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Equipment Considerations for Terrestrial Laser Scanning for Civil Engineering in Urban Areas

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Authors' contributions

This work was carried out in collaboration between all authors. Author LTH designed field data collection, was involved in writing the first draft of the manuscript, ran the surface reconstruction for façade patches and revised the manuscript for re-submission. Author Hamid Gharibi revised the first draft of the manuscript and submitted the paper. Author Himanshu Garg collected data point by the Leica P20 and wrote the first draft of the manuscript. Author DL collected data point cloud by Trimble GS200 and corrected the final manuscript. All authors read and approved the final manuscript.

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ABSTRACT

When renting or purchasing a terrestrial laser scanner, consideration must be given to a variety of factors including ease of use, accuracy, speed and cost. The following paper considers these aspects with respect to civil engineering applications in urban areas. One particular concern relates to the logistics of being in the field in terms of the equipment quality, the required space, power supply needs, and time needed for operation. Other factors relate to data acquisition, quality, and processing. To illustrate these issues, two terrestrial laser scanners (one from 2003 and one from 2013) were used to acquire a point cloud of three, masonry building facades in a dense urban setting. Also, sample solid models as required for computational modelling in civil engineering, were generated from these scan data sets. The resulting investigation showed that despite a 10-year age difference in the units, there was no appreciable improvement in the scan angle accuracy, and data from both units was successfully employed to reconstruct building models for

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computation. However, the newer scanner was significantly faster in data acquisition and possessed other features that made it easier and more effective to deploy in urban areas, where space is limited and vehicular and pedestrian traffic can be problematic. The paper also provides a cost comparison of the two units showing that financial competitiveness depends upon the workload. This paper provides information for firms considering purchasing, renting, or subcontracting laser scanners for civil engineering projects in urban areas.

Keywords: Terrestrial laser scanning; civil engineering; building model; real sampling step; cost-effect.

1. INTRODUCTION

Terrestrial laser scanning is playing an increasingly important role in Civil Engineering (e.g.[1-3]). Although many studies have been conducted to compare the performance and efficiency of terrestrial laser scanners (e.g. [4,5]), there is no published guidance about choosing appropriate scanners for Civil Engineering applications. A major issue for Civil Engineering practitioners is in defining contract specifications, whether this is for the subcontracting of work by an outside firm or for the selection of equipment for purchase or rental for the firm's direct deployment. To this end, efficient usage of terrestrial laser scanning in urban areas in the Civil Engineering domains demands application-specific equipment selection to generate the desired outcomes and avoid unnecessary expenses. This paper considers currently available commercial technology (both existing and brand new) from data capturing and processing perspectives for Civil Engineering in urban environments. Specifically, ease of use, scanning times, dataset sizes, actual scan angle, building reconstruction potential from the generated point cloud, and cost will be prioritized over the millimetre-level accuracy assessment that is typically reported for geomatics-based studies.

(a) 42 Grafton St. (b) 24 Dawson St. (c) 44. Westmoreland St.

Fig. 1. Three buildings used for comparison from city centre of Dublin, Ireland

The present study compares various practical aspects and challenges in the use of two scanners. One is an older but still highly functional unit (a 2003 Trimble GS200) [6]. The second is the most recently launched, terrestrial laser scanner by Leica Geosystems (a 2013 Leica Scan Station P20) [7]. Comparison is done through the evaluation of scanning and post-processing of three buildings in the city centre of Dublin, Ireland (Fig. 1). The goal of this work is not to benchmark the two units against each other (nor to recommend a particular product) but rather to give novice users a sense of the range of capabilities of units that they might encounter and the parameters that they may want to specify, as part of any subcontracting or purchasing arrangement.

2. EQUIPMENT INFORMATION

Technical and physical aspects of the two units are summarized in Table 1. The Trimble scanner requires an external device (e.g. laptop) to control the scanner and store the data, since the scanner has no internal memory. In contrast, the Leica scanner has a built-in touchscreen control with a full colour graphics display [*VGA* (640 x 480 pixels)], and the scanned data are stored on a 256 GB Solid State Drive. While both scanners can be powered by either batteries or directly with *AC* electricity, the Trimble's batteries are bulky and heavy (18 kg) and provide only 3 hours of scanning time. Because of this limitation, a generator is often required to power the scanner (and possibly the laptop). The generator causes noise and air pollution and must be co-located nearby. Alternatively, 4 internal batteries are provided with the Leica Scan Station P20 enabling around 14 hours of continuous scanning (7 hours per pair of batteries), there by omitting the necessity of a generator or the need for a laptop, the presence of which may complicate work in congested, urban locations.

