ACCURACY ASSESSMENT OF GEO-REFERENCING METHODOLOGIES FOR TERRESTRIAL LASER SCAN SITE SURVEYS

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ABSTRACT

Achieving accurate geo-referencing of 3D point clouds from terrestrial laser scanning depends on both the data quality as well as the registration procedures used to align the data. This paper presents a comparison of several common geo-referencing techniques for a limited number of scans across a site. The first approach performs resection of the scanner position and orientation from black and white targets printed on paper. The target centers are surveyed using a total station. Similarly, the second approach uses retro-reflective targets whose coordinates are also established using a total station. Software-based (Cloud-to-cloud) registration through surface feature matching of the point clouds is used for the third approach. This approach first matches scans on a pair-wise basis and then performs a global adjustment. The fourth approach (*PointReg*) constrains scanner orientation parameters to surveyed origins and internal inclination sensors. It then employs a least-squares, surface-matching adjustment to determine the azimuth of the scanner for each scan position. For comparison, scan origin positions are obtained (a) through a total station and (b) through RTK GPS.

A detailed comparison of the registration methods shows the time required to perform the data acquisition and geo-referencing, overall quality of the alignment, and comparison of the variability of scan transformation parameters (translations and rotations) for each method. The time required for alignment consists of: field time to collect the data, user-interactive processing time, and automated processing time. Quality of the alignment is assessed by comparing the accuracy of the target positions and the RMS values calculated for adjacent scans for each methodology. Overall, the methodologies compare well with one another in regards to accuracy. However, there are significant differences in time requirements and distribution between field and office processing time.
Finally, this paper can inform persons performing laser scans of the benefits, efficiencies, and limitations that exist when employing different geo-referencing methods in terrestrial laser scanning. One primary consideration for selecting an appropriate method for a project is the amount of available field versus processing time.

KEYWORDS: LiDAR, accuracy, registration, geo-referencing, alignment, laser scanning, target

INTRODUCTION

Multiple methods of terrestrial laser scan (TLS) collection and geo-referencing exist. Olsen (2011) provides an overview of several scan alignment approaches and quality control procedures. This paper provides a comparison of three of these techniques and variations, including:

1. Target registration
   a. Black and white paper targets
   b. 5 cm, retro-reflective, stick-on targets
2. Software based registration
   a. Cloud-to-cloud
3. *PointReg* hybrid registration
   a. Total station acquired scan origins
   b. GPS acquired scan origins

For all methods outlined, seven degrees of freedom need to be solved for in order to accurately geo-reference the scans using a similarity coordinate transformation. Providing scaling corrections for the atmospheric conditions lowers this to six degrees of freedom: translation in X, Y, and Z, and rotation about the X (roll), Y (pitch), and Z (yaw) axis. Silvia and Olsen (In Press) performed analyses related to the data quality provided by scanner inclination sensors (roll and pitch) and their utility in scan geo-referencing, particularly in validating control coordinates. The following methods were implemented to solve for these parameters:

- The first method, target resection, uses identifiable objects scanned at high resolution to provide common matching points between scans. The first variant uses black and white targets printed on paper to perform resection to determine the scanner position and orientation. The target centers are surveyed using a total station. Similarly, the second variation uses retro-reflective 5cm flat disk targets whose coordinates are also established using a total station.
- The second method, utilizing software registration, will simultaneously solve for four degrees of freedom after the operator provides a close approximation of the initial alignment. Two degrees of freedom, roll and pitch, will be provided by the scanners internal inclination sensors. This method first matches scans on a pair-wise basis and then performs a global adjustment.
- In the last method, *PointReg* (Olsen et al. 2009, 2011), translation (X, Y, and Z) will be provided by (a) total station and (b) RTK GPS. In addition, the use of the scanners internal inclination sensors will result in only the unknown yaw value to be solved for through a least-squares adjustment.

PURPOSE

The aim of this research is to compare geo-referencing methods for terrestrial laser scanning and to document information regarding time, accuracy, and possible introduction of error to assist a TLS surveyor in deciding which method is most appropriate for their projects.

METHODOLOGY

A test site was selected to evaluate the laser scan techniques. For efficiency, data required for all methodologies were collected simultaneously rather than completing multiple surveys of the site. Documentation of the time required for each process was recorded to allow a close approximation of the time that each individual geo-referencing method would have taken if performed individually.

