

Comparison of Building Measurements Acquired via Laser-Based Scanner and Modern Total Station

Gustavo O. Maldonado, Ph.D., PE
Georgia Southern University
Statesboro, Georgia

Marcel Maghiar, Ph.D., and
N. Mike Jackson, Ph.D., PE
Georgia Southern University
Statesboro, Georgia

Denzell M. Garrett and
Kenneth E. Givens
Georgia Southern University
Statesboro, Georgia

This study describes a procedure to generate a relatively accurate 3D point-cloud model of a Campus building via a laser scanner. It is based on establishing an accurate closed traverse around the structure. This traverse provides fixed vertices serving as benchmarks to reference various partial scans necessary to complete a full virtual 3D model of the building, including all its interior main hallways and roof. The selected one-story structure has approximate plan dimensions of 155 ft × 290 ft. A relatively more accurate, construction-grade, laser-based total station was employed to compare the magnitude of coordinates from 47 points and the lengths of 138 distances extracted from the generated point-cloud model. A full analysis of discrepancies was completed. It shows relatively low root mean square (RMS) values of the differences associated to measured point coordinates and also bounded discrepancies along distances between those points. These low values are attributed to the selected referencing scheme and strong survey control.

Keywords: Construction Surveying, laser scanner, LiDAR, Total Station

Introduction

Laser-based scanners have the ability to acquire large amounts of spatial data in a very short period of time. They are highly efficient instruments and are becoming widely used in the surveying and construction industry (Crawford, 2003; Kavanah, 2013). Depending on their brand and model, these modern scanners are able to collect spatial coordinates of 50,000 to 1,000,000 points per second. This ability strongly contrasts against that of modern laser-based total stations, which are capable of acquiring coordinates of only one point at a time. Today, scanning devices are used in numerous and varied practical applications. They range from the typical generation of as-built models to more sophisticated uses. For example, Abellán, et. al. (2013) use them to study rock slope instabilities and Pesci, et. al. (2013) proposes monitoring damaged buildings after an earthquake through a scanning technique that provides rapid and safe measurements in emergency conditions. Even though the technology supporting the scanning instruments is constantly evolving, and new models present improvements, scanners are still less accurate than numerous modern laser-based total-station instruments. This study uses both types of instruments to compare the spatial data acquired by them.

The motivation for this project is based on the fact it is perceived that the usual multiple successive scans, needed to complete a full model of a given structure, introduce additional errors as each of them is registered into the selected coordinate system of the whole model. That perception is not unfounded; especially if the registration of neighboring scans (stitching) is performed in a cloud-to-cloud fashion without fixed, ground-referenced targets. Even the use of targets introduces errors. In this regard, Becerik-Gerber, et. al. (2011) performed research on data acquisition errors caused by target setup, acquisition, and reorientation. They explored how different target types and target layouts affect registration accuracy.

Although the manufacturers of laser-scanning equipment will normally report the precisions of their equipment, the final accuracies obtained after completing a full 3D point-cloud model of a relatively large object (i.e., building), are not widely known. There are several factors affecting those accuracies, Boehler (2003). Some of them relate to the actual mechanical and optical limitations of the instruments and some are associated to the procedures employed to complete the full scanning of a large object/building. For instance, the fact that several scans need to be performed from different stations to fully cover a building, introduces errors. These errors are produced when data from each scan is transformed into a common system of reference. This procedure is known as registration. Those errors may increase if the registration process is done in a cloud-to-cloud fashion, that is, by attempting to identify several (three or more) common points acquired in two neighboring scans. Usually, this is a difficult task because it is unlikely to find a particular point that was hit exactly twice by the laser beams of two neighboring scans. Therefore, by selecting close, but not coincident points, errors are introduced. On the other hand, those registration errors can be reduced by using physical common targets in neighboring scanning stations. However, if neighboring scans are not performed immediately one after the other, the common targets may need to be relocated later in the same exact position to proceed with the other scan. This repositioning of targets could also introduce new errors.

In this work, a construction-grade, laser-based, seven-second total station instrument is used to compare the discrepancies in coordinates and distances measured with a laser-based scanning instrument, after the full model of a given, relatively large structure is completed. The main characteristics of these two instruments are presented in Table 1.

