CRUCIAL FACTORS IN SURVEYING WITH 3D LASER SCANNERS

Ehab Mina, PhD
Head of Geometrical Geodesy Dept
Survey Research Institute (SRI) EGYPT
Currently: Director of Geodetic Survey
NAIK Consulting Group, PC
1430 Broadway, Suite 300
New York, NY 10018
ehab_mina@hotmail.com

Jason Larson, PLS
Director of Scanning - Project Manager
NAIK Consulting Group, PC
1430 Broadway, Suite 300
New York, NY 10018
jlarson@naikinc.com

ABSTRACT

3D laser scanning is a powerful technology that uses advanced laser measurements to collect thousands of points per second. Surveying professionals are keen to adopt this new technology due to the dramatic productivity benefits that can be obtained. However, this technology has specific uses and limitations that include: system specifications, operating methodology and a potentially unfamiliar workflow. The specific application and scope of work will help determine the optimal type of scanner and methodology.

Providing professional surveying services in support of many of New York City’s major engineering projects has provided a diverse base of experience in 3D laser scanning and will be described and analyzed in this paper to demonstrate the great potential of 3D laser scanning as a powerful surveying tool. Some of these projects include:

- PANYNJ - World Trade Center
- TBTA - Verrazano Narrows Bridge
- NYSDOT - Gowanus Expressway
- MTA - Second Avenue Subway
- LIRR - East Side Access
- AMTRAK - Union Station Tunnel
- NYSDOT - Major Deegan Expressway

There are several key factors that control the overall survey accuracy when using a scanning workflow. They include scanner hardware type and specifications, field methodology, and data processing. This paper will discuss each and provide a case study that included extensive accuracy quality control checking.

INTRODUCTION

3D laser scanning is a recent technology that uses laser measurements to collect thousands of points per second in an automated fashion. This technology has the potential, when properly applied, to enable 100 to 150% increases in productivity in the field. Surveying professionals are always looking for dramatic gains in productivity in order to increase profits; however, the unfamiliar workflow, together with the unique system hardware may present pitfalls for the uninitiated.

The first commercially available 3D laser scanners were generally used for specialized applications rather than typical survey tasks. Scanner manufacturers now offer scanning systems that are truly designed for the surveying industry with software and hardware that mimic traditional surveying methodologies. As a result, the technology has become more accessible and surveyors have realized its significance as a survey tool for the future.

3D laser scanning is based on technology that is similar to that used in the typical reflectorless total station. The primary difference between a 3D scanner and the total station is the speed of measurement brought about through electronic and mechanical automation. The total station, on average, can provide 4 distances per second in direct reflex mode. In contrast, the scanner is capable of measuring thousands of points per second. Measurement science tells us that the more observations you have the more likely that the correct answer will be obtained.

Another difference between total station and laser scanning methodologies is that the laser scanner is an indiscriminate, purely line-of-sight instrument. It will collect points on whatever it hits. As a result, obstructions cause shadows in the data, and the closer to the scanner the obstruction is the corresponding shadow is larger due to the radial nature of the measurements. With the total station technique, if there is an obstruction the surveyor has the option of using a higher or lower rod, offsets, etc. With the scanner, the only option is to relocate the scanner to a new position that covers the shadowed area.

Scanner Types

Scanners generate 3D coordinates by using the same three measurements as a total station: horizontal, and vertical angles, and distance. Today, scanners are divided into two categories: phase shift or on time of flight, depending on the method that the distance is measured.

Figure 1. Time-of-Flight Scanner (left) Phase-Shift Scanner (right).

Time-of-Flight. Time of flight technology works by measuring, very precisely, the time taken for a laser pulse to go out, reflect off an object, and return. Combining the range with angle encoder measurements provides the 3D locations. Time of flight scanners are characterized by longer range measurement, low noise characteristics, tilt compensators, but slower data acquisition (4,000 to 12,000 points per second).

Phase Shift. Phase shift technology works by emitting a continuous laser beam with a sinusoidal wave at the center of a rotating mirror which deflects the beam out of the scanner and towards the target. After reflection from an object, the phase shift in the sine wave of the returned signal is measured by the instrument, deriving distance. Using encoders to measure mirror rotation and horizontal rotation of the laser scanner. The 3D coordinate of each point can be calculated. Phase shift extreme speed (up to 500,000 points per second) and point density, but a shorter range, and somewhat lower positional accuracy.

FACTORS IN SCANNING ACCURACY

As in traditional surveying, there are a number of factors that determine the positional accuracy of the finished product when using a scanning workflow. The primary factors are: equipment precision, field procedures, and data extraction techniques.

