EVALUATION OF 3-D LASER SCANNING FOR CONSTRUCTION APPLICATION

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Research Report ICT-10-068

A report of the findings of
ICT-R27-30
Evaluation of 3-D Laser Scanning for Construction Applications

Illinois Center for Transportation

April 2010
The objective of the project was to evaluate cost-effective means to implement laser scanning technology in the construction phase of IDOT projects. The primary goal was to study the use of a laser scanner for evaluating pay quantities for earthwork operations. The feasibility of using a scanner for other applications such as monitoring settlement due to pile driving, providing initial survey data for design, evaluating gravel and pavement thickness, assessing pavement roughness, surveying damaged bridges, and documenting archaeological investigations was also evaluated. Laser scans of ongoing construction projects were performed, and the workflow for operation of the scanner in the field was developed and documented. Software was developed using Visual Basic 2005 to process the data and to compare scanner data to a conventional survey. The research showed that laser scanning technology is a feasible means to measure earthwork quantities for payment in highway construction projects. Used in conjunction with traditional surveying techniques and equipment to establish horizontal and vertical control, the laser scanner can quickly map the terrain and provide data for earthwork quantity calculations.
ACKNOWLEDGEMENTS

The research described in this report was performed for the Illinois Center for Transportation (ICT).

The research was conducted by personnel from the Department of Construction in the School of Engineering at Southern Illinois University Edwardsville (SIUE). Professor Dianne K. Slattery, Ph.D., P.E. and Associate Professor Kerry T. Slattery, Ph.D., P.E. were co-principal investigators. Assistant Professor Chris Gordon, Ph.D. was an investigator and assisted in many of the field operations. SIUE undergraduate students Joseph Vickey and Brandon Egelhoff (Construction Management) and Brian Schuh (Civil Engineering) were instrumental in conducting laser scans and processing data. These students are pursuing a land surveying specialization offered through the SIUE Department of Construction (www.siue.edu/ENGINEER/CONSTRUCT).

IDOT personnel who served as the project Technical Review Panel (TRP) guided the research. Ted Nemsky, P.E., Director of Construction, District 8 chaired the TRP and assisted the researchers in many ways. The TRP members were: Rick Porter, IDOT District 8; Tim Hemmel, IDOT District 8; Herb Jung, IDOT District 3; Mark Neale and Mike Brand, IDOT Bureau of Design and Environment (Mike Brand was replaced by Tara Elston in March 2009); Chris Fraley, FHWA; Charles Wienrank and Patricia Broers, IDOT Bureau of Materials and Physical Research. The panel was also joined by Mark Gvillo, Madison County Highway Department, who coordinated with the SIUE researchers in making the Governors Parkway project and the associated plans, specifications and estimates available for performing much of the research. Roger Strong, superintendent for Baxmeyer Construction, was instrumental in alerting the researchers to the timing of construction operations and assisting them in gaining access to the construction site. IDOT District 8 personnel attended a day-long beta-testing of the software developed as part of this project, and were helpful in identifying desirable functionality and ways to make the software more useful to resident engineers and technicians. The researchers thank Dan Hartwig, Jeff Allison, Tom Borsch, John Brandon, John Jilg, Jim Cox, and Tim Hemmel for their contributions.

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Illinois Center for Transportation or the Illinois Department of Transportation. This report does not constitute a standard, specification, or regulation.

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Note that prior to the publishing of this report, Dianne Slattery and Kerry Slattery moved to the Department of Technology and Construction Management, College of Business Administration, at Missouri State University. However, this ICT research project remained as a contract with SIUE.
EXECUTIVE SUMMARY

OBJECTIVES

The objective of the project was to determine cost-effective means to implement laser scanning technology in the construction phase of IDOT projects. The primary goal was to study the use of a laser scanner for evaluating pay quantities for earthwork operations. This required comparisons between laser scanning and conventional surveying data to evaluate the accuracy as well as the development of procedures to optimize the use of the scanner; that is, to develop data with the required level of precision in the fewest crew hours. Recommendations for changes to the IDOT Standard Specifications for Road and Bridge Construction related to the use of laser scanning for quantity measurement were also studied. A second objective was to evaluate the use of the laser scanner for real-time monitoring of settlement during pile driving operations. Finally, the feasibility of using a scanner for other applications such as providing initial survey data for design, evaluating gravel and pavement thickness, assessing pavement roughness, surveying damaged bridges, and documenting archaeological investigations was also evaluated.

METHODOLOGY

The research methodology consisted of performing laser scans of ongoing construction projects at critical points to develop procedures to efficiently and effectively measure the position of the ground surface and, in some cases, surrounding structures. The workflow for operation of the scanner in the field was developed. Software was developed to process the data and to compare scanner data to survey data that had been developed using conventional surveying equipment and techniques.

RESULTS

The final report documents the results of the research and the software to enable IDOT personnel to assess and implement laser scanning technology on construction projects. The report includes chapters on the following key topics: 1) Workflow design for laser scanning, 2) Earthwork quantity calculations, 3) Proposed revisions to IDOT Standard Specifications and 4) Feasibility for other construction applications and design. The report also includes the user manual and documentation for a computer program developed using Visual Basic 2005 to allow IDOT personnel to efficiently implement scanner technology.

The software performs the following functions: 1) Scan Planning that imports digital terrain data in a triangular irregular network (TIN) format and allows the user to graphically select scanner locations that will efficiently scan the route; 2) Volume Calculation that imports point clouds, registers them given the coordinates of known points, and calculates the volumes of cut and fill between the “before” and “after” terrain surfaces; and 3) Settlement Monitoring that allows the user to register and compare periodic scans taken over a period of time to detect changes in ground surface elevations or the location of vertical surfaces over time. IDOT is given unrestricted license to use the software.

CONCLUSION

The research has shown that laser scanning technology is a feasible means to measure earthwork quantities for payment in highway construction projects. Used in conjunction with traditional surveying techniques and equipment to establish horizontal and vertical control, the laser scanner can quickly map the terrain and provide data for earthwork quantity calculations. The typical productivity for scanning is one hour per set-up. For route scanning on a suburban three-lane roadway being constructed on new alignment, the number of scans to provide good coverage of the initial ground surface averaged one scan
per 450 feet on or near the centerline, or approximately 12 scans (12 hours) per mile. To
scan the finished ground surface of the same route, scans every 300 feet on alternating
shoulders were needed to capture the pavement and roadside ditches, or approximately 18
scans (18 hours) per mile. By comparison, productivity for shooting 50 foot cross sections
with 20 shots per section across a 350 foot right of way in rolling terrains using a total station
was estimated at just under 30 hours per mile for a two-man crew. The average productivity
reported by the engineering consultant on Governors Parkway was approximately 1,500 feet
per day, or 28 hours per mile, a value that supports the estimate.

The quantity and quality of the data gathered by the scanner (roughly one thousand
points per second, accurate to within 0.1 feet on rough terrain at distances up to 600 feet)
enables the person analyzing the data to create new ways of displaying the data, such as
additional cross sections, skewed sections, or sections along intersecting roads, without
additional field time. The software developed as part of this research was beta-tested by
IDOT surveying technicians and resident engineers, who during a one-day training were
easily able to navigate through a variety of functions. It is anticipated that persons familiar
with other surveying equipment and software will easily adapt to use of the scanner without
extensive training.

The scanner is of limited use for performing reconnaissance surveys for design or
measuring for payment before the start of construction when the route is wooded or heavily
vegetated. Grass, weeds, crops, and other vegetation can prevent the scanner from
accurately locating the ground surface. Mowing, harvesting, or light clearing of the ground
was sufficient for determining the ground surface to the nearest 0.10 feet for earthwork
measurement.

Laser scanning was found to be feasible for detecting movements or perturbations of
a smooth surface in excess of 0.01 foot when performing a single scan, a function that could
be applicable to examining pavement smoothness or a damaged bridge girder. The scanner
was useful in gathering detailed data on the deformation of a damaged bridge beam on an
interstate route without putting surveyors in the traffic lanes, a significant improvement over
current techniques. For monitoring settlement over time due to pile driving or coal mine
subsidence, the precision of scan data was found to be within +/-0.10 foot, likely due to
slight movement of the scanner itself. Because of this likelihood, time-dependent scans will
require additional surveying support, including supplemental precise level circuits with
vertical control established outside the zone of potential ground movement in order to
establish and verify the scanner location and orientation over time. The research also
concluded that there is a need for the development of standard practices for error analysis
when incorporating the laser scanner into IDOT surveying practice.
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CHAPTER 1 INTRODUCTION

The use of laser scanning equipment to produce 3-dimensional representations of objects and surfaces is a new technology in land surveying and geospatial information technology. The equipment cost remains high in comparison to electronic total stations; however, the scans quickly produce a collection of data points, or "point clouds," which can be processed to provide 3-dimensional models, accurate to within a few millimeters (0.01 feet), with the potential of increasing field productivity and improving the integration of design and construction survey data. Laser scanning equipment has been used in specialty surveying applications, such as monitoring widespread ground subsidence, disaster recovery operations, landslides, and, volume calculation for stockpiles of rock or other stockpiled materials. The technology has significant potential for monitoring highway and bridge construction activities. Examples include obtaining accurate pre- and post-construction terrain models for determination of earthwork quantities; monitoring pavement smoothness and adherence to design grade; and monitoring ground movement near excavations, large embankments, or pile-driving operations. However, it was not clear whether data obtained using laser scanning technology would be comparable to the results of traditional surveying methods and quantity determinations as specified in the Standard Specifications for Road and Bridge Construction in Illinois.

A study was conducted to determine whether laser scanning technology can be cost-effectively implemented by the Illinois Department of Transportation (IDOT) for monitoring highway construction activities. Laser scans were performed on several construction projects in IDOT District 8, and the data analyzed to verify the comparability of laser scan results with currently specified construction measurement and quantity determination methodology. The researchers examined ways to integrate design drawings and geospatial project data with construction measurements and developed recommended procedures for implementation of the technology for specific construction applications.

The research was conducted using a Trimble GS 200 that is capable of scanning 360º horizontally and -22º to +38º vertically. The maximum scanning range is given by the manufacturer as approximately 1,150 feet (350m); however, the practical range of approximately 650 feet (200m) was used to increase speed and accuracy. The scanner provided real-time video acquisition with 5.5X zoom and scanning speed of up to 5,000 points per second. Trimble® PointScape™ software was used to operate the scanner and Trimble® RealWorks™ software was used to perform some data processing. The investigators coordinated with the IDOT District 8 Chief of Surveys, the Madison County Highway Department, and various engineering/surveying companies to obtain conventional survey data to compare traditional equipment and methodology to the study technology and methods.

The objective of the proposed project was to determine the feasibility and advisability of implementing laser scanning technology in the construction phase of IDOT projects. The primary goal was to study the use of a laser scanner for evaluating pay quantities for earthwork operations. This required comparisons between laser scanning and conventional surveying data to evaluate the accuracy and the development of field procedures to capture data with the required level of precision in the smallest number of crew hours. Scans were performed on representative sections of road construction projects at all stages of the construction from design to completion. Several projects were studied in order to completely evaluate the technology in a variety of settings and
uses. Recommendations for changes to the IDOT Standard Specifications for Road and Bridge Construction were developed.

A second objective was to evaluate the use of the laser scanner for real-time monitoring of settlement of adjacent structures during pile driving operations. The scanner was set up near a job site, and scans were taken periodically to plot changes in ground elevation and movement of structures.

The data provided by the laser scanner will have other applications in road construction and design. In the course of the research, scan results were evaluated to determine the feasibility of using a scanner to provide initial survey data for design, for evaluating gravel and pavement thickness, for assessing pavement roughness, for surveying damaged bridges, and for mapping archaeological sites. This report includes preliminary results with recommendations for further research.