Table 1: Instrument Comparisons

Item	**Laser-Based Scanning Instrument**	**7-sec Laser-Based Total Station (Construction grade)**
Type:	Pulse (time of flight)	Pulse (time of flight)
Range	300 m at 90% albedo. (It decreases for lower albedo values)	Using one prism: 3,000 m (under slight haze with visibility of 20 km)
Accuracy of single measurement	Within 1-to-50-meter range: Position = 6 mm Distance = 4 mm (Both one sigma)	Prism mode (RMSE=Root Mean Square Error): RMSE= ± [3mm + 2ppm × (Distance)] Non-Prism mode: RMSE = ±10mm (1.5-to-25-meter distances) RMSE = ±5mm (≥ 25-meter distances).
Angular Accuracies	Horizontal Angle = **12 sec** Vertical Angle = **12 sec**	Horizontal Angle = **7 sec** Vertical Angle = **7 sec**
Inclination Sensor	Dual-Axis Compensator, with 1.5-sec accuracy.	Dual-Axis Compensator.

As observed in Table 1, according to their manufacturers, both instruments have similar accuracies in single measurements of distances larger than 25 m. On the other hand, the total station instrument presents substantial more angular accuracy (7 sec) than the scanner (12 sec). When determining position coordinates of points with these instruments, the magnitudes of the corresponding position errors are affected not only by the distance from the instrument, but also by the angular accuracy of the employed devices. Thus, position errors increase with increasing distances and also increase when angular accuracies decrease. In that regard, the employed total station is considered almost twice as accurate as the referred scanner. The comparisons presented in this study involve the determination of coordinates via a polar scheme, based on the measurement of angles and distances. Consequently, those coordinates are directly affected by angular accuracies.

All measurements reported in this study were carried out by several undergraduate students attending CM and CE courses in the CECM Department at Georgia Southern University. They were guided and supervised by the faculty members who are co-authoring this article and have expertise in Land Surveying operations. In particular, two of the participating students played a crucial role in completing this study. They learned the operation of the scanning instrument, the related software from Leica Geosystems (2010), and performed most of the reported measurements while completing two undergraduate research projects sponsored by internal grants funded by the Georgia Southern College of Engineering and Information Technology.

Objectives of this Study

The main goal of this study is to perform a discrepancy analysis comparing measurements obtained by employing two different types of modern laser-based instruments, scanners and total stations. The referred measurements involve the determination of X-Y-Z coordinates of various points, at different external and internal locations on a selected building, and the measurement of numerous distances defined by those points. The associated objectives are as follows:

a) Establish an accurate closed traverse around a selected Campus building to serve as a system of reference and to provide needed benchmarks and control around that building.
b) Employ a modern laser-based scanner to obtain a 3D point-cloud model of the selected Campus building, including its exterior and interior.
c) Reference the point-cloud model into the same system of reference used for the closed traverse.
d) Employ a modern laser-based total station to measure coordinates of selected points in the exterior and interior of the building.
e) Compare coordinates and distance measurements between data points acquired by the scanner and the same ones acquired by a total station instrument.

Methodology

This section presents the work flow used to attain the mentioned objectives. It describes the procedures to establish benchmarks (control points), to scan, to register (reference) the resulting point clouds into the same system of reference, to acquire point coordinates from the final 3D point-cloud model, to determine the same point coordinates with a total station instrument, and to compare point coordinates and distances obtained via both instruments.

