Improving Transportation Projects Using Laser Scanning

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Abstract: This paper describes a case study investigating the use of laser scanning to acquire design and construction data. It is intended for both industry practitioners and academics who are interested in this relatively new technology. Included is a brief description of the technology, discussion of the case study, lessons learned, and results. Projects in the case study included an intersection, highway, pair of bridges, new pavement, bridge beams, a stockpile, and a borrow pit so that different perspectives (elevation, smoothness, camber, and volume) of the application were tested. The study proved that laser scanning is ideally suited for measuring the volume of soil and rock, determining road surface elevations and bridge beam camber, and assisting in the creation of as-built drawings in a three-dimensional environment. It was discovered that this technique can be used quite effectively for safer and more accurate construction measurement. Time requirements, cost comparisons to photogrammetry, and limitations are also discussed.

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Introduction

As transportation projects become more complex, it is important to take advantage of appropriate innovative technologies for reducing project cycle time. Laser scanning is one such technology that has potential benefits over standard surveying techniques, such as total station or aerial photogrammetry, for providing accurate as-built drawings. Laser scanning is a terrestrial laser-imaging system that quickly creates a highly accurate three-dimensional (3D) image of an object for use in standard computer-aided design (CAD) software packages. Laser scanners offer a wealth of information about a structure's surface in the form of a dense set of 3D point measurements using a laptop computer, laser scanner, and tripod. Images are developed from a pulsing laser beam capable of capturing approximately 2,000 data points per second up to 150 m away. Several terrestrial laser-imaging systems have been developed by the following companies: Cyra, Maptek I-Site, Soisic, and Mensi. The operating principle is similar for all devices (Patterson 2001). Fig. 1 shows a photograph of the Cyra 2500 Laser Scanning Unit that was used in this case study.

The laser's pulsed and visible green beam is moved across a target in a raster scan (Cyra 2002b). Once an object is encountered, the laser beam is reflected back to the unit with the time of flight, which generates a measurement of distance. These measurements produce an impact location, which is displayed as a cloud of points. Measurements taken from the "cloud" can be used to conduct interference detection and constructability studies. As an object is being scanned, each 3D measurement appears immediately as a graphical 3D point image on the laptop screen. This cloud of points is a dimensionally accurate representation of the existing object. The result is a 3D visualization that gives clear outlines and color differentiation to geometric elements.

Besides obtaining 3D images from laser scanning and the manufacturer's software, it is possible to export point cloud data to CAD applications such as AutoCAD, MicroStation, and 3ds max. This is because each point has embedded x, y, z data, so the point cloud can be directly loaded into a CAD program without any need of digitizing.

Laser scanning technology has been successfully demonstrated on numerous projects related to developing bridge as-built drawings, highway widening, refinery expansion projects, water utility construction project archives, rock face surveys, dam foundation surveys, cave scanning, tie wire inspection, and visual effects for movies (Cyra 2003). Laser scanning can capture fine detail from specific parts of a scene (Sawyer 2002); therefore, it will benefit the collection of existing structures data for reconstruction (Angelo 2003). In several cases, field and office time was reduced using laser scanning compared to conventional methods.

Project Objectives

The objective of this study was to investigate the use of laser scanning to assist the Iowa Department of Transportation (Iowa DOT) in delivering projects in a safer and more efficient manner. Specific tasks included:

1. Learn how to use the laser scanner and software.
2. Select appropriate pilot projects to test the capabilities of this technology.

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Fig. 1. Cyrax 2500 laser scanning unit

3. Determine the benefits and costs associated with using this technology and compare to conventional approaches.
4. Provide recommendations regarding the future use of laser scanning for the Iowa DOT.

Laser Scanning Training

A Cyra trainer provided the training of the Cyrax 2500 laser scanner and *CYCLONE* software (Cyra 2002a) to six people using a two-session format. The training was conducted in Ames, Iowa at the Iowa DOT facilities and took approximately five days to complete. Training began with an overview of the Cyclone software then moved to the field where a complete instruction of the laser scanner was provided. A training manual was also provided, which helped to further explain the details of the hardware and software. A more detailed discussion is provided of the field setup and data processing procedures in the following sections.

