Testing and Performance Evaluation of Fixed Terrestrial 3D Laser Scanning Systems for Highway Applications

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Word Count: 7414 including tables and figures  
Submission Date: November 14, 2008

Transportation Research Board 88th Annual Meeting, 2009
Testing and Performance Evaluation of Fixed Terrestrial 
3D Laser Scanning Systems for Highway Applications 
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ABSTRACT 
In many 3D laser scanner applications, high relative precision (relative dimensions within the registered point cloud) is sufficient; in contrast, DOT applications require good relative precision and high absolute accuracy. Thus, precise and robust geo-referencing is critical, and robust workflows are needed to reduce the likelihood and impact of human errors. DOT applications have a fairly unique combination of challenges, including longer range requirements, long linear geometry for complete jobs, tall structures, and dark pavement scanned at high incidence angle. These factors motivate standardized protocols and metrics for characterizing and evaluating scanner performance and to develop confidence limits for the scanner data in DOT applications.

The paper’s primary contribution is a set of vendor-neutral standard test protocols for the characterization and evaluation of 3D laser scanner performance, which users can conduct in easily accessible facilities. These evaluations focused on issues significant in DOT survey applications, workflows, and data flows. Example performance evaluation is provided for several commercially available 3D laser scanners. This paper provides the needed scientific basis for data-driven deployment of this valuable measurement tool. The paper also provides recommendations and guidelines which will promote consistent and correct use of 3D laser scanners by DOTs and their contractors. The guidelines clarify the common limitations of 3D laser scanners and recommend mitigation methods; this will help engineers and surveyors to select the right scanner and determine optimum scanning settings for survey applications.

INTRODUCTION
Terrestrial 3D laser scanners—a new class of survey instrument—have become popular and are increasingly used in providing as-built and modeling data in transportation applications, including land surveying, archeological studies, architecture, bridge structures, and highway surveys. These scanners measure thousands of data points (distance, angle, and reflected return signal power) per second and generate a very detailed “point cloud” data set. Laser scanner manufacturers suggest this new tool can reduce lane closures, decrease risk of injuries, and increase productivity. The resulting point cloud and detailed 3D model allows engineers to extract all the required data in the office, decreasing or eliminating the need for surveyors to return to the site for additional measurements. Using 3D laser scanners will dramatically improve safety and efficiency over conventional survey methods.

However, to fully realize the benefit of using 3D laser scanners, they must be used properly and in appropriate applications. Like any other instrument, the 3D laser scanner has its own set of limitations. The technical specifications of laser scanners as stated by individual manufacturers are typically difficult to reproduce in real-life applications. Generally, laser scanner performance, such as accuracy and detection range, varies with distance, object reflectivity, and angle of incidence to the reflective surface. Currently, each manufacturer provides their scanner specifications differently, using different accuracy terms and often their own trademark terminology. For example, one vendor may specify their target accuracy (one standard deviation) based on a white target at 100 m, while another vendor may specify their...
accuracy (95% confidence level) with no information regarding the target reflectivity or its range. Thus, direct comparison based solely on specifications is nearly impossible. Standards will increase confidence in 3D laser scanner measurements and encourage greater, more consistent, and more effective use of 3D laser scanners. Standard terminology definitions, standard test protocols and metrics, and reporting will enable fair comparisons of instrument capabilities. Despite manufacturers’ and users’ common desire for standardization in terminology and test protocols for 3D terrestrial laser scanners, no standard test protocols for the performance evaluation of 3D laser scanners have been established prior to this research.

