Ladars for construction assessment and update

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Ladars for construction assessment and update

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Abstract

Work at the National Institute of Standards and Technology (NIST) on laser radar imaging of a construction site is described. The objective of the NIST research is to make measurements required in a construction project quicker and cheaper than current practice and to do so without impacting existing operations. This can be done by developing techniques for real-time assessment and documentation in terms of 3-D as-built models of the construction process. Once developed, this technology may be used for other applications such as condition assessment of a hazardous environment where human intervention would be impossible. © 2000 Published by Elsevier Science B.V.

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1. Introduction

Recent studies by the Construction Industry Institute[1] have indicated that for a typical US$100 million construction project, between US$500,000 and US$1 million are spent purely on keeping track of where things are on the site (typically tens of thousands of items) and on monitoring the status of construction activity. Additional expenses are directed to the establishment of the state of the infrastructure following the actual construction work. Approximately 2% of all construction work is devoted to manually intensive quality control and tracking of work progress, including operations involving earthmoving and bulk materials handling. Any technology that can reduce this burden and decrease time to delivery will offer a significant competitive edge. It should be further emphasized that any technology that delivers automated, rapidly available information relating to project status and the position of components at the site would also leverage further cost savings by supplying that information to automated and semi-automated systems performing work at the site.

One of the more difficult tracking tasks at a construction site is the determination of geometry changes in construction materials that are not neatly

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[1] An industry consortium comprising some 100 of the USA's largest contractors, AE design firms, and building owners. See, e.g., "1997 Strategic Plan and Governance Plan," Construction Industry Institute, Austin, TX, February 1997 and the in-progress report of Committee 151, on RFID Technologies.

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classified as "components". The ability to capture such "amorphous" data becomes important if one is to achieve true automation. Amorphous data include such things as the state of excavation of terrain, the presence of raw materials (e.g. sand, gravel) storage; the location and extent of spoil piles; progress of concrete placement; highway alignment; paving operations; etc. The current state-of-practice for obtaining this type of information is to conduct site surveys. These surveys involve: (1) Field work and data acquisition-making measurements and recording data in the field; (2) computation and data processing-calculations based on recorded data to determine locations, areas, volumes, etc.; and (3) mapping or data representation — plotting of measurements to produce a map, chart, or plot, and, for earth moving, the placement of grade stakes on the site.

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 are complex situations where traditional metrology techniques are not effective due to the massive quantities of data needed to describe the environment. The research discussed herein focuses on the use of new, fast laser ranging technologies and 3-D analysis to automatically and non-intrusively scan a construction site and to mine useful information from that 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, wireless communications, and simulation research conducted as part of the National Automated Manufacturing Testbed (NAMT) collaboration [5]. The objectives of the project are to utilize new scanning technologies to improve critical construction status assessment needs by making these measurements faster and cheaper than traditional methods and to develop, in conjunction with industry, standard means for transmission and interpretation of such data.

1.1. Scope of project

The research project was initiated in October 1998. It focuses on the development of an integrated software and wireless remote sensing system that will accept input from a variety of high speed automated ranging sensors and create a 3-D model of the present state of a portion of a construction site. As an initial, full-scale practical demonstration, site topography during the construction of Building 205 Emission Control System at NIST (to begin in the fall of 1999) will be tracked. Emphasis is on the use of non-intrusive scanning systems that can acquire site geometry, yet do not require instrumentation to be installed on earthmoving machinery. This is important for initial introduction of the technology to the construction industry, as most contractors are reluctant to test new technologies and methods if it means an increase in their construction costs. The models generated in this fashion (from the actual Building 205 construction site) will be compared against those acquired by means of an all-terrain vehicle equipped with a real-time-kinematic (RTK) global positioning and attitude determination system. Derivative quantities such as remaining cut-and-fill volumes, overall progress rate, and projected completion date will be displayed by means of a graphical user interface at the construction site office; ultimately, the same information will be made available to the operator of the appropriate earth moving machinery.

The work focuses on:

1. scene update rate requirements and methods for improving scene update rates;
2. development of standardized means for transmitting and interpreting scan-data packets; and
3. development of practical post-processing routines that automatically operate on the 3-D data to produce useful derivative quantities identified in collaboration with the construction industry.

This is a base-technology development project combined with practical, full-scale demonstrations to industry. Its various elements will be subsequently used as building blocks to address more complex 3-D as-built assessment problems for the construction industry.

Collaborations are being established with construction industry partners to ensure that (1) the technology developed is responsive to industry needs, and (2) the technology developed is usable in a construction context.

After testing the excavation tracking technology during the construction of the Emission Control System structure, the procedures will be extended to the much larger Advanced Measurement Laboratory construction project during the 2000–2002 time frame. Long-term research is being directed to the use of high speed, precision laser radars (LADARs) as an automated means of as-built, discrete component identification and placement assessment.

To achieve these objectives, several tasks were identified:

1. Develop a laser ranging system that can image a construction area in "real-time".
2. Develop the ability to wirelessly transfer range data from the field to a remote office.
3. Link the rangefinder to GPS position and attitude measurement systems so that the range data can be registered to a known reference frame.
4. Develop a user interface to:
   (a) automatically operate the scanner.
   (b) display the 3-D data.
   (c) determine cut/fill requirements.

2. Laser scanner

There are two principle categories of scene imagers presently under development at research laboratories and commercial industry. The first bases its operation on measuring the time-of-flight of a coherent light pulse. The use of a pulsed diode laser will enable, presently, a range measurement to be made over several scores of meters in daylight to "non-cooperative" targets (i.e. natural targets without the use of retroreflectors) with an update rate of around 25 kHz maximum — that is, 25 000 range measurements per second. In order to develop a scene image, this type of unit must be swept in raster mode to create a field of radially spaced rows or columns of range measurements. The unit output is typically in the form of scan lines, with each scan line progressively stepping across the scene within the field of view of the instrument. A variant on the time-of-flight design is the "flash" or "coherent" LADAR [4] in which a relatively high energy, diffuse coherent light pulse "illuminates" the scene. The returned photons are then optically guided to a photomultiplier array which permits individual time-of-flight range measurements to be made simultaneously over a matrix representing the scene. In principle this approach offers the most direct path to "real-time" performance, yet it remains a research tool. The most advanced publicly known flash unit employs a 32 × 32 pixel matrix chip that produces crude images relative to that achievable with the slower raster scan devices.

