Practice Points NUMBER 20

Introduction to Mid-Range Terrestrial Laser Scanning

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Fig. 1.
Point cloud of Cedar Point Lighthouse, East Hampton, New York, built 1860. The top portion of the project point cloud is cropped to show the relationsip between the interior framing and exterior walls. All figures by author.

This paper concentrates on terrestrial laser scanning (TLS) techniques used on projects ranging in size from single rooms to entire buildings. TLS is the process of collecting light detection and ranging (LIDAR) data from a fixed location, typically mounted on a tripod; however, any fixed, stable location can be used (Fig. 1). Simultaneous localization and mapping (SLAM) could be considered a form of TLS but is not covered here. Some techniques described here may also apply to projects of a different scope.

TLS data is used in the documentation of historic structures to record existing conditions. The data is then used to inform the restoration and conservation process. Individual scans are captured from a fixed point in space and used to create a point cloud, which is comprised of individually captured points recorded in 3D space. Most surfaces within the line of sight and the range of the scanner have the potential to be measured. The spatial point data is recorded in a spherical coordinate system

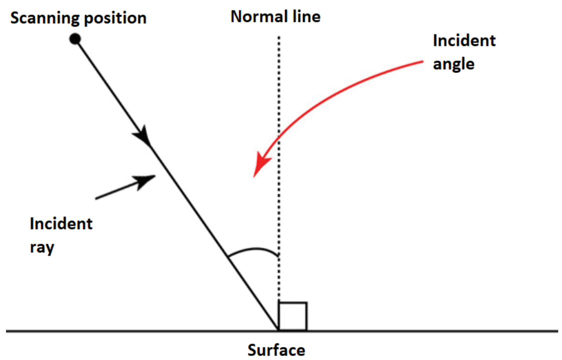


Fig. 2.
Incident angle. The angle between where the line created by the laser records the point on the wall (incident ray) and a perpendicular line from the surface being captured (normal line).

Fig. 3.
Laser scanner mounted on an extension jib at a private residence, New York, New York, 2016.

with the origin being the sensor of the laser scanner; measurements of the distance, horizontal angle, and vertical angle are converted to a Cartesian coordinate system (x, y, z). Color, intensity, and thermal values are additional information that can be assigned to each point. The type of additional information captured is dependent upon the functions available from the individual scanner, which vary considerably. Individual point clouds are registered together using software to create a project point cloud.

Terrestrial laser scanners (TLSs) were introduced commercially in 1997 with RIEGL and CYRAX being early developers. TLSs fall into two methods of data capture: time of flight and phase-based. Time of flight measures the time it takes for a pulse emitted from the scanner to bounce off an object and return to the scanner. Phase-based data capture emits a pulse and records the shift in the phase between the reference and return signal to determine the distance. Time-of-flight scanners can measure longer distances and are usually slower. Phase-based scanners capture data faster but can produce noisier scan data. Scanner noise is the represented thickness of the surface captured; points will be measured in front of and behind the actual measured distance. Consequently, greater measurement differences equate to thicker or noisier scan data. Since 2009, TLSs have integrated data storage and power within the unit. Cameras used to add color to the point cloud can be integrated internally or mounted externally. Compasses, GPS receivers, and altimeters (barometers) are other sensors that have been added. Compensators and dual-axis compensators have been added and improved. New data-capturing systems are being developed and introduced into the market with faster capture rates and lower price points.

Project Planning

Project planning is critical to obtaining useful data. Though capable of capturing many points of data quickly, TLSs are primarily a sophisticated measuring tool. Knowledge of what the point cloud will be used for, prior to field work, is critical to the success of a project. The point cloud will provide useful data only if positioned and set up correctly for the specific needs of the project.