Although both the scanners use a time-of-flight (*ToF*) based ranging system, there are significant technical differences in their data capture mechanisms. The Trimble GS200 archives 5,000 points per second with a noise range of 1.4 mm, while a combination of *ToF* range measurement and modern Waveform Digitizing (*WFD*) technology allows the Leica P20 to collect up to 1,000,000 points per second with a sub-millimetre noise range [6,7]. The *WFD* detects multiple returns of a pulse and provide more information of the target surface. Thus, the Leica's output after post-processing may contain more information than that from the Trimble and may assist in a range of specialized applications. Alternatively, these additional data points from the Leica may be considered irrelevant for the required application and, therefore, not warranted when the equipment's cost is a consideration.

Although nearly a decade older, the Trimble GS200 has a smaller beam diameter (3 mm @ 50 m) compared to the Leica's (reported as 2.8 mm at the front window of the unit) and a beam divergence of 0.2 μrad. The beam diameter is the diameter along any specified line that is perpendicular to the beam axis and intersects it. This parameter can cause positional uncertainty [8]. As such, in term of point and angular accuracy, the Trimble GS200 is superior to the Leica P20, where the angular accuracy is only 0.002º vs. 0.0018º for the Trimble. Another important parameter is the scan angle step, which is a function of the spatial sampling interval and the laser beam diameter. The scan angle step is the ability to resolve two equally intense point sources on adjacent lines of sight. At a specific scan distance, the footprint of the beam width on the object may be greater than the sampling step, which causes overlapping laser spots. In the technical specifications, equipment manufacturers often provide the sampling step, but not the scan angle step, which is the angle between two consecutive vertical profiles. According to the manufacturers, the Trimble GS200 can generate a sampling step of 3mm at the range of 50 m, while the Leica P20's sampling step is 0.8 mm at the range of 10 m, which should theoretically generate a sampling step of 4mm at 50m.

Table 1. Equipment specifications

Aspects	Trimble GS200 [6]	Leica scan station P20 [7]
Measurement method	Time-of-flight	Time-of-flight + WFD
User interface	Notebook PC	Onboard control
Data storage	External device (laptop)	Internal memory (*SSD*)
Scanning range	1m-350m	0.4m-120m
Maximum scanning rate	5,000Hz	1,000,000Hz
Point accuracy	1.4mm @ 5-50m	3mm @ 50m; 6mm @ 100m
Beam diameter	3mm @ 50m	≤ 2.8mm @ front window
Minimum sampling step	3mm @ 100m	0.8mm @ 10m
Angle accuracy (horizontal/vertical)	0.0018º/0.0018º	0.002º/0.002º
Field of view (horizontal x vertical)	360ºx 60º	360ºx 270º
Laser wavelength	532nm	658nm
Laser class	Class 3R (IEC 60825-1) / Class 2 (21 CFR 1041.10)	Laser Class (2IEC 60825-1 (2007-03) and EN 60825-1 (2007-10))
Standard battery Dimensions	41 mm *D* x 330mm *W* x 175mm *H*	40mm *D* x 72mm *W* x 77mm *H*
Standard battery Weight	18kg	0.4kg per battery
Standard battery capacity	3hrs	> 7hrs
Scanner dimensions	340mm *D* x270 mm *W* x 420mm *H*	238mm *D* x 358mm *W* x 395mm *H*
Scanner weight	13.6kg	11.9kg

However, a major difference between the scanners is the vertical scanning angle range. The Trimble's is 60º, while the Leica's is 270º. Thus, in this respect, the Leica is better suited to document high buildings in narrow areas where there is limited space to set up the scanner. The Trimble requires a greater off-set distance.

Furthermore, the Leica P20 has an integrated electronic level, internal laser plummet, and a dual-axis compensator, which corrects the scanned data for tilt error (in the range of +/– 00º 05'00"). The compensator warns the operator, if the instrument is out of the level state beyond the mentioned range. In contrast, the Trimble scanner must be manually manipulated, which requires a lengthier set up duration (typically 15 minutes for the Trimble versus 5 minutes for the Leica).