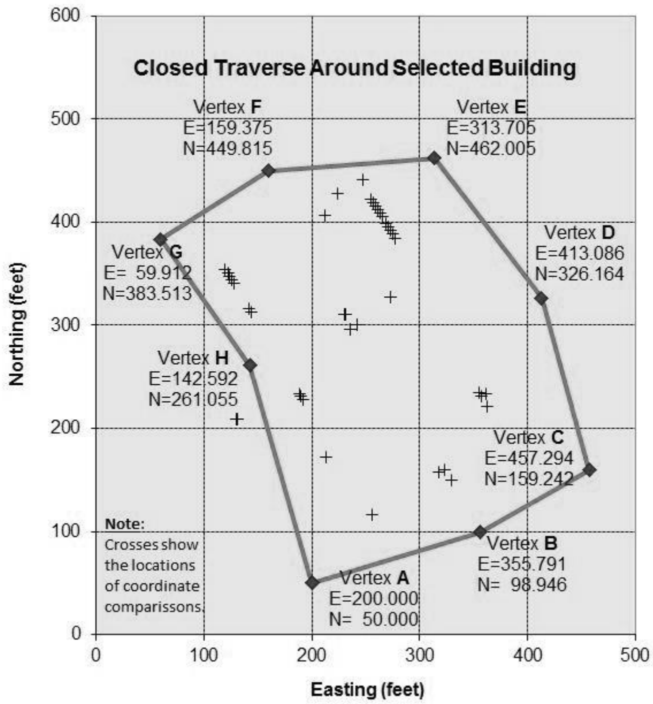
Closed Traverse for Control and Referencing

In order to reference, control and properly compare the spatial data to be collected, a closed polygonal traverse was established around the selected building within the university campus. That traverse is shown schematically in Figure 1(a). It consisted of eight fixed vertices (A-H). All traverse side lengths and internal angles were measured with the seven-second total station.

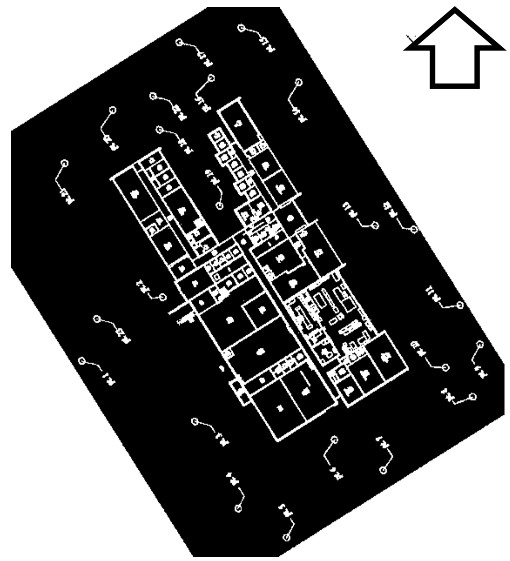
Initially, the azimuth (72° 33' 27") of the first side (AB) of the traverse was determined by acquiring coordinates of vertices A and B in the Georgia East State Plane Coordinate System (SPCS) via an accurate GPS instrument. This azimuth was only used to reference the traverse with respect to North. After balancing all traverse errors, final corrected X- and Y-coordinate of all vertices, including A and B, were obtained from traverse calculations. The final coordinates of A and B defined an azimuth of 72° 33'30". This 3" difference with respect to the original value is well within the angular precision of the employed seven-sec instrument. It represents a negligible transversal error of ±0.0024 ft in the relative position of B with respect to A, which is 163.30 ft apart. The resulting traverse characteristics and closures are: Angular Error of Closure = - 77.5 sec; Correction per Angle = 9.7 sec; Longitudinal Error of Closure = 0.021 ft; Longitudinal Precision ≈ 1 in 60,000. The elevations of all traverse vertices were determined via multiple repetitions of two different closed-loop procedures, differential leveling (using automatic levels) and trigonometric leveling (using seven-sec total station). These tasks resulted in accurate Easting (X), Northing (Y) and Elevation (Z) values for each of the eight traverse vertices. At this point, they were ready to be used as controlling benchmarks in subsequent tasks.

Scanning and Registration of the Point-Cloud Model

The traverse vertices served as reference to determine the coordinates of twenty-three (23) additional exterior points (stakes) around the selected building. For such purpose, the seven-sec instrument was used in coordinate mode. Each of these new stakes defined the base location of a common target. The common targets were necessary to register (reference) scans from different stations into the same reference system used by the closed traverse. Various types of targets were used: circular, single, dual and spherical ones. All of them were mounted on poles. Their relative positions with respect to the building are shown in Figure 1(b). Eleven (11) superposed partial scans were necessary to scan the full exterior of the building from an equal number of scan stations. Each of these stations was located near the building and their scanned areas included targets common to neighboring scans. Each scan was registered into the same coordinate system of the traverse. This was accomplished by inputting the corresponding target coordinates into the registration software.