An alternative approach involves the use of a continuous wave (cw) laser interferometer that determines range based on phase difference. This type of unit is typically operated in a raster scan mode, similar to the pulsed diode LADAR.

An obvious drawback to all of these rangefinders is that they cannot "see" through objects, and thus, scans from different locations need to be acquired and registered to obtain a composite, unobstructed view.

The majority of the rangefinders used in surveying employ lasers with wavelengths in the infrared region and are eyesafe. The maximum range of these range finders varies from less than 12 m to greater than 50 km with the penalty of reduced accuracy at the longer distances.

The accuracy of the measurement is influenced by many factors with the main ones being the reflectivity of the object and the existing environmental conditions. Bright sunlight, rain, snow, fog, smoke, and dust will adversely affect the accuracy of the measurement. Accuracy may be increased by increasing the measuring time, the signal power, and by taking multiple readings.

2.1. Description

There are a few commercially available LADARs. The criteria used in selecting a rangefinder for this project were (1) speed in acquiring the range data, (2) accuracy, (3) maximum range, (4) angular resolution, (5) cost, and (6) commercial availability.

The objective of any site metrology system is to permit real-time machine control and obstacle avoidance. This requires an update rate of at least 10 Hz, i.e. a full geometric site model being updated 10 times per second to simulate real-time or live updates. None of the commercially available LADAR systems can achieve this rate. Thus, real-time machinery control based on LADAR range data is still not yet achievable. However, there is still a great deal that can be done presently, even with slow instruments.

For purposes of obtaining an as-built model, positioning, alignment, etc., the required measurement accuracy needs to be on the order of millimeters to meet construction tolerance requirements and for accurate placement/positioning of elements. The minimum range required to scan a construction site is about 100 to 200 m.

The current focus of the NIST research is on exploring the utility of non-intrusive scanning techniques and to develop basic post-processing tools. Fundamental research efforts both within and outside NIST are underway on the development of the next generation LADAR that will seek to improve scene update rate, range, and accuracy.

Based on the above discussion, a custom scanner by Riegl[2] was obtained from a commercial vendor for the NIST research and is shown in Fig. 1. The laser profile measuring system consists of a high precision pan/ tilt mount, laser rangefinder, and laptop control computer. This system will henceforth be referred to as ''the laser scanner''.

The specifications listed for the laser scanner are the specifications given by the manufacturer and are as follows. The laser scanner is a Class 1 (eyesafe) system that emits an infrared laser pulse with a wavelength of 905 ± 5 nm. It can be set for automatic or manual scanning. The scanning field-of-view (FOV) is ±180° horizontally and ±150° vertically, which permits an exceptionally large area to be imaged. The positioning accuracy of the pan/tilt mount is ±0.009° and the angle readout accuracy is ±0.009°. The scan rate is 36°/s both in the horizontal and in the vertical directions. The range of the laser scanner is up to 150 m for objects with reflection coefficients, ρ, greater than 80% and 50 m for objects with ρ of greater than 10%. Distance measurements have a typical accuracy of ±20 mm and ±50 mm in the worst case (due to dust and atmospheric effects). Beam divergence is approximately 3 × 3 mrad.

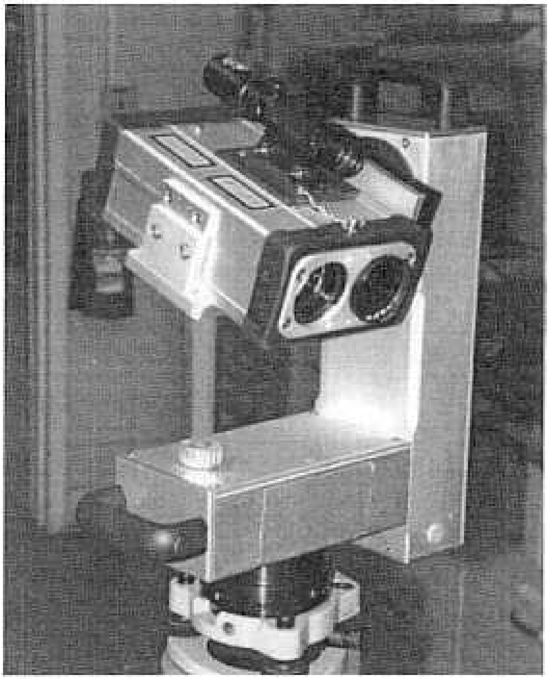


Fig. 1. Laser scanner.

Communications with the laser scanner is via an RS 232 serial interface. The user may interface directly with the laser using terminal emulation software or Microsoft© Windows-based interface software that allows the user to set the necessary parameters to operate the laser scanner. Basic input requirements are: start horizontal angle, start vertical angle, incremental angle in both the horizontal and vertical directions, number of data points in a scan line, and the number of scan lines.

2.2. Typical scan characteristics

A sample scan of the NIST Tri-Directional Test Facility was obtained and is displayed in the form of a point cloud in Fig. 2. The 2-1/2-D image consists of approximately 40 000 data points — 200 points

[2] 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.