Both scanners can collect data at night and in low light conditions, even though there is some dependency on ambient illumination. Both scanners can be operated in a wide range of temperatures. For example, the recommended operating temperatures for the Leica P20 are -20ºC to +50ºC. However, neither unit should be used where there is exposure to water due to rain or other means. Finally, both scanners are equipped with "eye-safe" classes of lasers. The functionality of the two scanners is further explored in following sections through experiments in collecting point clouds for the street-side façades of three buildings in the centre of Dublin, Ireland.

3. DATA COLLECTION

Three buildings were selected (42 Grafton St., 24 Dawson St., and 44 Westmoreland St.) to represent the diversity of building facades in Dublin and differing access conditions. However, in all cases, as these are city-centre buildings, there is limited space to set up the scanner, and scanning quality can be impacted severely due to pedestrian and/or vehicular traffic. The scanners were positioned to optimize data collection of the building façades and to minimize the need for multiple scans to obtain full data coverage of the façades. The scan station layout for each building is provided in Fig. 2. Notably, the buildings were scanned between 6:00 a.m. and 8:00 a.m. on weekend mornings to minimize pedestrian and vehicular interference.

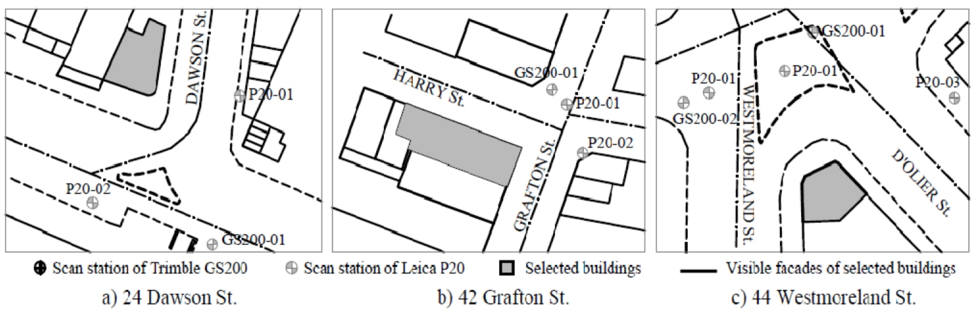


Fig. 1. Scan station layout for the three selected buildings

A critical question what a sampling step is used to scan objects in a project, as it affects the data quality and quantity, as well as the scanning time. With the larger sampling step, the point cloud data may not be sufficient for building modelling and represent incorrect objects' edges (i.e. the building's edges). Smaller sampling steps collect a high level of details on an object's surface but require longer scanning times and more data storage space. Overly small sampling steps may generate excess data, unnecessary levels of detail, and extended scanning durations. Therefore, an appropriate sampling step should be defined considering the required level of detail on an object and the available time for scanning. Notably, determination of the optimal sampling step is out of the scope of this study; however, an impact of the sampling step on edge detection from a TLS point cloud can be found in Pesci et al. [9], where the optimal sampling step was investigated to distinguish adjacent elements. The sampling step was empirically selected as summarized in Tables 2 and 3 for the Trimble GS200 and Leica P20, respectively. At 44 Westmoreland St., the offset distance (i.e. the distance between the scanners and the building) was twice that for the other two buildings. Thus, the smaller sampling step used was to achieve the same level of detail as that for the other two buildings. As the space to set up the scanner and scanning time for data acquisition were limited, because of increasing traffic considerations, only one scan station was used for the Trimble GS200 for 42 Grafton St. and 24 Dawson St., even though this choice precluded full façade documentation.

Limitations in the field of view can adversely affect scanning opportunities in narrow streets, as the requisite offset distance between the scanner and the target are restricted. Further restrictions may be caused by limitations of the field of view. For example, since the Trimble's vertical field of view is restricted to 60º in total (Table 1) when trying to capture the upper stories of a building, the instrument must be set further from the object than the Leica, or be required to take more scans from distinct positions. Fig. 3 shows the influence of this restriction for 44 Westmoreland St., where two scans were required with the Trimble GS200 but only one with the Leica P20.

a) Trimble GS200 point cloud (*)

b) Leica P20 point cloud

Fig. 2. Portion of 44 Westmoreland St

**Two scans were needed from the Trimble GS200 for full coverage, as shown in the two colours (pink for the lower portion and blue for the upper part)*

In addition, although the sampling step for the Trimble GS200 is larger than that of the Leica P20, the Trimble unit needs a longer time to complete the data acquisition (Table 2 versus Table 3). For example, for 44 Westmoreland St., the Trimble unit required 3,744 seconds, while the Leica completed the scan in 85.9 seconds (as obtained over 3 scans). Typically the Leica's scan rate was 150 times faster than that of the Trimble GS200. The rapidity with which data can be captured may be critical in crowded environments, where clear scanning intervals are short.