(a) Closed Traverse and Points for Coordinate Comparisons



(b) Location of Ground-Referenced Target Points around the Footprint of Selected Campus Building

Figure 1: Eight-Side Closed Traverse and Footprint of Scanned Campus Building.

After all exterior walls of the building were scanned and registered into the same 3D point-cloud model, eight (8) additional scans were completed to include the interior hallways and the roof of the building. Internal offices, classrooms, restrooms and laboratories were not scanned. To scan the interior hallways, an entrance scan station was located near the door at the northwest corner of the building. This station was crucial because it presented the capability to scan three exterior targets and, at the same time, one of the four interior hallways. That is, it served to produce a scan connecting the exterior with the interior of the building. Several internal targets were placed along the hallways to serve as connecting points for subsequent hallway scans. All four hallways of the selected building were scanned using four (4) scan stations. These interior scans were registered into the point cloud containing the exterior walls of the building. Similarly, to scan the roof of the building, a scan station was placed at the roof in a location able to capture three of the exterior targets used previously, during the scanning of the exterior walls. Therefore, this first roof station served to connect the scans of the exterior walls with those covering the roof. A total of four (4) scans were necessary to complete the roof. All of them were registered into the same point-cloud model containing the exterior walls and interior hallways. This completed the scanning tasks necessary to cover all selected areas of the building.

Acquisition of Coordinates and Distances for Comparison Purposes

Once all scans were completed, the same proprietary software that was used to operate the scanner was also employed to post-process the acquired data and produce the final 3D point-cloud model of the whole building. Then, spatial coordinates of selected forty-seven (47) points were directly obtained from that virtual model. They all were in the same reference system containing the traverse vertices. We refer to these coordinates as scanned coordinates. These 47 cloud points were chosen so their locations were easily identified in the actual building (corners of bricks, corners of door frames or windows, intersections of walls and roofs, etc.). This was necessary to later accurately aim at those same locations with the total station instrument to re-acquire their coordinates for comparison purposes. While re-acquiring these points, no targets or reflectors were used and the total station was operated in reflectorless mode. That is, in the same mode that the scanner worked. These second set of coordinates, acquired by the total station, are herein referred to as total-station coordinates. In order to complete these new measurements with the total station, it was set up at vertices of the closed traverse around the exterior of the building. Traverse vertices with unobstructed lines of sight into the interior hallways (through open doors) were useful to collect necessary coordinates of interior points. Traverse azimuths and coordinates of occupying vertices were already available from the previous traverse computations. That is, the X-Y-Z data (Easting, Northing, and Elevation) re-acquired with the total station was referenced in the same system used by the finalized point cloud model and by the closed traverse. Therefore, a direct comparison of coordinate measurements was possible.

(a) View toward East (b) View toward North

Figure 2: Final 3D Point-Cloud Model of Selected One-Story Campus Building

Additionally, three of the above forty-seven scanned points were selected as *center points* to calculate their distances to the remaining forty-six selected points. These center points are 1, 23 and 35. Point 1 is near the southwest corner of the building, point 23 is near the northeast corner of the building and point 35 is an interior point near the center of the building. Consequently, a total of 138 scanned distances were determined following this approach. Similarly, for comparison purposes, the same distances were calculated from the corresponding coordinates acquired via the total-station instrument.

Results

Coordinate discrepancies were calculated for all selected 47 points by subtracting the coordinates acquired by the total-station instrument from those captured by the scanning instrument. They are presented in Table 2. The ranges of these discrepancies (max and min values), their mean values, root mean square (RMS) values and standard deviations are summarized in Table 3. It is noticed that, most likely, the high-magnitude values indicated with an asterisk in Table 3 are the result of an erroneous field annotation corresponding to Point 36 which shows a large discrepancy of – 0.350 ft in its northing coordinate. Table 4, presents the same parameters shown in Table 3, but they have been calculated after discarding point 36. Thus, by not considering point 36, Table 4 shows that all three RMS values (and standard deviations) present consistent magnitudes of a few hundredths of a foot, ranging from 0.042 to 0.044 ft. That is about ½ inch each of them.

