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LASER SCANNING FOR BIM

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SUMMARY: *Obtaining useful data from reality capture devices, such as Terrestrial Laser Scanners (TLS), for the extraction of semantic information and its subsequent use to support Building Information Modelling (BIM) use cases (e.g. Scan-to-BIM or Scan-vs-BIM -based use cases) is a complex task that requires planning and execution expertise. Point clouds of quality need to be produced following a conscientious planning and execution of scanning. And once the point clouds are acquired, methodical pre-processing operations are vital to ensure the point clouds finally are of high quality. This paper summarises some guidelines to surveyors for a successful data acquisition campaign, especially when these data will be employed for automatic processes involving point clouds and BIM, such as Scan-to-BIM or Scan-vs-BIM. The guidelines are also useful to the recipients of the point clouds involved in those processes, such as BIM modellers or Quality Control (QC) managers.*

KEYWORDS: *laser scanning, BIM, best practice.*

1. INTRODUCTION: FROM DATA TO INFORMATION

The rapid evolution of 3D reality capture technologies, such as Laser Scanning (LS), supports digitalisation in various industries. The output of LS devices is under the form of point clouds, which are unstructured sets of often coloured 3D points. Although raw point clouds may be useful as is (even as pieces of art (Chapman et al., 2017)), these datasets are usually processed to extract meaningful information. In the particular case of the Architecture, Engineering and Construction (AEC) sector, point clouds obtained by LS devices have accelerated the generation of 2D and 3D drawings, are used to measure volumes (Porras-Amores et al., 2019), detect objects (Dimitrov and Golparvar-Fard, 2015, Maalek et al., 2019, Perez-Perez et al., 2021a, Perez-Perez et al., 2021b), and ultimately produce semantically-rich 3D models (Valero et al., 2016) or Building Information Models (BIM) (Bassier and Vergauwen, 2020, Valero et al., 2021). The process to generate BIMs from point clouds is commonly called *Scan-to-BIM*. In general, point clouds provide accurate representations of the scanned environments and are employed by modellers as a reference from which they manually produce semantically-rich BIM models.

Another use case of point clouds in the context of Building Information Modelling is to compare them against BIMs to, for example, monitor construction progress (Braun et al., 2020) or construction (or fabrication) quality (Bosché et al., 2009, Bosché and Guenet, 2014, Kim et al., 2016). These comparison use cases fall under the increasingly used umbrella term *Scan-vs-BIM* (Bosché et al., 2014). Scan-to-BIM and Scan-vs-BIM process use cases collectively illustrate the importance of 3D point clouds for the generation and management of building-related information.

Current practice in Scan-to-BIM and Scan-vs-BIM processes is predominantly manual. While point clouds used as reference for generating BIMs improve modelling quality and efficiency in comparison to the use of single, unstructured measurements from distometers, the modelling part remains a mainly manual process that is tedious, repetitive (and therefore error-prone), and time consuming, with outcomes significantly impacted by the expertise of modellers. Therefore, many research teams have been working to automate steps involved in the modelling phase (Son et al., 2015, Dimitrov and Golparvar-Fard, 2015, Valero et al., 2016, Maalek et al., 2019, Perez-Perez et al., 2021a, Perez-Perez, 2021b, Bassier and Vergauwen, 2020). However, despite great strides in this area, the quality of outputs remains highly dependent on the quality of the input point cloud. Ensuring that the input point clouds are of adequate quality is critical.

The acquisition of point clouds with the right quality for effective processing (both manual and automated) is challenging and requires experience and, importantly, knowledge of the study to be performed subsequently. This process of effectively acquiring point clouds to be used for BIM-related purposes is what we call here *Scan4BIM*.

In the following, we present ten simple rules for producing high quality point clouds to be used in BIM-related processes such as Scan-to-BIM, Scan-vs-BIM – although the majority of these rules remain broadly relevant when considering other point cloud processing tasks. These rules are grouped into four sections: the device (section 2), the environment (section 3), data acquisition (section 4), and pre-processing (section 5).