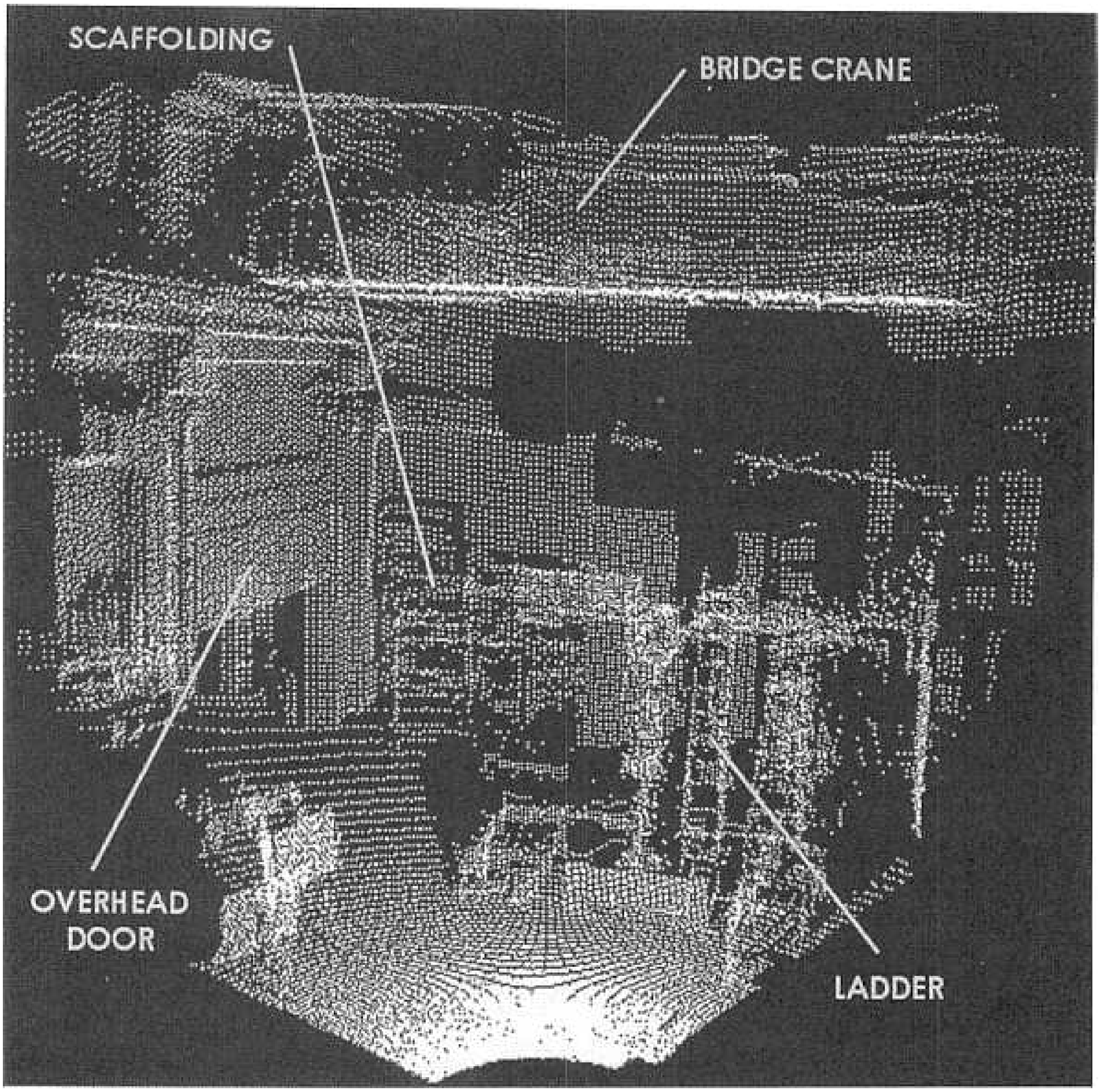


Fig. 2. Actual LADAR scan of a familiar NIST site: the Building 226, Structures Lab. Tri-Directional Test Facility (TTF). This image provides an example of the dense clutter to be expected at an everyday construction site.

per scan line and 200 scan lines. The actual number of data points shown in Fig. 2 is somewhat less than 40 000 because in some cases no signal was returned — typically, diffuse black objects make poor targets. The horizontal and vertical angles, scan ranges, were set to 90° and angle increments were set to 0.45°. The scan acquisition time was approximately 7 min. The range data contained in this very coarse image are still sufficient to easily pick out many components, including ladders, access doors, scaffolding, test fixtures, and an overhead crane. Dense data (closely spaced points — typically on the order of several millimeters), registered with similar data taken from other points of view, will provide the raw information needed as input information for automated non-intrusive component identification algorithms.

3. Automatic cut and fill surfaces

Current work at NIST involves automatically creating a 3-D surface image of the scanned excavation area as shown in Fig. 3. The composite data is wirelessly uplinked to a *temporal project database* [2], wherein the terrain data become available for subsequent derivative quantity calculations. The term "temporal" is used to indicate that each data entry in the database library contains a time stamp. This means that each complete registered terrain mesh acquired at a construction site will contain a time stamp at the moment it is wirelessly uplinked from the remote scanning system. Given an additional surface specifying the *desired* excavation profile (the architectural intent), the cut/fill requirements relative to a time-stamped terrain mesh can be determined.

The creation of the 3-D image as a surface necessitates the meshing of the *point cloud* data with polygons. This may be accomplished in one of several ways, with one way being the creation of a triangulated surface. The Delaunay technique [3] was chosen to create a triangulated mesh for a regularly or irregularly gridded point cloud because of its essential uniqueness. The Delaunay triangulation also tends to avoid the creation of interior triangles with long edges and long thin triangles, which is undesirable as they tend to distort the surface. In addition to triangulating the set of data points, the proposed method incorporates the capability of performing adaptive sampling to reduce the number of points in a region of dense data points. The method of least squares is used for smoothing the meshed surface. The ability to smooth the surface is important if the data are noisy.

A second method to create the 3-D surface image is to import the point cloud data into a data visualization software package to generate the surface. The software package used in this project was Data Explorer [1], which was an IBM product but now is open source software.

3.1. Scan from one location

Shown in Fig. 3 (created using Data Explorer) is a scan of a terrain that will be used as a sample excavation site. Assuming, for the purpose of a simplified example, the desired excavation profile is

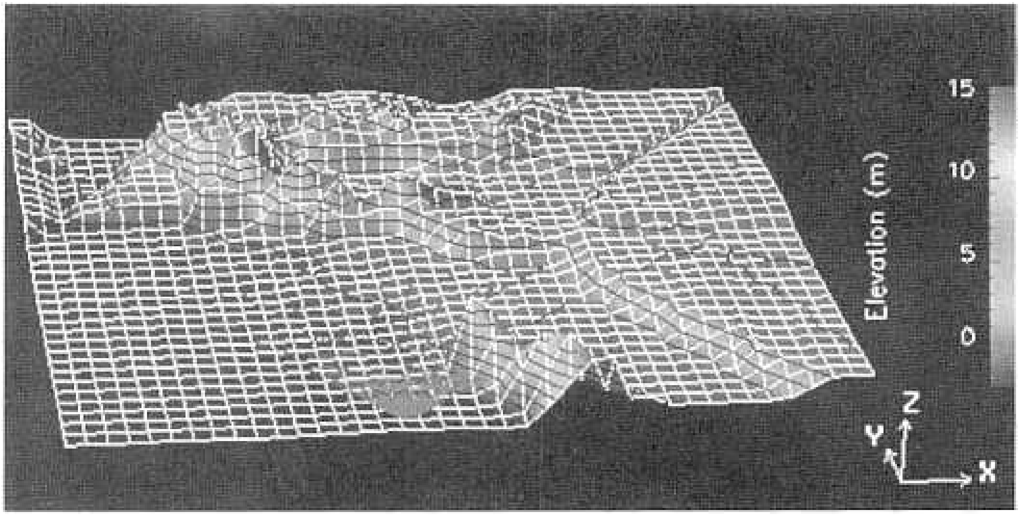


Fig. 3. Meshed surface of scanned terrain on NIST campus created using Data Explorer scripts.