The measured coordinates for the chosen center points (1, 23 and 35) are listed in Table 5. From each of these center points, a total of 46 distances were calculated twice, one time using coordinates obtained by the laser scanner and the second time by employing coordinates captured by the total station instrument. This resulted in 138 different distances ranging from approximately 4 to 325 feet. Again, the corresponding discrepancies were calculated by subtracting the total-station distances from the scanned ones. These discrepancies were plotted in Figure 3, where it can be observed that most of them are in the ±0.1-foot range, with only 9 (6.5 % of the calculated distances) outside that range. In particular there are two distances (one from point 36 to 23 and another from point 36 to 1) with high discrepancy magnitudes, close to 0.35 ft. Since both involve the coordinates of point 36, the authors observed that, most likely, the Northing coordinate of Point 36 has been erroneously annotated during field operations. Nevertheless, point 36 was kept within the collected data set and is the source of the large discrepancy observed in two points in Figure 3.

Table 2: Coordinate Discrepancies for All Selected 47 Points.

Point	Coordinate Discrepancies (ft)			Point	Coordinate Discrepancies (ft)		
	Easting X (ft)	Northing Y (ft)	Elevation Z (ft)		Easting X (ft)	Northing Y (ft)	Elevation Z (ft)
				24	-0.045	-0.022	-0.018
1	**-0.015**	**0.004**	**0.004**	25	-0.116	-0.090	0.040
2	-0.022	-0.005	-0.002	26	-0.028	-0.009	-0.025
3	-0.021	0.028	-0.022	27	0.027	0.014	0.008
4	-0.009	0.040	0.010	28	0.031	-0.103	-0.004
5	-0.037	-0.015	0.071	29	-0.022	-0.017	-0.055
6	-0.030	-0.018	-0.003	30	0.005	-0.009	-0.014
7	0.003	0.005	0.002	31	0.001	0.000	-0.019
8	-0.007	-0.065	0.009	32	-0.005	-0.011	-0.072
9	-0.011	0.047	-0.006	33	0.002	-0.017	-0.026
10	0.038	0.006	-0.008	34	-0.008	-0.110	-0.011
11	0.062	0.020	-0.005	**35**	**-0.024**	**-0.050**	**0.018**
12	0.004	0.010	-0.010	36	-0.070	-0.350	-0.031
13	0.044	-0.063	0.010	37	0.047	0.024	-0.100
14	0.039	0.116	0.036	38	0.007	-0.006	-0.005
15	0.005	-0.033	-0.119	39	0.008	0.023	0.001
16	-0.006	0.058	-0.119	40	-0.020	0.023	-0.004
17	-0.008	0.003	-0.005	41	-0.010	0.087	0.067
18	-0.016	-0.037	0.057	42	-0.169	-0.008	-0.003
19	-0.010	0.002	0.120	43	0.075	-0.010	-0.012
20	-0.006	0.020	-0.060	44	0.032	0.003	-0.003
21	-0.032	-0.088	0.055	45	0.009	-0.007	0.058
22	0.028	0.013	0.013	46	-0.100	0.002	-0.017
23	**-0.015**	**-0.005**	**0.002**	47	0.013	0.001	0.001

Table 3: Range and Statistics Parameters of Coordinate Discrepancies for All Selected 47 Points

Item	Discrepancies		
	Easting X (ft)	Northing Y (ft)	Elevation Z (ft)
Maximum Value	0.075	0.116	0.120
Minimum Value	-0.169	**-0.350***	-0.119
Mean Value	-0.008	**-0.013***	-0.004
RMS Value	0.043	**0.067***	0.044
Standard Deviation	0.042	**0.065***	0.045
***Note**: These high-magnitude values are due to an erroneous field annotation for Point 36			

Table 4: Range and Statistics Parameters of Coordinate Discrepancies for 46 Points (after discarding Point 36)