Equipment Dependent Precision

One of the easiest sources of error to quantify and control is the precision of the equipment used. The equipment precision is generally inherent in the design, construction, and calibration of particular scanner models and even particular units. Scanners that are capable of being set-up over control can be checked in a similar fashion as total stations by using a testing range. This procedure can uncover precision errors with the equipment. Problems at this level generally need to be addressed by the manufacturer through calibration and adjustment, and are not user correctable.

Angular Precision. Scanners typically have two rotational axis that enable the scanner to expand the field of view. Electronic encoders within the scanner (similar in technology to those in total stations) measure the horizontal and vertical angles related to these two axis. The horizontal angle, perpendicular to the vertical, may be changed using a mechanical axis or another rotating optical device. The laser pulse or beam is deflected by a small rotating device (mirror, prism) the angular position of this mirror is measured as the vertical angle. The error in the angle-reading device has a direct effect on the position computations in direction perpendicular to propagation path. The electronic encoders are typically subjected to calibration by the manufacturer at the factory prior to shipment, and it is recommended that scanners be re-calibrated, at least, on a yearly basis.

Range Precision. There are two different methods to calculate ranges in laser scanners. The first one is the so-called ranging scanners uses the time of flight or phase comparison between outgoing and the returning signal. Triangulation scanners solve the range determination in a triangle formed by the instrument's laser signal deflector, the reflection point on the object's surface and the projection center of a camera, mounted at certain distance from the deflector. The camera is used to determine the direction of the returning signal.

Ranging errors can be observed when known distances in range direction are measured with the scanner. The systematic scale error will be present in any spatial distance measured, a system constant (zero) error will be eliminated when distance difference in range direction are determined. The amount of the zero error will be duplicated if two points are in two different directions from the scanners.

The easiest way to visualize range error is to scan a perfectly flat surface; range error will be seen as points that fall short or long relative to the surface. Range error is generally referred to as "noise". Looking at a scanner's noise is a good method to evaluate the accuracy of a scanner for purchase. An easy check for noise in range measurements can be achieved when a plane target perpendicular to the observation direction is scanned and the standard deviation of the range differences of the points from an intermediate plane through the point cloud is computed.

Resolution. The term "resolution" is used in different contexts when the performance of laser scanners is discussed. From the user's point of view, resolution describes the ability to detect small objects or object features in the point cloud. Technically, two different laser scanner specifications contribute to this ability, the smallest possible increment of the angle between two successive points and the size of the laser spot itself at the object. The angular increment of the scanner is separated in horizontal and vertical direction, and most scanners allow manual settings by the user.

The laser spot size is an inherent characteristic of the laser used, and increases in size as the range increases. Currently, most scanners are capable of measuring finer angular increments than their spot sizes. This behavior creates a false sense of point density since the spots can potentially overlap. Objects that are smaller than the spot size cannot be properly modeled.

Since the combined effects of the angular increment, range, and spot size determines object resolution, a test object comprising small elements or small slots can serve to determine feature related resolution information.

Surface Reflectivity. Laser scanning is based on the reflected signal back from the object surface. The strength of the returning signal is influenced by the reflective abilities of the surface. Surface reflectivity at the high or low end of the range can result in systematic errors of a single range measurement; correct range is achieved only after a few points have been measured. For objects consisting of different materials or different surface coatings erroneous data is to be expected. Placing white targets on these surfaces can determine this effect after computing the target position then after relate the rest of the surface in accordance. Surface reflectivity affects the two types of scanners in different ways. Time-of-flight scanners are generally less susceptible to this type of error than phase shift scanners.

Scanning Field Procedure

In scanning, like in traditional surveying, proper field procedures and methodology can help to eliminate error. An experienced scanning crew chief will be aware of his scanners limitations and make adjustments to the field workflow to accommodate them. Factors like a scanner's effective range help to determine the number of set-ups required the accurate acquisition of data. It is also not advisable to scan in adverse weather conditions, such as under foggy, misty and rainy weather that cause noise and false signal detection for the measurements.

Data Processing

Following the field work, there are a number of steps in the workflow that occur in the office that contribute to the overall precision of the survey data.

Registration. Following the field work phase of the process the collected data results in a point cloud for each scan set-up. In most cases these individual point clouds need to be combined with other scans in order to complete the picture. This process is known as registration. Registration can be accomplished through different methods depending on how the field data was collected. The first method is cloud-to-cloud. In this method the software looks for data in two or more point clouds that overlaps and tries to match common surfaces. In traditional surveying, this would be laughable due to the limited amount of redundant data. With scanning, where you are dealing with millions of points, this process works very well.