Site Location

Reser Football Stadium (Figure 1) on the Oregon State University campus in Corvallis, OR was selected as the test site for three primary reasons:

1. It provided a large test area with very little disturbance due to pedestrian or vehicular traffic.
2. There were no overhead GPS obstructions, which allowed the use of RTK GPS using the ORGN (Oregon Real-time GPS Network).
3. Most of the site consisted of hard surfaces, eliminating registration uncertainty that can arise due to vegetation. The field itself is an artificial grass.

Field Collection

Data were acquired from four scan positions (Figure 1) using a Riegl VZ-400 scanner, with each scan origin's coordinates determined by (a) setting up over a control point (whose coordinates were obtained from a total station) and (b) RTK GPS with a GPS unit mounted above the scanner, with appropriate height corrections. Three independent, one minute GPS observations were recorded at each scan position for data quality assessment purposes. For all point sets, horizontal observations did not vary by more than 1 cm, and vertical observations did not vary by more than 2 cm. Averages of the three observations were reported as the final GPS location. Twelve target locations were used throughout the stadium; five located behind each end zone, and one on each side of the 50-yard line (Figure 1). These targets were staggered at various elevations providing complex target geometry to aid in scan alignment. Each target location consisted of an 8 ½" X 11" black and white paper target with a 5cm flat disk retro-reflective target placed in the lower left corner of the paper (Figure 2).

360° overview scans at each setup location were collected using a 0.03° angular increment (each requiring five minutes of scanning time to complete), collecting nearly 15 million points per scan. After completion of the overview scan, targets were acquired through two techniques. The first was a semi-automated approach, which located the retro-reflective targets and scanned them at a higher resolution with a window large enough to also capture the black and white paper targets. The second method required the scanner operator to provide a scan window for a high-resolution scan and select the target centers from within this window. The second method was needed because reflective targets at a distance greater than approximately 200m from the scan origin were not always detected automatically. Finally, a total station was used to find the center of the 24 targets, as well as to establish control points below each of the scan setup locations.

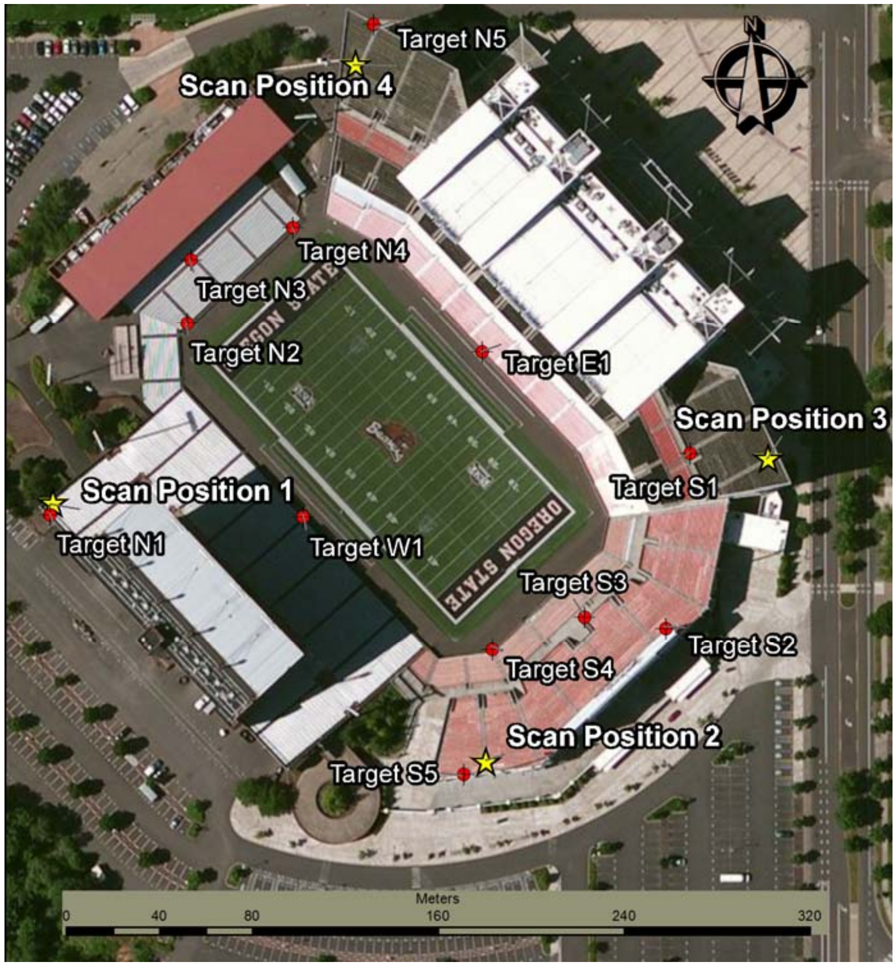

Figure 1. Scanner location and target layout, Reser Stadium. Background Image provided by 2010 Microsoft Corporation and its data suppliers through ESRI.