Lichti et al. (1) were perhaps the earliest to develop tests for calibration of terrestrial laser scanners, including a clear comparison between digital photogrammetry and laser scanning. Balzani et al. (2) followed with accuracy tests in the range direction for terrestrial 3D laser scanners. Boehler et al. (3) installed multiple test targets to investigate the quality of measurements obtained with laser scanners. In addition, Johansson (4) explored the behavior of three different high-resolution ground-based laser scanners in a built environment. Gordon et al. (5) detailed an investigation into the calibration of the Cyrax 2400 3D laser scanner by developing a series of rigorous experiments to quantify the instrument’s precision and accuracy. Fidera et al. (6) used a Cyrax 2500—a pulsed Time-of-Flight (TOF) laser scanner—to study the influence of surface reflectance of different materials on laser scanning, specifically on the maximum coverage angles of cylindrical objects and the resulting determination of their diameter from the point cloud. Jaselskis et al. (7) have performed pilot studies on applying laser scanning for Department of Transportation (DOT) projects for the Iowa DOT using a Cyrax 2500. Kersten et al. (8-10) compared the accuracy of several terrestrial laser scanning systems, and developed accuracy test fixtures and procedures for range accuracy, influence of the laser beam angle of incidence, range noise, influence of color on range measurement, and level compensator accuracy. Sternberg and Kersten (11) examined the workflow in as-built-documentation of plants using different scanners, and compared the amount of human labor time for each system (software and hardware) from scanning and registration to complete Computer-Aided Design (CAD) model. Cheok et al. (12) provide a status update on the National Institute of Standards and Technology (NIST) work on standards and the National Performance Evaluation Facility for 3D imaging systems. In close cooperation with NIST, the American Society for Testing and Materials (ASTM) International E57 Committee on 3D Imaging Systems has begun a consensus-based standards initiative for 3D imaging systems.

DOT applications have unique requirements. Accuracy of the work product carries certain legal implications. Moreover, pavement surveys create extraordinary challenge for laser scanners – measurements are often made at long ranges with large angle of incidences on dark asphalt surfaces. Software must be able to handle “ghost” point cloud images created by passing traffic. Earlier studies lack:

- Performance data on latest commercial laser scanners with dual-axis level compensator,
- Long-range test data (over 50 m) on and off pavement,
- Best practices for laser scanning survey workflow and geo-reference/registration methodology, and
- Point cloud post-processing software evaluation: geo-reference / registration features, Quality Assurance / Quality Control (QA/QC) reporting, and integration to existing CAD software.
This paper presents a set of vendor-neutral standardized test protocols and metrics for the characterization and performance evaluation of fixed 3D laser scanners for transportation applications. The protocols were designed explicitly to allow users to conduct evaluations in easily accessible facilities. These standardized test protocols and metrics provide a solid scientific and engineering foundation for wide-scale adoption of 3D laser scanners in transportation surveying applications. The paper also clarifies the common limitations of 3D laser scanners, and provides recommended methods for their mitigation.

Research Objectives
Previous testing and evaluation of 3D laser scanner performance has shown (1, 3, 4, 7, 8, 10, 11) that the performance influencing variables include: laser beam-width, angle of incidence, surface reflectivity and color, range, object edges, and geo-referencing error. Geo-referencing errors are tied to geo-reference methodology, geo-reference target recognition accuracy, and workflow. Moreover, workflow affects worker and public safety, productivity, and the likelihood of human errors in geo-referencing—geo-reference error can far exceed instrument error. Therefore, workflow and geo-referencing methodology is also closely examined here.

Our effort by no means replaces NIST’s and ASTM’s standardization efforts. Their work will serve the overall 3D imaging user community. We focused on commercially available TOF-based 3D laser scanners that are relevant to DOT applications. The test goals were to:

- Understand 3D laser scanner performance and related influencing variables,
- Provide recommended geo-reference / registration methodology and target setup, and
- Provide basis for DOT procurement of 3D laser scanners.