The quality of the data captured by TLSs will be affected by the incident angle of capture, the distance to the object being scanned, and the reflectance of the surface being scanned (Fig. 2). Surfaces that are perpendicular to the scanner will be recorded more accurately and at a higher point density; perpendicular surfaces are captured at a low incident angle. As the angle between the scanner and captured surface decreases, the point density and accuracy decreases proportionally. A decreased angle of capture is considered a higher incident angle. Objects closer to the scanner will have a higher point density and higher accuracy than objects farther away. Acquiring the best possible data often requires compromising between the distance to the object being scanned and the incident angle between the scanner and object being scanned.

Taking both the incident angle and the distance into consideration, multiple scan positions will be required to obtain the best point cloud. Scanning from locations close to the building will provide good data on horizontal details, such as the bottom of window lintels and other surfaces with low incident angles to the capture location. Scanning from distant locations will provide a lower incident angle to the vertical planar surfaces of the building. Elevating the scanning position can give a better angle of capture to a greater percentage of the facade and decrease the distance from the scanner to the higher elements of the facade. More details, such as the top of window sills, can be captured. Gaining access to buildings across from the building being measured and using mechanical platforms and custom-designed rigs are some of the methods that can be used to improve the incident angle of capture and reduce the distance of the scanner to the facade (Fig. 3). Scanning platforms require stability. Cables and bracing can be used to temporarily stabilize shaky platforms, rigs, and scaffolding to complete the scan.

Surfaces lighter in color will provide better reflectance than darker colors and thus provide better data. Highly reflective surfaces will provide false, noisy, or minimally useful data. When a surface is questionable, it is important to perform test scans at different settings to determine the optimal settings to collect the best data possible. Primary settings on scanners fall into two categories: a resolution setting, which determines the density of the points captured, and a quality setting, which determines how much time it takes to measure each point. Higher-resolution scans will be longer in duration and capture more detail. A higher quality setting will take more time to measure each point and will increase the accuracy of the measurement.

Limestone with a dull finish will return good data at a lower-quality setting, whereas shiny black wrought-iron railings require that the quality and resolution settings be increased. Mirrors and mirror-like finishes will return mirrored images in the scan and provide no useful data unless the surface is covered with another material. Polished stone will return noisy data; however, the same material with a rough, matte, or dirty surface will return cleaner data. Data captured through glass should be considered bad data. Interior data captured from the exterior, as well as exterior data captured from the interior, should be deleted.

Scanning Plan

Creating a scanning plan can be as simple as viewing a property on Google Earth and mentally noting where the scanner should be located to capture the data required for the project. Complex projects benefit from a more detailed plan based on existing building plans or from sketches notating the positions where the scans will be taken. If multiple operators and scanners will be used, file names must be assigned to each scanner and operator and included in the plan. Keep the plan flexible enough to account for unanticipated conditions that may occur at the site. The scanning plan also needs to take into consideration the positions needed for the line of sight to the building being scanned at a sufficient point density for the project requirements and registration as determined in the project planning.

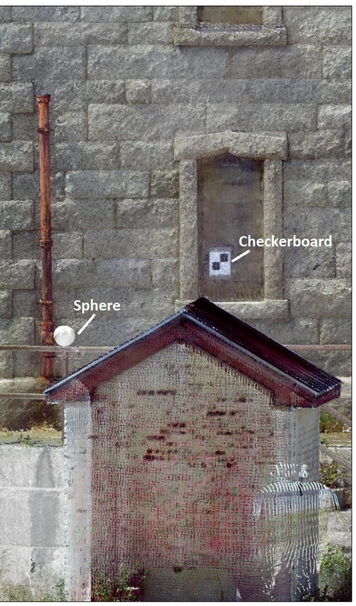
The individual scan is limited to capturing what the scanner can see in a line of sight from its position. To capture the information needed for most facades and building projects, multiple scan positions will be necessary. Scanning to provide basic elevations and plan views will require fewer scan positions and a lower resolution than scanning to create deliverables showing higher-resolution details. Two or three scan positions may be sufficient for a small facade, but thousands may be required for a large building capture. Large, open interiors with few details will require fewer scan positions than interiors with many rooms. Thus, scan positions are determined by the data that needs to be captured along with consideration of how the scans will be registered to each other.