a horizontal surface at an elevation of $z = 2$ m, the cut/fill requirements can be easily calculated. Fig. 4 shows the cut-and-fill contour surface. The desired excavation profile, the horizontal surface, was created using the same grid pattern as the terrain surface with all z-values set to 2 m. The contour surface was created by subtracting 2 m from the z-values of the original terrain mesh. The volume can also be calculated and the procedure is described in Section 3.2.

3.2. Scan surface from several locations

A small demonstration was developed to illustrate the viability of using a laser scanner for terrain status assessment and the ability to wirelessly transfer data from one location to another to achieve real time progress updates at a construction site. In this case, the NIST Large-Scale Testing Laboratory represented the construction site while the NIST NAMT computer laboratory represented the offsite engineering office. These laboratories are located in different buildings approximately 600 m from one another. In addition, the demonstration was used to determine the necessary post-processing tools needed to display and calculate the cut/fill requirements.

A small sand pile was used for the demonstration to simulate terrain. The Windows-based computer program on a laptop computer, instead of direct communication with the laser scanner, was used to control the laser scanner. The point clouds obtained from four different locations around the sand pile are shown in Fig. 5. The points from which the scans were obtained were previously surveyed using a total station and their relative coordinates were therefore known. For convenience, one of the points was selected as the origin of the reference frame from which the other three data sets would be referenced. In the future, GPS equipment will be used to determine the location and attitude (orientation) of the laser scanner. Algorithms will have to be developed to convert the scanned positions to a common frame of reference using the information obtained from the GPS equipment. The coordinate transformations may either be performed on the laptop computer in the field or may be performed on the offsite computer that receives the data from the field. For this demonstration, all transformations (translations and rotations) were performed semi-automatically. Even though the locations of the points were known to

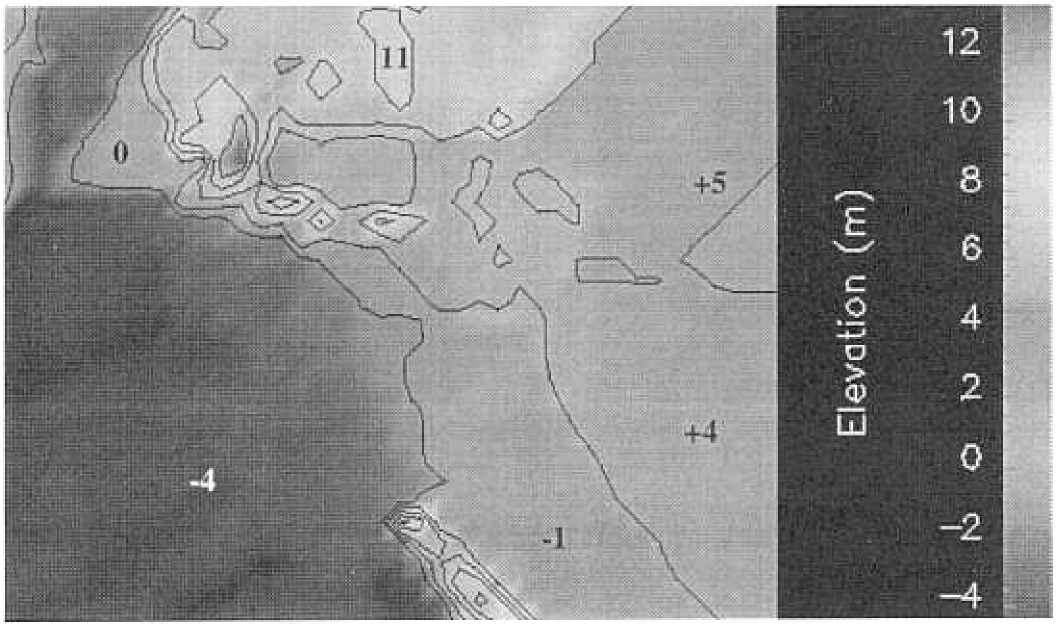


Fig. 4. Automatically generated cut/fill map created by operating on the 3-D terrain model of Fig. 3 with a final target elevation at $z = 2$ m. Negative numbers represent fill requirements (in m) while positive contours represent cut requirements.