Our tests were segregated into Control Test and a Pilot Study. The Control Test evaluated 3D laser scanner performance in an outdoor pavement environment with maximum repeatability for the available testing conditions. The Control Test was intended to be repeatable by Caltrans and others, perhaps at a different site, at a later date when new laser scanners become available. The Pilot Study evaluated the use of the 3D laser scanner in a ‘real-world’ Caltrans job scenario at a bridge over State Highway 113 with a clover-leaf ramp on either side (see Figure 1). The Pilot Study, along with the Control Test, clearly illustrated:

- The importance of accurate geo-referencing and registration methodologies,
- The advantage of reduced targets needed for registration for some scanners that have dual-axis level compensator,
- The importance for DOT applications of Field-of-View (FOV) in both the horizontal and vertical plane, and
- The importance of high resolution scans for feature identification.

This paper presents a subset of the Control Test; for more details, as well as the results of the Pilot Study, see (13), at http://ahmct.ucdavis.edu/images/AHMCT_LidarFinalReport.pdf.
The Control Test site is a 500 m deserted asphalt road. Test fixtures and pavement were scanned from one stationary point (Pt 200). Figure 1 shows an aerial view of the test areas including the geo-reference control points. Test fixtures were positioned on tripods on the side of the asphalt road (Figure 2). Each fixture was designed to test the scanner’s range precision, target recognition precision, resolution, and the effects of target reflectivity and laser incidence angle (13). The road surface elevation measurements by the laser scanner are compared with results from Total Station and digital level. Per one of the primary goals of this research, any similar site can support user Control Testing in the future.
Range Precision

The Range Precision test fixture was scanned at four different ranges: 25, 50, 75 and 100 m. It has two anodized flat aluminum plates—one with dull gray color finish (reflectivity ~ 40%) and one with flat black color finish (reflectivity ~ 10%)—mounted on a flat 102 x 51 cm (40 x 20 in) aluminum plate painted flat white (reflectivity ~ 80%). The fixtures are placed vertically using a bubble level at scanner height, with flat surfaces facing directly toward the scanner (incidence angle ~ 0°).

The scan point spacing varies from 3 to 10 mm depending on the scanner setting and range. The point cloud data were analyzed for root-mean-square error (RMSE) of Range Precision at 95% confidence interval. For each surface reflectivity region at each range, a rectangular window of point cloud data is cropped (~30,000 points) and analyzed in MATLAB. Care was taken not to include any points near edges. A least-squares fit method provided the best-fit planar surface for the cropped point cloud. Next, the orthogonal distance of each point to the best-fit plane is calculated. This orthogonal distance is the error, which is caused primarily by the range precision of the laser scanner—the range precision RMSE is shown in Table 1.
TABLE 1  RMSE (mm) of Range Precision of different vendor scanners at 95% confidence interval.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Color</th>
<th>Range 25 m</th>
<th>50 m</th>
<th>75 m</th>
<th>100 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leica ScanStation</td>
<td>White</td>
<td>4.65</td>
<td>3.23</td>
<td>3.23</td>
<td>4.78</td>
</tr>
<tr>
<td></td>
<td>Grey</td>
<td>4.72</td>
<td>4.31</td>
<td>4.68</td>
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<tr>
<td></td>
<td>Black</td>
<td>4.72</td>
<td>3.45</td>
<td>3.65</td>
<td>7.08</td>
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<tr>
<td>Trimble GX</td>
<td>White</td>
<td>2.10</td>
<td>1.65</td>
<td>2.20</td>
<td>1.84</td>
</tr>
<tr>
<td></td>
<td>Grey</td>
<td>2.98</td>
<td>4.82</td>
<td>4.92</td>
<td>7.74</td>
</tr>
<tr>
<td></td>
<td>Black</td>
<td>3.00</td>
<td>4.82</td>
<td>7.80</td>
<td>11.70</td>
</tr>
<tr>
<td>Optech ILRIS-3D</td>
<td>White</td>
<td>13.70</td>
<td>14.25</td>
<td>18.40</td>
<td>21.95</td>
</tr>
<tr>
<td></td>
<td>Grey</td>
<td>13.30</td>
<td>14.31</td>
<td>16.48</td>
<td>21.76</td>
</tr>
<tr>
<td></td>
<td>Black</td>
<td>13.07</td>
<td>14.07</td>
<td>18.93</td>
<td>18.37</td>
</tr>
</tbody>
</table>