Field Setup

Hands-on laser scanning training was performed using the intersection of Grand Avenue and Lincoln Way, and the Union Pacific railroad bridge at Grand Avenue in Ames, Iowa. Several important steps were learned during the field training exercise. First, it is important to create a database for the soon-to-be-scanned point cloud data to reside. A unique database is established for each pilot project. Second, it is important to establish a coordinate referencing system that ties all of the scans together during the registration process and identifies the location of all points in a known reference system. Globe targets were introduced into the scene as registration objects, and were scanned and surveyed to identify their x,y,z coordinate location. Each target needs to be acquired after the initial scan and given an identification number. A coordinate file from survey control is then imported into the scanworld (defined as the image captured for one single scan) database before the registration process begins. Third, it is vital to include at least three targets in each scan as this is essential for precise registration of the various scans. Fourth, laser scanning time varies depending on the scanner resolution. For example, the highest resolution (999×999 pixels) required about 16 min whereas a 250×250 pixel scan took about 5 min to complete.

Table 1. Purpose of Pilot Projects

Pilot project	Purpose
Intersection and railroad bridge	Learn about the Cyrax 2500 scanner and *CYCLONE* software (training exercise).
Section of highway and pair of bridges	Determine surface elevation of highway and compare to aerial photogrammetry. Also, determine the level of bridge detail available using laser scanner.
New concrete pavement	Determine smoothness of freshly paved concrete.
Bridge beams on unfinished bridge	Assess camber on bridge beams for determining optimal loading requirements.
Stockpile	Determine volume of stockpile and compare to traditional methods.
Borrow pit	Determine volume of borrow pit and compare to traditional methods.

Data Processing

Hands-on data processing was demonstrated during training and included point cloud registration, fitting and editing, mesh editing, developing contours and line drawings, and using the virtual surveyor function. A brief description of each data processing function is described below.

Registration is an essential step that ties together all of the individual scanworlds into a complete image of the scanned object. It is during this stage that errors are identified with the target numbering and coordinates assigned to the targets. After registration is completed, a model space is created for the registered scanworlds. Scanned images may contain superfluous points (or noise), such as vertical lines representing traffic, that need to be removed. The process of cleaning the noise and modifying the registered images is called fitting and editing. The *CYCLONE* software provides the capability to remove the superfluous data using segmenting, region growing, and other special editing tools. To make a cleaned and edited point cloud more manageable in *CYCLONE* or for further use by exporting to other CAD packages such as MicroStation, a Triangulated Irregular Network (TIN) mesh must be created. In order to measure the clouds and meshes and export the object to two-dimensional (2D) drawing software packages, contour and line drawings must be created.

Virtual Surveyor is a useful tool in *CYCLONE* to easily obtain information without physically being at the site. Using scanned point cloud data, one can easily select coordinates, assign codes and notes, and export data to other applications. It is possible, for example, to determine the x,y,z location of a manhole cover in the middle of a busy intersection without ever physically standing there.

Description of Pilot Projects

In total, there were six test areas involved in this pilot study: (1) An intersection including a railroad bridge, (2) a section of highway including a pair of bridges, (3) new concrete pavement, (4) bridge beams on an unfinished bridge structure, (5) a stockpile, and (6) a borrow pit. Table 1 summarizes the purpose for each pilot project. These projects were selected because they were of particular interest to the Iowa DOT as areas where greater efficiencies could be attained. The intersection of Lincoln Way and Grand Avenue in Ames, Iowa, was selected for training to learn how to use the laser scanner as described above. This site pro-