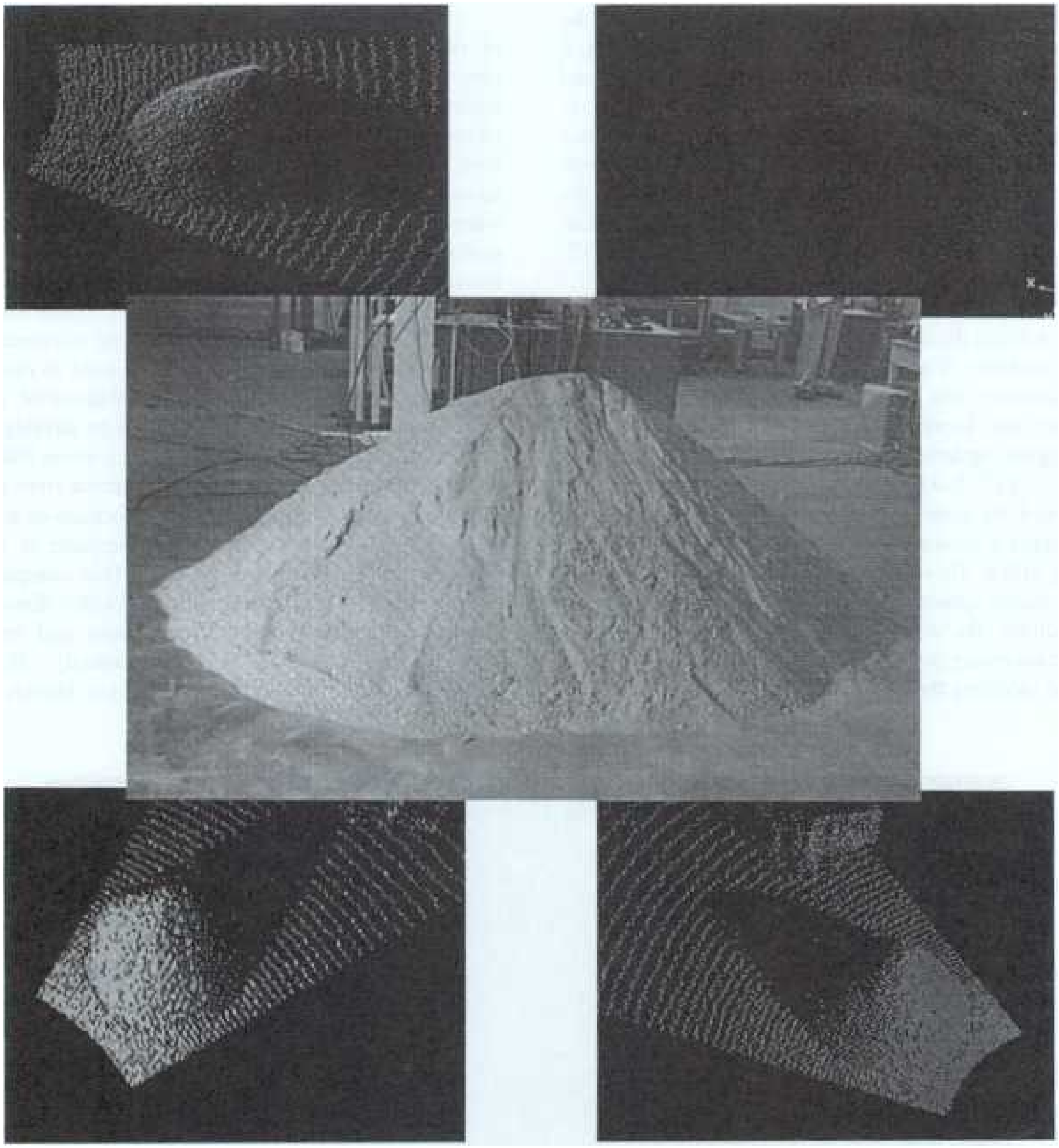


Fig. 5. Demo sand pile and the four point clouds obtained from the laser scanner.

within ± 2 mm[3], final registration of the point clouds was still required and was manually performed by visual means in Data Explorer. The need for further manual registration was due mainly to the inaccuracies associated with the angular measurements. These measurements were obtained using the scope on the laser to sight from one point to each of the other two adjacent to that point. The sources of measurement errors result from the scanner not being perfectly

[3] Reported accuracy of the total station.

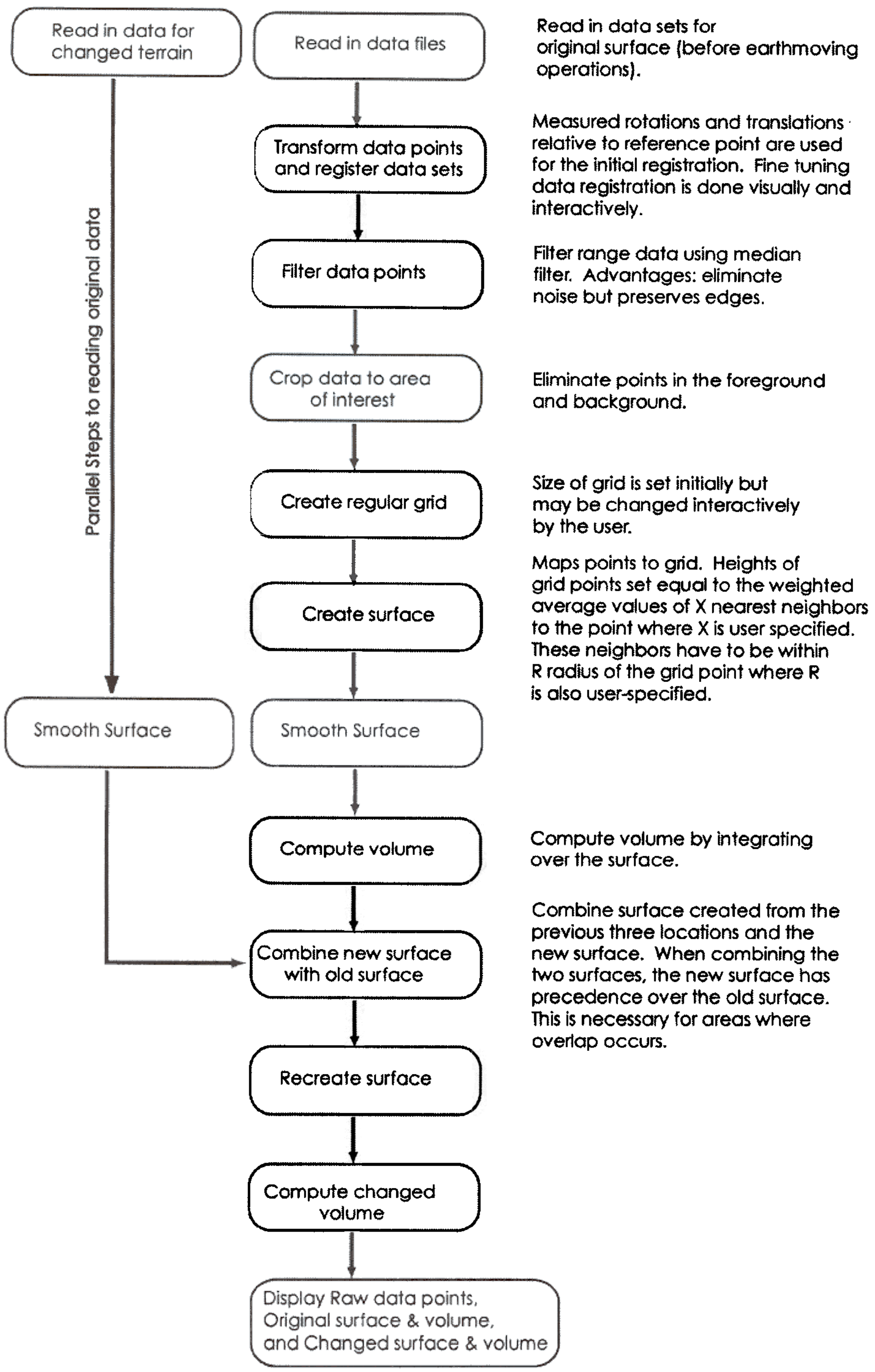
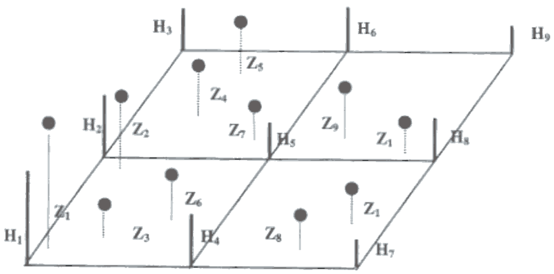