Target Recognition Precision
The Target Recognition Precision fixture has a 15-cm (6-in) diameter sphere and a vendor-specific planar registration target mounted on a linear stage driven by a high-precision lead screw that provides accurate and repeatable millimeter-level translation. The fixture is mounted at scanner height with the flat target facing directly toward scanner. The fixture was scanned at 25 and 75 m. After each scan, the sphere and target were translated horizontally 4.75 mm by rotating twelve complete turns of the lead screw. These steps were repeated at least three times. The sphere and vendor-specific target translation measurements in the point cloud were compared to the high-accuracy mechanical translation value.

The results shown in Figure 3 illustrate that the Target Recognition Precision error increases with range. The major component of this error is likely caused by target recognition and modeling rather than angular error caused by the scanner’s encoder. This experiment also shows proprietary flat target performs better than 15-cm sphere targets; therefore, a proprietary flat target is preferred for geo-referencing and registration. Target recognition accuracy is more important than individual point accuracy because large geo-referencing target recognition error will lead to poor geo-referencing. The positional error of any point in a geo-reference point cloud is equal to the sum of the geo-reference and individual point measurement errors.
Target Recognition Precision Estimates using Sphere and Vendor Targets

![Graph showing Target Recognition Precision values using sphere and vendor-specific targets for Leica (all dashed) and Trimble (all solid).](image)

**FIGURE 3** (a) Leica Target Recognition Precision point cloud and model, (b) Trimble Target Recognition Precision point cloud and model, (c) Target Recognition Precision values using sphere and vendor-specific targets for Leica (all dashed) and Trimble (all solid).
Incidence Angle

A 15-cm (6-in) diameter cylinder (Figure 4) was painted—white, flat grey and flat black—to test the limiting angle of incidence as well as the variation of coverage angle with different reflectivity. The fixture is mounted at approximately scanner height at 25, 50, 75, and 100 m. The resulting point clouds are shown in Figure 5. The three point cloud segments (each reflectivity) were cropped from the point clouds, and a best-fit cylinder was developed for each to determine distance $d$ as shown in Figure 4. $d$ is the distance between the two outermost points in the cropped point cloud segment that lie closest to the best-fit cylinder. The maximum incidence and coverage were then calculated using distance $d$ and the diameter of the cylinder. Figure 6 shows the coverage angle at the four range and three surface reflectivity values—clearly, the Optech coverage angle is the least influenced by surface reflectivity. Theoretically, the maximum laser incidence angle should be less than 90°, and thus, the maximum coverage angle should be less than 180°. However, due to the “edge effect” and the methods of calculating coverage angle, some of the estimated maximum coverage angles are equal to 180°. If larger cylinders (30 - 45 cm) are used, the results would be more accurate because the “edge effect” will be comparatively smaller.

![FIGURE 4 Incidence Angle test fixture, and illustration of Incidence and Coverage Angle.](image)
FIGURE 5  Point cloud snapshots of Incidence Angle test fixture for different vendors at four ranges.
Resolution

Resolution generally refers to the ability of a system to distinguish and detect details. The definition of resolution for a 3D imaging system such as a laser scanner is still subject to debate within NIST and the ASTM International E57 Committee on 3D Imaging Systems. Generally, laser scanner resolution may be described as the ability of the laser scanner to detect, differentiate, and record 3D details or features of an object within the scanner’s range and field of view. Unlike image resolution which can be generally described using the number of pixels, there is not a single or multiple numerical term(s) that adequately describe laser scanner “resolution”.