Another method known as “free station” uses targets placed within the scene that are visible in adjacent scans. In this method the location of the scanner is unknown and its position is calculated during the registration process. A minimum of three common targets are required, but it is more advisable to use five or more well distributed targets to ensure a good registration. Using this method requires less pre-planning in the field as the scanner location can be moved easily to a more advantageous location. The limitations of this method are that by resecting the position of the scanner it is subject to positional error due to poorly distributed targets, it does not allow for the reoccupation of the same position at a later date, and it does not provide for a way to calculate a traverse type closure.

A third method, and the most closely tied to traditional survey techniques, is the traverse method. Newer scanners now allow for set-ups to be made over ground control points in the same way as a total station. Some scanners also incorporate tilt compensators which maintain the vertical axis of the scanner. This addition greatly limits the error in registration. In essence by fixing the vertical axis, and by setting over control points orientation error is reduced to fewer variables including only the azimuth (backsight direction) and the instrument height.

Data Extraction / Modeling. All the previous steps in the workflow result in a registered point cloud. Aside from some visualization applications a point cloud alone is not that useful as a deliverable. It’s usually in a proprietary format requiring specific software and the file size is generally huge (anywhere from 1 to 120GB). Using scan oriented software, office technicians can use tools to extract specific locations that are analogous to the shots taken in a total station survey. Points, linework, and surface models can be extracted to serve as the basis for CADD drawings.

Most scanning software platforms allow the user to literally pick points in the point cloud to draw lines and planes, etc. as a way of extracting data. The picking method can be compared to the process followed by a rodman in the field. This method is quick and easy, but is subject to the level of noise in the scan data, and to inaccurate picks by the user. With proper care this method can be effectively used.

Another more accurate method leverages the vast number of points in the point cloud to determine planar patches and rigid know shapes. In many of the applications where scanning is currently used, flat planar surfaces (Buildings, structural members etc.) make up a large part of what is being located. Sub-selections in the point cloud can be analyzed by the software to establish an average surface. By using this method two adjacent walls of a building can be projected and the corner of the building can be very accurately determined. Most software packages also can model other objects like cylinders, piping, steel members, etc.

A primary benefit in terms of drawing accuracy that is gained by using a scanning workflow comes during the QC process. It is quite easy to compare the modeled object against the point cloud for both positional accuracy and completeness. In a total station survey the only way to QC the completeness of the survey is to revisit the field and visually inspect the drawing vs. the existing conditions (granted things may have changed since the original field work), and positional accuracy must either be assumed to be correct or re-measured. In addition, with a complicated object, there can be a question as to what exactly was shot in the field. With a point cloud, the linework can be viewed along with the scan data to see exactly what is being depicted.

CASE STUDY – REAL-WORLD TESTING

So, after the above discussion, what is the accuracy capability for current scanning systems? As discussed earlier each system has a built in hardware specifications for accuracy. The following is an example project where extensive quality control (QC) checks were employed to verify the scan data.

The Verrazano-Narrows Bridge in New York City is the longest suspension bridge in the United States and the seventh longest in the world with a center span of approximately 4260’. The bridge has two levels with six lanes on each level and connects Staten Island and Brooklyn. In 2006, NAIK Consulting Group, PC was contracted by Parsons Transportation Group and the MTA Bridges and Tunnels to survey, very precisely, the structural members of the upper deck to support the design for the replacement and expansion of the upper deck of the bridge. The project specifications required a survey that modeled the length, camber (longitudinal bend), and sweep (latitudinal bend) of the eight main stringers per bay, and the location and dimension of the floor trusses, all to a positional tolerance of ±0.01'. In the past as-built structural surveys requiring this level of precision were performed using tensioned piano wire to measure the camber and sweep. With approximately 1075 members to measure, this method is obviously extremely labor intensive.

Field Methodology

NAIK proposed the use of 3D laser scanning as a time and cost saving method. Much effort was expended in the planning of this project and several field tests were performed to ensure that the required precision could be met. The primary concerns were the instantaneous motion of the bridge structure due to live loading and wind conditions (the bridge vibrates quite intensely), and the long term motion of the structure due to steel expansion and contraction resulting from temperature changes (the center span experiences as much as 12' of vertical change over the year).