Table 2. Details of the scans from the Trimble GS200

Items	42 Grafton St. (*)	24 Dawson St. (*)	44 Westmoreland St.	
	Station 1	Station 1	Station 1	Station 2
Predefined sampling step	5mm @ 5m	5mm @ 5m	5mm @ 10m	5mm @ 10m
Total data points (pts)	828,924	305,367	1,318,481	1,063,998
Scan time (s)	1,494	594	2,088	1,656
Scanning rate (pts/s)	554	514	631	614
Average acquisition distance (m)	16.8	30.6	27.1	30.7
Coverage area of the total dataset	72%	76%	100%	

(*) The collected point cloud is insufficient to describe the entirety of that building's street facades

While the sampling step for the Trimble GS200 is larger than that of the Leica P20, the number of data points collected by Leica is larger than those from the Trimble scanner. Point quantities do not, however, control file size. As mentioned above, the Leica P20 may record more information than the Trimble GS200, but the resulting output data files from the Leica scanner are disproportionally larger (Table 4).

Table 3. Details of the scans from the Leica P20

Items	42 Grafton St.		24 Dawson St.		44 Westmoreland St.		
	Station 1	Station 2	Station 1	Station 2	Station 1	Station 2	Station 3
Predefined sampling step	3.1mm @ 5m	3.1mm @ 5m	3.1mm @ 5m	3.1mm @ 5m	1.6mm @ 5m	1.6mm @ 5m	1.6mm @ 5m
Total data points (pts)	2,272,729	1,723,657	2,075,434	787,662	4,729,847	3,136,145	2,863,514
Scan time (s)	35.8	24.4	26.9	14.7	34.0	28.2	23.8
Scanning rate (pts/s)	63,421	70,553	77,233	53,668	139,136	111,333	120,494
Average acquisition distance (m)	18.0	16.6	17.5	25.4	21.7	27.4	26.0
Coverage area of the total dataset	100%		100%		100%		

Table 4. Comparison of dataset sizes

Scanner	Items	42 Grafton St.	24 Dawson St.	44 Westmoreland St.
Trimble GS200	Total data points (pts)	828,924	2,229,069	2,382,479
	Dataset size (MB)	1.6	3.4	10.8
Leica P20	Total data points (pts)	3,996,386	2,863,096	10,729,506
	Dataset size (MB)	34	25	95

4. SCANNING RESULTS AND POST-PROCESSING

Beyond differences in surveying logistics of the two scanners, data quality was investigated in the application of façade reconstruction for computational modelling. For this activity, issues of real sampling points, resulting reliability, and the success of the building reconstruction were considered using data points from one surface patch containing two openings.

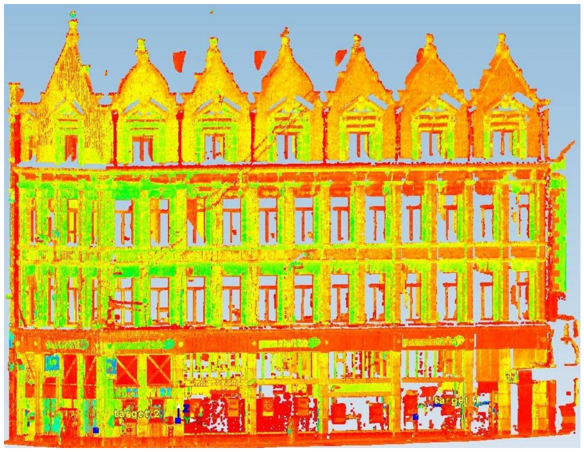
When multiple scan stations are required to capture the entirety of a façade, those data sets must be registered and merged together. To achieve this, the source dataset is mapped to the target based on pre-selected reference points by using (1) the point cloud data of an artificial target; (2) sharp angular features, or (3) an integrating Global Positioning System (*GPS*) receiver. In this work, two artificial targets were used for the Leica P20 data sets, while sharp features were used for the Trimble GS200 data sets. The choice to not use the artificial targets for the Trimble was made based on the fact that the Trimble's in-built camera is offset from the laser beam emission, which in the experience of the authors leads to excessive post-processing time when collecting data points of small objects such as artificial targets for co-registration.