Laser scanner “Resolution” depends on laser spot size and the smallest angle increment between two consecutive point measurements. Typically, a scanner’s laser beam is circular and collimated. Collimated laser beams diverge from the source over distance. However, some laser scanners use focused laser beams. In this case, the laser spot size is very small at a specific focal distance, but increases at a higher rate beyond the focal distance. Even though the beam divergence angle is very small, the laser spot diameter may be double that at the scanner. Smaller laser spot size results in higher energy per unit area at the target leading to higher probability of detection. Furthermore, a large laser spot size will illuminate a relatively large target area. The returned light reflection signal would be composed of the reflection from the large illuminated projected beam footprint. Depending on scanner’s proprietary internal light detection algorithm, the range measurement could be corrupted by the reflection signal from unintended target points;
for example, the range measurement could be corrupted by the reflection signal from objects in front of or behind the intended target area. The resulting range measurement may be any object within the laser beam footprint, or some combined average of ranges. Moreover, large laser spot size also increases the uncertainty in the angular location of the point to which the range measurement is made. The strongest reflected signal the scanner observes in the reflected signal may not come from the center of the laser beam; however, the laser scanner algorithm may assume the angular position of the feature is at the center.

Our test here aims to visually illustrate and compare the loss of “resolution” over long range. Test target boxes were scanned at four ranges: 25, 50, 75 and 100 m. These 61-cm (24-in) square boxes have a custom-machined front panel containing tapered slots decreasing from about 6.4 cm (2.5 in) width at the periphery to about 0.25 cm (0.1 in) at the center, as shown in Figure 2. Half of the slotted front panel is painted flat black (estimated reflectivity ~ 10%) and the other half is painted flat white (estimated reflectivity ~ 80%). The rear interior face of the box is painted flat white. Each target is mounted vertically on a tripod, facing directly toward the scanner so that the laser incidence angle is near 0°. As a representative sample, multiple views of the cropped point clouds of the “resolution” target at 25 and 100 m are shown in Figure 7 for the Leica ScanStation; additional point cloud images for all vendors are provided in (13). Figure 7 shows that a scanner’s ability to detect the small front panel taper detail at the center decreases as range increases, as anticipated. For further analysis of the resulting point clouds, a rectangular band (~6.4-mm (1/4-in) width across the 61 cm length of the front panel) of point cloud data was cropped across the same target location. These bands, taken close to the symmetric axis line across both the black and white surface reflectivity portions, are provided in Table 2.
FIGURE 7 Example laser point cloud (Leica) of Resolution test fixture at 25 m and 100 m.
TABLE 2  Laser point cloud data of central cross-section of the Resolution test fixture showing return from both front and rear panel. Top-down view, with back of fixture located at the bottom of each cross-section.

<table>
<thead>
<tr>
<th>Scanner</th>
<th>Range</th>
<th>Black Surface</th>
<th>White Surface</th>
</tr>
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<tbody>
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<td>25 m</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
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<td>Trimble GX</td>
<td></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>Optech ILRIS-3D</td>
<td></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>Leica ScanStation</td>
<td>50 m</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
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<tr>
<td>Trimble GX</td>
<td></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
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<tr>
<td>Optech ILRIS-3D</td>
<td></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>Leica ScanStation</td>
<td>75 m</td>
<td><img src="image13.png" alt="Image" /></td>
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</tr>
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<td></td>
<td><img src="image15.png" alt="Image" /></td>
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<tr>
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<td></td>
<td><img src="image23.png" alt="Image" /></td>
<td><img src="image24.png" alt="Image" /></td>
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</tbody>
</table>
Elevation Accuracy Comparison for Pavement Data with Conventional Instrument