Office Processing

Figure 3 outlines the processing workflow and data coordination for each method. In order to geo-reference the total station data (collected in a local coordinate system) for each scan position and target location, the total station coordinates were adjusted to the RTK GPS coordinates through a least squares adjustment using the 4 control points. This adjustment enables the total station data to maintain its high relative accuracy. The adjustment only allowed the data to translate in X, Y, Z, and rotate about the Z-axis only. Rotation about X and Y-axes was constrained so that the data did not become unleveled from the adjustment. Additionally, scaling was constrained because the total station data was previously corrected for environmental conditions (temperature, pressure, and relative humidity). The resulting RMS of this least squares fit (total station to GPS) was 0.017m. Once the adjustment was completed, all total station target values were imported into the laser scan software and assigned as control targets.

Target Registration. Target processing was very similar for the retro-reflective targets and the black and white paper targets. The key difference was that the black and white paper targets required that the target center was manually selected, and the retro-targets were automatically selected using Riegl's RiSCAN software. Leica Cyclone software provides the ability to auto-extract black and white paper targets; however, since the data was acquired from a Riegl VZ-400 scanner, the auto extraction was unsuccessful. After all centers had been selected in the high-resolution target scans, a registration was performed to match corresponding targets between scans. Figure 2a depics how a typical target appears in a high resolution scan at a distance of approximatly 150m. Note that the center of the retro-reflector (red points) is automatically selected in the software, while the user must manually decide the best point representing the center of the black and white target. The scanner used in this study has a beam divergence of 0.3mrad, which results in an approximate beam width of 60mm at a target 200m from the scanner. At 200m the beam width is larger than the retro-reflector, when a small portion of this beam strikes the retro-reflector and the remaining larger portion strikes the surronding paper a blooming effect is seen in the size of the reflector, Figure 2a (Vosselman and Maas, 2010). Due to the symmetric nature of blooming effects, the target center can still be reliably found.

Pesci and Teza (2008) determined that retro-reflective targets should only be used at normal incedent angles, and at longer distances from the scanner. Beyond 200m the retro-reflectors are still detected, while the centers of the paper targets can no longer be determined, this is seen as a drop in the corresponding number of points for scan positions 2 and 4 in Table 1. The manufacturer of the scanner used in this study specifically warns the user to not scan retro-reflective targets at a distance less than 50m from the scanner. Scans of paper targets are much improved at closer distances; hence, they are typically used for close range (<50m) scanning.

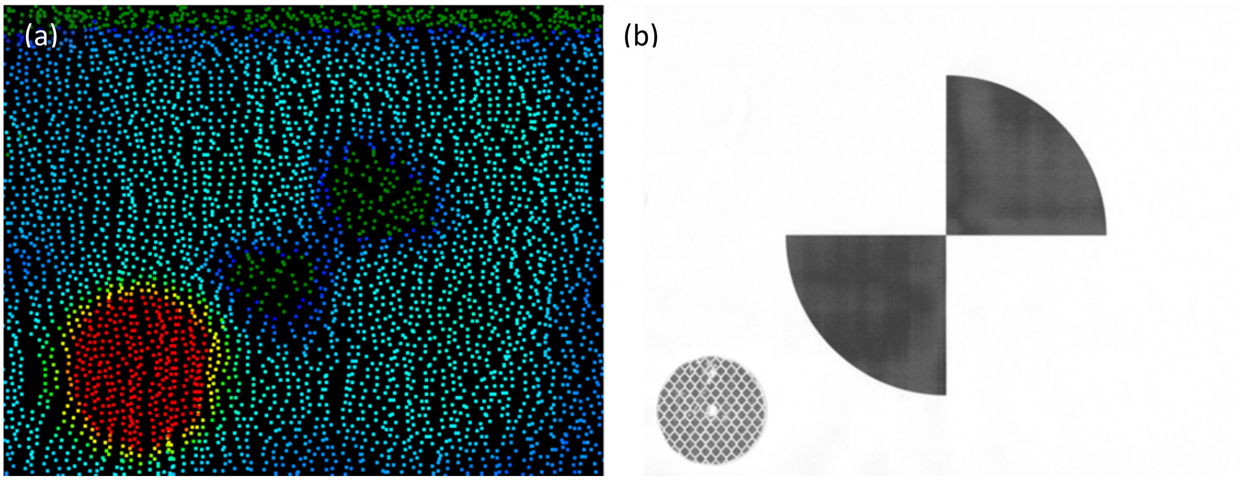

Figure 2. 8 ½" X 11" target with retro-reflector in lower left corner. (a): Point cloud of target at approximately 150m from the scan origin. (b): Image of actual targets used in study.