Initially a Riegl LMS-Z360 time-of-flight scanner was used. This scanner, which uses five year old technology, was proved not capable of delivering the required accuracy. The newly released Leica HDS6000 phase-shift scanner was then chosen to perform the production scanning. The combined speed and point density capabilities of this scanner combined to help reduce the effects of the bridge motion by completing each scan in three and half minutes and the entire bridge in ten nights (10pm to 6am).

The bridge is divided into 135 "bays" by floor trusses that are spaced approximately 50' apart. Two scans per bay were performed centered in each bound of the travel lanes. The primary scan area for each scan was 50'x50' box with large vertical columns at the corners. Control points (PK nails) were placed at each scan location and named using the bridge's panel-point numbering system. During scanning, five scan targets were placed on tripods on each of the adjacent control points (2 on the same bound, 3 on the opposite bound). The resulting target control enabled a large least squares network adjustment of the scan control.

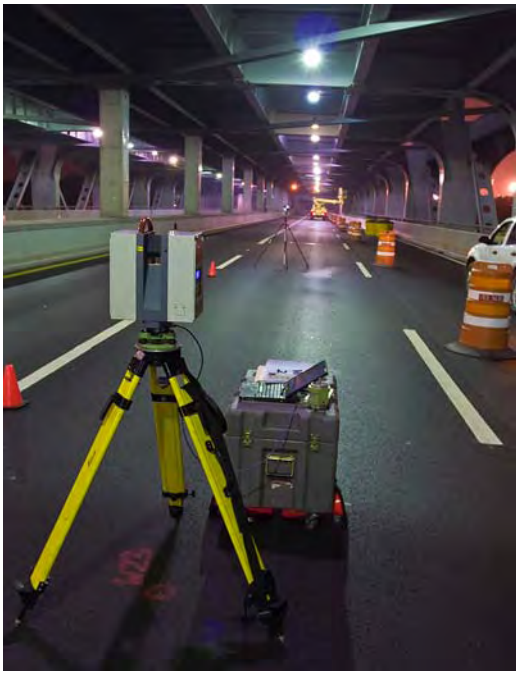
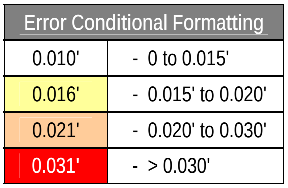


Figure 2. HDS6000 on Verrazano West Bound Lanes.

Quality Control

In order to report and verify the scan data's accuracy two separate quality control checking operations were employed.

Column QC Checks. During the scanning effort, small 2" square, checker patterned targets were placed on each surface of the columns. See Figure 1 for a diagram showing the layout. The direct slope distances between these targets were measured using Leica A5 and A6 DISTO laser ranging devices and recorded in fieldbooks. Each distance was shot several times to ensure a consistent reading. These devices are rated with a ±1.5mm ranging accuracy. Following the field effort, the distances were queried in the point cloud between the 2" targets. The results were recorded in an Excel spreadsheet along with the DISTO measurements. These values were then compared and the differences categorized into four levels: 0 to 0.015', 0.015' to 0.020', 0.020' to 0.030', and > 0.030'. See Table 1 below for an example of this comparison.



Error Conditional Formatting	
0.010'	- 0 to 0.015'
0.016'	- 0.015' to 0.020'
0.021'	- 0.020' to 0.030'
0.031'	- > 0.030'

Table 1. Sample Column Target Comparison

Bay #	Longitudinal Direction									Transverse Direction					
	South			Mid			North			WB			EB		
	Disto	Scan	Δ	Disto	Scan	Δ	Disto	Scan	Δ	Disto	Scan	Δ	Disto	Scan	Δ
117'	46.64'	46.619'	0.021'	46.74'	46.746'	0.006'	46.61'	46.60'	0.012'	43.81'	43.815'	0.005'	43.83'	43.842'	0.012'
115'	46.60'	46.586'	0.014'	46.73'	46.715'	0.015'	46.66'	46.64'	0.020'	43.84'	43.847'	0.007'	43.83'	43.829'	0.001'
113'	46.66'	46.661'	0.001'	46.72'	46.725'	0.005'	46.59'	46.60'	0.007'	43.84'	43.824'	0.016'	43.85'	43.837'	0.013'
111'	46.58'	46.588'	0.008'	46.74'	46.750'	0.010'	46.63'	46.62'	0.008'	43.85'	43.842'	0.008'	43.82'	43.809'	0.011'
109'	46.58'	46.601'	0.021'	46.74'	46.739'	0.001'	46.64'	46.62'	0.016'	43.83'	43.840'	0.010'	43.83'	43.815'	0.015'

