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Viability Assessment of Terrestrial LiDAR for Retaining Wall Monitoring

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ABSTRACT: The decreased cost and increased processing speed for terrestrial laser scanners have made this remote sensing procedure much more attractive. The approach has two major advantages over traditional surveying: (1) a registration of the survey instrument independent of any physical benchmarks. Thus, if the entire area is experiencing subsidence, the quality of the final results will not be compromised as they will be absolute measurements, as opposed to relative ones because they are based on a global positioning registration; (2) the ability of the technologies to highlight cracks in masonry. Unfortunately, despite major advances in the equipment and software, the technology is arguably not fully ready for the task of automated retaining wall monitoring. This paper will outline the challenges that remain with respect to registration and displacement monitoring.

INTRODUCTION

Retaining wall systems represent a two billion dollar a year industry of increasing complexity. As urban densification continues to grow and above ground space increases in value, retaining wall systems need to be installed deeper and under greater difficulty. The crowdedness of the sites, third-party permissions, and the installation geometries will increasingly complicate the use of traditional monitoring. Furthermore, the heightened risk of litigation has increased pressure to develop a more objective, permanent record regarding retaining system performance. As such, the attractiveness of terrestrial laser systems [usually referred to as light detection and ranging (LiDAR) systems] has gained increasing attention. This paper provides a technical overview of the current equipment and important installation and operating factors related to its potential application for retaining wall monitoring.

BACKGROUND

Lasers have been used for over a decade to detect defects in a wide variety of industries such as coke plants (Grosse-Wilde 1998) and petroleum facilities (Ogawa 1993), while LiDAR itself has been used for risk evaluation for a wide variety of

Civil Engineering subjects from predicting slope failures (Kwak and Jang 2006, Jones 2006) and selecting evacuation routes based on possible downed trees (Laefer and Pradhan 2006). LiDAR is potentially attractive for retaining wall monitoring as it provides the capability to rapidly make multi-point measurements over a large area. Typical equipment is shown in figure 1a along with an associated target in figure 1b.

(a) Scanning unit and laptop   (b) Spherical target
FIG. 1. LiDAR equipment

Recent research-oriented work has advocated use of terrestrial LiDAR scanning for architectural documentation (English Heritage 2006), to integrate field data in a real-time manner (Oliveira Filho et al., 2005, Su et al. 2005, Hashash et al. 2005), to generate a more accurate permanent record of construction sequencing and performance (Su et al. 2006), and to improve the design quality and construction based on better performance monitoring (Hashash et al. 2005), in combination with digital photogrammetry (Hashash et al. 2006). Despite a significant decrease in the equipments cost coupled with major improvements in its flexibility and speed, the unit's price tag of over $100,000 has prevented a major marketing push into this area, but its enhanced use for condition assessment and bridge monitoring and generation of as-built drawings clearly show that it is simply a matter of time before retaining structures are seen as a viable market. Consequently, questions arise as to the benefits and drawbacks that terrestrial scanning offers today.

Terrestrial laser scanning, or LiDAR, is a non-contact method for making physical surface measurements, allowing visualizations of scanned surfaces in a digital 3D environment. The technique converts 'bounce-back' information [i.e. time of flight, and 2D angular components of the laser path with reference to a 0,0 position to fix a point in a 3D space for each laser pulse, thus building (in the form of a point cloud)] a 3D digital model of the surface being monitored. The technology is based on the facts that light travels in a straight line at a known speed.

The laser machine has an in-built digital camera that has two functions:

1) a digital image can be recorded during the scan to be "draped over" the point cloud resulting in a realistic 3D image of the scan subject.

2) the surveyor is aided in framing the scan area by the digital camera acting as the eyes of the machine, displaying an image of the scan area on the computer screen, while the surveyor frames the object to be scanned.

Provided the scan is carried out under suitable atmospheric conditions using adequate reference targets, it is possible to quantify measurements of surface features and orientation, with reference to surrounding features, such as a building or to reference targets placed within the scan area. The laser pulse is emitted in a controlled vertical sweeping motion as the machine rotates in the horizontal to sweep the scan area. The laser pulse bounces back from the first reflective surface that it encounters. Quality or intensity of laser bounce back depends on surface characteristics and atmospheric conditions. Dust and moisture in the atmosphere degrade feed back quality resulting in noise or rouge points, while moisture can result in void areas due to scatter.