SCANNING OPERATIONS

The IDOT Technical Review Panel (TRP) and the research team developed a list of potential projects to scan during the research project timeframe of September 2007 to August 2009. Due to the timing of the projects in relation to the research, much of the scanning was done on a Madison County Highway Department project, the construction of Governors Parkway. For this project, a three-lane Portland cement concrete pavement on new alignment in Edwardsville, Illinois, the researchers were able to coordinate closely with the contractor to perform scans at each stage of construction. Illinois 157 in Cahokia, Illinois was scanned during pile driving and construction of an embankment. A lane widening project on Illinois 159 in Swansea, Illinois was scanned to study the feasibility of scanning for urban intersection projects. An intersection reconstruction at Illinois 162 and 157 in Glen Carbon and a new section of Illinois 255 north of Alton were used to examine the feasibility of scanning to provide reconnaissance surveys for design. Table 1 is a summary of scanning conducted on the project.

<table>
<thead>
<tr>
<th>Construction Phase</th>
<th>Recon survey</th>
<th>Light clearing</th>
<th>Clearing/grubbing</th>
<th>Final grade</th>
<th>Base course</th>
<th>Paving</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Governors Parkway</td>
<td>Complete</td>
<td>Complete</td>
<td>Complete</td>
<td>Complete</td>
<td>Complete</td>
<td>Complete</td>
</tr>
<tr>
<td>Route 157 Cahokia</td>
<td>Complete</td>
<td>Complete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Route 159 Swansea</td>
<td>Complete</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Route 255 Jersey County</td>
<td>Complete</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Illinois 162 at 157</td>
<td>Complete</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In addition to the planned scanning projects, the TRP requested the use of the scanner on several additional applications during the course of the research, including scanning a suspected coal mine subsidence in October 2007, a bridge beam struck by a truck in April 2009, and an archaeological dig in July 2009.
CHAPTER 2  WORKFLOW DESIGN FOR LASER SCANNING

One of the hypotheses for the use of laser scanning in highway construction operations was that the use of the scanner would reduce the crew time needed to collect data required to measure or verify pay quantities, primarily for earthwork operations. The research tested this hypothesis by developing efficient field procedures for collecting the required data, and by monitoring the field time required to complete scans on a variety of project types.

SCANNER SPECIFICATIONS AND OPERATIONAL REQUIREMENTS

The scanner used for this research was a Trimble GS 200. Product information provided by the manufacturer claims that the scanner can deliver up to “80% manpower savings in many applications” (Trimble 2009). While this model of scanner has many features that make it suitable for civil surveys, it cannot be leveled or set up over a point in the same way as a conventional survey instrument. Instead, the location and axis of orientation of the scanner is calculated by resection by sighting on a minimum of three targets placed on points of known location and elevation. The scanner range is rated at approximately 656 feet (200m) with a 1,150 foot (350m) OverScan™ capability. The speed of data collection is rated at 5,000 points per second, with accuracy of 0.005 feet (1.5mm) at 164 feet (50m). The scanner has a 360° field of view, collecting points from +38° to -22° of the scanner’s horizon (Figure 1).

Figure 1. Trimble GS 200 scanner.

The scanner weighs 29.9 lb (13.6kg) and is approximately 13.4 in (340mm) deep, 10.6 in (270mm) wide, and 16.5 in (420mm) high. The scanner requires electrical power to operate. A 1000 watt portable generator, a 750 watt power inverter with a 1500 watt peak rating connected to a 12V car battery, or two 12V deep discharge batteries
connected in series are required. Operation of the scanner requires a data collection device; a Trimble® Recon™ data collector with PocketScape™, or a dedicated PC notebook computer with Trimble® PointScape™ software. The scanner data interface is TCP/IP with a wireless WiFi optional. The computer may also require external power (Figure 2).

Figure 2. Set-up of Trimble GS 200 scanner.

For comparison, the next generation of survey laser scanner, a Trimble GX, was used on one site to compare the field requirements and workflow design. The GX is of comparable size and weight and has similar power requirements and range. However, it has several features not found on the GS 200: an automatic level with dual axis compensation, the ability to set up over a point with an optical plummet, and Trimble® SureScan™ technology to better control point spacing.

A proposed field workflow has been developed for two different types of scanners. However, the similarities of the two instruments result in considerable overlap in the field requirements.

CONTROL NETWORK

Scanning operations should be tied to a horizontal and vertical control network set up using conventional land surveying techniques. Route surveys using conventional surveying equipment (levels, electronic transits or total stations) require the location of control points approximately every 800 to 1000 feet along the highway alignment. For scanning, these control points must be supplemented with additional, temporary control, and good surveying techniques should be used to identify and eliminate sources of systematic error in data collection.
The coordinates (northing and easting), elevation, and orientation of a GS type scanner must be established through resection by referencing the scanner to at least three points whose location and elevation are known. Initially, it was determined that good results were obtained by setting four hubs to support spherical targets at a distance of approximately 100 feet (30m) from the scanner. These temporary control points were located with GPS and tied to the existing control network established by the owner’s consultant. By trial, the maximum effective range of the scanner for scanning terrain was determined to be approximately 300 feet, creating an effective point cloud diameter of 600 feet (Figure 3). When scanning the completed road, two rows of temporary control points spaced every 100 to 300 feet along the length of the project were found to be effective. Adjacent scans could then be registered, or tied to each other to create a continuous point cloud along the length of the roadway.

Figure 3. Temporary control points for GS-type and GX-type scanners.

The number of temporary control points is reduced by approximately 50% for a GX-type scanner since it can be set up over a known point and backsighted to a known point to determine its coordinates (northing and easting) and elevation. Temporary control points for the GX-type scanner would be established every 600 feet on each side of the roadway, in an alternating pattern so that foresights and backsights would be approximately 300 feet (Figure 4). The height of instrument is measured to the optical center of the laser, indicated on the body of the scanner. The instrument’s horizon is maintained by means of a self-compensating level bubble, and its azimuth is referenced to an arbitrary direction indicated by a point on the exterior of the scanner body.
Maximum spacing of control points for the GX-type scanner varies with terrain, but for the Governors Parkway project, temporary control points for scanning were located on alternate sides of the roadway alignment and spaced approximately 300 feet apart. These points were tied to the roadway control network established by others, and the state plane coordinates and elevations of the scanner control points were established using real-time kinematic (RTK) GPS.

FIELD PROCEDURES
The research project was initiated in the fall of 2007, at the same time as a Madison County Highway Department (MCHD) project, Governors Parkway, was getting underway approximately 3 miles from the campus of Southern Illinois University Edwardsville. The researchers were given access to the project and worked in close cooperation with MCHD engineers, the consultant performing the surveying, the general contractor, and the consultant performing quality assurance. This cooperation, and the researchers’ proximity to the project, enabled the researchers to gather data at critical stages, use the surveying consultants’ control network, and compare the scanning results to design and construction survey data. The first 1.4 mile section of the Governors Parkway project began in January 2008 and continued through August 2008, allowing the scanner to be field-tested in a variety of weather conditions.

The scanner was used in conjunction with a GPS system to tie into the control network established by the surveying consultant. The RTK GPS was used to determine the location and elevation of the targets, from which the location and orientation of the scanner was computed. The use of GPS for determining elevation was considered to be sufficiently precise (+/- 0.10 feet) for earthwork computations, but for applications
requiring greater precision, a level survey would be required to establish target elevations to the nearest 0.01 feet.

The Trimble GS 200 scanner was found to perform slowly and erratically at temperatures less than 40° F. Protecting the scanner from the wind with an improvised bonnet or blocking the fans with cardboard had some positive effect. The scanner will shut down when it reaches an internal temperature of 122° F (50°C). At air temperatures above 95°F, the scanner was close to overheating and had to be protected from direct sun or periodically placed in an air-conditioned vehicle. The scanner cannot be operated in rain or snow, and may return inaccurate, residual points in dusty or foggy conditions. The laser will reflect from water, shiny metal, or glass surfaces, returning residual points. Solid objects, including the ground, trees, foliage, vehicles (moving and parked), tools and people block the laser, producing “shadow zones” where no points are recorded. Scan planning (Chapter 3) can alleviate some, but not all, of these limitations.

For both GS- and GX-type scanners, transporting and setting up the instrument is not a trivial matter. During earthwork operations it was difficult and sometimes hazardous for passenger vehicles to enter the construction site, and the scanner and its auxiliary equipment were transported on foot or hand-drawn cart, requiring a crew of at least two. Figure 5 shows the limited number of access points to the site during construction. When the subgrade was brought to grade, the site was accessible by truck and some work was done by a crew of one. However, the two-person crew appears most efficient for either the GS- or GX-type scanners.

![Figure 5. Location map for Governors Parkway in Edwardsville.](image)
**GS-type Field Workflow**

The initial scanning of Governors Parkway was done during clearing and grubbing of the route. Centerline stakes and vertical control points had been established by a surveying consultant, and were used by the researchers. The design TIN of the original ground surface, provided by the design consultant, was used to plan the location for scanner set-ups. These set-ups were then located by pacing off the distance, using the centerline stations as a guide. The field procedure for a two-person crew at each set-up is given in Table 2.

<table>
<thead>
<tr>
<th>Action (scanner operator)</th>
<th>Action (assistant)</th>
<th>Approximate Time Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport scanner and auxiliary equipment to first scanner set-up</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Assemble tripod and attach scanner</td>
<td>Transport GPS receiver to first scanner set-up</td>
<td>10</td>
</tr>
<tr>
<td>Set up notebook computer, connect to scanner, open Pointscape software</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Attach power cables to power source</td>
<td>Establish four target locations 100’ +/- from scanner</td>
<td>10 10</td>
</tr>
<tr>
<td>Initialize scanner and do a 360 degree photograph</td>
<td>Sight the targets and do a detailed scan of each</td>
<td>10</td>
</tr>
<tr>
<td>Obtain XYZ coordinates of each target hub using GPS</td>
<td>Retrieve targets</td>
<td>20 5</td>
</tr>
<tr>
<td>Check in to control point</td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

The required time of approximately one hour per set-up was characteristic of the GS-type scanner in all weather conditions, and did not improve significantly as the scanning crew developed more experience. The time required to transport the scanner to each set-up is based on use of a non-motorized wagon in open, fairly level terrain. Use of a motorized all-terrain vehicle (ATV) is possible, but the presence of an ATV near the scanner would create an unwanted shadow zone. In addition, the scanner should be detached from the tripod and returned to its case for moving, so the total set-up time would not be significantly improved by using motorized transport.

The workflow for a GX type scanner is similar (Table 3). The field work to establish the necessary temporary control points can be completed in a separate operation before scanning to facilitate real-time analysis of scanner data. In rough terrain, however, the two activities should be coordinated to assure that the scanner and targets set up over each temporary control point are inter-visible.
Table 3. Activities Per Set-up for GX Type Scanner

<table>
<thead>
<tr>
<th>Action (scanner operator)</th>
<th>Action (assistant)</th>
<th>Approximate Time Required</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Scan</td>
</tr>
<tr>
<td>Establish first temporary control point, visible and down-station from scanner</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Transport scanner and auxiliary equipment to first scanner set-up &lt; 300 feet from first temporary control point</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Assemble tripod and attach scanner; rough-level</td>
<td>Set up GPS receiver over temporary control point and perform 3 minute RTK reading.</td>
<td>5</td>
</tr>
<tr>
<td>Set up notebook computer, connect to scanner, open Pointscape software</td>
<td>Set up scanner target over control point and measure and record height</td>
<td>5</td>
</tr>
<tr>
<td>Level and read height of instrument. Input heights of instrument and target into software</td>
<td>Establish second temporary control point, visible to and up-station of scanner</td>
<td>5</td>
</tr>
<tr>
<td>Initialize scanner and do a 360 degree photograph</td>
<td>Set up GPS receiver over second temporary control point and perform 3 minute RTK reading.</td>
<td>10</td>
</tr>
<tr>
<td>Backsight on initial control point to establish scanner location and orientation</td>
<td>Set up scanner target over second control point and measure and record height</td>
<td>5</td>
</tr>
<tr>
<td>Foresight on second temporary control point &lt; 300 feet from scanner</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Do a detailed 360 degree scan of the route</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Total cycle time, scanner operator (minutes)</td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>Total cycle time, assistant (minutes)</td>
<td></td>
<td>45</td>
</tr>
</tbody>
</table>

The time requirement, approximately one hour per, is reported to be typical of other experienced GX-type scanner operators. Because the scanner can collect several thousand points per second, the time required to collect data is significantly less than conventional survey methods. However, the field time to complete a scan is currently limited by the time to complete a 360 degree scan. Office time to process and interpret scan data was not directly compared to the time to process traditional survey data. However, the amount of data points that can be collected per hour of field time may increase the time needed to process and interpret the data, while also reducing the need for return trips to the field to gather needed data. The software provided in this project is designed to make post-processing of the data more time efficient for office personnel.
The primary objective of this research was to test the applicability of laser scanning technology to compute one of the most common and significant pay items in highway construction—earthwork. The research approach was a) to determine the field procedures required to capture the data to quantify earthwork (Chapter 2), b) to develop software to enable users to plan efficient scanning, c) to develop software to calculate earthwork, and d) to verify the results obtained through scanning by comparison to quantities determined by the conventional means of survey cross-sections and application of the average end area method.