Irrespective of the approach adopted, the registration process is completed when the registration error is less than a user-defined threshold; for example, Truong-Hong [10] previously used the threshold of 5mm.This value was the maximum standard deviation of the noise of the data points when the incident angle varied from 0^0 to 50^0 and the distance from the scanner to the object ranged from 0 to 50m [11]. Additionally, Truong-Hong [10] found that when this threshold was used, the data registration did not negatively affect the accuracy of the resulting building models. The registration process is conducted within proprietary software of the scanners (Cyclone V8.1 [12] for the Leica P20 and Real Works Survey (*RWS*) V6.3 [13] for the Trimble GS200). The resulting data registration of 42 Grafton St. from the Cyclone V8.1 and of 44 Westmoreland St. from *RWS* V6.3 is shown in Fig. 4. Notably, several methods can be used to automatically register a point cloud and improved registration quality, for example surface matching algorithms [14,15].

Theoretically, the Trimble GS200 offers higher accuracy than the Leica P20. However, the real sampling step can be influenced by several parameters (e.g. the material of an object's surfaces, surface curvature, scan angle, and environmental factors), thereby causing uncertainty in any subsequent building reconstruction stage. To investigate the real sampling step for each building, three sample patches were extracted randomly with respect to scan angle and range. The comparison between the theoretical and real sampling steps underlying the scan angle step is shown in Table 6. Differences between the theoretical and real scan angle steps for the Trimble were larger than that for the Leica P20. Interestingly, the mean difference, which is an indication of the average absolute error, is often equal to the scan angle step, which implies that the scan angle step has a high level of control for the final error level. For example, with 42 Grafton St., the scan angle step is 0.0573ºfor the Trimble GS200 (which corresponds to the sampling step of 5 mm at 5 m) and 0.0367º for the Leica P20 (which corresponds to the sampling step of 3.1 mm at 5 m). Thus, in both cases the scan angle step is a strong indicator of the final outcome.

Although the real angle step differed from the theoretical one, in both cases the sampling step was larger than expected. However, visualization of the point cloud of each building indicated the likelihood of there being sufficient data for building model generation for structural analysis (i.e. a case where architectural detailing is not needed) (Fig. 5). The missing points in both data sets from the Trimble and Leica scanners are due to self-occlusions caused by the orientation of the scanner with respect to the building. To understand completely the impact of the acquired point cloud on building reconstruction, the point cloud of a façade surface patch (shown within the dashed boxes in Fig. 5) of 42 Grafton St. was used.

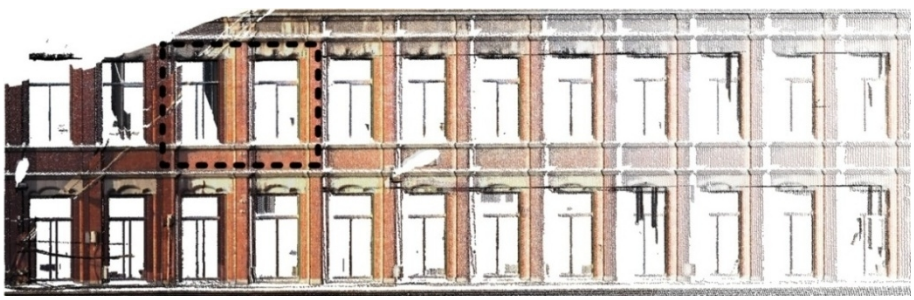
Point clouds from both the scanners were used as input data for automatic generation of solid models for finite element computation using an established technique by Truong-Hong [16]. The resulting solid models are illustrated in Fig. 6. Both point clouds were used successfully to generate the solid model of the façade patch. The patch contains two windows, where real window dimensions are 1.25 m wide by 2.30 m high. However, the resulting window width differed from that recorded in measured drawings from independent manual surveys. The window width derived from the Trimble data differed an average by 0.15 m but only 0.06m with the denser Leica data. The height differences were less pronounced, with output from the Leica data 0.01 m larger than the actual, and the Trimble only 0.0015m. While some of the error in the window widths may be caused by the transformation algorithm, the output also seems to be negatively influenced by data density.