Table 2. Column Comparison Statistics

	Longitudinal Direction			Transverse Direction	
	South	Mid	North	WB	EB
# of Orange Flags	25	13	31	20	18
# of Red Flags	5	1	5	1	1
Average Δ	0.015'	0.009'	0.016'	0.012'	0.012'

Camber & Sweep QC Checks. The second QC operation was designed to show the resolution and accuracy of the scans and their ability to determine the camber and sweep of the stringers. The amount of bend in the stringers was measured to be in the 0 to 0.03’ range over the 46.5’ length. As the base measurement the old procedure of stringing a tensioned piano wire and manual measurements were made on a selection (±20%) of bays across the length of the bridge. The inside and outside stringers “A” & “D” were measured. The point cloud was modeled using the steel section modeling routines in the software in short segments at the quarter points along the stringer. The horizontal and vertical offsets were then compared and categorized in the same fashion as the column measurements. In addition, the distances between the floor-trusses, at the end of each stringer, were measured using the DISTO’s. See Table 3 below for an example of this comparison.

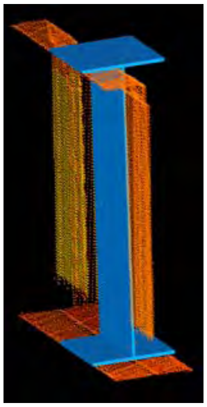


Table 3. Sample Camber & Sweep Comparison

BAY	Stringer			West				East	Largest Offset	Stringer Length	
			Stiffener	1	3	5	7	9	11			
EB 83	A	Vertical	Manual	0.417'	0.417'	0.411'	0.411'	0.422'	0.417'	0.005'	Manual	46.730'
			Scan		0.421'	0.421'	0.422'	0.422'		0.005'		
			Δ		0.004'	0.010'	0.011'	0.000'			Scan	46.722'
		Horizontal	Manual	0.385'	0.396'	0.385'	0.370'	0.370'	0.385'	0.016'		
			Scan		0.391'	0.374'	0.360'	0.357'		0.028'	Δ	0.008'
			Δ		0.005'	0.011'	0.010'	0.013'				
	Stringer			West					East	Largest Offset	Stringer Length	
			Stiffener	1	2	4	6	8	10			
	D	Vertical	Manual	0.417'	0.417'	0.411'	0.411'	0.411'	0.417'	0.005'	Manual	46.730'
			Scan		0.415'	0.417'	0.417'	0.416'		0.002'		
			Δ		0.002'	0.006'	0.006'	0.005'			Scan	46.753'
		Horizontal	Manual	0.344'	0.354'	0.370'	0.380'	0.354'	0.344'	0.036'		
			Scan		0.352'	0.387'	0.385'	0.356'		0.043'	Δ	0.023'
			Δ		0.002'	0.017'	0.005'	0.002'				

Table 4. Eastbound Camber & Sweep Comparison Statistics

	A Stringer		D Stringer		Stringer Length
	Horizontal	Vertical	Horizontal	Vertical	
# of Orange Flags	5	2	4	0	2
# of Red Flags	2	1	1	0	0
Average Δ	0.010’	0.009’	0.008’	0.006’	

Table 5. Westbound Camber & Sweep Comparison Statistics

	A Stringer		D Stringer		Stringer Length
	Horizontal	Vertical	Horizontal	Vertical	
# of Orange Flags	3	3	6	3	2
# of Red Flags	2	0	7	1	0
Average Δ	0.010’	0.010’	0.012’	0.010’	

In reviewing the statistics for the two QC comparisons it can be seen that the modeling method used to determine the camber and sweep produced more precise measurements (as was expected). The precision and accuracy achieved by using 3D laser scanning has been accepted by the client on this project and resulted in a huge cost savings to the MTA.

CONCLUSION

Undoubtedly, the 3D laser scanner is an effective tool for conducting as-built survey tasks. Scanning can produce results of a sub-centimeter or better level accuracy that fit most topographic, structural, and architectural survey requirements. It has the advantage of being able to survey roads and bridges remotely, without the need of road closures.

Laser scanning technology provides an attractive high productivity survey saving up to 80% of field time. The superiority of laser scanning method in terms of data acquisition rate is overwhelming. It should also be noted that features of interest may change over the length of the project and may be extracted from the point cloud where as with a total station survey a return trip to the field is required.

The accuracy/precision, density, and productivity gains seen with the use of 3D laser scanning makes this technology a very powerful tool in the surveyors arsenal, and its use in the future is sure to increase.