SCANPLAN SOFTWARE

The scanner field of view is +38°/-22° from the scanner horizon, but its field of view is limited to line of sight. Obstacles, including terrain, create shadow zones in which no points will be returned (Figure 6). Directly under the scanner there is a “hole” in the point cloud with a diameter equal to \[2 \times (\text{Ht. of scanner}) \times \tan 68°\], or about 24 feet for a typical scanner height of 5 feet.

![Diagram showing scanner field of view and shadow zones](image)

Figure 6. “Shadow zones" with line of sight scanner.

To capture as much data as possible at each set-up of the scanner, the limitations due to terrain shadow zones should be minimized. Scan planning software was developed to allow scan operators to pre-plan the field locations of the scanner that would most efficiently scan the area within the construction limits of a typical roadway project. Pre-planning allows location of scanner set-ups to maximize the coverage area (Figure 7). ScanPlan software is more fully described in the user manual (Appendix A).
VOLUME CALCULATION APPROACH

Earthwork volumes are calculated by comparing two surfaces defined by TIN models. The TIN models are created from laser scan data and may be modified manually when the point density is inadequate to accurately model critical terrain details. In order to allow the engineer/surveyor to control the interpretation of laser scan data, the point cloud is displayed in cross section views. These points can be superimposed on cross sections extracted from TIN models of the existing terrain or on photographs taken by the laser scanner.

AUTOCLEAN ALGORITHM

Because laser scan data will have extraneous points above the ground surface, caused by vegetation, vehicles, personnel, and equipment on the site, an AutoClean algorithm was developed that determines the location of the ground surface by finding the lowest points in each cross-sectional slice through the data. The line through these points is used to construct a TIN model of the scanned surface. Other residual or irrelevant points (for example, points outside the limits of construction) can be removed through a manual cleaning process. Given the road station and cross section thickness, all laser scan points within a slice centered on the designated station are extracted, sorted from left to right, and plotted (Figure 8).
The AutoClean algorithm begins with the first point to the left of the left construction limit. The slopes of lines to all points within a user-defined distance to the right of that point are calculated, and the point with the lowest slope is retained. The default value for the distance is 2 feet. If there are no points within that distance, the first point to the right is retained. This procedure is then repeated using the latest retained point until the cross section is complete. The width of the slice of points should be limited to about 2 feet (i.e. ±1 foot) to minimize error caused by slopes in the road direction (Figure 9).
TIN MODEL CREATION
A TIN model (Figure 10) is created from laser scan data given the beginning and ending stations, the station interval, the offset interval and the slice thickness. Points in the TIN model are generated along all cross sections between the beginning and ending stations at the designated interval. These points are connected by triangles between the stations. The offset interval is the approximate spacing between points across the cross sections. Points are selected with the AutoClean algorithm using this value as the “user-defined distance.”

The TIN model for the finished project should have the pavement, base material and modified subbase removed to establish accurate pay quantities. Information from the road geometry file is used to automatically create this TIN. The pavement surface is established in the cross section by performing a linear regression on points between the crown and the edge of pavement. The cross section of the new surface is created by subtracting the pavement, base, and modified subbase layer thicknesses from this line. The process is repeated for the shoulder.

![Figure 10. TIN model created from scan data.](image)

TIN MODEL MODIFICATION
A TIN model can be modified by manually moving points along a cross section. This will normally be done to match the scan-created TIN model to a design TIN for such situations as a ditch that the resident engineer has field-verified was properly placed but was not adequately captured by scans.

CUT AND FILL CALCULATION
Cut and fill volumes are calculated by comparing the TIN model of the existing terrain to the TIN model of the finished road after the thickness of the pavement, base and modified subbase layers are removed. Each triangle in the TIN file for the existing terrain between the designated beginning and ending stations is analyzed. The elevation
of the finished surface at each corner of the existing triangle is determined, and the volume of the resulting triangular prism is calculated. In most cases the entire volume will be either cut or fill so this quantity is added to the appropriate total. The volume between triangles involving both cut and fill is split by determining the zero cut/fill line and calculating the volumes of the cut and fill portions. Cut and fill quantities can be output between stations at user-defined intervals.

VERIFICATION OF RESULTS

Four different comparisons were conducted between the laser scanning data and conventional survey measurement techniques.

Cross Section Data from Existing Terrain

Total station data was obtained from 50-foot cross sections taken by an engineering consultant prior to construction on Governors Parkway in Madison County. The results were compared with TIN models derived from the laser scan data. The difference in elevation between each survey point and the TIN model was computed for all points in the area covered by scans taken by the researchers in January/February 2008, before construction began. Figure 11 shows a cross section plot in which the scan points and TIN model cross section are shown in magenta. The magenta line represents all the scan points collected in a five foot “slice” measured longitudinally along the roadway on either side of the station in question. The six survey points taken by the engineering consultant at this station are plotted as black squares. The vertical scale on the left has one foot increments.

A total of 849 survey points fell in the area scanned in January/February 2008. The mean and standard deviation of the Scan TIN elevation minus the survey point elevation are 0.51 feet and 2.44 feet, respectively. However, if outliers are removed and only points within 1 foot (83% of points) are evaluated, the mean and standard deviation become, -0.003 feet and 0.373 feet, respectively. When the allowable range is increased to 2 feet (92% of points) the statistics are 0.033 feet and 0.549 feet. Significant outliers are expected in regions where there is limited scan data to create the TIN file. Errors of this magnitude in the TIN file are usually obvious and can be corrected by manually “cleaning” the data.

Figure 11. Cross section plot.
Cross Section Data of Completed Road

The engineering consultant, using a total station to shoot cross sections every 50 feet, provided data on the entire project after completion of Governors Parkway in Madison County. The data included the survey points, the TIN file constructed from the survey points and the cut and fill area calculated at each cross section. Figure 12 shows the survey data points (red rectangles) and scan points from the Trimble GX scanner within one foot of Station 190+00. The vertical scale is exaggerated by a factor of five in Figures 12 and 13. Agreement between the two sets of points is excellent on the road surface, with a mean error of -0.03 feet and standard deviation of 0.10 feet in paved areas. Grass interfered with the laser scan in the right ditch and the scan did not capture the foreslope of the left ditch. When points in unpaved areas were added to the calculation, and outliers with errors greater than 0.5 feet were excluded, the mean error was 0.08 feet with a standard deviation of 0.19 feet.
Figure 13 shows the survey data points (red rectangles) and scan points from an adjacent scan performed using the Trimble GS 200 scanner at Station 190+00. Agreement between the two sets of points is very good, but slight differences between points from the overlapping scans performed with the second-generation GX scanner are evident. It appears that the addition of dual axis compensation in the GX scanner has reduced minor changes in orientation as the scanner rotates during operation. The difference in elevation between the TIN model constructed from the GS 200 data and the survey points was calculated. The mean error was -0.10 feet with a standard deviation of 0.12 feet in paved areas. When points in unpaved areas were added to the calculation, and outliers with errors greater than 0.5 feet excluded, mean error was 0.02 feet with a standard deviation of 0.23 feet.
Earthwork Quantities Determined from Plan Cross Sections

Earthwork quantities were calculated from the difference of the before and after laser scans from Governors Parkway in Edwardsville and Illinois Route 157 in Cahokia. These were quantified for each 50-foot section of roadway. The Governors Parkway results were compared to the values computed from cross section areas determined by the engineering consultant using traditional surveying techniques and the Average End Area method. Figure 14 shows the cumulative cut and fill volume over a 1600-foot section of the road. The laser scan and traditional earthwork computational methods show good agreement.
Figures 15 and 16 are cut and fill volumes, respectively, for each 50-foot interval in the section from Station 188+00 to Station 204+00 on Governors Parkway. Over this interval, the cumulative quantity of fill determined by the engineer was 42,160 CY versus a cumulative quantity of 40,210 CY calculated from scan data. The cumulative quantity of cut over this interval determined by the engineer was 10,310 CY, versus a cumulative quantity of 8,960 CY measured by scanning. The similarities between the trends in the cumulative data indicate that laser scanning provides a robust result. It is difficult to isolate individual causes for the difference in the two results. The average end area method is approximate and based on limited data, so some variability will be observed. The scan point density in some regions was inadequate to accurately model the berms and ditches. Grass in the ditches and on the berm also affected the result. The primary source of error in the GS 200 laser scan data can probably be attributed to drift in the scanner orientation during scanning operations. This problem is largely eliminated with the newer technology.
Figure 15. Governors Parkway cut volumes.
Scans taken before and after construction of a berm for the east approach of a new Illinois 157 railroad overpass in Cahokia were used to calculate the fill volume before surcharge settlement. A comparison of scan data and survey data is shown in Figures 17 and 18. The cut quantities are multiplied by 10 in Figure 17 for clarity because these quantities are small. There was no vegetation on the berm to interfere with scanning. One scan was taken from the top of slope on each side of the berm near the midpoint. These results demonstrate that scans of terrain without vegetation and adequate data point density can produce excellent agreement with conventional earthwork volume calculation methods.
Figure 17. Illinois 157 in Cahokia cumulative earthwork volumes.

Figure 18. Illinois 157 in Cahokia fill volumes
Constructed versus Designed Road Geometry

The laser scan data for the finished paved surface between Stations 187+00 and 205+00 was superimposed on a TIN file based on the road design for Governors Parkway. Differences in elevation were computed and summarized. Scans in this section were performed using both the first generation Trimble GS 200 scanner and the second generation Trimble GX scanner, yielding almost identical results. The error in data from nine overlapping GS 200 scans in this section had a mean of -0.05 feet and a standard deviation of 0.12 feet. The mean and standard deviation of the error in data from three GX scans were -0.07 feet and 0.05 feet, respectively, when vegetation and other outliers more than 0.5 feet above the computed ground surface were excluded.

ANALYSIS

The results of this research indicate that laser scanning is a feasible means of measuring earthwork quantities for payment on highway construction projects. The field productivity of 18 hours per mile with either the GS-type or GX-type scanner is competitive with that of a survey crew shooting cross sections at 50 foot intervals with a productivity of 30 hours per mile. The quality of results obtained by scanning is similar to that for conventional cross sections, with accuracy to 0.1 foot at distances of up to 600 feet. A 20-minute scan typically produces about 600,000 data points, but the resolution of the data varies with distance from the scanner and obstruction of line of sight. Scans must be planned so that there are sufficient data points to define important features such as ditches and berms. Vegetation, rough terrain, vehicles, and other obstacles can reduce the visibility of the scanner and necessitate more closely spaced scans to obtain adequate coverage.

Obviously, productivity is dependent upon the number of scans required per mile of road. A completed suburban or rural roadway will generally require scans to be taken on both sides in order to develop complete data for modeling ditches and, in the case of Governors Parkway, earth berms. With a scanning range of 600 feet, scans are required at 1200 foot intervals on both sides of the road. These scans should generally be staggered. Figure 19 shows the coverage from three scans roughly 600 feet apart taken from the berms alongside Governors Parkway. While the range of the scanner was adequate to cover this area, the density of points more than 200 feet from the scanner is not adequate to fully map the terrain. Figure 20 shows the coverage from alternating scans spaced at 300 feet. In this case there were still not enough points to adequately map the outside of the berms. Figure 21 shows the data used in the earthwork analysis with scans spaced at 300 feet on both sides of the road. The point density is adequate except in the “shadow” under the scanner and in some regions on the outside of the berm. This scanning strategy would require about 36 scans per mile which would probably not be cost effective.
Figure 19. Scans from top of berm, 600 foot spacing, alternate sides.