Fig. 6. Flow chart to display the LADAR data as point clouds and surfaces.



$$H_i = \frac{1}{n} \sum \frac{Z_i}{r_i^a}$$

$$n = \sum \frac{1}{r_i^a}$$

Z_i = z - values of the data points

r = distance of data point to grid point

a = user specified integer

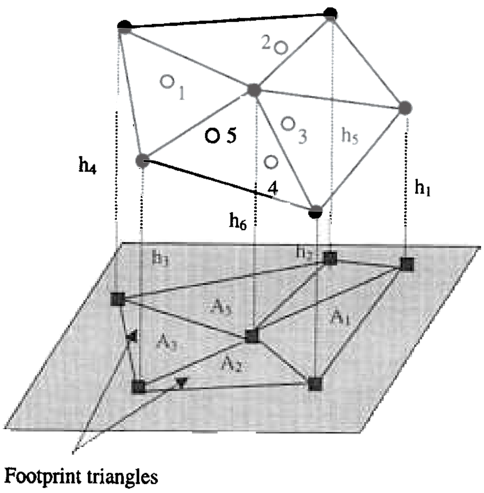
Volume = Total Grid Area $\sum H_i$

Fig. 7. Meshing of data points and volume calculation using Data Explorer script.

level — when obtaining the scan data and when reading the angular measurement, the line-of-sight of the scope not being exactly parallel to the laser, human limitations, and from errors in the laser's ability to measure angular moves.

The point cloud data were visualized using Data Explorer following the approach outlined in the flow chart shown in Fig. 6. In brief, the 3-D surface was created by first cropping the data to eliminate any points beyond the sand pile. Then a regular 2-D grid was created in the cropped region. The grid size was typically between 5 and 10 cm. At each grid point, the height at that point (H_i in Fig. 7) was set equal to the weighted average of the heights (Z_i in Fig. 7) of the point cloud data within a user-specified radius of the grid point. The number of points, radius, and type of filtering are user-specified parameters and may be changed interactively. The volume was computed by summing the heights over the grid and multiplying the sum by the area of the grid, see Fig. 7.

The Mathematical and Computational Sciences Division (MCSD) of NIST has developed in-house software for automated cut-and-fill analysis where data is received from the scanner. The MCSD method of volume calculation is based on representing the surface by a triangulated mesh over a Delaunay triangulation. The nodes of the mesh are a subset of the data points. The points in the subset are successively selected by minimizing the residual volume



● Subset of data points or node points

○ Data points not included in subset. They may be located above or below the triangular mesh surfaces.

To obtain h_6, h_1 to h_5 are held constant while varying h_6. h_6 is set equal to value at which the RMS of the residuals of the data points 1 to 5 and the triangular surfaces is a minimum.

$$\left(\frac{h_1 + h_2 + h_6}{3}\right)$$

$$V_{total} = \sum V_i$$

Fig. 8. MCSD method of meshing and volume calculation.