Scanning requires that the laser is set up at the first location (station 1), the object to be monitored is framed, and the scan parameters are selected in terms of required accuracy and feature detail, and then the scan begins; the scanner cannot be moved from this position, until all the required data is collected. If further scans are to be conducted at a future time, as in the case of sheet piling monitoring, a number of reference targets must be established which are scanned in each subsequent survey. Subsequent scans are merged into one model using the reference points generated from these targets, and any alteration in sheet piling position can thus be visualized and measured. Reference targets are also used where a number of scan stations are required to build a complete image of a subject area.

CAPABILTIES AND CHALLENGES

There are several major companies in the terrestrial LiDAR market; some with multiple models. Each varies to some degree but can be categorized as very near range, mid-range, and far range. As most excavations of concern are within 100 m, this paper will focus on the capacities of units in that range. An exhaustive comparison of recent equipment is provided by Mechelke (et al., 2007), thus only a brief overview is herein provided. Data collection speeds are in the order of 5,000 points per second. This translates to a scanning time for $1m^2$ at 5 x 5 mm point spacing (36,481 data points) of about 7.29 seconds. Speed is range dependent (i.e. long range scans reduces the data point collection rate). Thus, at a 100m stand-off distance from the object a data point at every 5mm vertical and horizontal (fig. 2),is returned where the unit is orthogonal to the monitored surface; degradation occurs with obliquity. If the scan was conducted at a third of the distance, point density would approximately triple. Alternatively, the scanner can be set for slower data collection, thus increasing the point density. Figure 2 shows a 2 x 2 mm point spacing at 100 m.

Selecting a scan density does not mean collecting the maximum data possible. Figure 3 shows the ability to detect cracks in a building at resolution of approximately 2 mm spacing. Collecting excessive quantities of data only make storage and processing problematic. A common error is in the framing of the object to be scanned. Unnecessary time, resources, and effort are expended, if unessential back-

ground elements are included, instead of only the objects of interest (FIG. 4). A sample field program at UCD showed that results were optimized, where the scanning occurred within 50 m of the object of interest.
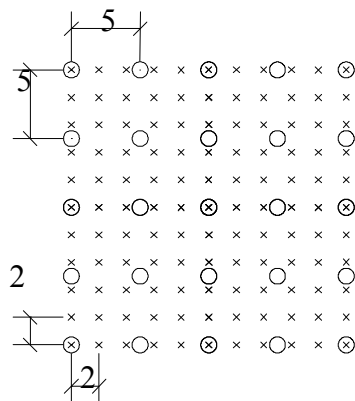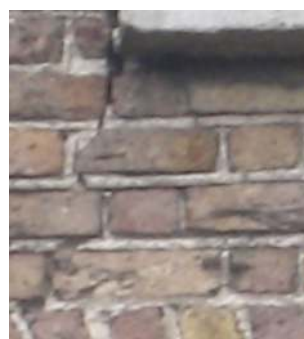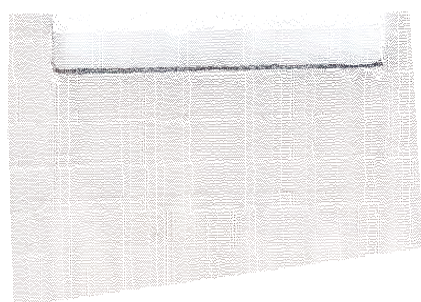

FIG. 2. Spacing of a 2mm x 2mm resolution scan overlaying
a 5mm x 5mm resolution

(a) Overview of window

(b) Brick work close up

(c) LiDAR image viewed orthogonally

(d) Rotated LiDAR image

FIG. 3. Damage detection for a brick building in Dublin, Ireland

Most units now provide a view 360˚ radially by 60˚ vertically, (40˚ above the horizontal centre line of the machine and 20˚ below), which provides significant flexibility in unit placement. Because of issues with obliquity, the unit should be positioned as perpendicular to as many of the main surfaces as possible (fig. 5). Multi-