Figure 20. Scans from top of berm, 300 foot spacing, alternate sides.
The resolution for most scanners is set by selecting the horizontal and vertical angle between points at the initiation of a scan. This spacing could be selected to give very dense coverage; however, increasing the density of points also increases the time required to complete a scan. For this project, the horizontal point density was typically selected to be 800mm at 100m (.008 radians) with a vertical density of 50 mm at 100m (0.005 radians). This spacing resulted in a scan time of approximately 20 minutes for a 360 degree scan.

Ideally, a scanner would return points on uniform grid on the terrain. However, the scanner records points on a uniformly spaced angular grid, so that on a horizontal surface the scanner will return fewer points per unit area as the distance from the scanner increases. Using the typical angular intervals described above, Figure 22 shows the point spacing as a function of increasing distances from the scanner, out to the 350m limit of scanner range.
As the distance from the scanner increases, the spacing of points returned by the scanner increases at an increasing rate in the radial direction and linearly in the circumferential direction. Thus, for distances of 600 feet from the scanner, points are being returned at a spacing of approximately 35 feet radial to the scanner and 5 feet circumferential to the scanner, while the point density at 100 feet is approximately 1 foot radial and 1 foot circumferential.

It is more effective to have all points in the scan spaced, for example, 1 foot apart than to have points spaced at less than an inch near the scanner and at several feet near the full range of the scanner. Two options are available to create more uniform point spacing: multiple scans can be performed from each location with varying resolutions, or scanners can employ technology that automatically changes the angular resolution at different ranges.

In order to employ the first option efficiently, software for the scanner should allow the user to accurately segment the scan area and define resolutions for each band. The typical scan on this project required 20 minutes of scanning time to record about 600,000 points. The point spacing was less than 1 foot in both the radial and circumferential directions up to a range of 100 feet. A scanning strategy with variable resolution was developed to provide points out to a 600-foot radius without exceeding 1 foot spacing. This would require 11 different scanning bands and approximately 3,000,000 points. The scanning time would increase unless a faster scanner was used, but the area effectively covered by the scan would be 36 times as large with only 5 times as many points. Some commercially available scanners allow users to develop macros to automatically run a series of scans from one set up with no additional user interaction.

The Trimble GX scanner implements the second option through Trimble®SureScan™ technology. This allows the user to set the desired point spacing. The scanner automatically adjusts its operation to approximate that spacing. This
eliminates very closely spaced points near the scanner and provides useful point densities at longer ranges. The actual time required for each scan will depend on the available technology. Technologies that produce more efficient point clouds were not evaluated in this research project, but the researchers are confident that the scanning strategy shown in Figure 20 (alternating scans at 300 feet) will be able to produce adequate data with currently available technology.

Finally, a study of the “overscan” mode of the GS scanner was done on an unopened stretch of Governors Parkway to determine the maximum distance that the scanner could return points, and at what cost in terms of time. On a stretch of concrete pavement that is on a tangent downward grade, points were returned at a distance of more than 1,000 feet from the scanner. Using the panoramic photo taken by the scanner, an attempt was made to frame a small area of pavement and roadside ditch at this distance, and to specify a very dense scan of points of that area. This experiment was done to test whether enough points would be returned to clearly interpret the geometry of the roadway at that distance. However, the scan time for collecting these points was more than 40 minutes (twice the normal time required for a full 360° scan), and the point spacing was too large to accurately interpret the scan in the office data processing. While the scanner does possess the range specified, it is our conclusion that for outdoor scanning the practical limit of the scanner is a 600 foot range.
CHAPTER 4 PROPOSED REVISIONS TO IDOT SPECIFICATION

The 2007 Standard Specification for Road and Bridge Construction was reviewed, and paragraphs relating to earthwork calculation are reproduced below.

CURRENT LANGUAGE

Article 202.07 of the 2007 Specification states:
(b) Measured Quantities. Earth and rock excavation will be measured in their original positions, and the volumes in cubic yards (cubic meters) computed by the method of average end areas. The volume of any unstable or unsuitable material removed will be measured for payment in cubic yards (cubic meters).

In rock excavation, the Contractor shall strip ledge rock of overburden so that necessary cross sections for measurement may be taken. Vertical measurements for determining end areas shall extend from the surface of the rock to an elevation not more than 6 in. (150 mm) below the subgrade of the proposed pavement structure, as shown on the plans, or to the bottom of the rock where that point is above the subgrade of the proposed pavement structure. Horizontal measurements for determining end areas shall extend not more than 6 in. (150 mm) beyond the slope lines fixed by the Engineer for the work. Boulders and rocks 1/2 cu yd (0.5 cu m) or more in volume will be measured individually and the volume computed from average dimensions taken in three directions.

Subbase granular material used for replacement will be measured in tons (metric tons) or in cubic yards (cubic meters) according to Article 311.08. Subbase granular material used for replacement of rock excavation more than 6 in. (150 mm) below the subgrade of the proposed pavement structure, will not be measured for payment.

PROPOSED LANGUAGE

The following language is currently being used as a supplemental specification on selected projects for which the contractor is using digital terrain mapping to control earthmoving equipment:

(b) Measured Quantities. Earth and rock excavation will be measured in their original positions, and the volumes in cubic yards (cubic meters) computed by the method of average end areas or as calculated by digital terrain mapping. The volume of any unstable or unsuitable material removed will be measured for payment in cubic yards (cubic meters).

In rock excavation, the Contractor shall strip ledge rock of overburden so that necessary cross sections for measurement may be taken. Vertical measurements for determining end areas shall extend from the surface of the rock to an elevation not more than 6 in. (150 mm) below the subgrade of the proposed pavement structure, as shown on the plans, or to the bottom of the rock where that point is above the subgrade of the proposed pavement structure. Horizontal measurements for determining end areas shall extend not more than 6 in. (150 mm) beyond the slope lines fixed by the Engineer for the work.
lines fixed by the Engineer for the work. Boulders and rocks 1/2 cu yd (0.5 cu m) or more in volume will be measured individually and the volume computed from average dimensions taken in three directions.

Subbase granular material used for replacement will be measured in tons (metric tons) or in cubic yards (cubic meters) according to Article 311.08. Subbase granular material used for replacement of rock excavation more than 6 in. (150 mm) below the subgrade of the proposed pavement structure, will not be measured for payment.

This language, currently being used as a supplemental specification, allows the use of digital terrain mapping (DTM) as a data source from which to compute earthwork quantities. The source of such DTM may be from traditional construction surveying, machine grade control, laser scanning, aerial surveying, or other methods. There does not appear to be a need to write a new specification to accommodate the use of laser scanning in earthwork quantity measurement. However, there may need to be an addition to the Survey Manual to specify field techniques for laser scanning.
CHAPTER 5  FEASIBILITY FOR DESIGN, INSPECTION, AND OTHER APPLICATIONS

RECONNAISSANCE SURVEY FOR DESIGN
A region for future construction of Illinois Route 255 was scanned with a GS type scanner in the fall and winter of 2008/2009 after the crops had been harvested. This area had been surveyed by others using conventional route surveying methods during Summer 2008. Scans were also performed in early Spring 2009 of the proposed region for a redesigned intersection of Illinois 162 and Illinois 157. Even though the scanning was performed at times when the effect of natural vegetation was minimized, interference from trees and ground cover was still significant. The results showed that there was little utility in using the scanner for reconnaissance surveys.

EVALUATE GRAVEL AND PAVEMENT THICKNESS
Scans were performed on a three-lane wide, half-mile section of Governors Parkway immediately after trimming and again after the placement of the granular base course. The full road was scanned after the completion of construction. Rectangular regions of points from the three scans were selected and fit with planes using a standard regression algorithm. The layer thicknesses were calculated by determining the distance between the planes. While the thickness values were reasonable given the design gravel thickness of 4 inches and pavement thickness of 8 inches, the accuracy using the GS 200 scanner was not adequate to calculate granular base or pavement thickness for quality control purposes. It is expected that a GX-type scanner with dual axis compensation would produce significantly better results.

OBSERVATION OF MINE SUBSIDENCE SETTLEMENT
The pavement of Illinois Route 157 just north of the intersection with Illinois Route 162 in Maryville, Illinois was damaged by a suspected coal mine subsidence event in October 2007. A scan of the road surface was performed from off the right of way, requiring no lane closure. The resulting scan data was processed to determine the extent of the subsidence in the X, Y, and Z directions. A region of pavement 16 feet wide by 50+ feet long was identified that had sunk approximately 0.1 feet. Figure 23 shows a cross section plot. The vertical scale is exaggerated by a factor of 20. Figure 24 shows those points superimposed on the photograph taken by the scanner.

Figure 23. Cross section of laser scan showing apparent mine subsidence in northbound lane (right).
The scan also identified a “bump” of 0.1 feet transverse to the pavement, which might reflect the compression zone at the center of a mine subsidence event (Figure 25).

Scans of the pavement on Governors Parkway were studied using a “virtual roughness gauge.” Given offset distance, elevation is determined from the TIN model at two points a fixed distance apart. The angle of the line connecting these points relative to the horizontal is calculated. This procedure is repeated every foot for a designated region of the road, and angles are plotted as a function of the station.

The results for data using the GS-type scanner were inconclusive, as the vertical accuracy of the scans was on the order of 0.10 feet. However, by incorporating more precise vertical control for the temporary control points and using a GX-type scanner, it is anticipated that scanning could be an efficient way to monitor pavement smoothness over wide areas in real time.
SURVEY DAMAGED BRIDGES

The Illinois Route 162 bridge over I-55-70 in Troy, Illinois was damaged by impact from a northbound truck in March, 2009. The bridge was scanned in April from points off the shoulder behind the guardrail. The right lane was closed during the scan, which took 90 minutes. During the closure, two truck-mounted devices and signs were provided by IDOT District 8. Figure 26 is the photograph of the two damaged bridge girders. Figure 27 is the photo taken by the scanner, indicating a 2-foot wide slice of points used in the analysis.

Figure 26. Damaged girders on Illinois Route 162 bridge over I-55/70, Troy, Illinois.
Scan points on the web of the first girder were extracted and analyzed. A regression analysis was performed on points in two 5-foot long sections in undamaged regions on both ends of the damaged zone to find the “plane-of-best-fit” which is assumed to be the original location of the web. The distance from points on a 3” by 2” grid on this plane to the surface defined by the scan points on the damaged web are calculated (Figure 28). These values can then be used to help complete the District 8 Operations Impact Damage Form.

Figure 28. Damaged bridge girder.

Figure 29 is a section taken through the two damaged girders and a third, undamaged girder, looking right (east), showing a plot of the displacements.
Points from Station 0 to 60 (stationing in inches, based on an arbitrary datum west of the damaged area) and from Station 480 to 540 were considered to be in undamaged regions and were used to establish the original planar surface. A cross brace is located near Station 300. The height is measured (approximately) from the top of the bottom flange. The maximum displacements of the web are shown in Figure 30: maximum displacement of the web of Girder 1 was 10 inches at the center of the strike.

The laser scanner was able to quickly provide data to assess damage to a bridge girder from a safe location behind the guard rail. One lane on the highway was closed at times during scanner setup, but all operations could have been performed without disrupting traffic. Because it is not necessary in most cases to tie the scan in with any survey control, a bridge girder scan could be completed in 15 minutes.
SETTLEMENT MONITORING NEAR PILE DRIVING

Pile driving operations were monitored at bridge construction sites on both Governors Parkway in Edwardsville and Illinois 157 in Cahokia. Scans were taken periodically of both the general terrain as well as nearby structures. The location of control points was verified periodically using GPS, and spherical targets at those points were also scanned regularly to check for movement of the scanner or control points. Scan results can be superimposed in real time to assess movement. An algorithm was developed to fit a plane through points from all individual scans in a designated area and display the movement of the centroid of the planes in feet. Figure 31 is the plot of the analysis of a 50-foot slice of the wall of an apartment building in Cahokia. Figure 32 is the plot of the analysis of a 50-foot slice of the parking lot in front of the building. The baseline scan was performed at 8:11 a.m. on 08/25/08. The date and time of the five subsequent scans and the movement in feet are displayed on the plot. When examining a vertical plane, the measured movement is in the horizontal direction. The parking lot movement is measured in the vertical direction. Because movements were less than 0.1 foot and no trend was observed, it appears that these values are within the error of the laser scanning operation; that is, movement less than 0.1 feet cannot be detected with confidence.
Figure 31. Adjacent building displacements.