Registration

Registration is the process of aligning the individual scans with each other. This can be done by two methods: cloud-to-cloud and target-based. Cloud-to-cloud (C2C) registration uses points in the point cloud common to two or more individual scans. Target-based registration uses three or more targets common to two or more individual scans and can be enhanced using a control network. The two methods can be used individually or in combination with each other.

C2C registration requires overlap between the scans. Higher percentages of overlap between scans and among multiple pairs of scans increase the quality of the registration. The minimum percentage of overlap can be hard to quantify; low-accuracy projects could overlap 25 percent or less, and high-accuracy projects could require an overlap of at least 70 percent. In general, structured geometric objects help with C2C registration. Planar objects, such as buildings and geometric objects like cylinders and pipes, assist the software in C2C registration. C2C software can have difficulty identifying scan positions in environments with repeating elements of equal spacing. C2C software would have

Fig. 4.
Checkerboard and sphere targets at Cedar Point Lighthouse, East Hampton, New York.



a difficult time distinguishing individual hotel or office rooms from each other and could place them in the wrong location. Open areas with no structure are not recommended for C2C registration.

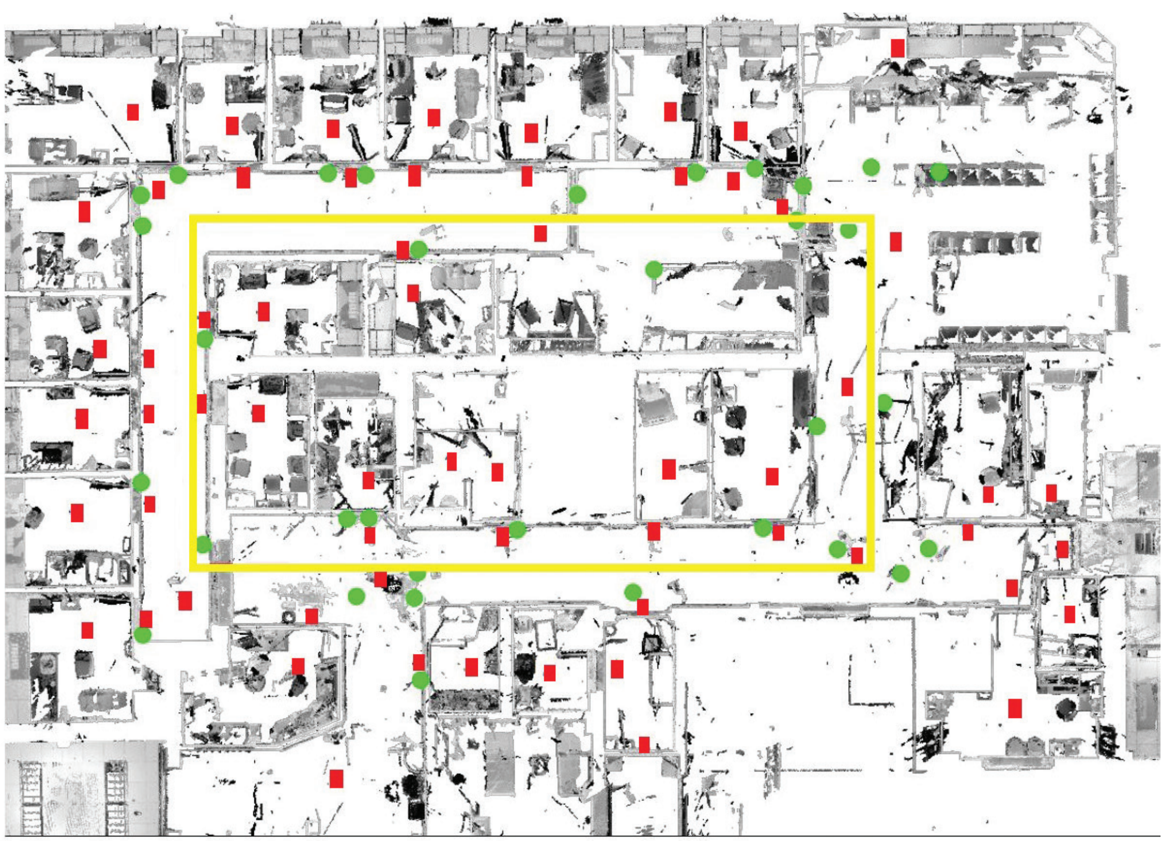
Target-based registration requires a line of sight to a minimum of three targets common to two or more individual scans. Capturing a minimum of five targets in each scan is good practice. Targets identify a point in space and are used for registering individual scans together. Two common types of targets are checkerboards and spheres (Fig. 4). Checkerboard targets identify the intersection point of black-and-white squares. Capturing the checkerboard target's planar surface is limited to 45 degrees from perpendicular. Sphere targets identify a point in the center of the sphere. Using the center point of the sphere as the point identified allows for 360 degrees of capture.