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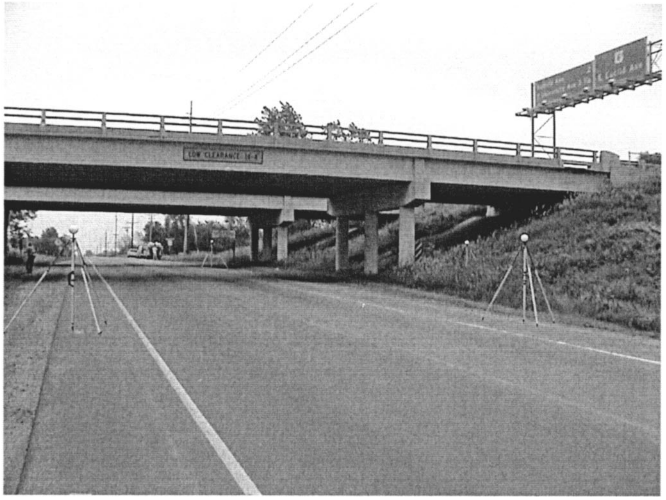

Fig. 2. Southbound Broadway Bridge (pair of bridges)

Fig. 3. Top view of stockpile

vided a suitable location since it is across the street from the Iowa DOT facilities where the training class was conducted.

The Iowa DOT is particularly interested in comparing the elevation accuracy using both laser scanning and aerial photogrammetry for roadways surfaces and determining the level of detail that can be provided on bridge structures. Thus, approximately 400 m of I-235 and a pair of bridges (Fig. 2) at Broadway Avenue, located immediately south of the I-80/I-235 intersection in Des Moines, Iowa, was scanned.

In order to investigate the accuracy of the laser scanner in determining the smoothness of pavement and to perform a comparison to a profileometer, a newly paved concrete pavement was chosen for the study. The location was Highway 5 approximately one mile west of Highway 28 at mile marker 98. Meanwhile the beams on an unfinished bridge, located on Highway 520 in Hardin County, Iowa, were selected to determine the camber on the main bridge beam members prior to the deck placement.

It was suggested by a materials engineer at the Iowa DOT that the research team should test how accurately the laser scanner can determine the volume of a stockpile, which is important for determining contractor pay quantities. A selected stockpile was approximately 1/4 mile west of the railroad bridge on Highway 520 in Hardin County, Iowa (Fig. 3). Similar to the stockpile, a borrow pit was scanned in order to accurately determine pay quantities to the contractor. The location of the test borrow pit was in the northeast corner of the I-35/I-80 East mix master. However, there were some difficulties registering all of the scanworlds associated with the borrow pit pilot test. This was because only two targets were used in several scans and there was no overlap with other scanworlds. This meant that the research team was unable to register the entire borrow pit into one complete 3D image. Consequently, it was decided to discard this borrow pit project and rely on volume-measuring capabilities using the stockpile pilot project.

Field Operations

Field operations involved two major tasks: (1) Set up survey control points and targets (i.e., globe targets mounted on tripods) and (2) scan the desired objects and acquire targets. The research team consisted of the surveying crew and the scanning crew. The scanning operation involved several activities related to properly using the *CYCLONE* software such as creating a database, operating the scan control window, and acquiring targets.

The survey crew consisted of five surveyors and one coordinator (actually, two surveyors are enough to complete the task). The survey crew used traditional methods to set up targets and tie them into the Iowa state plane coordinate system. Thus, different scans could be registered and matched to each other with a high degree of accuracy. The surveying time was not specifically tracked but should be similar to the scanning time. This is because the surveyors worked the same hours as the rest of the team.

The scanning crew consisted of two operators. Table 2 shows the basic information related to the number of scans and duration of each scan. Scanning time defines the difference between start and end times of scanning. Start time is when the scanner begins to take the point cloud image while end time is the time point of disconnection from computer to scanner. Scanning times varied per scan primarily because scans were performed using different resolutions.

There were several lessons learned during the field portion of the laser scanning pilot test. Since the research team had adequate control on each target, it was not necessary to have common targets in every scan. Overlapping targets are necessary when there is no knowledge of the x, y, and z coordinates for each location. To obtain proper registration, at least three targets need to be common in each scan when control is not established on the targets.