Figure 32. Parking lot displacements.

SCANNING ARCHAEOLOGICAL EXCAVATION

Laser scans were performed at the site of an archaeological excavation at the National City Stockyards in East St. Louis, Illinois. An area approximately 200 feet by 300 feet was scanned to document the location of points of interest. The Illinois Laser Scanning Implementation program was used to process the scan results. Figure 33 shows a band of scan points superimposed on the scanner photo of the site. The cursor can be moved to display the coordinates of any scan points in the N, E, and Z text boxes at the right side of the bottom of the form. The units are in meters. This tool can be used to quickly identify the location of any feature in the photograph.
Figure 33. Scan results for archaeological project.

A thorough map of the site was created with a single scan requiring about one hour. While it was not feasible to determine characteristics, such as the depth of an excavation, that are not in the scanner’s line of sight, this tool can provide a valuable, detailed 3D summary of the location of visible features.
CHAPTER 6 SUMMARY AND CONCLUSIONS

The results of this research indicate that the use of laser scanning technology has several feasible applications in highway construction, including measuring earthwork quantities, surveying ground or structure displacement or damage, and monitoring widespread ground movement due to pile driving, excavation, or other causes. The data generated by laser scanning is comprehended well by survey personnel and resident engineers and is compatible with existing software currently being used by IDOT. The software provided as part of this project provides a user-friendly graphical interface for viewing, manipulating, and using scanner data. Field techniques used in collecting data and office work used in interpreting the data will require skill sets already possessed by survey personnel and resident engineers. The addition of laser scanning to existing surveying equipment and methods will not require extensive training.

However, it appears that standards for the use of laser scanning would need to be written in order to achieve the level of precision required for some activities, such as determining pavement smoothness or detecting small ground movements. In these instances, the laser should be referenced to first order vertical control, not to elevations determined by GPS alone. While the cost of laser scanning equipment remains high (lowest cost on the order of $75,000), there are quantifiable benefits in terms of reduction of crew time in the field for earthwork quantity computation, more complete data collection that allows for additional analysis to be made without additional trips to the field, and increased safety for some construction operations, such as surveying bridge strikes, by keeping workers out of the traffic lanes. The next generation Trimble GX-type scanner, which can be set up over a point and leveled, seems to provide clear benefits over the first generation GS-type scanner. Other manufacturers also produce survey-quality scanners, and some possess features, such as the ability to scan directly overhead, that would provide more functionality in such applications as bridge inspections.
APPENDIX A

USER MANUAL FOR ILLINOIS LASER SCANNER IMPLEMENTATION (ILSI)
ILLINOIS LASER SCANNER IMPLEMENTATION

USER'S MANUAL

VERSION 1.0 – DECEMBER 2009

Written by:
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As part of Research Project R27-30
for the Illinois Center for Transportation
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Illinois Laser Scanner Implementation (ILSI) is a Windows-based software program used for planning and analyzing 3D laser scans of road construction projects. The program is designed to allow users to import point cloud and Triangular Irregular Network (TIN) files, quickly develop efficient plans for scanning operations and then analyze that data to accurately calculate earthwork quantities. The software can also be used to evaluate scan data taken during pile driving operations.

ILSI was developed by researchers at Southern Illinois University Edwardsville (SIUE). The program is the product of research sponsored by the Illinois Center for Transportation (ICT) and SIUE. Principal researchers on the project were Dianne K. Slattery, Ph.D., P.E, Kerry T. Slattery, Ph.D., P.E. ILSI was designed and written by Kerry Slattery. Program documentation and a user manual were written by Kerry Slattery and Dianne Slattery. Project guidance was given by a Technical Review Panel consisting of members from the Illinois Department of Transportation and Madison County Highway Department. Special thanks is due to committee chairman Ted Nemsky. Construction personnel from IDOT District 8, Dan Hartwig, Jeff Allison, Tom Borsch, John Brandon, John Jilg, Jim Cox and Tim Hemmel participated in a one-day review of the program and provided many valuable suggestions that were incorporated in the final version.
DEFINITIONS AND ACRONYMS

AEA – Average End Area
ICT – Illinois Center for Transportation
IDOT – Illinois Department of Transportation
ILSI – Illinois Laser Scanner Implementation
SSRBC – Standard Specification for Road and Bridge Construction
TIN – Triangular Irregular Network
BACKGROUND INFORMATION

The Illinois Department of Transportation (IDOT) identified a need to evaluate whether laser scanning technology can be used effectively in construction applications. This research was conducted as part of the Illinois Center for Transportation (ICT) project R27-30 “Evaluation of 3D Laser Scanning for Construction Applications.”

The primary objective of this research was to determine the feasibility of using laser scanning to determine earthwork quantities on construction projects by comparing “before” and “after” scans. While general purpose software is available to analyze laser scan data for some applications, the development of special purpose software was required to (a) provide a planning capability to improve crew efficiency, (b) create an application that could be used by IDOT personnel without extensive training and practice, (c) provide functions that are not available in commercial software that are focused on IDOT construction tasks, (d) display results in a familiar format for user verification. The project began on September 16, 2007, and was completed on August 15, 2009.

The researchers used data from extensive laser scans performed on a new road construction project in Madison County, Illinois to develop and test the software. The software was also used to evaluate the feasibility of using laser scans to monitor settlement during pile driving and to measure damage to bridge girders after an accidental vehicle strike.
EARTHWORK QUANTITY DETERMINATION

Earthwork on typical road construction projects is bid on a “unit price” basis by the contractor, e.g. $4.00/cubic yard. Approximate quantities are given in the project plans, but payment is based on actual quantities measured in the field. The IDOT Standard Specification for Road and Bridge Construction (SSRBC) calls for the use of the Average End Area (AEA) method to determine cut and fill quantities from cross section profiles. Cross section profiles are created, typically at 50 or 100 foot intervals, using conventional surveying techniques before earthwork begins and after construction in complete. These cross sections are superimposed; the profile from the completed construction is corrected for pavement, base and modified subbase materials that are not included in the earthwork quantity, and the areas between these profiles are determined. The cut or fill volume between cross sections is simply the average of the cut or fill areas in the cross sections multiplied by the distance between the sections. This method is labor intensive because a large number of points must be “surveyed” both before and after construction. Inherent errors from the limited sampling of points are expected to “average out” over a large project, but disputes can still arise if the selected cross sections miss significant terrain irregularities. The AEA method is designed to work on long, narrow projects; it is difficult to apply on more general areas, e.g. at road intersections.

Laser scanning provides much more data in less time allowing for more accurate models of the before and after surfaces. Because the laser scanner can only record points in the line of sight, vegetation, vehicles, and other foreign objects must be removed from the data. While algorithms were developed to automatically remove clearly irrelevant points, some manual processing and verification will be needed.
GETTING STARTED

System Requirements

ILSI will run on computers running the Windows XP or Windows Vista operating systems. While minimum memory requirements have not been established, a system with 1 GB RAM and 1 GB of available hard drive space is recommended. Laser scanning produces large data files so the user will need to manage data when hard drive space is limited. Display resolution should be at least 1024 X 768 pixels. The program uses default font sizes that are not adjustable. For information on your computer's current resolution, check Settings under your computer's Display option under the Control Panel menu. Contact your systems administrator for questions regarding your computer's display properties.

Installing ILSI

ILSI Version 1.0 is distributed on compact disc. Insert the ILSI CD into your computer's CD drive. Run Publish/Setup.exe.

Uninstalling ILSI

To remove ILSI from your computer, use the Add/Remove Programs option under the Control Panel menu on your computer and select Illinois Laser Scanner Implementation. This will remove all ILSI related program files on your computer. ILSI project files will not be removed.

Uses for ILSI

ILSI was designed to plan laser scanning operations on natural terrain, create TIN files from the laser scans and calculate volume between two surfaces. It also provides viewing tools for laser scan data.

Exiting ILSI

To close ILSI, use the File function on the Menu bar and Select Exit. This ends the program, and you will lose any unsaved models.
FILE SYSTEM

Several file types are used by the ILSI system. A more detailed description of the file formats is provided later in the manual.

Triangular Irregular Network (TIN)

Two TIN formats can be read: XML and IDOT Ascii. All TIN files are saved in the IDOT Ascii format.

XML File

The program will read point and facet data from TIN files saved by other programs in XML format. These file names are expected to have a “*.xml” extension.

IDOT Ascii File

TIN files are read and saved in a simple Ascii format. The files contain point and triangle (or facet) data. The boundary of the TIN map may also be defined in the file. These file names are expected to have a “*.tin” extension.

Road Geometry Data

A description of the road geometry is required to display and analyze scan data in station/offset coordinates and to account for pavement, base and modified subbase material from the cross sections measured after construction. An Excel spreadsheet, RGDTemplate.xls, is included on the distribution CD to assist the user in developing this file. A Visual Basic for Applications (VBA) Macro is embedded in the Excel spreadsheet to automatically write the file. The user must enable Macros in Excel to use this feature.

Scan Job Files

A scan job consists of three types of files each with the same initial name but different extensions. The *.sjf file is an Ascii file containing information about the scans. The *.bdf file is a binary data file containing the point cloud data for all scans. The names of the JPEG picture files from the scans are the scan job name followed by the scan name. For example, a job named MyScans consisting of three scans, Scan_1, Scan_2 and Scan_3, would use the following files:

MyScans.sjf
MyScans.bdf
MyScans_Scan_1.jpg
MyScans_Scan_2.jpg
MyScans_Scan_3.jpg

These files must be kept in the same directory.

Point Cloud File

Laser scan data must be exported from the laser scanner software into a standard text file format. The common file name extension is *.pts. The file contains coordinate, intensity, and color data.
**Scanner Target File**

The scanner target file (*.tgt) is a comma separated file listing the location and height of targets that were scanned to locate the scanner.

**Survey Point File**

Survey point files are comma separated files listing the location of survey points. These are standard file formats exported from surveying data collectors.
ROAD GEOMETRY

The user is prompted to select the Road Geometry file when the program is executed. The user should select Cancel if the road geometry is unavailable or not relevant. No station and offset data can be calculated and stored if the road geometry is not available when the scan job is defined. After points are imported, the program will require the user to draw a centerline on the plan view of the point cloud if no road geometry is provided. This will allow the user to view cross sections in this arbitrary geometry. This option is especially useful when viewing bridge strike data by defining a centerline parallel to the girders.

Two road geometry file examples are provided on the distribution CD. The sample data is from the Governors Parkway project and the Hwy 157 project in Cahokia. Macros must be enabled when opening the Excel files in order to use the VBA program to write the *.rgd file. Entries in Column A must not be modified. If additional rows are required to define the curb profile or more than two sub layers, the rows should first be inserted in Excel. Do not leave additional blank rows in the spreadsheet. Each segment of the horizontal and vertical alignment requires one column. The user can add any number of segments. Blank columns are not allowed between horizontal and vertical segments. Each typical RoadSection requires two columns in order to define a curb. The second column is blank when there isn’t a curb. The Left and Right RoadSideProfile are defined for each RoadSection.

Open the Visual Basic Editor in Excel and run the program and click Save to write the RGD file. This operation will overwrite old versions of the file.
USER INTERFACE

The Illinois Laser Scanner Implementation (ILSI) user interface provides a menu bar to access program functions and tools to manipulate views of the scan points, display TIN files and contour plots, and present information about the points. Figure 1 shows the IDOT Laser Scanning form.