A large majority of survey work performed for transportation applications involves pavement survey. Pavement elevation data of the controlled test site collected using conventional means (Total Station for x-y or Easting-Northing, and digital leveling instruments for z or Elevation) were compared with data from the 3D laser scanner. Measurements were made on five points for each cross-section of the roadway at intervals of 5 m along the roadway pavement, out to a maximum range of 120 m in both directions from the scanner. The x-y coordinates as measured by conventional instrument were used to select the closest point in the point cloud for elevation measurement comparison. The x-y distance offset between the closest point in the cloud and the surveyed point is usually within 1-5 cm. Figure 8 shows the difference in elevation measurement at various ranges for Leica, Trimble, and Optech scans. During the creation of these comparison plots, the data revealed that some initial point cloud geo-referencing was not optimal. In these cases, the error showed that the geo-referenced results were slightly tilted, resulting in positive error on one side of the scanner, and negative error on the other the other side. In these cases, the point cloud were re-registered by using backup target(s) and/or fixing any human error. The importance of proper geo-referencing and registration were clearly highlighted in this process. Human error in geo-referencing can gravely decrease the accuracy of the resulting point cloud. Figure 8 shows that both the Leica ScanStation and the Trimble GX meet the Caltrans hard surface survey vertical accuracy requirement (7 mm) at up to 80-90 m range, while the Optech ILRIS-3D meets the Caltrans soft surface vertical accuracy requirement (30 mm) at all ranges tested. Note that the pavement texture on this road is quite rough—the elevation differences may be result of the roughness. In addition, the vertical accuracy is highly dependent on the surface reflectivity and other site-specific conditions. The range at which the vertical accuracy is met is only an estimate to provide general indications; for more statistical significance, further experiments would be required.
FIGURE 8  Elevation errors of laser data for Old Hutchison Drive obtained from: (a) Leica ScanStation, (b) Trimble GX, and (c) Optech ILRIS-3D.
RECOMMENDATIONS FOR 3D LASER SCANNING AND WORKFLOW

A few key attributes and specifications of terrestrial 3D laser scanners are critical and of most interest to prospective Caltrans and other DOT users. They may not be applicable to other areas such as plant survey and cultural heritage studies—at a minimum, the order of importance may vary. Here, for conciseness and easy reference, we merely note the key specification areas in order of importance, particularly with respect to DOT procurement and use of laser scanners—for detailed discussion, specifications, and recommendations please see Chapter 7 of Hiremagalur et al. (13):

1. Range Accuracy within useful range,
2. Registration and Geo-reference methodologies,
3. Scanner Instrument Field-of-view (FOV),
4. Survey-grade Dual-axis Level compensator,
5. Useful range of scanner,
6. Scanner control software,
7. Average scanning speed (points per second),
8. “Resolution”.

The productivity of terrestrial 3D laser scanning is very much dependent on the workflow used. For detailed workflow recommendations, including preparation, scanning, and post-processing, as well as DOT or contractor Quality Assurance / Quality Control, see Chapter 7 of (13); here a brief summary is provided. In the scanning phase, an optimum scan field layout is of critical importance. As an example, Figure 9 provides a suggested survey layout for a typical 2- or 4-lane Caltrans highway job with curb, gutter lines and bridge structures. In the case of a highway having a large median, the scanner should be placed in the median with about 130-160 m (430-520 ft) between each setup position; shorter separation will be needed for new asphalt. The targets should then be positioned in a range of 50-75 m (160-250 ft) radius on either side of the scanner. The recommended overlap of scan areas is in the range of 30-37 m (100-120 ft).
Specific situations and conditions may be different. For example, newly overlaid dark asphalt pavement dramatically reduces the scan range, and the user should shorten the scan setup spacing accordingly. The number of target(s) may be reduced with the use of dual-axis level compensator. Testing should be done to determine the specific job-site situation and adjust the control points if needed.

In the post-processing phase, ideally, at least one extra registration target should be captured in every scan setup for the dual purposes of redundancy and Quality Assurance/Quality Control (QA/QC). At a minimum, there should be at least one extra registration in every other scan setup for QA/QC purposes. In addition, point cloud recipient(s) should examine overlapping point cloud areas from two different scan setups to determine if there is any significant mismatch. Alternatively, a contractor may compare the point coordinates in the point cloud to those made by using traditional instrument such as Total Station and digital level. A surveyor may perform additional QA/QC by comparing elevation of point cloud points with survey points collected via traditional survey means. Care should be used with reflectorless Total Station measurements in the QA/QC process, as reflectorless measurements can include large errors.