2. THE DEVICE

2.1 Rule 1: Type of Scanner

Laser scanners are utilised for reality capture purposes and deliver data on the shape (i.e., 3D geometry) and appearance (i.e., colour and texture) of the environment surrounding them. According to the state of the devices during the scanning works, these can be:

- **Stationary scanners**: these devices are placed at strategic locations in the environment, from which the scans are taken to maximise the documented volume. These can subsequently be classified in two sub-groups (Angelopoulou et al., 1999): `phase-based' (mid-range, up to around 100m, e.g., https://www.faro.com/en/Products/Hardware/Focus-Laser-Scanners), often used for interiors and facades of not very tall buildings; and `Time of Flight' (long range, beyond 100m, e.g., http://www.riegl.com/nc/products/terrestrial-scanning/produktdetail/product/scanner/48/), used for larger environments, such as quarries or infrastructure.

- **Mobile scanners**: these devices are mounted on mobile platforms (a person or a vehicle) that are moving during the scanning process. The methodology behind these devices typically requires further advanced sensing and data processing algorithms (i.e., Simultaneous Localisation and Mapping (SLAM) (Cadena et al., 2016), to deliver the 3D data, and they can be used indoors (e.g., https://geoslam.com/solutions/zeb-revo-rt/) or outdoors (e.g., https://leica-geosystems.com/products/mobile-sensor-platforms/capture-platforms/leica-pegasus-backpack).

The specifications of stationary mid-range scanners have made them the tool of choice for most *Scan4BIM* use cases. However, it is the surveyor who will decide the tool to be employed according to the context, their expertise, and previous experiences.

2.2 Rule 2: Precision

Accuracy, as illustrated in FIG. 1 and described in ISO 5725-1:1994 (ISO, 1994), is a combination of two parameters: trueness and precision. Generally, the trueness of point clouds delivered by Terrestrial Laser Scanning (TLS) devices (or by means of photogrammetric techniques in adequate conditions) is acceptable, meaning that 3D coordinates of points are very close, on average, to the right values. Campanelli et al. (2015) have evaluated and compared the accuracy of both low- and high-cost laser scanners. Trueness remains acceptable as long as devices are frequently calibrated, as specified by the device manufacturers. Precision, in contrast, impacts each measurement, and importantly varies from one device to another. So, precision is a crucial parameter to bear in mind when choosing a scanner for *Scan4BIM* use cases.

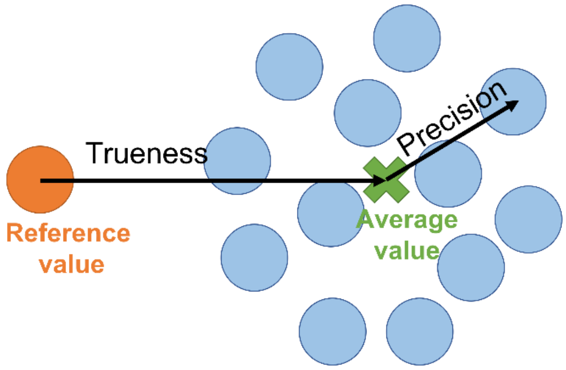

FIG. 1: Graphical definition of accuracy

Error! Reference source not found. illustrates the differences in precision of two point clouds, one delivered by a Faro Focus S 150 mounted on a tripod (stationary) and placed at key locations, and the other one produced by a Geoslam ZEB Revo RT (mobile). Although a BIM modeller could approximately visually detect walls or other structural components in both clouds, modelling, for example, the wall on the right in the GeoSlam cloud is still challenging to achieve within typical tolerances, and even more so for an automatic algorithm.