ple scans that can be integrated into a single composition are well within the capabilities of the technology, but each repositioning requires a semi-manual meshing of the scans, which are time consuming. Some of these issues are address by Ratcliffe and Myers (2006) in their comparison of LiDAR and photogrammetry for open pit mines.
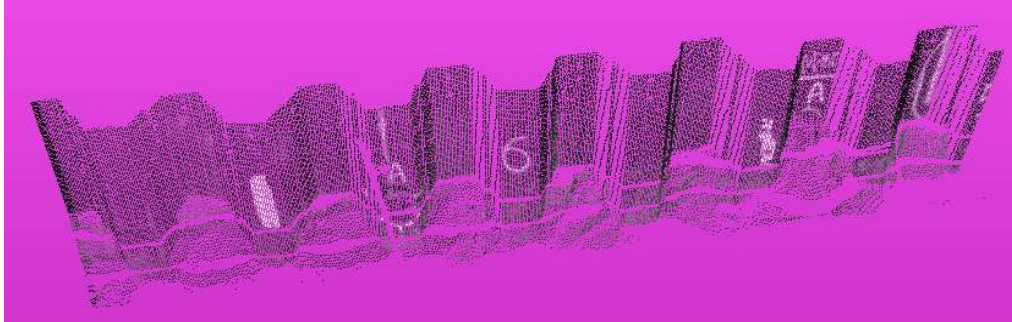

Fig. 4. Point cloud of a section of sheet piling.

The unit can be handled by one person, but a special transport box with wheels is recommended due to its weight. Additionally, in inclement conditions a van is strongly recommended as the unit can be operated from within the van despite the rain. Under heavy rain or without the protection of an external means, the unit cannot be used as the water interferes with the laser beam. Theoretically the unit can be used as a traditional survey instrument and is marketed as such (e.g. http://www.trimble.com/gs200.shtml).
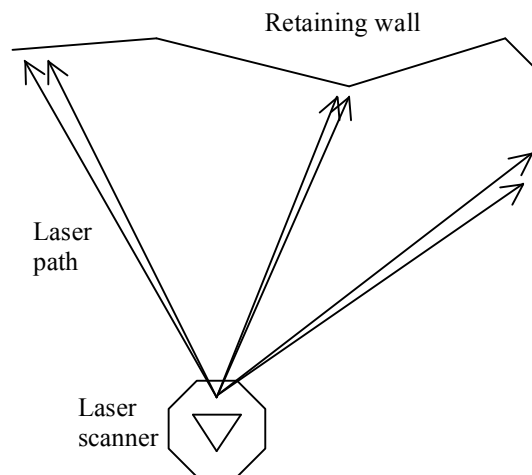

FIG. 5. Optimizing unit placement for a single scan approach to a complicated site

Since the laser scanning process is non-tactile, it need not interfere with ongoing earth works, especially since there is no need to install any monitoring equipment directly onto the retaining wall. Despite these advantages, the technology is not a panacea. To detect and measure movement in a sheet piling installation by the laser scanning method requires that a number of scans be recorded over a period of time. These scans are compared to detect and measure any movement in the sheet piling.

For this comparison to be made, each scan must contain common reference points that are not subject to subsidence or other earth movement effects on the site. Spherical targets (Fig.1b) are commonly used as reference points. The target must be placed in exactly the same place for each scanning operation. Ideally, the targets are left in situ for the duration of the monitoring program. However, this may not be possible and a method for accurately re-placing targets must be found (e.g. gluing a mounting in situ on the site onto which the target can be placed during scanning)
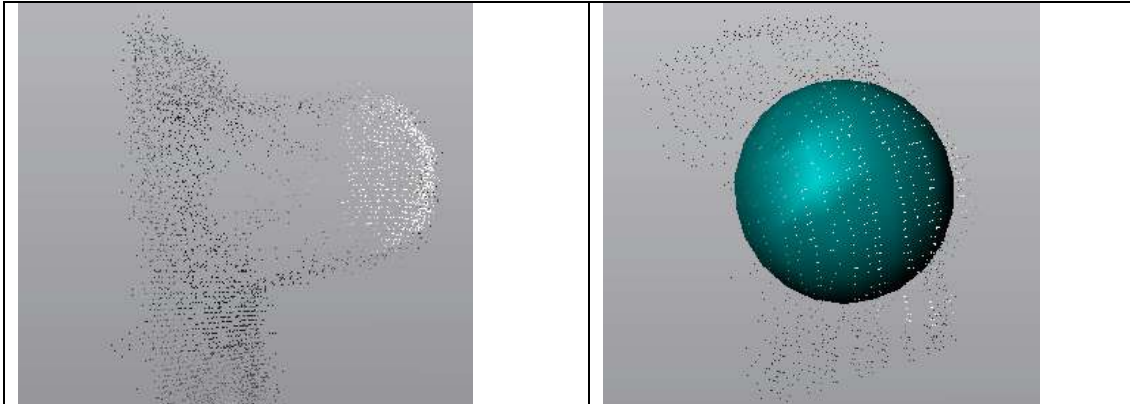
(a) Point cloud of spherical target   (b) Post-process solid fitted to point cloud

