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Lateral Image Degradation in Terrestrial Laser Scanning

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Summary

The use of aerial laser scanning to detect change in infrastructure and buildings after major disasters has become increasingly common in recent years to help prioritize interventions. More recent efforts are being invested to apply laser scanning in the assessment and structural health monitoring of buildings to simplify and quicken building damage surveys by the automatic detection of defects and deformations. Technology application must, however, be done in cognizance of equipment constraints regarding scan angle, sampling size, and beam width. This article reports a series of laboratory and field experiments designed to begin to quantify and minimise the possible errors for effective defect detection via terrestrial laser scanning during surveying. Varying geometric positions that cause either over- or under-prediction of crack thickness and length as a function of both standoff distance and angle of obliquity between the scanner and the defect are presented. These may over-predict horizontal crack thickness by 15 mm and failing to detect others. To help minimise such errors, a standoff distance of 12–15 m with a maximum obliquity of 45° between the scanner and target object are recommended.

Key words: cracks; defects; digital techniques; field investigations; imaging techniques; site evaluation; laser scanning.

Introduction

Increasingly, there is a demand for faster and more economical methods to create accurate, permanent records of the state of structures at a particular point of time (e.g., just prior to adjacent construction or immediately following an earthquake). Terrestrial laser scanning (TLS) is a relatively new technology that is garnering attention as a potential solution. TLS is a form of light detection and ranging (LIDAR)—a radar-based scanning system—which works by sending and receiving laser pulses at regular intervals from surface target objects, thereby creating a “point cloud” of the target object, which can then be studied using associated firmware. The viability of using TLS for condition assessment and structural health monitoring is still in its infancy, and the quantification of error and recommendations for best practice in such applications has yet to be well established. This paper will begin to bridge that gap.

Background

Terrestrial laser scanners operate on one of three principles: triangulation, time-of-flight, and phase comparison.¹ Triangulation uses the principle of trigonometry to determine a target object's shape. Time-of-flight scanners measure the time between the emission and detection of laser pulses and use this information to calculate the distance to the target object. Phase scanners work on the principle of the phase shift between the transmitted and received wave, in order to calculate the range to the target object point.² A three-dimensional (3D) model can, thus, be created with associated proprietary firmware. The distance to a target object can be measured by means of a time delay between transmission of a pulse and detection of a reflected signal.¹ LIDAR has applications in many fields from highway maintenance,³ to forestry,⁴ to mining,⁵ but there are as yet no formal standards written about the use of TLS for the purpose of condition assessment or health monitoring of buildings. According to Park *et.al*⁶ advantages of TLS over traditional sensors for this purpose include: (a) no *in situ* instrumentation of sensors, (b) no difficulties in reaching structures or structural members, (c) independence of natural light sources, and (d) no wiring costs. Recent developments in LIDAR technology allow the user to specify the degree of resolution that is required for a given scan. Resolution is described as a function of offset distance of the unit to the point of the target object orthogonal to the unit and is further influenced by the time spent scanning and equipment particulars. Theoretically, TLS can provide cost-effective, permanent, as-built records of buildings due to high spatial resolution and rapid data capturing capabilities.⁷

Unfortunately, error propagation (the cumulative addition of incremental discrepancies) and the precision of point clouds have often been overlooked by users because of the attractive appearance of the derived TLS models.⁷ Nonetheless, 3D coordinates of a target structure have commonly horizontal and vertical standard deviation of errors of 10 mm and 7 mm (respectively) in the distance field, when configured at a 100 m resolution, which is typically insufficient for health monitoring and condition assessment.^{8,9} Published experiments have illustrated that these error figures published by equipment manufacturers are often misleading. As an example, Licthi and Jamtsho⁷ presented an error budget for a directly geo-referenced terrestrial laser.⁷ Their paper analysed random and systematic error sources for TLS point clouds, with the aim of improving user understanding of the limitations of the instrument and the data cloud it produces.

Included was a historical heritage survey of Wat Mahathat in Ayutthaya, Thailand. A Reigl LMS-Z210 scanner was used to capture a 13-scan network of the site. The TLS unit's beam width was found to be the most significant random error source equating to an error distance one-quarter of the laser beam's diameter.⁷ The laser pulse diverges with distance from the scanner, thereby causing the instantaneous field of view to grow.¹ To quantify related errors, Lichti and Jamtsho⁷ identified image degradation occurring, where the beam intensity level drops below 37%. This phenomenon (further investigated by Mills and Barber¹) results in many of the errors in the reading of scanned images.