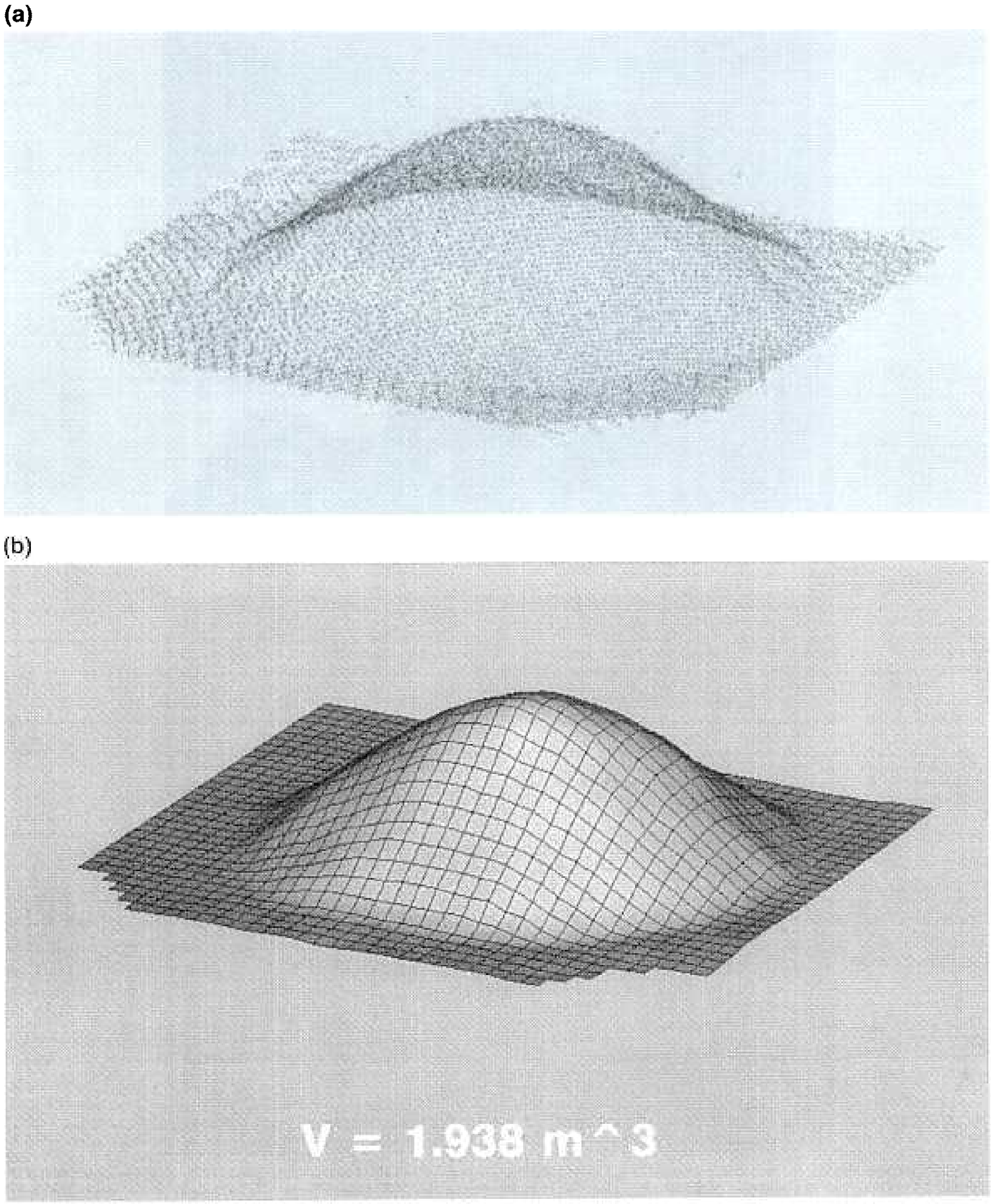


Fig. 9. 3-D surface of sand pile. (a) Combined point cloud from four scans. (b) 3-D surface.

(a)

(b)

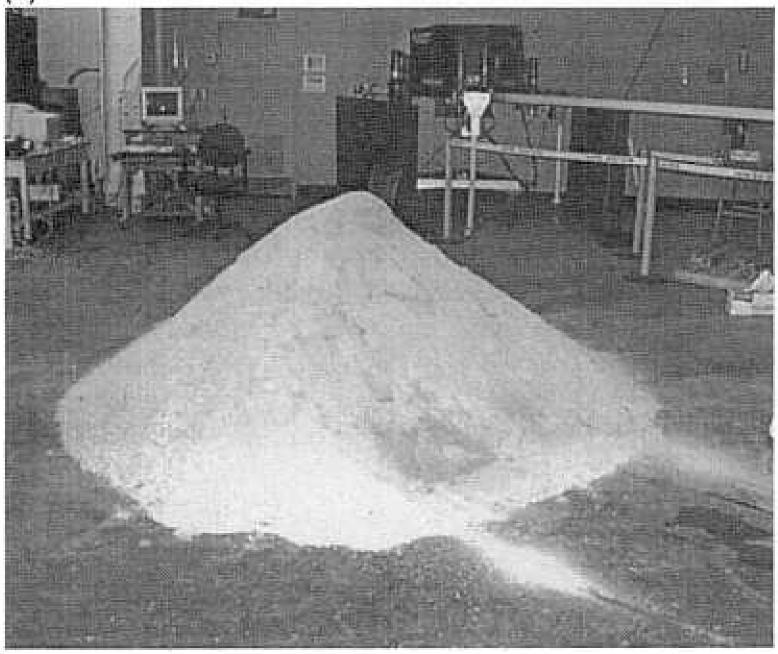


Fig. 10. (a) Modifying the pre-scanned scanned sand pile. (b) Photo showing the "changed terrain". (c) Re-scan of the sand pile from one location (facing removed material). (d) Combine new scan with old scans from other three locations and regenerate 3-D surface. Color fringe contours denote depth of material removed. The total volume remaining, and the volume removed is listed.

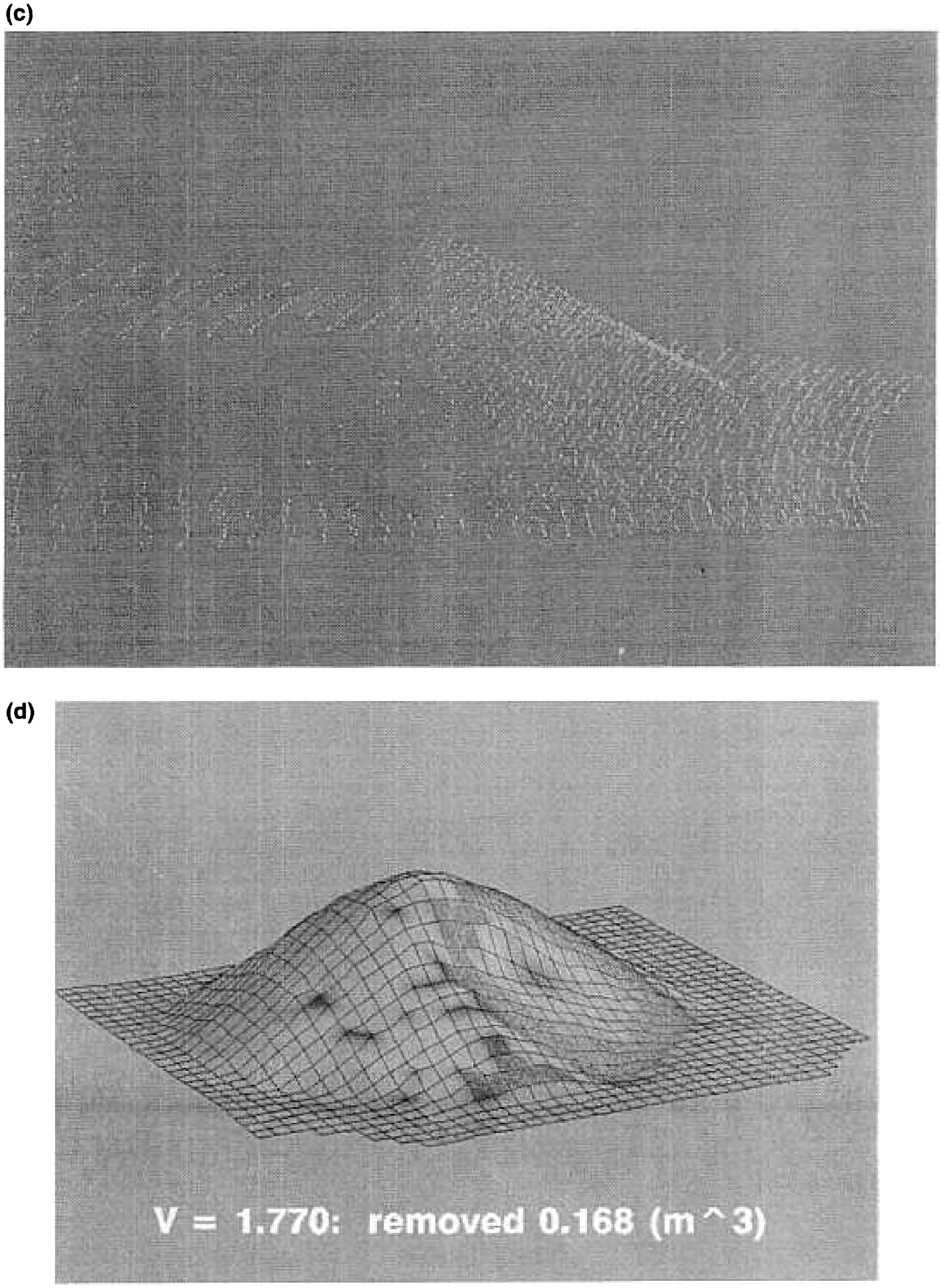


Fig. 10 (*continued*).