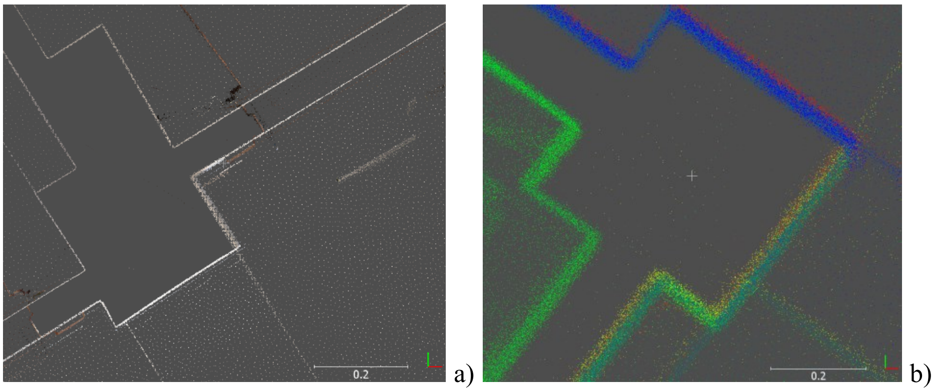

FIG. 2: Top view of the interior walls of a building scanned with two different devices: a) Faro Focus S150. b) Geoslam ZEB Revo RT

3. THE ENVIRONMENT

3.1 Rule 3: Completeness and Occlusions

"Gestalt is a theory of perception that describes the manner in which humans perceive the components of an image and organize them into broader structures or interpretations" (Tait, 2018). Amongst its principles, proximity, similarity, closure, and continuity are particularly relevant in point cloud analysis. Points that are next to each other and have similar orientation (i.e., normal vector) are most likely part of the same entity (e.g. plane).

Object detection or recognition build on such basic observation and as a result completeness of point clouds is paramount to successful scan-to-BIM or scan-vs-BIM -based processes. Holes in the data (see FIG. 2b) can at times be successfully handled by humans thanks to their extensive cognitive capability. In contrast, missing data can more significantly reduce the effectiveness of algorithms for detecting features or objects (e.g. walls), as shown in (Adan and Huber, 2010).

Delivering (sufficiently) complete point clouds requires detailed planning. Planning for Scanning (P4S) (Aryan et al., 2021) is the process of identifying the right set of locations from which the target objects can be scanned as required, avoiding occlusions produced by other objects present in the scene, as well as self-occlusions. For example, when scanning the interior of a building, attention should be paid to the impact of furniture on the scanning of walls and openings (see Subsection 3.2 – Rule 4: Openings) when the goal is to create a 3D BIM of that interior environment.

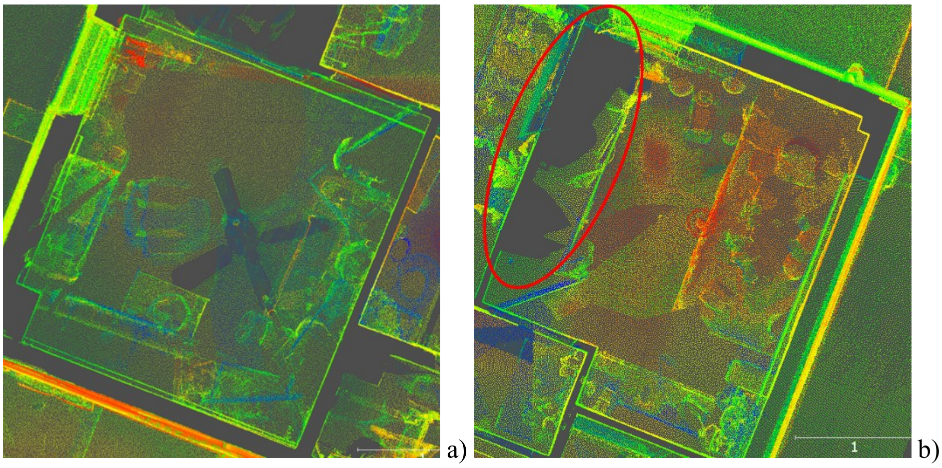

FIG. 2: Top view of two scanned spaces, where the point clouds are complete (a) and incomplete (b).