In a laboratory experiment tracking a simply-supported, mid-point loaded beam, a TLS unit was compared to three other instrumentation systems (a) linear variable displacement transducers, (b) electric strain gauges, and (c) a long gauge fibre optic sensor.⁶ The procedure for this displacement model was as follows: (a) the shape information of an unloaded I-beam was acquired using TLS, (b) base vectors were then generated using the least squares method, (c) the TLS coordinate system was then transformed into the structural system using the base vector, and (d) displacements were then computed within the structural coordinate system. A retro-reflective target was not used to geo-reference a particular point as is normally done. Instead, an intersecting or baseline of two intersecting planes was generated from numerous TLS points. From this, measured displacements were quantified. The maximum deflection at mid-span was estimated successfully within 1,6% of those measured directly by the transducers.⁶ Unfortunately, this approach cannot be extrapolated for most geometries and loading situations due to (a) a potentially infinite number of planes, (b) the possible existence of torsion, and (c) the absence of rigorous point-by-point matching systems between independent scans for targets that have displaced. Furthermore, there is still an on-going investigation as to whether TLS is viable for on-site monitoring and the assessment of existing building conditions in terms of cost and reliability.^{6,10-12} The two issues of contention revolve around issues of resolution and repeated positional accuracy.

A related field study was done in anticipation of the installation of Ireland's first metro.¹³ In this case, four buildings were surveyed using up to four inspection techniques: manual inspection from the footpath, digital photography, TLS, and manual inspection via boom lift.¹³ The study aimed to locate all visible cracks and document their thickness, lengths and locations. As an example, for one building, 95 cracks were thought to be found across the four methods (*Fig. 1*). TLS detected no cracks above a height of 12 m due to image degradation or below 2 m due to visual interference from railing, signage, etc. In brick, the minimum detectable crack length was found to be 90 mm compared to 17 mm via digital photography. Results in concrete were only slightly better (88 mm) with TLS. With respect to thickness, TLS tended to overestimate crack thickness by more than 7 mm when compared to measurements taken with Vernier callipers.

Fig. 1: Comparison of cracks detected as a function of height (data from Ref. [13])

The discrepancy is in part because point clouds are difficult to interpret as they present discrete data points and not a surface mesh, and to date no easy, systematic methodology has yet been developed to identify which point corresponds to the exact location on the

scanned surface. Al-Manasir and Fraser¹⁴ devised a system of cloud point registration known as the image-based registration. This system is based on the principle of photogrammetry. In that, a digital camera is mounted on top of the TLS unit, where the co-ordinate system of both the scanner and digital camera are known. The relative orientation between the overlapping images from the two stations can then be recorded in order to subsequently merge the two accompanying point clouds. Traditionally the iterative closest point method was adopted, where two scans are assumed to be in approximate registration with one another. The orientation difference is then reduced by matching a number of points on one surface with the closest points on the other surface. Image-based registration is faster, can yield an accuracy of 3 mm, and is used in all modern terrestrial laser scanners with integrated digital cameras.¹⁴

An inability to reliably document crack thickness is highly problematic for condition assessment and structural health monitoring. For example, much of the geotechnical community relies upon variations of *Table 1* to perform either risk assessment or to prioritize repair intervention. If a crack's thickness is over estimated by 7 mm, it is likely to result in a more damaged description (e.g., moving from slight to moderate or moderate to severe). The problem would be especially acute if the result of TLS were compared to a previous survey undertaken with an alternative documentation method. As such, for TLS to be most effectively and reliably used a fuller understanding of its limits is needed by the structural engineering community both with respect to crack thickness detection and obliquity related image degradation, as described below.

Table 1: Grading system for degradation (adapted from Ref. [15])

Damage level	Degree of damage	Description of existing damage	Approximate crack thickness (mm)	Maximum tensile strain (%)
0	Negligible	Hairline cracks		<0,05
1	Very slight	Fine cracks easily treated during normal decoration	0,1 –1	0,05–0,075
2	Slight	Cracks easily filled. Several slight fractures inside building; exterior cracks visible	1–5	0,075–0,15
3	Moderate	Cracks may require cutting out and patching; doors and windows sticking	5–15 or a number of cracks >3	0,15–0,3
4	Severe	Extensive repair involving removal and replacement of walls, especially over doors and windows; windows and door frames distort; floor slopes noticeably	15–25 but also depends on number of cracks	>0,3
5	Very severe	Major repair required involving partial or complete reconstruction; danger of instability	>25 but depends on number of cracks	