Table 2. Field Scanning Information for Pilot Projects

Pilot project	No. of scans	Total scanning time (h)	Average scanning time (min)
Intersection and railroad bridge	—	—	—
Section of highway and pair of bridges	30	14.0	28.0
New concrete pavement	3	1.6	32.0
Bridge beams on unfinished bridge	5	2.9	34.8
Stockpile	3	1.5	30.0
Borrow pit	17	4.4	15.5

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Table 3. Analysis of Pilot Projects

Analysis and facts	Pilot projects: Section of highway	Pair of bridges	New concrete pavement	Bridge beams	Stockpile	Borrow pit
Importing coordinates	X	X	X	X[a]	X	X
Registration	X	X	X	X	X	X
Fitting and editing	X	X	X	X	X	
Mesh editing	X	X	X	X	X	
Contouring		X	X		X	
Using Virtual Surveyor	X		X	X	X	
Exporting	X	X		X	X	
Two-dimensional drawing		X				
No. of scans	18	12	3	5	3	17
No. of valid scans	17	12	3	4	3	17
Coordinate control problems	Many	Many	None	Few	None	Many
Amount of cleanup required	Substantial	Substantial	Less	Average	Average	Less
Extra procedures	Yes	Yes	Yes	Yes	Yes	Yes

[a]Not tied to state (of Iowa) plane coordinate system.

Target acquisition is a critical issue for scanning and registration later. During the scanning process a few different types of mistakes were made that created additional work in the field and office. Some of the more common examples are listed below:

- Targets were completely missed during the initial scan because the targets were out of scanning scope or blocked by barriers. This reduced the number of targets in the scanworld and caused difficulty during the registration process.
- Failure to scan the correct targets because the nontargets were accidentally treated as targets. This was typically detected during the acquisition process and required the operator to reacquire the correct target.
- Paired targets were mislabeled (switched). This could be corrected during the registration process.
- Targets with labels that do not exist in the control files. This could be corrected during the registration process by including the correct coordinates.
- Targets without labels. This lead to difficulties during the registration process because it was hard to tell which target was being used.
- Targets with double labels. This happened because the same two targets were acquired during the acquisition process using different labels. This problem was corrected during the registration process.

It was found that vibrations or scanner movement during the scanning operation makes it very difficult to align images during the registration process. This is because the scanned image becomes distorted once the scanner is moved from its initial position. Thus, it is important that the laser scanner be mounted on a stationary, nonvibrating surface. The scanning can be affected by heavy earth moving equipment or traffic on roadway and/or bridges. It was found that the wind created by trucks driving at highway speeds affected the quality of the scan.

Data Analysis

Not all of the projects required each of these steps above (see data processing of laser scanning training section) as the requirements were dependent upon the desired outcome. Sometimes special steps were necessary in order to meet the unique requirements of the pilot tests. Table 3 provides details related to the image processing for each of the pilot projects (except for the intersection and railroad bridge training exercise).

Section of Highway and Pair of Bridges

This project has 30 scanworlds, with one scanworld not being used due to scanner movement during scanning. The roadway portion of I-235 has 17 valid scans out of 18.

Registration

This project was the first one that the research team did on its own after training. As a result, there were many mistakes related to correct target acquisition, which made the registration process more time consuming. A total of nine targets in eight scanworlds had target problems. It was found that checking and measuring target locations and distances between targets in the control space is an efficient and effective way to identify the problems once large errors appear. Corrective action was taken in the model space and a new control space was created.

Because some mistakes were made with the first few scanworlds, extra work was required to minimize the registration errors. After registration and related cleanup work, there were still some targets with errors slightly larger than the original tolerance of 0.009 m although most targets with errors ranged from zero to 0.007 m. Those errors could have been caused by either not properly setting the targets or distortion of the laser beam. Because the greatest errors were in pairs of targets with distances greater than 50 m, distortion is most likely the reason.