Targets are sometimes inadvertently moved or obstructed during the project. In those cases, they cannot be considered for registration. Scanner point-density settings affect the range of capture to the target. Higher point-density settings allow longer distances between scanner and targets. Some scanners have the ability to capture the targets at a higher resolution and combine them with a lower-resolution scan, thereby allowing for more distance between the scans and good registrations.

One method of combining C2C and targeted registration is to create a central core with targets and branches with C2C (Fig. 5). The central core is any registered group of scans. In this instance, the central core is a closed loop—a good general scanning principle when possible. The central core, one continuous group of scans, represented by the yellow line, is registered using targets, while the branches going into each room are registered to the central core using C2C. To create the connection from the central core to the branches, the scanner is placed at the doorway of each branch to provide a scan that will extend from the central core with a good view of the targets and overlapped scan data in the branch room. Additional scans will extend into the branch and will be registered to each other through C2C registration. The groups of branch scans will be registered to the central core, providing a singular group of registered scans for the project.

A control network is a series of identified measured points in a project. The measured points are called control points. A theodolite, a precision optical single

Fig. 5.
Plan view layout of scan positions and targets for combined registration. The green dots represent the locations of targets; the red squares represent the scan positions; and the central core is represented by the yellow line.



point-measuring tool, is used to measure the control points. Total stations (electronic theodolites using electronic distance measurement in addition to the angular measurement) commonly are used to measure the control network points. Control networks can increase accuracy in the overall point-cloud registration by taking advantage of the longer-distance measuring capabilities of single-point measuring devices. The control network can be used to increase the accuracy of the registration within the group of scans and between groups of scans. Registration using a control network measured to a fixed ground point from windows of multiple floors is more accurate than using TLSs registering up a stairwell. Control networks allow the point cloud to be registered to geospatial datums and with other data sets.

Using a survey tripod with a range pole is one way to locate a point for a control network with a sphere target (Fig. 6). In this instance, a magnetic survey nail is driven into the asphalt for a semipermanent point (Fig. 7). The offset height from the center of the sphere to the point on the ground is used to translate the center of the sphere elevation recorded by the laser scanner to the ground point, which can then be measured by a total station. Control points are used to tie the scanned point clouds to the control network. With permanent or semipermanent control points, the control network can be used to locate the point-cloud registration over time. Conditions can be recorded in the same coordinate system at various intervals to identify and record changes. Control points do not have to be destructive; if properly documented, any item—such as a nail head, stone corner, or other small visible object—on a flat surface can be located with the range pole and a target. Prisms, checkerboard targets, and others can be mounted to the range pole allowing this method to be used by many measuring instruments. Identifiable stationary points on a wall can be used as a control point by locating the center of a target over the point and capturing the target with TLSs.