Experimental Program

Since crack thickness has traditionally been the basis of categorizing a building's damage level,¹⁵ and the value of a 7 mm over-prediction would generally raise the assigned damage category to one further level of severity (*Table 1*), a manufactured sample target object was scanned at set offset distances using a Trimble GS200 TLS in a controlled laboratory experiment; beam width 3 mm at 50 m. The sample target object was produced with a number of predetermined slots to represent cracks (*Fig. 2*). A total of six slots were cast into the plaster sample target object: two horizontal, two vertical, and two diagonal. Each slot was 100 mm long and for each orientation one slot was 5 mm thick and the other was 10 mm thick (*Fig. 2a*). The scanner's beam was aligned to be at the same elevation as the centre of the target object.

Initially, the TLS unit was offset 3 m orthogonal from the target object. After scanning, the target object was moved 2 m to the side along the baseline (*Fig. 2b*) and scanned. This was repeated every 2 m, until the target object was 32 m from its original position. Once these 17 scans were completed, the target object was returned to its original position and the TLS unit was set a further 3 m away from the baseline (*Fig. 2b*), and the scanning cycle was repeated. The cycle of 17 scans was done six times, each 3 m further away from the baseline, until the TLS unit was 18 m away from the initial target object position. This resulted in 85 scans of the sample at differing distances and angles from the scanner using a point sampling grid of 2 mm × 2 mm with a focus distance of 100 m to cover the differing distances of the scanner from the sample.

Fig. 2: Specifics of sample and details of the experimental program setup

Results

Significant image degradation was recorded with respect to detecting test sample slots. This was especially true with respect to accurately determining thicknesses and less apparent for determining lengths. Detection discrepancies were in general more consistent for horizontal slots and less consistent for vertical slots, with diagonal slots exhibiting discernability similar to the vertical slots. Interpretation of the scans by two independently working operators both overestimated the thickness of the horizontal slots by as much as four times the actual thickness (*Fig. 3a*). over-prediction increased the more oblique the target object's position was from the scanner, mostly as a function of the increasing angle from the scanner. This can be seen most clearly when the scanner was positioned at 3 m from the target object's baseline and the target object was located at 32 m from its origin, which generated the most acute resultant scanner sample angle. For the diagonal (*Fig. 3b*) and vertical slots (*Fig. 3c*), initially there was a tendency to overestimate slot thickness by up to 50% (2–3 mm), but as the target object was positioned more obliquely from the TLS unit, under-prediction occurred with increasing severity, until clear cut-off points emerged, beyond which the slots could not be discerned at all. Such boundaries need to be established to ensure consistent, accurate scans. In *Figs. 3d–f* a fixed angle of 36° is shown, to better understand the interplay between the distance-based degradation of the obliquity controlled aspect. These images, when compared to *Figs. 3a–c*, help emphasize the dominance of the problem with obliquity in defect detection, in that degradation with offset distance is much more consistent and less severe.

The issue of scanner angle obliqueness to the target object is an issue well documented in aerial LIDAR swath mapping and is the reason for 30–40% swath overlaps and flight height optimisation, with respect to scanning swath angle. For TLS, the angular divergence along with the sampling interval and beam width combine to add distortion and inaccuracies to the resultant scan. As noted by Lichti and Jamtsho,⁷ fine angular sampling does not produce high-resolution point clouds, in cases where the beam width is significant and the angular position of target area is at an incidence, where the beam width is equal to or greater than the sampling interval. For the experimental work featured herein, the problem was more acute because when the angle increased, the slot thickness became less visible, as a function of the apparent rotation of the image (*Figs. 4 and 5*), which elongated with obliquity. From this a rule of thumb can be derived. Namely, if the sampling interval is 55% of the beam width, the beam width accurately describes the resolution of the scan. The deformation of the scanner's beam width as noted in this experiment, further reduces the resolution of the scan and makes the detection and analysis of the target object slots inaccurate and in certain cases undetectable.