Fitting

The process of removing the noise and modifying the registered scanworlds went smoothly for I-235 and primarily involved removal of superfluous data representing traffic on the roadway surface. Because the scanned images are 3D objects, different

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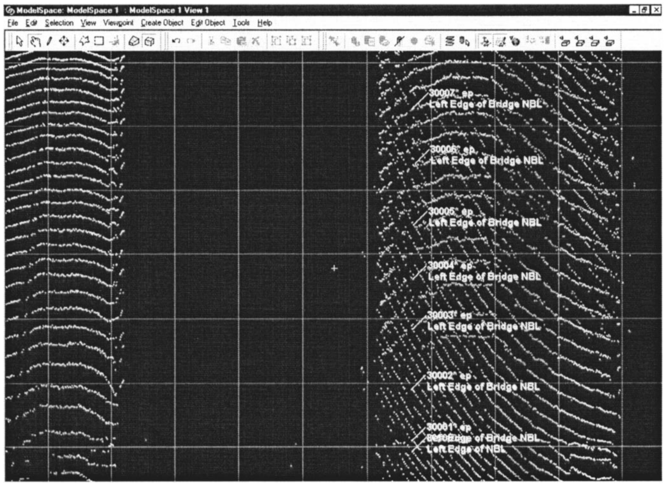

Fig. 4. Virtual surveying at left edge of I-235 northbound lane

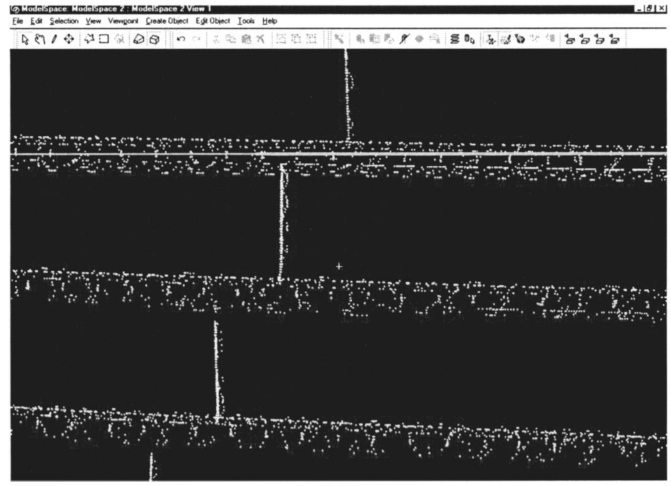

Fig. 5. *X*-axis reference plane used on Hardin County Bridge

perspective views had to be checked in order to make sure the traffic noise was completely removed. Although the research team expended a significant amount of effort on mesh editing the point cloud file, this step was not really necessary since elevations could be measured directly using the Virtual Surveyor routine.

Using the Virtual Surveyor Routine

Fig. 4 shows the virtual survey of I-235. The surveyor generated a text file by picking points along the desired path. The coordinate text file for I-235 includes the identification number Y, X, Z coordinates, features (location of points) and codes (the abbreviation of the features). The identification number for each point can be integrated into any identification system.

Identification of the elevation coordinate values (z) of the I-235 roadway was the major goal of this pilot project.

Bridge Beam Camber

This project has five scanworlds, one of which was disregarded due to a deficient field scan (two of the targets were acquired twice using a different identification number). This problem was solved by deleting the extra target and correcting the incorrect labels during registration. A total of 11 beams on the bridge were scanned. Five analysis trials were performed for the Hardin County Bridge. The last (fifth) trial resulted in the final analysis results. Because the Hardin County Bridge was under construction, there was no traffic noise and thus minimal data cleanup was required. Determining camber involved measuring the elevation of many points along the top of each beam. Therefore, meshing is not necessary and the virtual surveyor can be used directly on the point cloud image.

A few new special features were applied to the Hardin County Bridge because the beams were not parallel to the reference plane axis, and establishing the true top of the beam surface was challenging because of the protruding steel reinforcing loops present on the top surface. To be able to use the virtual surveyor routine along the beam, a new coordinate system was created by drawing a line on the beam, which was set as a new x axis instead of the default system (Fig. 5). Also, one end of that beam was set as the new origin. The new x-z cut plane was used as a new reference plane to cut the beam into slices. By defining a proper thickness of each slice, the top boundary line can clearly be determined by the front view of the beam slice. After this step, the normal virtual surveying process can be applied.

Stockpile

This project involved most of the data processing steps. Registration of targets and scanworlds was simple and without any major problems due to a small number of scanworlds and satisfactory target acquisition in the field. Because of the irregular shape of the stockpile, the fitting and editing processes were more difficult than those for the other projects. In particular, it was difficult to remove some of the brush and vegetation without removing portions of the stockpile.