3.2 Rule 4: Openings

Openings usually provide access to spaces. Although these are, in general, cleared to allow movement across the building (doors) or let the light in (windows), at times doors and windows can be closed or occluded by other entities. For example, in FIG. 3, while doors are open, curtains are drawn over windows, preventing their easy detection in a point cloud and subsequent modelling. A human may be able to guess that there is likely a window behind a curtain, but they may still not have enough information to model that opening correctly. As can be appreciated in many research works (Díaz-Vilariño et al., 2015, Assi et al., 2019), researchers working on automatic detection of openings usually ensure during data acquisition that doors or windows are not or minimally occluded, although some researchers have developed opening detection algorithms that aim to be more robust to occlusion using various strategies (Quintana et al., 2018, Nikoohemat, 2018).

Besides, the presence of closed curtains in a point cloud can result in additional planes that can be confused as wall segments by algorithms. Similarly, blinds, air conditioning units and other objects can affect the size of detected openings (Quintana et al., 2018).

Having doors open while scanning not only facilitates the detection of openings, but it also increases the overlap between consecutive scans (see Subsection 4.3 – Rule 8: Overlapping) and, therefore, eases the registration process (see Subsection 5.2 – Rule 10: Registration).

FIG. 3: Example of windows covered with curtains

3.3 Rule 5: Mirrors

All the elements reflected in a mirror are considered to be *Through the Looking-Glass* and, as illustrated in FIG. 4, a mirrored scene is added to the real one. These artefacts may also occur with glass, metals and other polished, reflective surfaces. Some research has been done on the identification of rectangular mirrors to remove erroneous points (Käshammer and Nuchter, 2015). If such highly reflective objects cannot be removed from the scene or covered (e.g. with a cloth), the affected point clouds should be removed (Gao et al., 2022) (see Subsection 5.1 – Rule 9: Cleaning) before subsequent processing, starting with registration.

A particular exception to this is when mirrors are actively used to scan the back surfaces of objects alongside their visible surfaces, as done by (Li and Kim, 2021) to obtain nearly complete point clouds of pre-fabricated concrete components from a single scan.

Note that, in the case of transparent surface, such as windows, the diffraction of laser beams when traveling through them similarly lead to incorrect measurements. Those points should similarly be removed from the cloud.

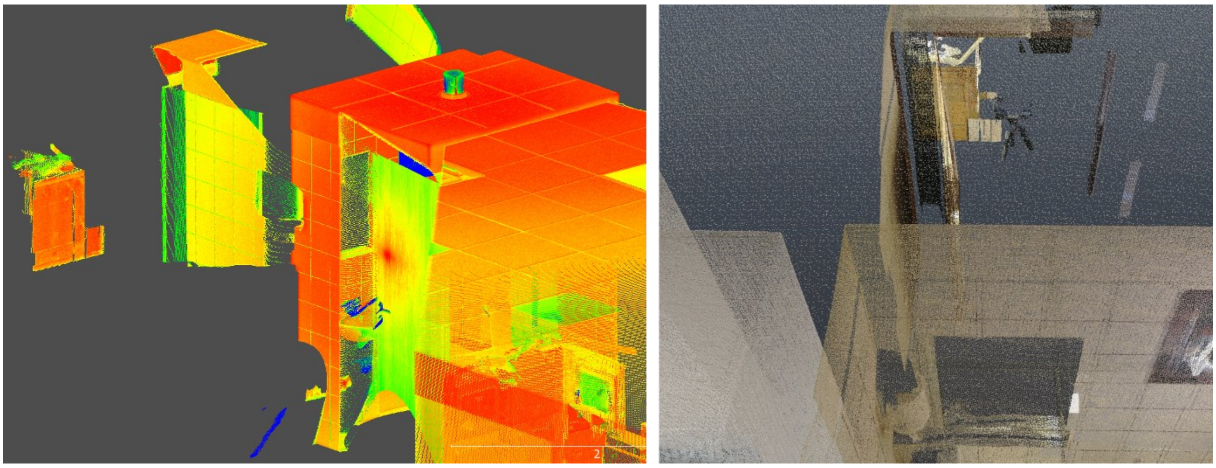

FIG. 4: Effects of mirrors in point clouds

4. DATA ACQUISITION

4.1 Rule 6: Resolution

One of the parameters to be selected before starting a scan is the resolution. Resolution is defined by two angles that are the horizontal and vertical angular intervals between successive scanned points. Resolution is also commonly expressed as the distance between consecutive points in the cloud at a given distance from the scanner, such as "*x millimetres @ y metres*" (Faro, 2020). Note that the same value is commonly used for the horizontal and vertical scanning resolutions.