Fig. 3: Sample of scanning results for crack thickness and length detection

Fig. 4: Detectability impacted by slot orientation

Fig. 5: Swath distortion as function of angle between the target and the scanner

Using data shown in *Fig. 3* to establish mean error minimisation, an optimum standoff distance between 12 and 15 m would be recommended combined with a maximum target object obliquity generally not exceeding 45°. This in effect limits the scan area. Being able to quantify this for the purpose of field guidance is not a fully straightforward process and the combined effect between distance angle sample spacing and beam width needs to be more fully investigated to achieve more dependable and mathematically based set of field collection procedures.

Field Investigation

How image degradation manifests itself in a real building scan was investigated at an actual Irish site. The TLS unit was placed at three points (A, B, C) with respect to the 6,5 m² target area (D) (*Fig. 6*). Each position was set 21 m away from the building (the equivalent as the baseline in *Fig. 2b*). Scanning density was set at 3 mm × 3 mm; this is the industry's way of conveying that if the unit was set 100 m away from the target, then the data collected on an orthogonal surface will be captured at a density of one data point within every 9 mm² patch. When the unit is set closer, the data will increase largely proportionally until the data density converges with the beam width, which represents an upper bound of the potential data density.

Point A resulted in data capture at 80° from orthogonal. Point B was 70° from orthogonal, and point C was directly in front of the scanner (0°). There was a clear difference in quality in the scans. As the scanner position became less oblique, the quality improved.

In the scans from both positions A and B, the background scanning software colour seeped through due to the low point density. The point density in the scans from positions A (24,686 points/m²) and B (58,216/m²) were only 8,5% and 20% that of position C (287,947/m²). Depending upon the desired level of detail required for the documentation (e.g., geometric, material, damage) different densities and accuracies must be specified explicitly.

Fig. 6: Castletown scans at three angles of offset

Conclusions and Implications for Practice

Parameters relevant for accurate and reliable terrestrial laser scanning for condition assessment and structural health monitoring are substantially more restrictive than those for general, geometric documentation. Experimental work shows a significant loss in defect detection, when the scanner is oriented more than 45° from the target object. Furthermore, to maximize data capture in terms of minimizing the necessary number of scans and their subsequent registration, a positional offset of 12–15 m is recommended. Even within these more restrictive parameters, practitioners must note that crack thickness determination is not currently compatible with producing a scan in a timely manner. As well, depending upon the orientation of the crack and the obliquity of the scanner thickness, over-prediction may occur, in some cases up to 15 mm ,while in other cases cracks may not be detectable, thereby leaving great doubt as to the current use of TLS as a means for generating an objective, permanent record of a specific building at a particular point in time using the current generation of this technology.

Acknowledgments

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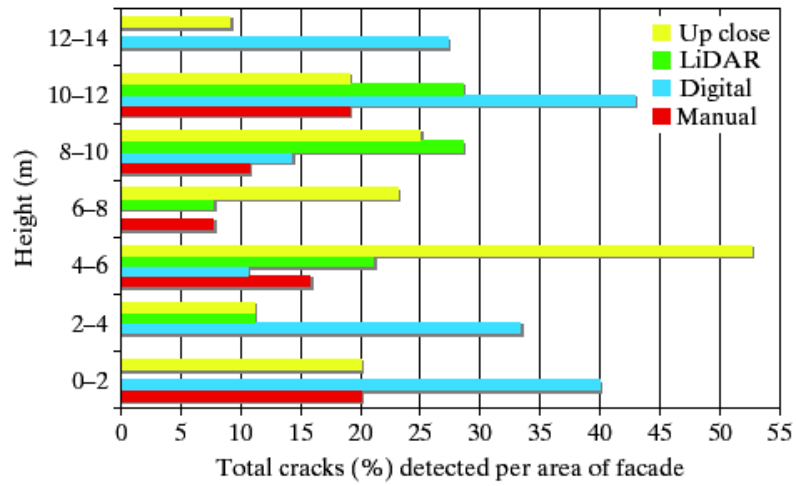


Fig. 1: Comparison of cracks detected as a function of height (data from Ref. [13])