Table 1. Target alignment results

Target alignment statistics				
	Retro-reflective target		Black and white paper target	
Scan Position	Overall Std. Deviation (m)	Number of corresponding points	Overall Std. Deviation (m)	Number of corresponding points
1	0.0033	5	0.0077	5
2	0.0048	6	0.0116	5
3	0.0028	6	0.0066	6
4	0.0036	6	0.0093	5

Cloud-to-Cloud Registration. This method used a cloud-to-cloud alignment technique, through an iterative closest point (ICP) algorithm. However, the exact variant (Rusinkiewicz and Levoy, 2001) is unknown because it is included in proprietary software. This variant samples the point clouds at random, selecting a subsampled set (~2,000) of points for determining the alignment to increase efficiency. Point density is typically much higher closer to the scan origin. Hence, a random sampling will likely sample more points close to the scan origin. Additionally, slight error between these point pairs found closer to the scan's origin will have significant influence on an accurate scan alignment, particularly rotation. To avoid this problem, one can either (a) remove points within a certain range of the scan origin, or (b) provide a minimum separation filter so that all points are separated by the given minimum value (any closer points are removed). For this study a minimum separation filter was set to 0.01m. Points outside of the study area were manually cropped. The four scans were imported into the alignment software with only the scanners roll and pitch values applied, all other transformation parameters remained zero. One scan was selected to be the reference surface. The remaining scans were then manually moved until a close visual alignment was achieved for an initial approximation to seed the ICP surface match. Each scan was aligned, pair-wise, to the reference scan. This was then followed by a global, cloud-to-cloud adjustment that adjusts all scans simultaneously. Because the data were on a local coordinate system for the surface registration, all scan origin coordinates obtained through the surface matching were then adjusted, using least squares, to the geo-referenced total station coordinates. Assessment of this fit (cloud-to-cloud to geo-referenced total station) produced a RMS of 0.053m.

PointReg Registration. The *PointReg* method was specifically developed for dynamic environments where traditional controls, such as targets, were not a feasible option (Olsen et al., 2009) due to spatial and temporal limitations. Olsen et al. (2011) provides an in-depth description of the *PointReg* algorithm. *PointReg* constrains translation parameters as well as leveling information to avoid error propagation. It then finds matching points that are spatially distributed and implements a point to plane distance minimization approach to determine the optimal azimuth adjustment of each scan in the alignment. One of the key differences between *PointReg* and other techniques is that during a pair-wise adjustment, both scans are able to rotate simultaneously. Most cloud-to-cloud methods require that one of the scans remain fixed as a reference for the adjustment. The freely available program utilizes a CSV file containing the scanner origin coordinates and the scanner's internal roll and pitch values, and an estimated yaw value, within a couple of degrees. This estimated yaw value is determined by manually aligning the scans until an approximate visual fit is found. It can also be estimated through a digital compass or directly acquired if the scanner has the ability to perform back sighting.