These control points can be used to register the interior and exterior of a building (Fig. 8). With points located near door openings, they can be captured during the scanning of the exterior and during the scanning of the interior. If the points are permanent or semipermanent, the scanning can be completed at different times. Registering the closed scanning loops around the buildings with C2C, the control points can be used to verify the C2C registration results by comparing the coordinates of the control point in the start scan and the end scan. The exterior facades and roofs were captured first, while allowing the interior to be captured at a later date and still be registered in the same coordinate system by using the control network. Additional exterior data sets can be added to include additional areas or record changes. Building elements can be recorded at timed intervals to evaluate movement. Nondestructive evaluation (NDE) data can be added into the same coordinate system as the point cloud.

Post-Processing

Usually, more data is captured with TLSs than is required for the product delivered to the end user. Copies of the original scan data should be stored before post-processing. Large file sizes can create challenges with storage and efficient use of software used to create the final product. Areas not relevant to the final product can be cropped. Highly detailed areas can retain the density of the point cloud, while low-detail areas can have the point density reduced. Point clouds can be reduced randomly by reducing the number of points uniformly or reduced to a specific point spacing. The point cloud is filtered to eliminate points that could be inaccurate or false. The file size is reduced by these procedures. Developing profiles, documenting masonry jointing, and modeling complex existing mechanical, electrical, and plumbing (MEP) systems are some examples requiring a higher point density. Using a lower point density for simple floor plans, elevations, and models can reduce the computer resources needed.

Color that is captured can allow for easier identification of materials and their separation lines. Intensity values are captured separately from the RGB (red, green, blue) values. Overexposure and underexposure can create an appearance of areas of lower resolution in a point cloud when using the RGB value assigned to it from the camera alone. Post-processing software can combine the intensity value and the RGB value of the points to enhance the overexposed and underexposed areas.

The processed point cloud is then exported to software to create the deliverable for the client (Fig. 9). Some of the deliverables include orthographically rectified photographs (orthophotos), 2D CAD drawings, BIM, and deviation analysis. Orthophotos are created with scanning or with third-party software by creating a scaled photograph from a specified viewpoint. This can be done for elevations, sections, plan views, etc. The orthophotos can be attached in CAD programs as a background for creating a vector drawing. Slices of the point cloud can

Fig. 6.
Laser scanner and range pole with sphere. Laser scanner on a tripod capturing a sphere mounted on a range pole.

Fig. 7.
Range pole and magnetic survey nail control point.

Fig. 8.
Site-plan view of point cloud of the Aldus Chapin Higgins House, Worchester, Massachussetts, built 1921. The red dots represent the control point locations, and the purple squares represent the scanner positions.

be imported into CAD programs allowing the lines to be created by snapping to the actual points of the point cloud. Feature-recognition software can identify some geometric shapes, such as planes and cylinders, and locate the intersections of these features allowing 3D modeling directly from the point-cloud information.

Conclusion

Terrestrial laser scanning is a valuable tool for documenting existing conditions of historic structures. There is currently no software that will automatically process the point-cloud data captured by TLSs and translate the data into CAD or BIM models. Determining the intended use of the point-cloud data for immediate and future needs is critical in planning the capture of the data in the field.

Unobstructed lines of sight between the TLSs and the subject to be captured are critical. Obstructions must be moved or workarounds created in order to capture the required data. The scanner can capture only what it "sees."

The level of detail and accuracy required for the delivered drawing or model needs to be defined before the method of capture is determined. TLSs vary in the quality, range, and density of data captured. Hardware and software improvements are occurring at a rapid pace, making the data captured easier to process and develop into helpful documentation tools.

Every project is different and may require special solutions to capture enough accurate data to document the building for the desired purpose. Experience and knowledge of the equipment, techniques, and the item captured are critical to a successful outcome.

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Fig. 9.
Processed point cloud of the Aldus Chapin Higgins House. Registered point cloud of the exterior.

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