Higher resolution angles result in sparser point clouds. This can enable accurate scanning of smaller object, but it can also negatively impact data processing performance. To ensure adequate resolution of a given target object (i.e. enough but not too high), the surveyor needs to know or estimate the scanning distance to select the correct resolution settings. But, it must also be highlighted that the incidence angle of the laser beam on the scanned surface also affects the resolution of the obtained point cloud. The lower incidence angle (i.e. the scanning direction is more perpendicular to the scanned surface), the higher the resolution. Surveyors may also have to consider this, for example when scanning structures that are high above ground, such as upper parts of high-rise buildings.

4.2 Rule 7: Colour

The surveyor needs to know if colour will be required for further processes. This is because colour acquisition can slow overall data acquisition, depending on the scanning technology used.

Colour acquisition is done from the scanning device with reasonable, but not necessarily, high-quality cameras. If high-quality imagery is required, then scanning may need to be supplemented with additional image acquisition and the colour information transferred to the point cloud using texture mapping, e.g., through alignment with photogrammetric reconstructions (Alshawabkeh et al., 2021, Valero et al., 2019). But this process is both time-consuming and challenging.

4.3 Rule 8: Overlapping

As mentioned in Subsection 3.1 – Rule 3: Completeness and Occlusions, a well-designed plan for scanning an environment is crucial to obtain a complete point cloud of that environment. But, the selected scanning locations must ensure not only that the target objects are scanned with the right levels of quality and completeness, but also that the resulting scans can be effectively registered together in a unified point cloud (see Subsection 5.2 – Rule 10: Registration). This requires adequate overlap between consecutive clouds, as considered by many research works (Ahn and Wohn, 2016, Chen et al., 2018, Huang et al., 2021, Li et al., 2020, Aryan et al., 2021).

As illustrated in FIG. 5, when scanning indoors, placing the scanner in doorways (see green point cloud in FIG. 5), enables capturing data from the two connected spaces and facilitates the co-registration of other point clouds acquired in those two adjacent spaces and beyond.

Outdoors, when scanning a building envelope, it is important to connect the individual clouds representing the facades. When using stationary scanning devices, placing the device at the corners of the building will deliver a cloud containing data from two (or more) connected facades, which will enable co-registering other point clouds acquired of those facades.

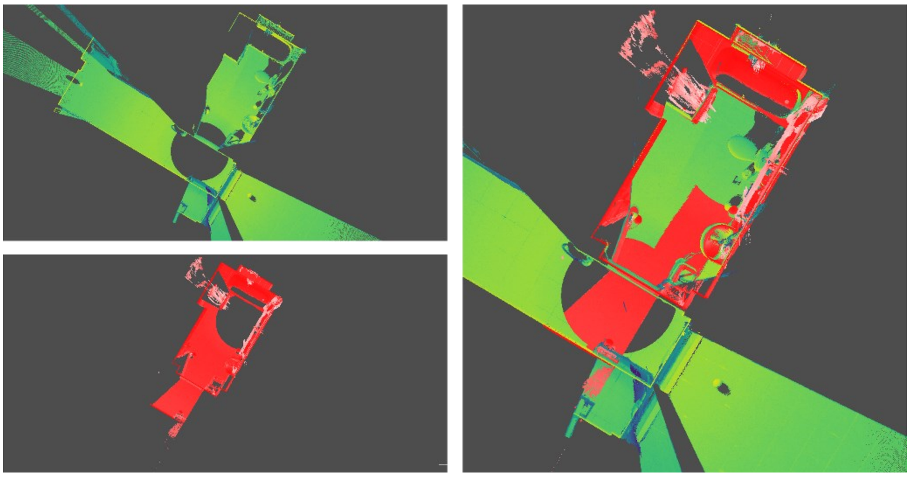

FIG. 5: Overlapping point clouds. Advantages of placing a device in a doorway.