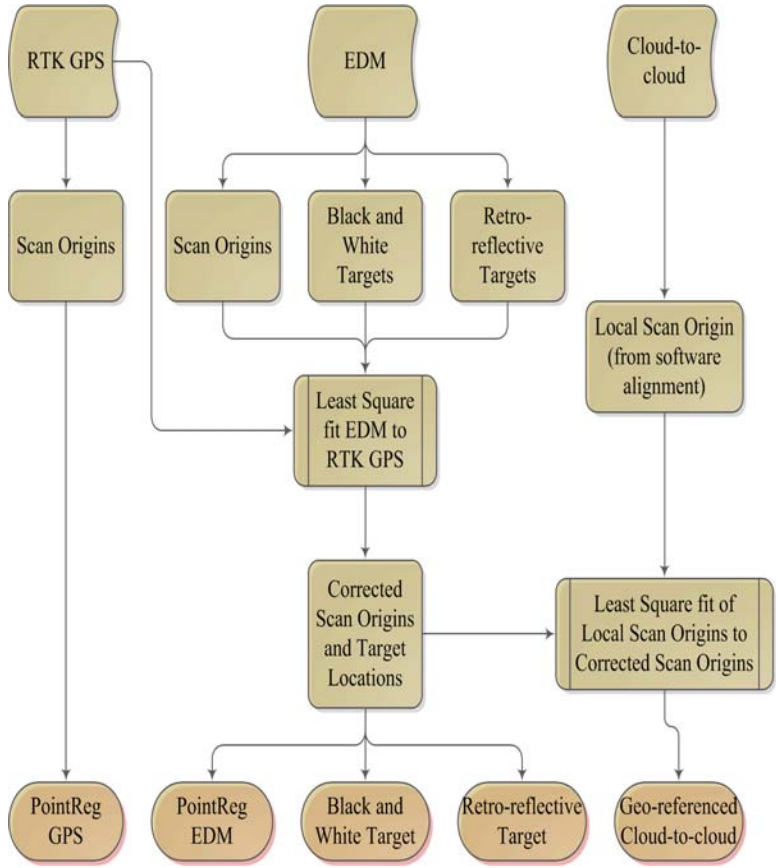

Figure 3. Flowchart depicting the processing procedures necessary for geo-referencing.

Accuracy Assessment. The resulting scan data from all five methodologies and variants were run through a RMS calculation mode (where the scans remain fixed) of *PointReg* to produce an RMS accuracy report of the alignment. This process uses a CSV file setup with the X, Y, and Z scan origin values, the yaw value, and the roll and pitch values. Note that the roll and pitch values were acquired from the scanners internal inclination sensor for all cases except the target registration, where they were found through resection. *PointReg* then outputs a report stating the RMS, number of points used to calculate the RMS, and the distances between scan origins for all scan combinations. A distance threshold value of 0.1m was used for the analysis (points were not considered matching if they were greater than 0.1m apart).

RESULTS

The quality of alignment can be analyzed through RMS values (Tables 2 and 3). The results of transformation (translation and rotation) for all scans and methods can be seen in Table 4. For this analysis, it is difficult to determine which coordinates would be the most accurate. If the scanner origin could be obtained directly using a total station, *PointReg* EDM in Table 4 would provide the most accurate translation values; however, because the scanner was setup over a point on the ground, the coordinates contain centering and height measurement errors. It is also possible that the target alignments may provide a better measure of the true scanner origin due to redundancy of target placement, and the target centers being measured directly with the total station. For comparison of rotation values, the values measured from the scanners internal inclination sensor (used in the cloud-to-cloud and *PointReg* methods) are reported to have an accuracy of ± 0.008 degrees. In the target methods, these values are obtained through resection, using the total station derived control to establish the level plane. For short range scanning, inclination sensors can be more reliable, due to the precision at which target centers can be determined. However, properly placed targets and control may achieve improved results for leveling compared to inclination sensors at longer distances. In Table 3, the bold items represent the best RMS achieved between the adjoining scans.

The scan data from each alignment were analyzed visually for quality control, as well as the quantitative analyses discussed previously. Figure 4 demonstrates a visual technique used to help verify that scan geo-referencing has been successful. Each scan has been colored differently allowing a user to see each point cloud as an individual entity, therefore making it possible to see gross misalignment errors, or un-level setup errors. Along flat surfaces there should be a smooth blending of colors with some amplification of individual scan color as viewed closer to the scan. In addition, viewing geometric primitive shapes that are centered between scans should result in the geometric primitive shape with the individual scan colored points blending around the perimeter of the shape.

In addition to the RMS report (Table 3) generated by *PointReg,* target registration provides statistics (Table 1) of how well target locations correspond between adjoining scans and the control, empowering the user with an additional technique to evaluate scan geo-referencing performance.

Table 5 summarizes the total time required, divided into field time, manual (user interaction required) time, and automated (no user interaction required) time.

Table 2. Average RMS values for each method

Average RMS	
Retro Target	0.033
Paper Target	0.034
PointReg GPS	0.035
PointReg EDM	0.033
Cloud-to-Cloud	0.052

