process.

In addition, two types of sensor calibration are required. The first type involves sensor evaluation. Establishing the accuracy of a sensor's range-measurement is straightforward. However, the calibration is more complex for scanning sensors since some scanners use lasers outside the range of visible light. Determination of the aiming accuracy of the sensor is, therefore, less straightforward.

Further, the accuracy of numerical results, in particular volume calculations, based on the sensor data, needs to be ascertained. Therefore, the second type of calibration involves measures of performance for algorithms that are used to generate surfaces from the point clouds. These metrics are harder to establish. In general, performance is assessed by comparing calculated results with a reference model or ground truth. The accuracy of surface generation algorithms can be tested using objects of known shape and volume.

Finally, object identification will facilitate the removal of objects that are not part of the terrain. Additionally, object identification will enable the tracking of parts around a construction site. There are several methods available to extract an object from a point cloud. The methods that are currently used to extract, replace, and/or remove objects within a scene are time consuming and require user intervention. Methods to extract objects automatically are, at this time, mainly research tools and have been successful for single objects in a scene. Other possible aids in object identification include the use of color, intensity of the returned signal, and pattern recognition. These methods do not identify objects per se, but are used to aid in object identification. Additional intelligence will have to supplied/added to pick out and extract the data (points) from a point cloud for further processing and to correctly identify the object. In the first instance, user intervention is the most likely source of this intelligence. In the latter instance, the intelligence could be in the form of user intervention, image processing algorithms (if a camera is used), and/or a database containing objects such as trucks, trees, and buildings that would most likely be found in a particular scene. If a database is utilized to provide this intelligence, probability analyses will have to be performed to determine confidence limits.

5. FUTURE WORK

Based on the early findings of the project, NIST is directing research towards developing methods of semi-automatic registration of scan data. The emphasis of this registration work is on numerical methods rather than visual methods. In the current research work, the data points are in Cartesian coordinates (conversion from polar coordinates is done internally in the scanner) and the meshing of the data is done in this coordinate system. However, filtering of noise in the data is not easily accomplished in Cartesian coordinates as it is in polar coordinates (in the range direction). Conversely, meshing in polar coordinates would require image or surface integration since each scan would be in its own local frame of reference; this task would not be required if meshing were done in Cartesian coordinates as different scans would be transformed to a global frame of reference.

In addition, NIST is developing metrics and protocols for calibration of instrument uncertainty and its propagation to calculated quantities such as volume. Finally, work in the area of object recognition through sensor fusion will also be investigated with the purpose of adding "intelligence" either via software or hardware improvements to a laser scanner to aid in object identification.

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