5. PRE-PROCESSING

5.1 Rule 9: Cleaning

As mentioned in Subsection 3.3 – Rule 5: Mirrors, reflecting and transparent surfaces will introduce spurious points to a cloud. FIG. 6 shows the case of a scanned bathroom where objects were scanned through reflection on glass and plastic surfaces, creating `ghost' 3D points (Gao et al., 2022). Besides, the scene may contain moving objects, e.g. people, at the time of scanning. These points should be removed as much as possible before co-registering the individual scans to avoid confusion, especially when running automatic procedures (Cheng et al., 2021, Hang et al., 2017).

Additionally, points corresponding to objects that are not the subject of the study should ideally be removed to improve processing performance (in terms of both time and quality). Such cleaning effort may involve human intervention, which may itself be time-consuming and prone to error. The amount of cleaning should thus be assessed using a cost/benefit analysis.

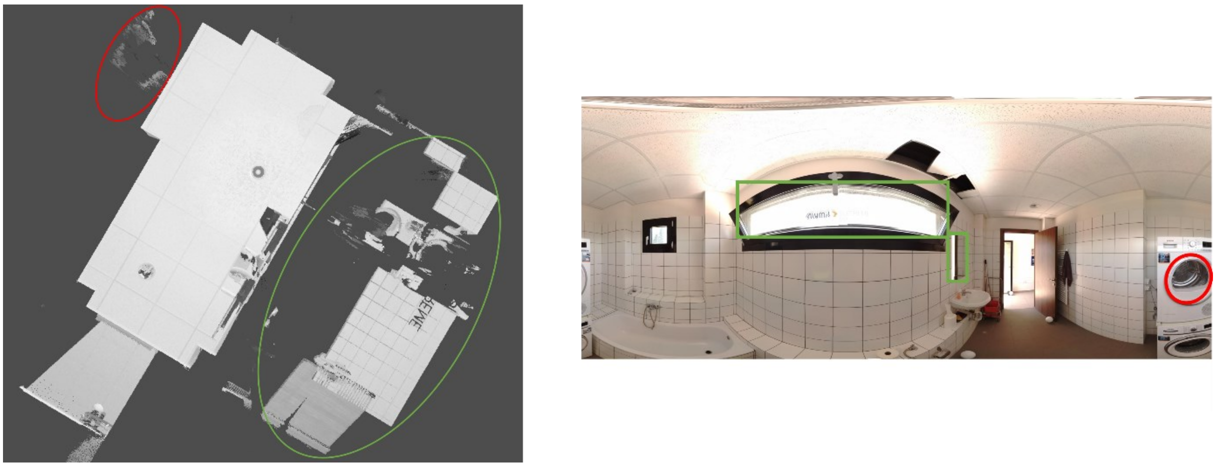

FIG. 6: Incorrect points produced by plastic and glass surfaces. The washing machine door introduces incorrect points (highlighted in red), and a window and a mirror on the opposite wall produce a similar effect (highlighted in green).

5.2 Rule 10: Registration

A careful registration of consecutive point clouds is crucial to produce a complete cloud that accurately represents the scanned environment. Meticulousness is important in this process, especially when the point cloud is to be used in automatic processes. Indeed, registration errors can result in misalignment that can impact processing far more than single point precision and accuracy – e.g. overlapping scans of a wall that are correctly co-registered will result in two close but distinct planes. Although most software packages devoted to handling point clouds (e.g., Faro Scene https://www.faro.com/en/Resource-Library/Tech-Sheet/techsheet-faro-scene, Cyclone https://leica-geosystems.com/products/laser-scanners/software/leica-cyclone, Autodesk ReCap https://www.autodesk.co.uk/products/recap) can automatically robustly register point clouds through natural and artificial features as well as internal sensor data (e.g., IMU) (Ridene et al., 2013), it is important to verify the results, including by checking that overlapping scans of elements of interest (e.g., walls) are properly aligned (Mora et al., 2021).