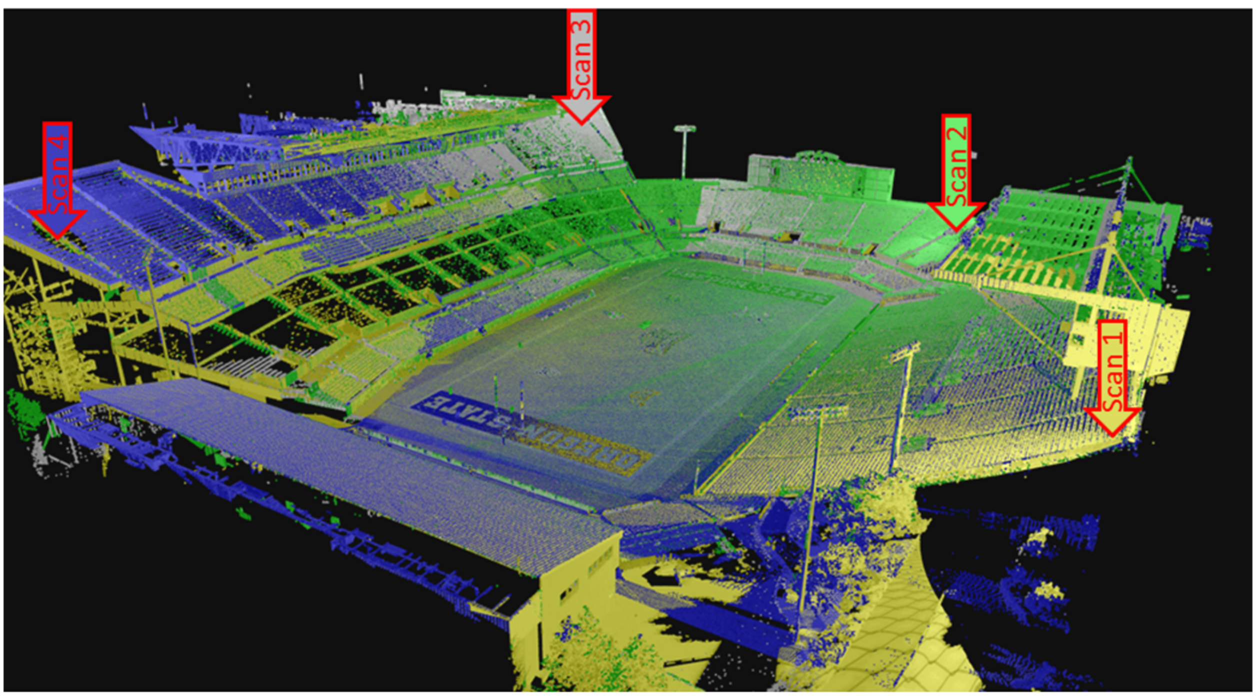

Figure 4. Geo-referenced point clouds of Reser Stadium with each scan shown in a different color.

Table 3. RMS comparison values (bold values indicate best results)

Comparison of scan 1 and scan 2			
Method	RMS (m)	Number of point pairs	Distance between scans (m)
Retro Target	0.036	272616	154.114
Paper Target	0.034	273740	154.123
PointReg GPS	0.034	275720	154.087
***PointReg* EDM**	**0.032**	**276788**	**154.112**
Cloud-to-Cloud	0.037	274559	154.047
Comparison of scan 1 and scan 3			
Method	RMS (m)	Number of point pairs	Distance between scans (m)
Retro Target	0.035	198184	225.568
Paper Target	0.036	196597	225.576
PointReg GPS	0.039	198140	225.542
***PointReg* EDM**	**0.033**	**200186**	**225.565**
Cloud-to-Cloud	0.066	115089	225.509
Comparison of scan 1 and scan 4			
Method	RMS (m)	Number of point pairs	Distance between scans (m)
Retro Target	0.033	275659	171.068
Paper Target	**0.032**	**276817**	**171.070**
***PointReg* GPS**	**0.032**	**276833**	**171.058**
PointReg EDM	0.033	275081	171.066
Cloud-to-Cloud	0.052	258841	171.042
Comparison of scan 2 and scan 3			
Method	RMS (m)	Number of point pairs	Distance between scans (m)
Retro Target	**0.031**	**248084**	**128.705**
Paper Target	**0.031**	**248297**	**128.709**
PointReg GPS	0.034	247423	128.678
***PointReg* EDM**	**0.031**	**248360**	**128.692**
Cloud-to-Cloud	0.051	134497	128.663
Comparison of scan 2 and scan 4			
Method	RMS (m)	Number of point pairs	Distance between scans (m)
Retro Target	**0.034**	**221586**	**217.267**
Paper Target	0.036	219773	217.291
PointReg GPS	0.036	222829	217.233
PointReg EDM	0.036	220280	217.263
Cloud-to-Cloud	0.059	205041	217.214
Comparison of scan 3 and scan 4			
Method	RMS (m)	Number of point pairs	Distance between scans (m)
Retro Target	**0.029**	**244318**	**175.662**
Paper Target	0.034	240269	175.689
PointReg GPS	0.034	241456	175.645
PointReg EDM	0.031	242874	175.668
Cloud-to-Cloud	0.045	235968	175.644

Table 4. Scan transformation parameters (translation and rotation) determined by the different methods.