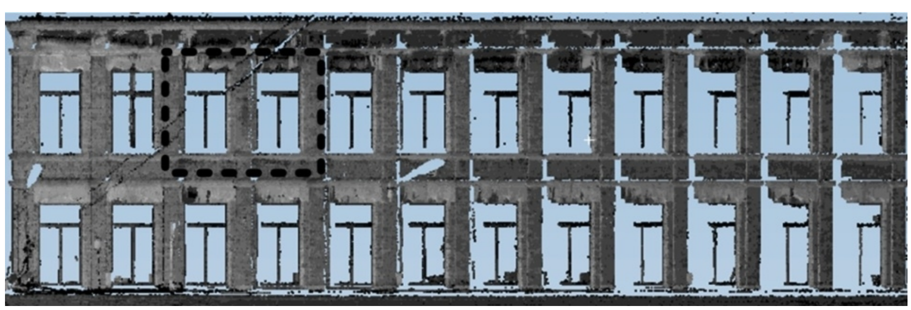
a) Target based registration (3 mm error) – 42 Grafton St. with Leica data

b) Feature based registration (6.7mm error) – 44 Westmoreland St. with Trimble data

Fig. 3. Results of point cloud registration

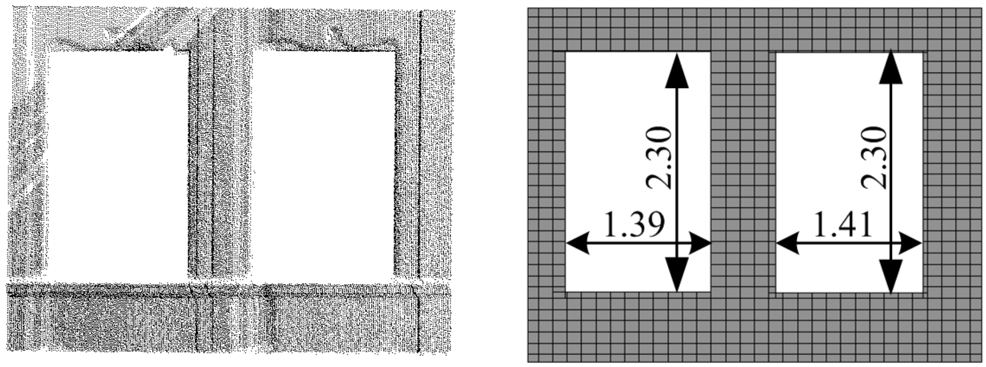


a) Data from Trimble GS200(*)

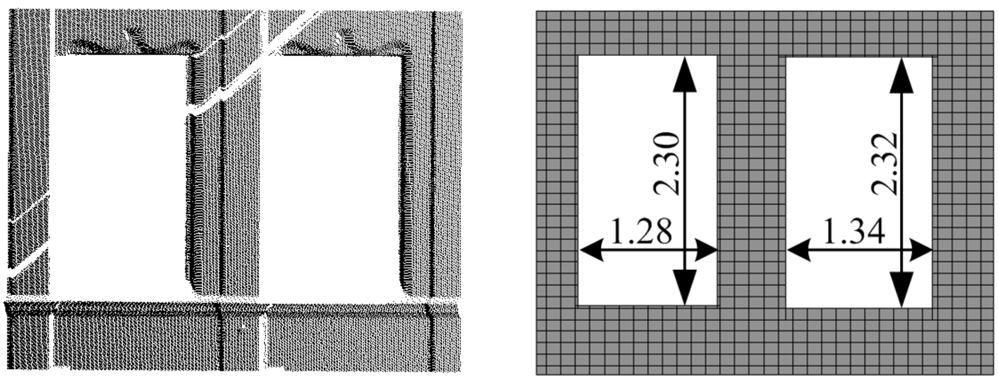


b) Data from Leica P20

Fig. 4. Point clouds of the first and second-story of 42 Grafton St.
(*) Missing data points on the left upper part of the second story is due to the limited field of view of the Trimble, GS200, as discussed previously



(a) Point cloud from Trimble GS200 **(b) Resulted solid model based the point cloud in (a)**



(c) Point cloud from Leica P20 **(d) Resulted solid model based the point cloud in (c)**

Fig. 5. Generated solid models for surface patches (dash box in Fig. 5) of 42 Grafton St. (unit-m)