![Figure 1. IDOT Laser Scanning form.](image)

**View Controls**

View Controls (Figure 2) are located in the lower left corner of the form.

![Figure 2. View controls.](image)

**Zoom In**

Clicking Zoom In doubles the scale of the plot while maintaining the same center.

**Zoom Out**

Clicking Zoom Out halves the scale of the plot while maintaining the same center.
Fit View

Fit View adjusts the plot scale so that all entities are plotted.

Box Zoom

Clicking the Box Zoom button activates the Box Zoom function. The user clicks the upper left hand corner then clicks the lower right hand corner of the desired region of the current plot to zoom in to that region.

Pan

Click the Pan button to activate the Pan function. The function is active when the button shows white arrows on a black background. Holding the mouse button down while dragging the mouse moves the image. Click the button again to deactivate the function.

Photo On/Off

When viewing cross sections, the point cloud can be superimposed on the panoramic photograph taken by the laser scanner. The point locations are converted to photograph coordinates by mapping the horizontal and vertical angles to the corresponding pixel location. The photographs cannot be scaled. Clicking Fit View centers the plot on the road centerline. Clicking the arrow buttons around the On/Off button moves the view.

Cross Section

Clicking the Cross Section button displays a cross section view of a slice of the point cloud. The thickness of the slice in feet is entered in the XThick box. The slice is centered on the Station value entered in the Station text box to the right. Subsequent cross sections can be viewed by scrolling the mouse wheel. The StaStep value is the distance in feet by which the Station is incremented.

Automatic Fit View

When the Automatic Fit View is on, the scale of the plot is set to show all points after every update. It is sometimes desirable to disable this function by clicking this button. Clicking again reenables the Automatic Fit View function.
Longitudinal Section

Click the Longitudinal Section button to display the Longitudinal Section form shown below. Enter the Begin Station, End Station and Offset (left is negative) of the desired section. Click OK to display it.

![Longitudinal Section form](image)

Location Display

The location of the mouse is displayed in text boxes at the bottom of the IDOT Laser Scanning form (Figure 3). The Offset, in feet, is negative to the left and positive to the right. Northing (N), Easting (E) and Elevations (Z) are also displayed as appropriate.

![Location display](image)

Display Controls

Display Controls (Figure 4) are located on the upper right side of the form. The first seven check boxes are enabled when the corresponding entities are available in the model. The last four allow the user to control other program features.

Scan Points

Scan Points are plotted when checked.

E TIN

The Existing TIN model is plotted when checked. This model is assumed to have been generated from preliminary surveys of the existing terrain before construction. When the TIN file is read, the user will be prompted to designate it as the Existing TIN file.
The Existing Scan TIN model is plotted when checked. This model is assumed to have been generated from laser scan data taken of the existing terrain before construction. When the TIN file is saved or read, the user will be prompted to designate it as the Existing Scan TIN file.

The Final TIN model is plotted when checked. This model is assumed to have been created during the road design process. When the TIN file is read, the user will be prompted to designate it as the Final TIN file.

The Final Scan TIN model is plotted when checked. This model is assumed to have been generated from laser scan data taken of the terrain after construction. When the TIN file is saved or read, the user will be prompted to designate it as the Final Scan TIN file.

The Pay TIN model is plotted when checked. This model will be derived by the user from the Final TIN model and the Final Scan TIN model. Modifications may be made to the Final Scan TIN model by the user to determine valid pay quantities. For example, if fill on a ditch slope is higher than the level required by the design, the TIN file would be modified to reflect the actual design elevation.

Conventional Survey Points read into the model are displayed when this box is checked.

When processing Final Scan data, pavement and sublayer materials should be removed before plotting the surface. This program does this automatically when the Remove Pavement box is checked. This box should be checked when generating the Final Scan TIN model. This function does not perform well in regions of sparse data.
Rem Culv
When the Remove Culvert box is checked, TIN models generated for ditch culverts defined in the road geometry data file are accounted for in volume calculations.

Near Cam
The default when the panoramic photo is displayed in cross section views is to use the photo from a scanner setup at an lower station so the user is always looking in the direction of increasing station numbers. It is sometimes desirable to view the points on the photo taken from the same scanner location. This is the case when Nearest Camera is checked. The user should be aware that this view frequently faces in the direction of decreasing stations. Do not click this box when the photo is displayed.

Plot Line
The Plot Line box is checked by default. When cross sections of scan points are plotted, the program sorts the points from left to right and attempts to fit a line through the lowest points in the cross section. The sorting operation can be very time consuming and this line is frequently irrelevant. The box can be unchecked to skip this routine. It must be checked when generating TIN files from scan data.

Other Controls
Other Controls (Figure 5) are provided on the lower right side of the form.

Plot View
Select the desired view for the display.

Active TIN
Select the active TIN model.

TIN
Click the TIN button to modify the cross section of the Active TIN.
**ContourPlot**
Click to display a contour plot in the plan view with the major and minor contour interval in feet defined in the Parameters form (Edit|Parameters).

**Undo**
Click to replace the last set of points removed during cleaning operations.

**Polygon**
Click to outline a polygon in the picture or plan view.

**Limits**
Click the Limits button to toggle through options for limiting the points used to construct a cross section.
Figure 6 shows the File menu options.

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<th>Edit</th>
<th>Scan Job</th>
<th>Rout</th>
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<td></td>
<td></td>
</tr>
<tr>
<td>Exit</td>
<td></td>
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</tbody>
</table>

Figure 6. File menu items.

**SaveActiveTIN**

Select **SaveActiveTIN** to save the current active TIN model to an IDOT Ascii file.

**Exit**

Select **Exit** to exit the program.
EDIT

Figure 7 shows the Edit menu options.

![Edit menu items](image)

 Parameters

Select **Parameters** to open the **Parameters** form. The user can access this form at any time to change the default values of various parameters in the program.
SCAN JOB

A scanning project will typically consist of multiple scans taken along a route. The scan data is assembled into one job by creating a scan job and adding scans to the job. If necessary, the scan data is transformed to a common coordinate system and can be filtered to remove closely spaced points. Figure 8 shows the Scan Job menu options.

![Scan Job menu options](image)

**Figure 8. Scan Job menu items.**

**New Scan Job**
Select **NewScanJob** to create a new scan job.

**Scanner Units**
The user is prompted to input a multiplier to convert scanner data to feet. The default value converts millimeters to feet. If the scanner was set to record data in feet, this value should be 1.

![Scanner Units dialog box](image)

**Create Job File**
The user is then prompted to create a job file. All files used to store job information will be saved in the selected directory, and job files names will begin with the name entered for the Scan Job File.

**Scan Point Spacing**
The user will be allowed to enter a minimum scan point spacing to reduce the point cloud size. As most scanners record points at equal angular increments, the point spacing is much closer near the scanner. This can lead to an excessive number of points that slows processing without significantly improving the results. The program only saves a point if it is more than the minimum distance from the last recorded point. Points are typically scanned by holding the horizontal angle fixed while varying the vertical angle across its full range before incrementing the horizontal angle. In this case the function will only control spacing in the radial direction.
Add Scan
Select AddScan to add the data from a scan to the scan job.

Scan Name
Enter a unique name for each scan. The default is Scan_n.

Select Point Cloud
Browse to and select the Point Cloud file in the *.pts format.

Georeference
If the laser scanner is set up over a known point and backsighted on another known point, the data should already be georeferenced. If the scanner was not set up over a known point and three or more targets at known points were scanned to locate the scanner, the point cloud data is probably stored in a local coordinate system and must be georeferenced to transform this data to the state plane (or other) coordinate system.

Select Target File Exported from Scanner
If the data is not georeferenced, the user must select the Scanner Target File in the *.tgt format containing locations of three or more targets in the scanner coordinate system.
Select the Panoramic Photo File
Select the file containing the panoramic photograph taken from the scanner. Select **Cancel** if a panoramic photograph is not available.

Select Target File with State Plane Coordinates
If the data is not georeferenced, the user must select the State Plane Coordinate Target File. This file will be in the standard survey point format. This data gives the locations of the targets State Plane Coordinates or some other coordinate system common to all scans. It is expected (although not necessary) that all of this data for a scan job will be in one file taken from GPS or total station reading of the control points for the job.

New Scan Data
If the data is not georeferenced, the user must match the scanner target locations with the state plane coordinate target locations. The **New Scan Data** form (Figure 9) allows the user to select the available targets from each file by name. The height of the target above the control point is read from the *.tgt file but should be verified. Click **Match** to pair the two target locations. The program uses an iterative procedure to determine the scanner location and orientation. The algorithm attempts to minimize the RMS error between the scanner locations and the actual locations of all targets pairs. The error for each pair is displayed. Clicking target pair displays the **Error Components**. A minimum of three targets pairs is required. The user can uncheck the **Keep** box to remove the pair designated in the **Pair Number** box from the calculation. This would be necessary if targets were paired incorrectly or if there is a significant error in the location of a target. The user can experiment by “unchecking” various targets to determine which set gives an acceptable error. Targets 1001 and 1009 were removed from consideration in the example in Figure 9 as indicated by zero error.

![New Scan Data form.](image-url)

Figure 9. New Scan Data form.
When **Save** is clicked, the program transforms and saves the point cloud. The Transforming Point Data progress bar is displayed. If the Scan Point Spacing is not zero, the progress bar will appear to stop before completion. Only points that are retained are transformed, so if 50% of points are removed because they are too closely spaced, only 50% progress is required.

**Automatic Target Matching**

It is good practice to label the scanner targets and the control points using a consistent numbering system. The program will automatically match targets with the same number designation. For example, a scanner target named Sphere_107 would be matched with a surveying point, CP107. Any labeling system can be used, but it is strongly recommended that the user create these labels in a consistent manner during data collection. The user can uncheck the **Keep** box to remove any inappropriate matches.

**Georeferenced Data**

If data is already georeferenced the program will prompt the user for the scanner location and orientation: Northing, Easting, Elevation, and Horizontal Angle. These values should be available from the scanner’s operating software.

**Open Scan Job**

Select **OpenScanJob** to open an existing scan job in order to add additional scans to it. Respond to the **Scanner Units** and **Scan Point Spacing** prompts. These values may be different from the original scan job.

**Save Scan Job**

Select **SaveScanJob** to save the scan job under a different name. This would be appropriate if the user had cleaned irrelevant points from the file. These points would be flagged in the new versions while the old version would display all points.

**Compress Scan**

Select **CompressScan** to delete points that have been flagged as irrelevant and save a new version with a “C” appended to the scan job name. This will produce a smaller binary data file.
ROUTE DATA

Figure 10 shows the Route Data menu options.

<table>
<thead>
<tr>
<th>Route Data</th>
<th>Plan Scan</th>
<th>Point Cloud</th>
<th>Add Data</th>
<th>Surface</th>
<th>File Drive</th>
<th>Bridge Str</th>
<th>Open Road Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIN File</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>IDOT Ascii</td>
<td>XML</td>
<td>Read</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Boundary</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Grid</td>
</tr>
</tbody>
</table>

Figure 10. Route Data menu items.

**TIN File**

Read
Terrain data is input to the program through TIN files. Two TIN formats can be read: XML and IDOT Ascii. After reading the TIN file the user should designate what type of TIN file it is from the list shown in Figure 11.

![AssignTIN form](image)

Figure 11. AssignTIN form.

**Boundary**
Selecting Boundary after reading a TIN file determines which triangle sides are on the boundary of the TIN model. Only the boundary is plotted during scan planning operations. The boundary definition can be saved in the TIN file (File | Save ActiveTIN) so it will not have to be recalculated.

**Grid**
Elevation data in the TIN file can be converted to a Grid definition. The elevation is calculated at every point in a rectangular grid with the X and Y spacing defined on the TINGrid form (Figure 12). This is a fast operation so the results are not saved. This function is called automatically before some processing operations because extracting elevations from the grid is much faster than extracting these values from the TIN file.
Open Road Geometry

A Road Geometry Data file can be opened by selecting this menu item. It is automatically called when the program is initiated.
SCAN PLANNING

To optimize scanning operations, the surveyor should develop a plan based on available terrain data to preplan scanner locations. The goal is to ensure that data is collected to provide adequate coverage of the area of interest using a minimum number of scanner setups. A TIN file of the terrain is required. The user can plan scans manually or automatically. With the manual procedure the user moves the mouse to a proposed scan location on the plan view of the TIN file. The area in the line of sight of the scanner up to its maximum range is highlighted on the view. The user can click to save this location or move the mouse to a new location. Previously selected scan locations are shown in order to evaluate the entire plan. The Plan Scan menu items are shown in Figure 13.