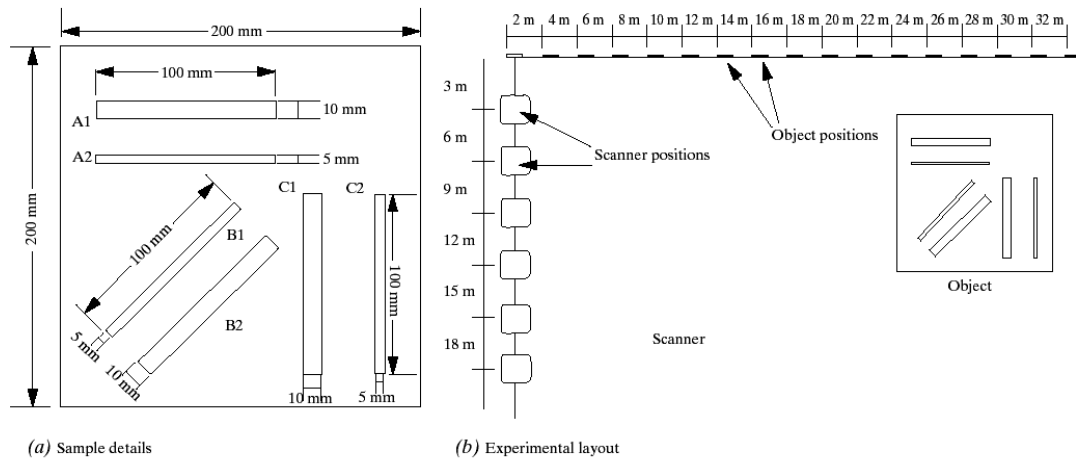
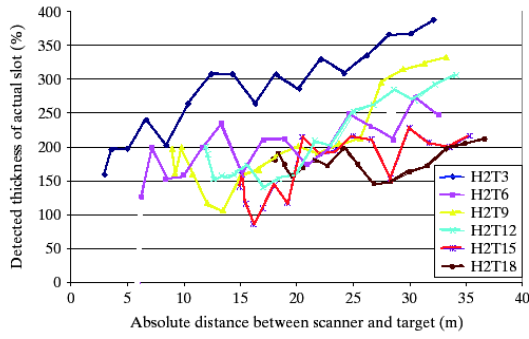
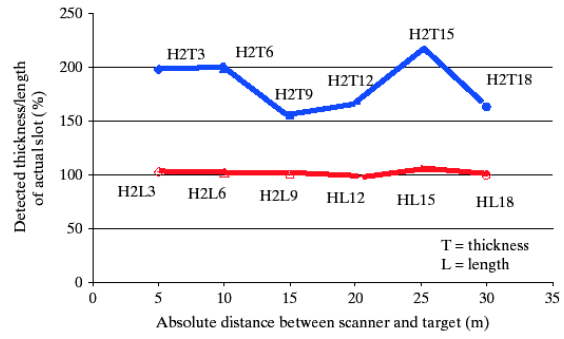


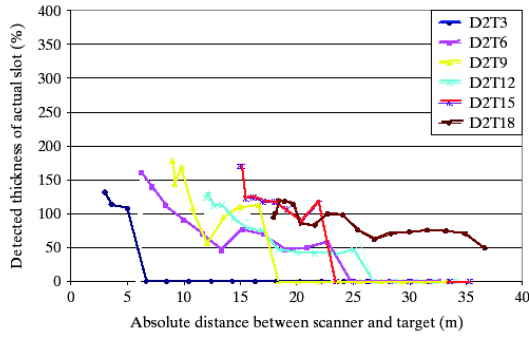
Fig. 2: Specifics of sample and details of the experimental program setup



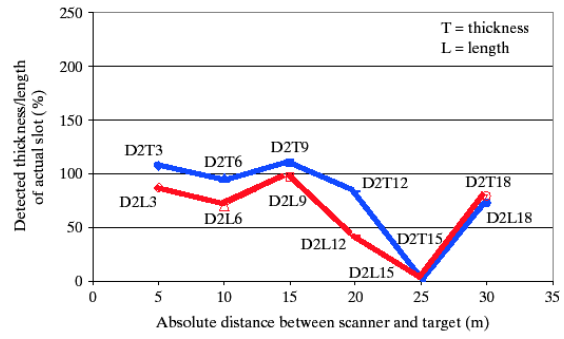
(a) Horizontal slot (H2) 5 mm thick



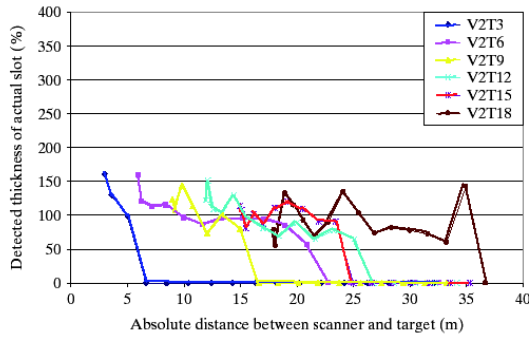
(d) Horizontal slot (H2) image degradation at fixed angle