Fitting

Vegetation removal on the stockpile was the most difficult part of the editing process. After numerous trials, a set of parameters was determined as a best solution to remove the brush and vegetation with minimal disruption to the stockpile. After applying the region growing routine, some leftover target tripods still required removal using a manual approach. This usually also deleted some of the stockpile but did not influence the final result because the density of the point cloud was sufficiently high. Fig. 6 shows a graphical representation of the contours on the stockpile pilot project.

To measure the volume of the stockpile correctly, the mesh volume had to be measured taking into consideration the sloping ground below the stockpile. Since it was not possible to establish a curved reference plane that follows the upward sloping stockpile, it was necessary to create two separate meshes with one reference plane. The top mesh is based on the entire cleaned point cloud (Fig. 7). The bottom mesh is based on the surrounding area of this point cloud (Fig. 8). The desired volume of the stockpile is calculated by taking the volume difference between the top mesh relative to an arbitrary reference plane and bottom mesh relative to the same reference plane. The reference plane can be randomly chosen but must be below the top of the bottom mesh in order to simplify the calculation.

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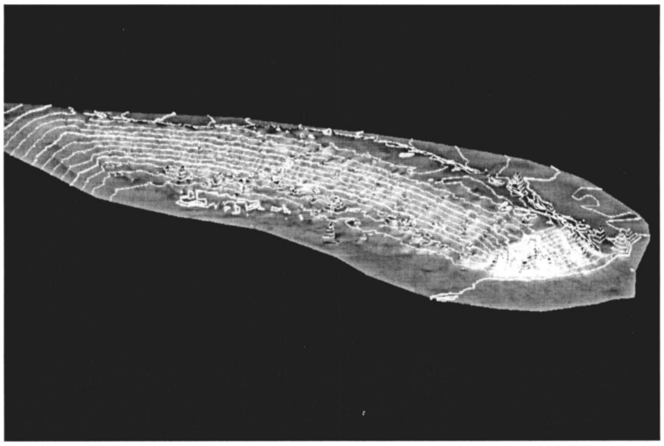

Fig. 6. Contour lines for stockpile

Study Results

The results include information from the pilot tests, time expended to perform the pilot tests, and a cost comparison between aerial photogrammetry and laser scanning.

Technical Results

Elevation measurements of the I-235 roadway centerline, lane edges, and shoulders were taken using the *CYCLONE* Virtual Surveyor. The results were exported into an ASCII format file. To determine the accuracy of those data points and to compare them with those from other surveying methods such as aerial photogrammetry, an ASCII file was converted into a *GEOPAK* file to create the plan views of I-235. While the difference between those methods can be clearly seen from the MicroStation file, a detailed accurate comparison was also conducted. The average difference for measuring elevation at the lane edges between traditional surveying and Cyra laser scanning ranged from 0.001 m to 0.009 m, while the difference ranged from −0.006 m to −0.023 m between aerial photogrammetry and Cyra laser scanning. This comparison demonstrates that much more accurate measurements can be obtained from Cyra laser scanning technology than from the photogrammetry method.

The stockpile volume was calculated assuming that the reference plane is established at 300 m. Using this assumption, the top and bottom mesh volumes are 2,176.85 and 1,669.78 cubic meters, respectively. Thus, the stockpile volume is 507.07 cubic meters. The volume of this stockpile was calculated using a traditional surveying approach and *GEOPAK* software and was found to be 512.96 cubic meters. It can be seen that the results of both surveying methods are fairly close to one another (1.2% difference, or approximately 6 cubic meters).