Item	Discrepancies		
	Easting X (ft)	Northing Y (ft)	Elevation Z (ft)
Maximum Value	0.075	0.116	0.120
Minimum Value	-0.169	-0.110	-0.119
Mean Value	-0.007	-0.005	-0.004
RMS Value	0.042	0.043	0.044
Standard Deviation	0.042	0.043	0.044

Table 5: Coordinates of Chosen Center Points

Item	Center Point 1			Center Point 23			Center Point 35		
	Easting X (ft)	Northing Y (ft)	Elevation Z (ft)	Easting X (ft)	Northing Y (ft)	Elevation Z (ft)	Easting X (ft)	Northing Y (ft)	Elevation Z (ft)
Scanned	255.955	116.374	246.994	268.990	398.340	241.192	241.681	299.955	229.313
Tot-Sta.	255.970	116.370	246.990	269.005	398.345	241.190	241.705	300.005	229.295

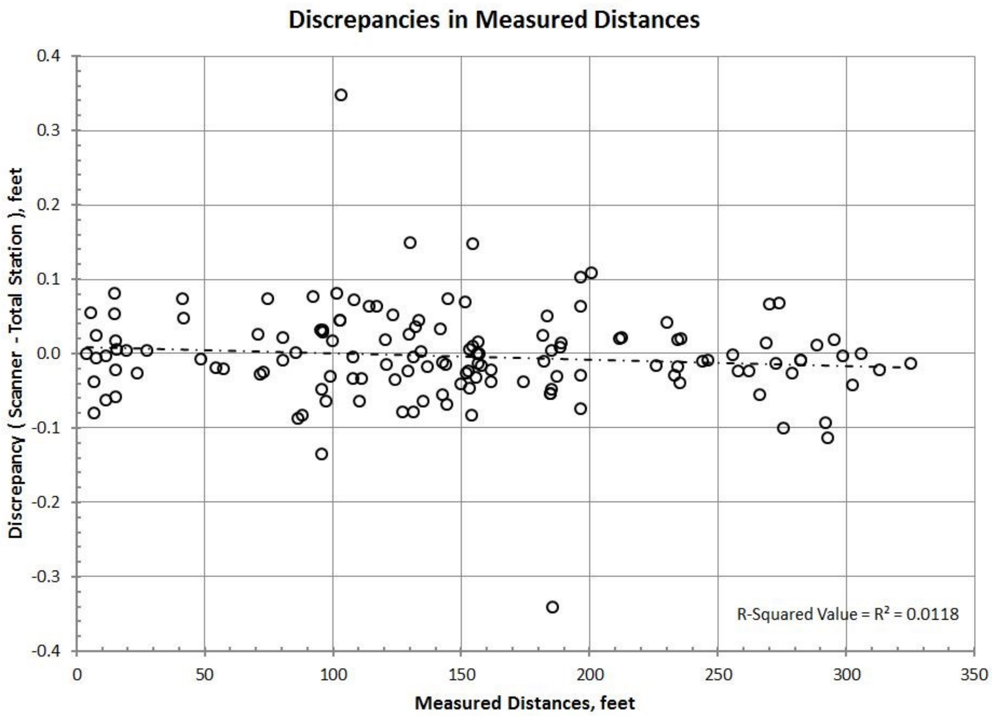


Figure 3: Discrepancies in Measured Distances from Chosen Center Points (1, 23 and 35)

Conclusions and Closing Remarks

Figure 3 shows that by having employed the reference procedure presented in this study, which is based on a relatively accurate closed traverse around the selected building, the calculated spatial coordinates of numerous points on the existing building, do not significantly differ if they are captured either by a laser-based, seven-sec, construction-grade total station or via a less accurate, twelve-sec, laser scanner. After considering 46 points widely distributed along the exterior walls and interior areas of the building (i.e., discarding 1 of the total points), the RMS values (and standard deviations) of the discrepancies in their position coordinates are: RMS_X=0.042 ft, RMS_Y=0.043 ft, and RMS_Z=0.044 ft. That is, the standard deviations of such discrepancies are all close to half an inch in the considered one-story, 155ft×290ft building.