FIG. 6. Scanner output

At least three fixed reference targets, for each scanner position, must be set up adjacent to the inspection site and within line of site of the laser scanner position, in such locations that are immune to any earth movements due to excavation works. However for improved accuracy and to mitigate against any of the target areas being compromised or occluded over the course of the monitoring program, it is advisable to use up to six reference target positions per scanner position (station). Only three reference points are required per scan, however the changing landscape of a busy site will result in the loss of line of sight to some targets locations over time and target reduncy will save time in such situation. For this to be viable, it is necessary to scan in all target points during the first scan of the site, and it is recommended to scan as many targets as possible in subsequent scans. Redundant targets, thus, prevent costly delays in having to wait to scan when lines of sight are free. Similar consideration is required when picking a location for the laser scanner. It is best to identify a number of possible laser scanner positions that provide line of sight to all or most of the six reference target positions, as well as line of sight to the subject area under consideration, if the site lay out allows it. To fully address this issue, the subsequent construction must also be considered. In all of this, however, what is foremost is that both the subject of the scan and the targets are recorded from the same zero position.

Additionally, when selecting the scanner position at a scan site it is best to select a site such that the spread of points on the surface to be measured will be as even as possible across the total length of the scan (FIG. 5). The laser scanning process is designed to register a point in a three dimensional space for every bounce back event during the scan. This is achieved through a calculation that includes the time of flight of the laser pulse and the vertical and horizontal angles of the laser path through the intervening space with reference to a zero position. The spread of points on the sur-

face to be measured is an important consideration and is set by the surveyor when setting up the scan parameters. For example a setting of 50mm x 50mm at 100 meters while the scanner is true to a surface at 100m distance, the points collected that represent that surface will occur at 50mm intervals on the surface, vertically and horizontally. However as the distance to surface increases (as a result of the radial motion of the scanner), the points spread will increase. Equally as the angle of the laser path to the surface changes, the points spread also changes. Therefore, the laser scanner position should be selected to minimize the distortion of the point's matrix over the total scan. It may be necessary for the surveyor to use multiple scanner locations.

The normal sequence of events in a laser scanning exercise is to set up the equipment in the first scan position, 'scan station one'. The reference targets in line of sight of station one are scanned using manufacturer default parameter setting, the subject wall is then scanned at surveyor required density. If further scans from other vantage points are required, each pair of stations (scanner positions) must have line of sight of at least three common reference points to facilitate merging of the individual scans into one full three dimensional image of the whole sheet piling installation. The major disadvantage of multiple scan stations is the time needed to set-up the equipment in each location plus the time required to scan the reference targets (up to six) from each new scanner location. There is also some added processing time required in the office to 'register' each of the scans into one document. Accuracy can rival very high quality traditional surveying – the 2mm level for differential measurements.

Measurements of horizontal and vertical movement of a sheet piling installation are made by comparing initial scan results with subsequent scans using common reference targets to merge the scans as one document/model. Any out of position of the sheet piling in the subsequent scan with reference to the first will be apparent and can be measured by using the built-in measuring tools in the modeling software.

Use of a global position system (GPS) offers additional registration opportunities, but the canyoning effect in an urban environment has yet to be surmounted. Finally, temperature is a known source of error for all instruments as objects expand and contract diurnally, as well as seasonally (e.g. Buttry et al. 1996). As such, efforts should be made to take readings of the subject wall, when no movement is expected so that temperature related effects can be discounted as part of the baseline noise.

CONCLUSIONS

If set up with care, terrestrial LiDAR scanning can offer some additional benefits over traditional survey methods with respect to an objective permanent record that can be free from any large-scale subsidence that the area may be experiencing. Whether these advantages bear the high cost of the equipment and the more extensive need for a technically sophisticated survey crew remains an issue for the industry to judge.

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