![Figure 13. Plan Scan menu items.](image)

**New**

A TIN file with the boundary should be opened before creating a new plan. The desired TIN file must be the Active TIN. If Grid elevations have not been calculated, the TINGrid form will be displayed after selecting **New**. Select the grid spacing and click OK. The Scan Plan form (Figure 14) will be displayed after the grid is calculated.

![Figure 14. Scan Plan form.](image)

Instrument parameters are entered in the Scan Plan form. **Height** can be an approximate value. **Maximum Angle** and **Minimum Angle** refer to the vertical angle. The **Horizontal Increment** and **Vertical Increment** refer to the angular resolution of the scan. If the **Maximum Space** would be exceeded as some ranges by the **Vertical Increment** value, the
program will consider those points to be out of range. The approximate **Number of Points** is displayed for the scan.

The user clicks **Read Cntrl Pnts** to read a file of survey points where targets may be located to determine how many targets will be visible from the scanner location.

The user selects **Add** to create a new scan. The user then moves the mouse over the plot of the TIN file. The scan area is displayed. Clicking the mouse sets a scan location. A scan may be moved by selecting the corresponding **Scan Number** and moving the mouse to the new location. Click the **Save** button to save a Scan Plan report to a *.txt file. The file can be opened and printed from various word processing applications. It lists both the state plane coordinates and station and offset coordinates of the planned can locations.

**Open**
Select Open to open an existing Scan Plan file in order to make changes or add scans.

**Control Points**
Select Control Points to read a survey point file with control point coordinates to determine which control points are visible from each scan location.

**Auto Plan**
Select **Auto Plan** to develop a plan automatically. The **Auto Scan Planning** form will be displayed. Enter the **Begin Station** and **End Station** and select whether the scan is for **Existing Terrain** or a **Finished Road**. Click **OK**.

![Auto Scan Planning](image)

After calculating the TIN Grid (if necessary), enter scanner properties in the **Scan Plan** form and click **Auto Plan**. The initial scanner location is set on the road centerline at the Begin Station. The scanner moves toward the End Station in 10-foot increments. The coverage of the terrain between the construction limits from the Begin Station to the scanner is monitored. When less than 95% of that terrain is in the line of sight of the scanner, the first scanner location is set. This percentage (the Efficiency) should start near 100% and decline as the scanner moves. A new scan is initiated 10 feet beyond that position and moved in 10-foot increments until the coverage of terrain between the previous scan and the current scan is less than 95%. This scanner location is set and new scan initiated until the End Station is reach. The user can modify this plan as required.
PROCESSING POINT CLOUD DATA

Scan job files are imported to create TIN files describing the terrain. Several functions are provided to assist the user in removing irrelevant points. The Point Cloud menu items are shown in Figure 15.

![Point Cloud menu items](image)

Figure 15. Point Cloud menu items.

**Import**

Click Import to select the scan job to process. A progress bar will display the name of the scans being read.

**Remove Distant Points**

Many scan points will be outside the construction area and/or significantly higher than the surface. If a sufficiently accurate TIN file is available, points that are either outside the area covered by the TIN file or more than a specified distance away from the TIN surface can be flagged as irrelevant by selecting the Remove Distant Points option. The TIN model must be the Active TIN. The user must enter the maximum allowable distance, in feet, from this surface. All more distant points will be flagged as irrelevant. Irrelevant points are not used when constructing the surface.

![Maximum Distance](image)

**Clean**

The user can manually select points to be flagged as irrelevant using the Clean option. Points are selected in the cross section view by left clicking opposite corners of a box enclosing a set of points or right clicking near points. Points can be reinstated by clicking the Undo button. The previous 10 cleaning actions are saved for undoing. The Clean menu item is renamed Stop Cleaning when the cleaning mode is active. Select Stop Cleaning when finished.

**Generate TIN**

Select Generate TIN to create a TIN file from the scan data. Fill in the requested parameters on the Generate TIN form (Figure 16). The TIN file is constructed by generating a
cross section at stations spaced at the **Station Interval**. This line connects the lowest points at spacing roughly equal to the **Offset Interval**. The **Slice Thickness** is the width of the slice from the point cloud considered when defining the lowest point. It is the same as the **XThick** parameter on the main form. All units are feet.

![Generate TIN form](image)

**Figure 16. Generate TIN form.**

**Remove Ditches**

The **Remove Ditches** function reviews the properties of the culvert ditches defined for the roadway and determines where each would intersect the Active TIN surface. A separate TIN model is created for each ditch. This is a submodel under the Active TIN model. Both surfaces can be plotted, that is, with or without ditches. This function should be executed after generating the Final Scan TIN model. This feature can also be used to account for other situations, for example, bridge excavation.
ADDITIONAL DATA

Conventional surveying data can be read and displayed in cross section plots. Data files must be in an Ascii text file in the Survey Points format. This is a typical output format from surveying data collectors. Figure 17 shows the menu item.

![Additional Data Menu Item](image)

Figure 17. Additional Data menu item.
MANIPULATING AND ANALYZING SCAN TIN FILES

Volumes are calculated based on the surfaces defined by TIN files derived from the scans. TIN files designated as Existing Scan and Finished Scan must be available. The Surface menu items are shown in Figure 18.

Interpolate

The Interpolate function is used to smooth the TIN file by creating a planar surface between lines defined in two cross section plots. This is particularly useful when creating TINs from final road scans. The “planes” are derived in Station/Offset coordinates accounting for the road alignment so the function follows curves accurately and will also account for smooth changes in slope between the two cross sections.

When the Interpolate form (Figure 19) is displayed, enter the locations of Stations A and B at the ends of the region to be adjusted. These stations must be aligned with points in the TIN file so the program will find the nearest allowable station to the value entered. Clicking the - button will display the nearest station. Clicking < or > will move to the next allowable station.

Clicking the Plot button displays the TIN file from a cross section view between Stations A and B. Moving the mouse wheel in this display rotates the view about a horizontal axis for clearing viewing.

Click Select A to define a line on the Section A plot. The line must connect points currently in the TIN file. Click Select B to define a line on the Section B plot. Click Smooth to modify the TIN file. Additional planes can be defined for smoothing, but the user must work from left to right. The user is prevented from selecting points on either Station A or B to the left of previous points.

CalculateVolume

Select CalculateVolume to calculate the cut and fill volumes between two surfaces using TIN files of the surface between two defined stations from before and after construction. The user is prompted to identify the Save Volume File, a comma separated variable (*.csv) file. This is an Ascii file that is also a standard format for reading into Excel.

Enter the Begin Station and End Station for the region of interest in the Calculate Volume form (Figure 20). Enter the Station Interval in feet at which output will be saved.
PlotCrossSections

Select **PlotCrossSections** to create plots of cross sections at regular intervals displaying the cut and fill areas. Enter the **Begin Station** and **End Station** in the **Plot Cross Sections** form (Figure 21).
The first cross section is displayed on the screen as shown in Figure 22. Clicking on the figure displays subsequent sections.

Figure 21. Plot Cross Sections form.

Figure 22. Plot of cross section.
**PlotSingleSection**

Select **PlotSingleSection** to create a plot of any arbitrary cross sections and calculate cut and fill areas. Click **OK** when prompted to select points to define the cross section and click the end points of the desired section on the plan view.

![Cross Section Areas](image)

**VolumeUnderArea**

Select **VolumeUnderArea** to calculate cut and fill volumes under an area traced as a polygon on the plan view. Enter the Pavement Thickness on the **Volume Under Polygon** form (Figure 23). This will be subtracted from the finished surface. Enter the **Begin Station** and **End Station** of the approximate region of interest. A rectangular region will be constructed between these stations as a starting point for the area. This can be modified in the plan view before completing the calculation. The **Mesh Refinement** can be modified. Higher values will create a finer mesh over the region for calculating volumes. Click **Trace** and move to the **IDOT Laser Scanning** form.

![Volume Under Polygon](image)

Figure 23. Volume Under Polygon form.

The default rectangular region is displayed. The nodes can be moved by left clicking and dragging. New nodes can be added by right clicking. The Polygon button in the lower right corner of the form is now labeled with a capital S. Click S to display the Cut Volume and Fill Volume in the Volume Under Polygon form.
MONITORING SETTLEMENT DURING PILE DRIVING

Figure 24 shows the **Pile Drive** menu option.

![Pile Drive menu items]

Points from individual scans in a cross section plot are fit with planes by clicking **FitSurfaces**. The **Fit Surfaces** form is displayed. Click **Select Area** and frame a rectangle around the points. The stations at the two ends of the points in the cross section plot are displayed. These are controlled by setting the **XThick** and **Station** values in the **IDOT Laser Scanning** form. Click **Fit** to perform a regression analysis over the points from each scan and display the distance between the centroids of those surfaces from the surface from the first scan.

![Fit Surfaces form]
FILE FORMATS

Several file types are used by the ILSI system.

**Triangular Irregular Network (TIN) – XML File (*.xml)**

Two types of data are extracted from the XML file: Points (P) and Facets (F). The Point id must be a number. Examples of the XML formats are:

```xml
<P id="1">772227.375545 2359359.054315 556.1378</P>

<F>3784 3633 3785</F>
```

The double precision numbers in the Point data are Northing, Easting and Elevation. The Facet data are the three Point ids defining the vertices of the triangle.

**Triangular Irregular Network (TIN) – IDOT Ascii File (*.tin)**

<table>
<thead>
<tr>
<th>Line 1:</th>
<th>Number of points (nPts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 2:</td>
<td>Number of triangles (nTri)</td>
</tr>
<tr>
<td>Lines 3 to nPts+2:</td>
<td>X Y Z of point (note X is easting, Y is northing)</td>
</tr>
<tr>
<td>Lines nPts+3 to nPts+nTri+2:</td>
<td>P1 P2 P3 of triangle</td>
</tr>
<tr>
<td>Line nPts+nTri+3:</td>
<td>Number of boundary line segments (nBnd)</td>
</tr>
<tr>
<td>Lines nPts+nTri+4 to nPts+nTri+nBnd+3</td>
<td>P1 P2 of boundary line segment</td>
</tr>
</tbody>
</table>

These files are expected to have a “*.tin” extension.
**Road Geometry Data (*.rgd)**

Number of segments in horizontal alignment

Segment type, Tangent or Curve  
Begin station in feet  
End station in feet  

If Tangent  
  Begin point Northing  
  Begin point Easting  
  End point Northing  
  End point Easting  

If Curve  
  Center point Northing  
  Center point Easting  
  Radius in feet  
  Curve direction, Left or Right  
  Begin angle in degrees (North is 0°, clockwise is positive)  
  End angle in degrees  
  Station, in feet, at which transition to superelevation begins  
  Station, in feet, at which transition to superelevation ends  
  Station, in feet, at which transition from superelevation begins  
  Station, in feet, at which transition from superelevation ends

Repeat from [Segment type, Tangent or Curve] for each segment

Number of segments in vertical alignment

Segment type, Tangent, Curve or CurveCurve  

If Tangent  
  Begin station in feet  
  End station in feet  
  Begin elevation in feet  
  End elevation in feet  

If Curve: Geometry is derived from Tangents on either side. No additional data is needed.