5. DISCUSSION

Both the Trimble and Leica scanners acquired sufficient point cloud for building model reconstruction. For the case urban usages for building documentation, where space and time are restricted, the Leica P20 is more convenient than the Trimble GS200. However, when the buildings are scanned with a high scan angle, erroneous measurement of the feature edges (e.g. edges of the building and windows) the noise in the point cloud increases [11,17]. Moreover, choosing suitable scan stations is necessary. The scan stations must ensure that the building is scanned with a small incident angle to minimize noise in the data and missing data points of the buildings' edges. For example, Soudarissanane et al. [11] reported that, the noise in the data is exceeds 1cm when the scan angle is in excess of 700. In addition, when the building is close to a traffic light or bus stop, vehicles will be especially problematic with respect to causing occlusions, which leads to missing data, thereby forcing multiple re-scans. Thus, the scan stations must be selected to minimize such occlusions.

When either purchasing or renting a scanner for a specific project, cost should be considered. For example, for 44 Westmoreland, data acquisition with the Trimble GS200 required 79 minutes (15minutes for set up and 64 minutes for data collection). In contrast, the Leica P20 required only 6.4minutes (5 minutes for set up and 1.4minutes for data acquisition). This clearly shows that the use of the Leica P20 could reduce field time by a significant margin. Two scenarios are presented in Table 5, where cost is consider by using current Irish salary levels of €52,000 per year (including benefits) for a technician and equipment rental rates of €1000 per week for the Leica and €200 per week for the Trimble, and assuming a 20 minute relocation time and an 8 hour work day. If there were a lot of buildings to scan, the expense of using the Leica would be slightly less than half of that of the Trimble to operate. However, this is rarely the case. Typically only a single building needs to be scanned at any particular time. Thus, by reconsidering the scenario where only 4 buildings needed to be scanned in a single day, the cost of using the Trimble would be notably less, despite the more extended required scanning duration.

Table 5. Cost-effect of two scanners

Aspects	**Daily technician wage**	**Daily equipment rental**	**Scans/week**	**Cost/scan for a week of scans**	**For 4 scans**	**For 91 scans[+]**
Trimble	€200	€40	24	€50	€240	€4560
Leica	€200	€200	91	€22	€300*	€2000

**Assumes half day technician time but full day equipment rental*
[+] Conducted sequentially

Table 6. Difference between theoretical and real scan angle step

Sample	**Trimble GS200**				**Leica P20**			
	Vertical angle step (°)		**Horizontal angle step (°)**		**Vertical angle step (°)**		**Horizontal angle step (°)**	
	Mean	**RMSE**	**Mean**	**RMSE**	**Mean**	**RMSE**	**Mean**	**RMSE**
42 Grafton St.								
1	0.0575	2.15E-07	0.0574	2.86E-08	0.0358	4.44E-08	0.0358	6.65E-09
2	0.0610	3.35E-06	0.0575	2.28E-08	0.0388	1.49E-05	0.0251	5.42E-06
3	0.0582	6.08E-07	0.0574	1.61E-08	0.0360	2.16E-07	0.0307	2.64E-06
24 Dawson St.								
1	0.0574	2.83E-05	0.0569	2.76E-05	0.0358	1.06E-08	0.0358	4.42E-09
2	0.0575	2.84E-05	0.0573	2.81E-05	0.0358	9.83E-09	0.0358	3.78E-09
3	0.0574	2.82E-05	0.0574	2.83E-05	0.0358	1.18E-08	0.0358	5.32E-09
44 Westmoreland St.								
1	0.0283	1.48E-05	0.0284	1.46E-05	0.0190	3.82E-06	0.0121	1.58E-06
2	0.0283	1.48E-05	0.0286	1.44E-05	0.0182	7.85E-07	0.0147	9.02E-07
3	0.0282	1.48E-05	0.0289	1.41E-05	0.0406	4.90E-04	0.0130	1.32E-06

6. CONCLUSION

This paper presented various aspects of two terrestrial laser scanners produced 10 years apart when used in urban areas, where space is restricted and pedestrian and vehicular traffic may interfere in the scanning process. Three masonry buildings with different architectural styles in Dublin city centre were selected in this demonstration. The investigation showed that newer unit was significantly faster in scanning rate and easier to use because of longer battery life and built-in view screens for control, thus avoiding the need for a generator and external laptop. However, there was no improvement in the accuracy of the scan angle despite a decade difference in the age of the units. Also both scanners were able acquire sufficient data points for reconstructing building models for computation for civil engineering application. A cost comparison showed that depending upon project size and usage needs that there are cases that the older unit can provide better value for money.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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