TEST RESULT SUMMARY AND CONCLUSIONS

This paper presented standardized test methodologies, metrics, fixtures, and analysis techniques to quantitatively and qualitatively evaluate 3D laser scanner hardware for accuracy, repeatability, and usability, all for DOT applications, including highly demanding pavement surveys to produce Digital Terrain Models. These results provide the means to directly compare scanners and software from multiple vendors in a consistent manner, and to evaluate their effectiveness in field situations. The paper also discussed surveying and 3D laser scanning workflows, including approaches for establishing controls, performing field surveys and scans, and post-processing of the data. To illustrate the methodologies, testing and evaluation of three laser scanner systems (Leica ScanStation, Optech ILRIS-3D, and Trimble GX) was included, with key points summarized below.

For Range Precision, the Trimble GX is more influenced by surface reflectivity at different ranges than for the Leica ScanStation. However, both scanners have similar range precision of about 5 to 6 mm (95% confidence level). The Optech ILRIS-3D range precision is about 19 mm (95% confidence level).

The Target Recognition Precision test revealed that vendor-specific proprietary target recognition error is generally smaller than for a 15-cm diameter sphere. Therefore, vendor-specific targets should be used for geo-referencing and registration. Moreover, each vendor-specific target has an optimal range for accurate automatic target recognition. If the target is placed too far outside of this range, the increased target recognition error far outweighs any associated gain from improved geometry, resulting in higher overall geo-referencing error.

The Elevation Accuracy comparison showed that Leica and Trimble scanners meet the stringent Caltrans hard surface survey accuracy requirement of 7 mm, and that the useful range for Leica and Trimble is in the 80 - 90 m bracket for point cloud elevation accuracy to meet this requirement. Other DOTs may have a lower vertical requirement; as a result, the user may extend this “useful range” further. All the tested scanners can provide point measurement beyond 90 m. However, Leica Geosystems ScanStation and Trimble GX have a “practical” range of approximately 90 to 120 m, beyond which the scanners receive only sporadic measurement points from high-reflectivity objects, resulting in unusable point clouds. On the other hand, the Optech ILRIS-3D has a “practical range” of approximately 300 to 500 m—this long “practical
range” makes it well-suited to scan large soft-earth surfaces where Caltrans vertical accuracy requirements (30 mm) are less stringent, such as large land slides or high cliffs.

The tests also emphasize the importance of proper and accurate geo-reference methodology and workflow. Registration targets should be scanned at much higher density. Target recognition accuracy should be higher than that of single-point measurement, and is crucial to the overall point cloud accuracy. Good geo-referencing / registration workflow could significantly reduce the likelihood of human error, which can be far greater than any instrument error.

The current evaluation results, the methodologies for future evaluations, and best practices for workflow and data management will greatly facilitate DOT use of 3D laser scanning for surveying. The technology will prove to be useful in other DOT application areas, including roadside maintenance, cultural heritage preservation, structures evaluation and design, and generation of 3D digital world models for broad use in advanced DOT applications, including machine control and guidance. The tools developed herein provide the needed scientific basis for data-driven deployment of this valuable measurement tool.

ACKNOWLEDGMENTS
The authors gratefully acknowledge the Division of Research and Innovation of the California Department of Transportation which has supported this work through the Advanced Highway Maintenance and Construction Technology Research Center at the University of California, Davis, under contract 65A0210 T.O. 06-21. The authors are particularly thankful to Mr. Kevin Akin for his active support and participation in the research, and Mr. Mark Turner for his ongoing support and enthusiasm for this emerging technology; both are with the Caltrans Office of Land Surveys. The authors also thank all of the Caltrans personnel who participated in the research. Finally, the authors thank the vendors (Leica Geosystems, Optech, and Trimble)—without them this research would not have been possible.
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