Additionally, it is observed that the discrepancies related to the measurement of distances are not correlated to the magnitude of those distances. The R-Squared value for these two variables is very low (≈0.01). Overall, most distance discrepancies remain in the ±0.1-foot range (within ±1.2 inches) for lengths as short as 4 feet and as large as 325 feet within the building.

The authors understand that the attained low and consistent discrepancies are due to the established strong and dense control around the building. That is, the performed scans were properly referenced to the established benchmarks (control points) via targets with accurate position coordinates. Those coordinates were determined from relatively nearby accurate benchmarks, i.e., the vertices of the closed traverse. In particular, in this study, the longitudinal error of closure of the controlling traverse was 0.021 feet in a 1,263.18-ft perimeter which corresponds to an approximate longitudinal precision of 1 in 60,000. This indicates that the longitudinal error in control (0.021 ft) was an order of magnitude less than the observed bounding limit of 0.1 ft for the discrepancies in the measured distances with the scanner and the total station. Therefore, the reported final errors are larger than the sensitivity limit associated to the employed control approach and should be considered valid detections. Therefore, for a building of this size, if accuracies should be maintained within one inch, the combination of several accurate benchmarks around the structure and the use of a twelve-sec, laser-based scanner should suffice. Definitely, the advantage of using the scanner is the large amount of spatial data that can be collected in a relatively short period of time.

In summary, when performing scanning activities in civil structures, the authors recommend to follow a procedure similar to the one described in this article. Mainly, it consists of the following tasks: (i) Establish several control benchmarks via a closed, accurate traverse around the structure or establish them by employing accurate GPS devices. (ii) Use targets on fixed and easily identifiable locations, such as nails, stakes, etc. This will allow interrupting the procedure and continuing it later without significant loss of accuracy. (ii) Use the established benchmarks as base points to position needed common targets. If those benchmarks were not conveniently located, or if it more targets were necessary, obtain coordinates of the new location of the added targets from the previously established nearby benchmarks or via GPS. (iii) Use more than three targets to register neighboring scans. Occasionally, some of the targets may introduce larger errors during the registration process. In those cases, the removal of that particular target may reduce registration errors. Certainly, having redundant targets is usually beneficial during the registration stage. (iv) Preferably, use spherical targets. They do not need to be rotated between scans and are more likely to remain at the same position during two or more scans. This focus on targets to improve accuracy is also shared by other users (Becerik-Gerber, et. al., 2011).

In addition to the study of discrepancies, this work has added educational value to a considerable number of undergraduate students in the CM and CE programs at Georgia Southern University. During several semesters, various groups of undergraduate students were exposed to proper techniques to establish accurate benchmarks and learned the use of modern laser-based scanners while performing undergraduate research.

Acknowledgements

The authors extend their gratitude to the Undergraduate Research Committee of the Allen E. Paulson College of Engineering and Information Technology of Georgia Southern University for funding two undergraduate research proposals on this topic.

References

Abellán, A., Oppikifer, T., Jaboyedoff, M., Rosser, N., Lim, M., and Lato, M. (2013). Terrestrial laser scanning of rock slope instabilities. *Earth Surface Processes and Landforms*, Vol. 39, Issue 1, pp. 80-97, January 2014.

Becerik-Gerber, B., Jazizadeh, F., Kavulya, G., & Calis, G. (2011). Assessment of target types and layouts in 3D laser scanning for registration accuracy. *Automation in Construction, 20*(5), 649-658.

Boehler, W., Bordas Vincent and Marbs A. (2003). Investigating Laser Scanner Accuracy, XIX th CIPA Symposium at Antalya, Turkey, 30 Sep – 4 Oct 2003.

Crawford, W. G. (2003). *Construction Surveying & Layout* (3rd Edition). Creative Construction Publishing.

Kavanagh, B. and Mastin, T. (2013). *Surveying: Principles and* Application (9th Edition). Prentice Hall.

Leica Geosystems (2010), Leica ScanStation C10, User and System Field Manuals, Version 1.0.

Pesci, A., Teza, G., Bonali, E., Casula, G., & Boschi, E. (2013). A laser scanning-based method for fast estimation of seismic-induced bldg. deformations. *ISPRS Journal of Photogrammetry and Remote Sensing,* Vol .79, 185-198.