Scan Position 1						
Method	X	Y	Z	Roll	Pitch	Yaw
Retro Target	2278972.026	103001.052	93.438	-0.051	-0.007	134.413
Paper Target	2278972.021	103001.043	93.448	-0.051	-0.008	134.414
PointReg GPS	2278972.036	103001.048	93.433	-0.062	-0.008	134.413
PointReg EDM	2278972.025	103001.054	93.447	-0.062	-0.008	134.409
Cloud-to-Cloud	2278972.060	103001.043	93.482	-0.062	-0.008	134.416
Scan Position 2						
Method	X	Y	Z	Roll	Pitch	Yaw
Retro Target	2279103.254	102920.242	81.775	-0.011	0.093	113.920
Paper Target	2279103.262	102920.237	81.766	-0.019	0.091	113.926
PointReg GPS	2279103.248	102920.263	81.763	-0.012	0.086	113.917
PointReg EDM	2279103.253	102920.248	81.767	-0.012	0.086	113.918
Cloud-to-Cloud	2279103.238	102920.279	81.812	-0.012	0.086	113.911
Scan Position 3						
Method	X	Y	Z	Roll	Pitch	Yaw
Retro Target	2279197.490	103007.903	107.887	-0.032	0.186	-143.870
Paper Target	2279197.492	103007.911	107.918	-0.027	0.195	-143.865
PointReg GPS	2279197.474	103007.896	107.921	-0.029	0.192	-143.880
PointReg EDM	2279197.486	103007.894	107.907	-0.029	0.192	-143.879
Cloud-to-Cloud	2279197.465	103007.889	107.839	-0.029	0.192	-143.891
Scan Position 4						
Method	X	Y	Z	Roll	Pitch	Yaw
Retro Target	2279077.231	103135.945	103.730	0.022	0.014	117.928
Paper Target	2279077.200	103135.959	103.696	0.037	0.019	117.941
PointReg GPS	2279077.235	103135.934	103.749	0.011	0.009	117.925
PointReg EDM	2279077.228	103135.946	103.746	0.011	0.009	117.926
Cloud-to-Cloud	2279077.231	103135.930	103.736	0.011	0.009	117.931

Table 5. Time requirements for each method

Acquisition and processing time (minutes)				
Method	Field time	Office Manual	Office Automated	Total Time
Retro Target	170	35	11	216
Paper Target	170	45	11	226
***PointReg* GPS**	**60**	**30**	**24**	**114**
PointReg EDM	80	55	24	159
Cloud-to-Cloud	60	80	61	201

DISCUSSION

The RMS values produced through the various methods were very similar with the exception of cloud-to-cloud registration. In general, a user should feel comfortable with the results achieved by either target registration or the *PointReg* method. For similar and larger sites and when scanning at longer ranges, the cloud-to-cloud registration may not be suitable as the primary technique. However, it would still be useful as a back-up option for small sections in the event that field collection data was lost or misreported. This correlates with the findings of Olsen et al. (2011) who determined that significant error propagation could occur when using cloud-to-cloud alignments along extended, linear segments. Bae and Lichti (2006) note that variants of the ICP algorithm, like that used in cloud-to-cloud, will produce different results. These algorithms are tailored to work with specific datasets. It is anticipated that the cloud-to-cloud method would likely have performed better if there had been more scans in closer proximity to each other, providing denser data and more overlap. Hence, there are many cases where it would be an appropriate technique.

Target resection bases the transformation on a limited number of points (3 or more) that are generally more precisely defined that pick points in a point cloud. The cloud-to-cloud method typically uses around 2,000 points for determining the coordinates. The *PointReg* method uses substantially more points by default since it operates in batch mode. However, should a user desire it to run faster, they could limit the number of point pairs used.

A user should also consider many factors about the equipment that they are using before selecting any of these methods. For example, if the scanner has poor, or no, inclination sensors, then the *PointReg* method would not be an acceptable registration technique. If target geometry is poor (linear target setup allowing rotation about the line) then the *PointReg* method could provide better results. A user will need to carefully consider scanning conditions prior to deciding which method to use.