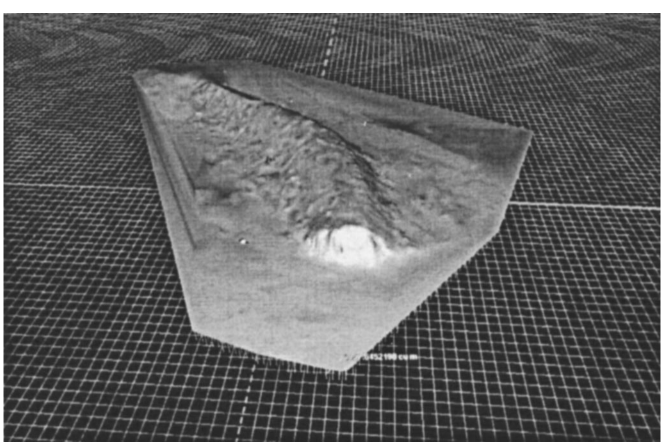

Fig. 7. Top mesh of stockpile

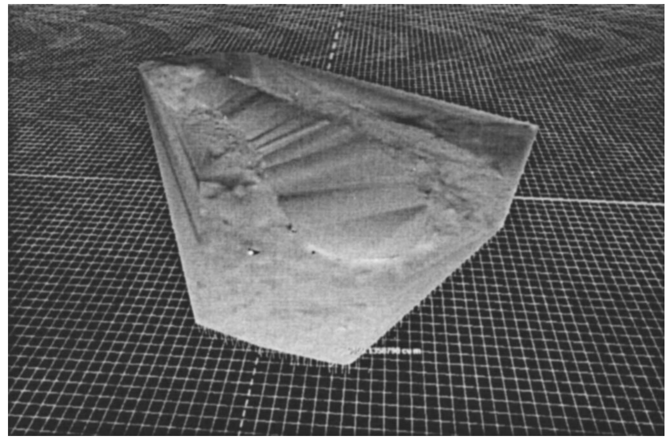

Fig. 8. Bottom mesh of stockpile

Results show that it is possible to measure bridge beam camber using the virtual surveyor routine in the Cyclone software. Camber differences varied from 0.4 mm to 10.1 mm. It was not possible, however, to adequately determine the smoothness of the pavement surface. The primary reason is because the laser scanner has an accuracy of two to six millimeters. Most smoothness irregularities will fall within or below the accuracy range of a laser scanner. Therefore, the application of this new technology, in its current state, is not sufficiently sensitive to monitor the smoothness of freshly paved concrete.

Time Requirements

Overall, a total of approximately 870 effort-hours (15.1 effort-hours per scan) were spent on this pilot study, including 403.1 effort-hours for fieldwork, 153.5 effort-hours for lab analysis, and 313.0 effort-hours for training. Different groups of participants, including a training group, a scan crew, a survey crew, and lab analysts were involved in different phases of the learning process. Some people who attended the training course did not participate further with the project. Also, an assumption was made that the same field time was spent by the scan crew and the survey crew. All of these facts make the time tracking and analysis a complicated process.

Table 4 summarizes time spent on the entire project. In order to evaluate the project more accurately, the time spent by people who attended training but who were not involved in any other tasks was removed from the total hours, yielding the actual hours. Clearly, the learning time is more significant than may be expected. In order to maximize production and efficiency, the size of the training and scan crew can be reduced to one scanning operator and one coordinator while the survey crew can be reduced to three surveyors and one coordinator (the same person as the scan coordinator) without influencing work quantity or quality. Therefore, projected hours were calculated based on these crew sizes and are also listed in Table 4. The total effort-hours are reduced to 477.5 from 805.6 (a 40% reduction). The field time, lab time, and learning time account for 55, 17, and 28% of the

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Table 4. Summary of Total Time Spent on Pilot Study

Type	Actual time (h)[a]	Projected time[b] (h)
Field time[c]	403.1	262.5
Scanning operation	187.4	121.0
Transportation	114.0	75.0
Breaks	57.0	37.5
Setup	38.0	25.0
Support	6.7	4.0
Lab analysis time[d]	153.5	80.0
Learning time[e]	249.0	135.0
Training course	120.0	80.0
Reading and studying	40.0	20.0
Watching videos	30.0	15.0
Defining procedures	9.0	10.0
Discussion	20.0	10.0
Meetings	30.0	0.0
Total	805.6	477.5

[a]Actual effort-hours equal total effort-hours minus learning time from one participant (64 effort-hours).

[b]Projected effort-hours are projected time to complete the same study by reducing unproductive resources.