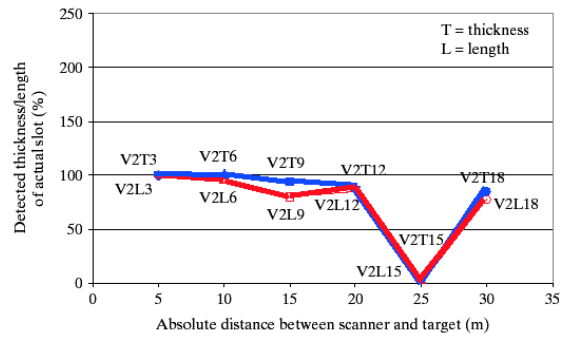
(b) Diagonal slot (D2) 5 mm thick



(e) Diagonal slot (D2) image degradation at fixed angle



(c) Vertical slot (V2) 5 mm thick



(f) Vertical slot (V2) image degradation at fixed angle

Fig. 3: Sample of scanning results for crack thickness and length detection

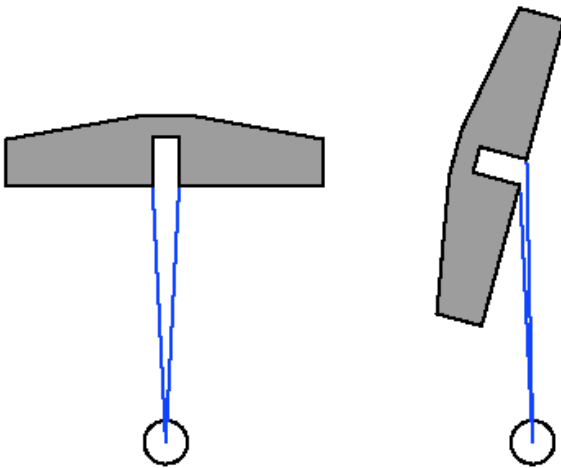


Fig. 4: Detectability impacted by slot orientation

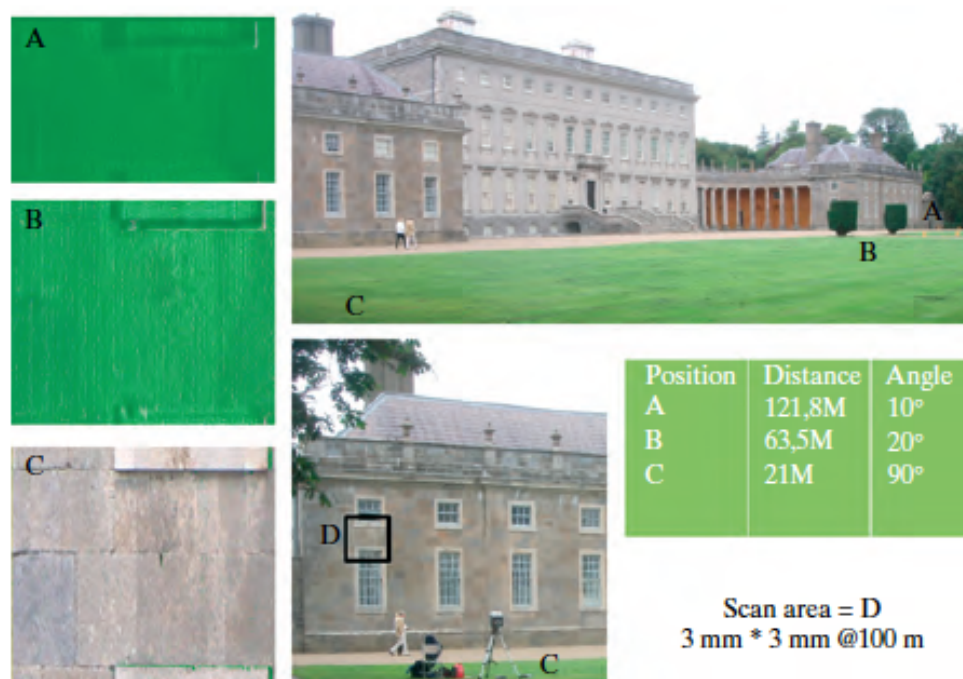


Fig. 6: Castletown scans at three angles of offset