Consideration should be made with regards to how much time can be allotted to field processing and office processing (manual and automatic). For TLS, more time spent in the field typically equates to less time spent in the office and vice versa (Table 5). Total station usage adds a significant amount of additional time, and has the potential to introduce error with additional processing steps. The total station, however, generally will provide improved accuracy across a site, and may be necessary in cases where RTK GPS is not available due to forest or urban canopy. Most cloud-to-cloud processing techniques require significant manual user interaction time to permit the algorithm to work correctly. This includes filtering the point cloud to eliminate erroneous points, and applying a minimum separation between points. However, work is underway to develop automated procedures to estimate a scan's initial pose. Field time can also vary significantly depending on the conditions encountered. In the case of this study, many targets were not automatically detected, which required the user to manually find them within the point cloud. In some cases, more closely placed targets may be initially scanned at high enough resolution to not require any human intervention to extract them. This can significantly reduce acquisition time, with target setup being the only additional time required.

CONCLUSION

With the exception of cloud-to-cloud registration, all methods provide similar RMS results. Total time to geo-reference a point cloud varies significantly, with external surveying (e.g., total station) adding the bulk of time. *PointReg* using RTK GPS provides the overall most efficient method and greatly lowers the possibility of introduced error. This method, however, can only be as accurate as the RTK GPS coordinates, and is not possible where RTK GPS is not feasible. *PointReg* using EDM scan origins eliminates the RTK GPS requirement, and also requires less field time than target methods. A key point to remember with the *PointReg* method is that geo-referencing accuracy is also related to the accuracy of the scanners internal inclination sensors. Target registration eliminates the need for inclination sensor values, but requires significant field time, as well as pre-planning, to ensure that required target correspondence is met between scans. Cloud-to-cloud provides an acceptable means of geo-referencing a scan that has a pair of adjoining scan neighbors, but may require additional accuracy verification if it is used as the primary registration technique when limited scans are obtained across a large site. In this case, all scans were at a long distance from each other, which is not ideal for the cloud-to-cloud method as it tends to work better with many scans situated closer together. Different scanners will also have varying influential effects on the alignment methods due to variations in beam divergence, range, pulse repetition rate, and the overall accuracy of the scanner. The user will have to choose the most appropriate method based on the variety of factors discussed in this paper as well as the requirements of the final geo-referenced point cloud (Figure 5).

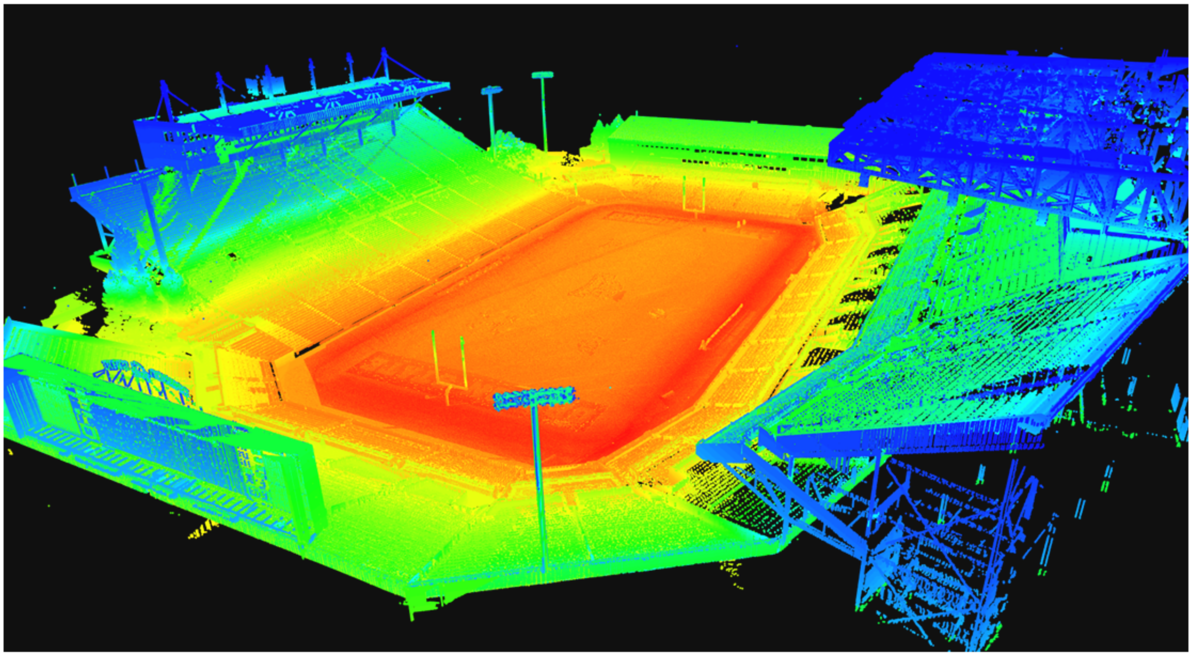

Figure 5. Geo-referenced point clouds colored by elevation values.

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