deviations from intermediate mesh surfaces. Subsequently, the elevations of the node points are adjusted to minimize the RMS of the deviations of all data points from the mesh surface (Fig. 8). This involves iteration of single node adjustment with respect to the data points that fall within the footprint triangles adjoining the node. The volume is the summation of the average of the heights of the prism multiplied by the area of the triangle (Fig. 8).

Fig. 9 shows the point cloud after registration of the four scans and the 3-D surface of the sand pile. The initial volume of the sand pile as computed using the Data Explorer script was 1.938 m^3 as compared to 1.964 m^3 computed using the MCSD algorithm.

To simulate a change in the terrain, a small front-end loader (Fig. 10a) was used to remove some sand from the pile. The sand pile was then re-scanned. In the interests of simplicity and saving time (the demonstration was conducted live before a remote audience 1 km from the construction site) only a single scan was obtained. This scan was taken from approximately the same angle of entry used by the loader. In general, it will not be possible to record all changes to an excavation site with a single scan. Therefore, it will be necessary to rescan the terrain from two or more locations followed by subsequent registration of the point clouds.

Once the revised sand pile data was acquired (Fig. 10c), the data file was sent via FTP to the NAMT lab where the volume calculations were performed and the new surface was regenerated and displayed. The data transmission, volume calculation, and surface regeneration were accomplished in a matter of seconds. The volume of sand removed was estimated as 0.15 ± 0.015 m^3, which is close to the computed value of 0.168 m^3 obtained using the Data Explorer script and the MCSD algorithm. Major source of difference between the estimated value and the computed values is compaction of the sand during removal from the sand pile and during placement of the sand into buckets. The estimated volume of sand removed was obtained by shoveling the sand into buckets and calculating the volume of the bucket. Compaction of the sand would result in a lower estimated value for the amount of sand removed.

The data transmission from the laptop was achieved by using wireless Ethernet to establish the uplink in the field with the remote site. Procedures are being developed at NIST for fully automated transmission of the field data, volume calculation updates, and re-generation of 3-D simulation scene updates.

The sand pile demonstration illustrated the viability of using a laser scanner to provide real-time updates of construction progress. The next step is to develop a mobile platform for the LADAR. This will be accomplished by mounting the LADAR unit on a heavily instrumented all-terrain vehicle (ATV) which automatically registers the LADAR data to the job site using precise (millimeter level) GPS position and attitude reporting and a geometry transformation to adjust for instrumentation that are not co-located. Registration of the vehicle-based data will involve more elaborate calculations, owing to the additional sources of error from the vehicle position and attitude sensors. The advantage of this approach is significant as it opens the route to fully automated terrain status sensing at a job site using small, unmanned vehicles.

From these studies, we anticipate the development of automated information transfer protocols for the uplink of both construction site terrain data as well as discrete component locations. This work is concurrently being conducted by other researchers at NIST [2] under the FIATECH construction metrology and automation initiative.

4. Future work

Future work planned at NIST includes registering data from different scan locations using RTK global positioning devices to establish a common reference frame for the data points; developing a mobile platform for the LADAR, and using scanning technology to track the progress and to document the construction of the Emissions Control Facility for Building 205 at NIST. A more robust cut/fill algorithm is being developed that can accommodate terrain features such as undercuts and vertical surfaces and to perform automated registration of two or more point clouds.

Alternative post-processing approaches to compute and display the cut/fill requirements, using commercially available software packages such as Interactive Data Language (IDL), and products from

Intergraph and AutoDesk, will be investigated. The purpose of this process being to compare the accuracy of the results (e.g. volume calculations) of different methods and the ease of use of different methods. Verification of the existing methods of volume calculations will also have to be conducted.

Additional verification of the scanner in various climatic and topographic environments is needed to determine its limitations. Climatic conditions such as bright sunshine, overcast skies, light rain, etc. Topographic conditions such as hilly terrain, relatively flat terrain, large and/or deep pits, trenches, tunnels, etc.

In the longer term, object recognition (human-assisted in the beginning with the end goal of full automation) will also be investigated. This will allow dense scanned data to be replaced by more compact 3-D model (e.g. VRML) representations and will advance the goal of obtaining automated 3-D as-built models. NIST is also pursuing the fundamental development of more advanced imaging and ranging devices through its Advanced Scanner Initiative for higher scanning rates and more accurate distance measurements (in the millimeter range for distances of 100 to 500 m).

References

[1] IBM, Visualization Data Explorer, Version 3, Release 1, Modification 4.

[2] L. Pfeffer, Mobile sensor platform for construction metrology and automation: design and initial results, in: Proceedings of the 15th International Symposium on Automation and Robotics Conference (ISARC 15) Madrid, Spain, September,1999, in press.

[3] F.P. Preparata, M.I. Shamos, in: Computational Geometry — An Introduction, Springer-Verlag, New York, 1985.

[4] J.T Sackos, B.D. Bradley, C.F. Diegert, P.W. Ma, C. Gary, Scannerless terrain mapper, Proceedings of the SPIE — The International Society for Optical Engineering Space Sciencecraft Control and Tracking in the New Millenium, Aug. 6 2810 (1996) 144–153.

[5] W. Stone, K. Reed, P. Chang, L. Pfeffer, A. Jacoff, Toward Automation in unstructured environments: NIST research on real-time job site information closure, ASCE Journal of Aerospace Engineering 12 (2) (1999) 50–57, Special Issue on Construction Automation, April.