If CurveCurve: Indicates a curve with a tangent on one end and another CurveCurve on the other  
  Station where curves meet  
  Elevation where curves meet

Repeat from [Segment type, Tangent, Curve or CurveCurve] for each segment

Number of typical cross sections  
Cross section name
Begin station in feet
End station in feet

Left pavement width in feet
Left pavement slope
Left pavement thickness in inches
Left curb exists, True or False

If Left curb exists:
  Number of points defining curb profile
  0 0 (coordinates of first curb profile point, always 0 0) (See Figure 25)
  X2 Y2 (coordinates of second curb profile point relative to first)
  X3 Y3 (coordinates of third curb profile point relative to first)
  Repeat for all points

Left shoulder width in feet
Left shoulder slope in feet
Left shoulder thickness in feet (use 0.0 if there is no shoulder)

Left aggregate shoulder exists, True or False

Left sidewalk exists, True or False

If Left sidewalk exists:
  Left sidewalk width in feet
  Left sidewalk slope
  Left sidewalk thickness in inches
  Left sidewalk shoulder width in feet

Left superelevation exists, True or False

If Left superelevation exists:
  Left superelevation slope

Number of left sublayers
Left sublayer 1 name
Left sublayer 1 width in feet
Left sublayer 1 thickness in inches
Repeat from [Left sublayer 1 name] for all sublayers

Repeat from [Left pavement width in feet] for Right side

Number of culvert ditches
Station at centerline in feet
Skew angle in degrees
Left slope
Right slope
Bottom elevation
Top elevation
Bottom width
Slope
**Point Cloud File (*.pts)**

Line 1: Number of points in first scan (nPts)
Line 2 to Npts+1: X Y Z Intensity Red Green Blue (7 space delimited values)

Repeat for all scans in the file

**Scanner Target File (*.tgt)**

TargetName,Northing,Easting,Elevation,HeightTypeName,HeightValue

**Survey Point File (*.txt or *.csv)**

PointNumber,Northing,Easting,Elevation,PointTypeName
EXAMPLES

All files required to run the examples are provided on the distribution disk in the ExampleFiles directory.

Scan Planning

Run ILSI and select the ExampleFiles\ScanPlan\GovPkwy.rgd road geometry file when prompted.

Open the TIN file containing the terrain model for the area to be scanned. The file ExampleFiles\ScanPlan\Ex_Surface.xml contains terrain for Governors Parkway.

Route Data | TIN File | Read | XML

Designate TIN File Type and Click OK. The selected file type is not critical as the Active TIN will be analyzed. There should only be one TIN file open during scan planning.

As the XML TIN file does not contain a boundary description, the boundary must be calculated before planning.

Route Data | TIN File | Boundary

You will be prompted to save the TIN with the boundary for future use. It will be saved in IDOT Ascii format.

A Grid should also be calculated to increase the efficiency of the planning algorithm. The grid spacing, in feet, is entered in the TINGrid form. Values between 1 and 5 feet are recommended. This operation is fast so the Grid is not saved. It must be recalculated every time the TIN is used for planning.

Route Data | TIN File | Grid

Initiate the planning process by selecting

Plan Scan | New

The Scan Plan form is displayed as shown in Figure 26. Start with the default values.
Click Add to create a new scan. Move the mouse over the plan view of the TIN file and view the area covered from a proposed scanner location. Left click to save the location of the scanner. Modify a previously selected scan location by selecting the Scan Number and moving the mouse to the new location. Click Add to plan additional scans and Save when finished. View the Scan Plan file using Notepad.
Creating Scan Job

Files required for this example are contained in the ExampleFiles\NewScan directory. Run ILSI and select ExampleFiles\NewScan\GovPkwy.rgd as the road geometry data file. A new scan job is started by selecting

Scan Job | NewScanJob

Accept the default factor (0.003280839895 ft/mm) to convert scanner distances to feet. Select a path and name for the job. All files for the job will be stored in this directory. Enter the minimum point spacing. Values between 0.0 and 1.0 feet are recommended. Use 0.5 feet. Add scans by selecting

Scan Job | AddScan

The data consists of twelve scans taken of the finished Governors Parkway east of District Drive. A Trimble GS200 was used for nine of the scans. A Trimble GX was used for three. The Trimble GX scans are georeferenced; that is, the point cloud data is in state plane coordinates. These scans are stored in the ExampleFiles\NewScan\GovernorGX subdirectory. The scans are labeled using the approximate Station and whether the scanner was set up on the Left or Right berm. It is not necessary to add all scans.

Input the scan name. The default, Scan_n, can be used, but a more descriptive name is recommended. Use Scan_1_Sta189L for the first scan.

Select the point cloud file, ExampleFiles\NewScan\station_189L\ Station_189L.pts, and click No when asked if the data is georeferenced. Select the target file exported from scanner, ExampleFiles\NewScan\station_189L\Station_189L.tgt. Select the panoramic photograph file, ExampleFiles\NewScan\station_189L\ Station_189L_Panorama_1.jpg. Select the target file with state plane coordinates, ExampleFiles\NewScan\SphereSPC.csv.

The program will automatically attempt to pair targets from the two files by matching names with the same numerical value. The New Scan Data form shown in Figure 27 lists the matched pairs of points. The RMS Error is high so some pairs should be removed. Select the last pair and uncheck the Keep box. This reduces the RMS Error to about 0.05 feet (Figure 28). Click Save to save this result. A progress bar is displayed indicating that the program is transforming the scanner coordinates into state plane coordinates. If the minimum point spacing is greater than zero, some points will not be transformed and saved, so the progress bar will stop before filling the block. This is an indication of what percentage of the points were removed. Repeat this process for other scans taken by the Trimble GS200 scanner.

When adding scans from the Trimble GX scanner add a scan, input the scan name Scan_n_GXSta195R, select the point cloud file, e.g. ExampleFiles\NewScan\GovernorsGX\GX195R.pts, and answer Yes when asked if the data is georeferenced. Select the file of the panoramic photograph, ExampleFiles\NewScan\GovernorsGX\GX195R_Panorama_1.jpg. Enter the Northing, Easting, and Elevation of the scanner origin and the Horizontal Angle; that is, the direction of the center of the scan. This will align the 360° photograph with the points. These values for the three scans are available in the ExampleFiles\NewScan\GovernorsGX\StationLocations.txt file.

Note: The photograph for the GX189 scan is not 360° so, although it can be displayed, the scan points and the photograph will not be coordinated.
Figure 27. New Scan Data form after automatic matching.

Figure 28. New Scan Data form after removing questionable point.
All information is automatically saved in the \textit{scanname}.txt and \textit{scanname}.bdf files. There is no need to save the scan job. When finished the job can be imported and viewed by selecting

Point Cloud | Import

Additional scans can be added to the job by selecting

Scan Job | OpenScanJob

and adding scans.

\textbf{Creating TIN Files from Laser Scans}

Run ILSI, select the ExampleFiles\CreateTINModel\GovPkwy.rgd road geometry data file, and

Point Cloud | Import

the ExampleFiles\CreateTINModel\AfterAltAll.sfj scan job. Select

Route Data | TIN File | Read | IDOT Ascii

Open ExampleFiles\CreateTINModel\GovFinalTIN.TIN. Designate TIN File Type as Finished. View cross section plots between Station 187+00 and 205+00 by clicking the Display/Update Cross Section Plot button and either typing in the desired station or moving the mouse wheel. The laser scan data will be superimposed on cross sections of the TIN file. Note that the TIN file was constructed from the design drawings for research purposes. There are regions that do not match what was actually constructed. The user can activate the clean points function by selecting

Point Cloud | Clean

Remove points that distort the model. In many cases it is better to create the TIN model first and modify the TIN. Select

Point Cloud | Stop Cleaning

to disable the clean points function. Click the No Limits button to display Construct so the edges of the TIN file will be aligned with the construction limits extracted from the original drawings.

Select Point Cloud | Generate TIN.

Fill out the Generate TIN form as shown in Figure 29 and click OK. Designate TIN File Type as Finished Scan. View a contour plot of the TIN model by entering a contour interval in feet and clicking the CPlt button. Look for irregularities in the contours that might indicate errors in the TIN model. Errors are likely in regions with insufficient laser scan points or overgrown vegetation. The TIN model can be modified in the cross section view. Click the Display/Update Cross Section Plot button and scroll through the model using the mouse wheel to identify errors. The cross section plot of the design TIN model will provide a guide to the desired geometry.
Go to Station 200+00 by entering the values in the Station text boxes and clicking the Display/Update Cross Section Plot button. Figure 30 shows the cross section in which the left side of the pavement was not properly modeled due to insufficient points. We will add one point to the TIN model and then move it to improve the agreement of the model and the design.

Click the TIN button and right click at a point on the blue line to the left of the center line to create a new point. The caption on the TIN button has changed to Save. Click this to save the new point. (The caption changes back to TIN) Click TIN again to modify the point. Move the TIN point to the desired location by dragging while holding the left mouse button. Click Save when finished. Ensure that the Finished Scan is the selected in the Active TIN box then select File | SaveActiveTIN.

Figure 29. Generate TIN form.

Figure 30. Cross section showing TIN to be modified.
Calculating Earthwork Quantities

Run ILSI and open the road geometry file, ExampleFiles\VolumeCalculation\GovPkwy.rgd. Open the TIN file derived from the laser scans taken before construction.

Route Data | TIN File | Read | IDOT Ascii

Select ExampleFiles\VolumeCalculation\Before.tin. Designate TIN File Type as Existing Scan. Open a second TIN file ExampleFiles\VolumeCalculation\After.tin and designate it as Finished Scan. Select

Surface | CalculateVolume

Name the volume file and save. Enter the Begin Station and End Station. Select the Station Interval for the output. Use the values shown in Figure 31. Click OK.

![Figure 31. Calculate Volume form.](image)

A file is generated giving cut and fill quantities, in cubic yards, within each station interval and cumulative quantities. This file can be read in Excel to allow further analysis of the data. The Excel file is shown in Figure 32. Some user formatting was performed in Excel.
Assessing Movement during Pile Driving

Scans were taken of the region around pile driving operations on Illinois 157 in Cahokia, Illinois on three different days during a week of pile driving operations. Run the ILSI program and select Cancel when prompted for a road geometry data file.

Point Cloud | Import
to Import the ExampleFiles\Settlement\Cahokia360sp1ft.sfj scan job. Click OK in the Define Centerline box. Click Yes when prompted to replot with a sparse point cloud. Click two points in the point cloud image to define the centerline. Any centerline can be used, but it is best to make the centerline roughly parallel to a vertical surface of interest. The front wall of a nearby apartment building is visible in the circled region in Figure 33. The black line is the selected centerline. Figure 33 shows all points in the point cloud. The sparse point cloud displays only 1% of the points. Response is very slow with large point clouds.

Click at the second point when the red line is at the proper orientation. It is not necessary to place the centerline on top of the desired surface, just parallel to it.
Figure 33. Plan view of Cahokia point clouds with selected centerline.

Click the Display/Update Cross Section Plot button to view the cross section. Scroll the mouse wheel until the apartment wall is visible in the cross section. The Station must be greater than 0+00 which is at the beginning of the centerline. The user may wish to select Edit|Parameters to change the Vert To Horiz Scale parameter under the X Sect Plots tab. Click Yes when the Large Number of Points to Sort message is displayed. It may be necessary to modify the XThick and StaStep parameters. Turn off Automatic Fit View After Update and use the Box Zoom to zoom in on the apartment. Adjust the XThick value to the maximum reasonable value that is as wide as possible while still getting a fairly clean plane as shown in Figure 34. (Note that the centerline was drawn from bottom to top in this case. The orientation of the building may be reversed if the centerline was drawn differently.)

Figure 34. Points on wall from each scan.
Click Pile Drive | FitSurfaces to open the Fit Surfaces form. Click Select Area then click the upper left and lower right corners of a box surrounding the points on a plane on the apartment wall as shown in Figure 35.

Figure 35. Select points on a plane.

Click the Fit button and refresh the images by clicking the Display/Update Cross Section Plot button. The scan names in the upper left corner of the image will be followed by a number indicating the distance the plane from each scan is from the first, baseline scan (which will be followed by 0). If these numbers are significant and increasing, significant movement may be occurring. The movement value is horizontal if the box around the points is tall relative to its width indicating a vertical surface. The movement is vertical if the box around the points is wide relative to its height indicating a horizontal surface. Repeat this exercise with the parking lot to the left in front of the apartment. The Display Scanner Photo button can be clicked to display the point superimposed on the panoramic photo after updating the cross section plot.