[c]For field time, some nonoperation time (e.g., transportation, breaks, setup, and support) were counted because these are necessary for performing fieldwork and are counted in the total work time.

[d]Lab analysis time includes time for all of the trials regardless of productivity as well as note-taking time.

[e]Learning time includes several different learning methods: Training, reading, video watching, and discussion. Among them, the two-session training (basic and advanced) is the primary approach to starting this project while the video watching is the review of the training course.

total hours, respectively. The total hours above can be converted into hours per scan (Table 5). The actual effort-hours per scan are 14 (7.0 in the field, 2.7 in the lab, and 4.3 for learning). Learning time is a one-time investment and will have less impact on total time as more projects are scanned and analyzed. Also, the time spent on field operations contains some nonoperational activities that can be reduced in future projects. If the training and nonoperational time are excluded, the time per scan is 3.7 effort-hours for field operations and 2.5 effort-hours for lab analysis.

Cost Comparison

According to the data from the Iowa DOT, aerial photogrammetry costs approximately $2.66 per linear foot. Based on the pilot study on elevation of I-235 roadway, laser scanning costs $3.43 per foot. It is anticipated that the cost will actually be reduced as the scanning crew becomes more proficient with the laser scanning operations. Therefore, the long-term cost would be lower. Although the laser scanning cost is approximately 30% higher than that for aerial photogrammetry, laser scanning offers advantages in terms of accuracy. Due to this characteristic, it may be possible to use laser scanning for the initial project planning and design phases. However, scanning would need to be carefully coordinated, as the scan makes no distinction between the differing surfaces involved. Aerial photogrammetry does offer some benefits here because features such as centerlines and shoulders can be visually identified. Laser scanning costs can be reduced if the scanner were to be mounted on platform vehicle, allowing both sides of the divided highway to be scanned at the same time. It is surmised that the costs would then be comparable to aerial photogrammetry.

The above time and cost comparison has its limitation. This is because the time and cost of laser scanning contain a significant amount of time spent on the learning process. Therefore, once people have become familiar with this technology, the actual time and cost requirements would be reduced. Also, the accuracy of technical results would probably improve as well.

Table 5. Actual Scanning Time by Classification

Classification	Total time (h)	No. of scans	Time per scan (h)
Field	403.1	58	7.0
Lab analysis	153.5	56	2.7
Learning	249.0	58	4.3
Total	805.6		14.0

Conclusion and Recommendations

Laser scanning appears to have applications for transportation projects. Applications requiring a significant amount of detail that needs to be captured and/or applications where safety may be an issue (such as providing accurate measurements on an active roadway) will benefit the most from the strengths of this technology. Laser scanning performed quite well on determining quantities of soil and rock. Laser scanning was also able to determine the beam camber quite efficiently and accurately.

The laser scanner is not yet suitable for measuring concrete pavement smoothness on newly paved concrete. It takes a significant effort to become proficient with this technology and continued practice to maintain a level of sharpness. If there are sufficient opportunities to use this technology, then it is recommended that the user purchases the *CYCLONE* software and purchase or rent the scanner; initially, it may be prudent to rent the scanner. Surveyors should use more traditional approaches to capture these data or hire a consulting firm with this expertise to provide the laser scanning services if they would only use laser scanning infrequently.

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Appendix. Definitions

- *ControlSpace*—A view space used as a container for all objects in its parent ScanWorld for possible use in registration constraints.
- *Cut Plane*—A user-specified plane that generates line segments at the intersections with objects in the scene.

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- *Target*—a reflective target with a special pattern whose center can be accurately determined.
- *ModelSpace*—A collection of geometry, usually defined with respect to a ScanWorld that specifies the default coordinate system and other information.
- *Photogrammetry*—A technique of measuring objects (2D or 3D) from photographs,
- *Registration*—A collection of ScanWorlds and the constraints between them.
- *ScanWorld*—A collection of registered scanned point clouds (or scans) that are aligned with respect to a common coordinate system.
- *TIN mesh*—a mesh of contiguous triangles in which no two vertices share the same X and Y coordinates, and no two triangles overlap the vertical axis.

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