If the automatic registration of consecutive clouds is not satisfactory (see walls in **Error! Reference source not found.**a), a manual registration should be carried out, by selecting at least three (but preferably four or more) pairs of matching points as in (Aiger et al., 2008, Li et al., 2021). **Error! Reference source not found.**b shows an example of the manual correction of mis-registration. Note that geometric features other than points can also be used, e.g. planes (Förstner and Khoshelham, 2017, Kim et al., 2018, Bueno et al., 2018).

Note that geometric features used for registration (e.g. points) should be located widely throughout the space and should not lie on the same plane. This makes the registration process more robust.

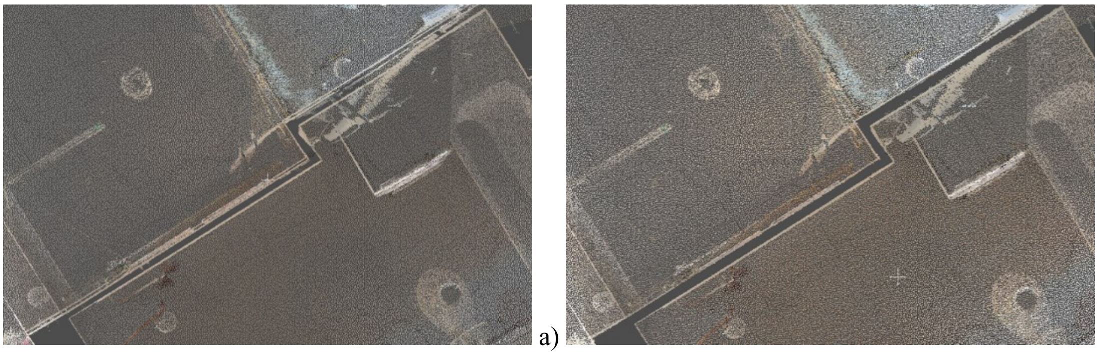
a) b)

FIG. 8: Consecutive point clouds registered (a) automatically and (b) manually.

6. CONCLUSIONS

This paper presented ten simple rules to surveyors to deliver high quality point clouds to be used in BIM-related processes (e.g., Scan-to-BIM, Scan-vs-BIM). The guidelines are also useful to the recipients of the point clouds involved in those processes, such as BIM modellers or Quality Control (QC) managers. These rules are especially useful when automatic processes are applied to the clouds, because the performance of algorithms can be significantly improved by ensuring that the acquired input clouds are complete and accurate.

Although the recommendations summarised in this manuscript can assist in the generation of point clouds for various *Scan4BIM* use cases, it should be emphasised that a good communication of the requirements between the end user (e.g. BIM modeller or QC manager) and the surveyor is very important. Laser scanning is a tailored process, which presents a unique and challenging task with every new environment (e.g. building, infrastructure) and where experience plays an important role alongside the application of best practice.

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8. REFERENCES

Adan, A., Huber, D. (2010). Reconstruction of Wall Surfaces Under Occlusion and Clutter in 3D Indoor Environments. *Technical Report CMU-RI-TR-10-12.* Robotics Institute: Pittsburgh, PA, USA.

Ahn, J. & Wohn, K.Y. (2016). Interactive scan planning for heritage recording. *Multimedia Tools and Applications*, 75(7), 3655.

Aiger, D., Mitra, N. & Cohen-Or, D. (2008). 4-Points Congruent Sets for Robust Pairwise Surface Registration. *35th International Conference on Computer Graphics and Interactive Techniques (SIGGRAPH'08)*, 27(3), 1-10.

Alshawabkeh, Y., Baik, A., & Miky, Y. (2021). Integration of laser scanner and photogrammetry for heritage BIM enhancement. *ISPRS International Journal of Geo-Information*, 10(5), 316.

Angelopoulou, E., Wright, J. R. & Jr. (1999). Laser scanner technology. University of Pennsylvania Department of Computer and Information Science Technical Report No. MS-CIS-99-16.

Aryan, A., Bosché, F. & Tang, P. (2021). Planning for terrestrial laser scanning in construction: A review, *Automation in Construction* 125, 103551.

Assi, R., Landes, T., Macher, H., Grussenmeyer, P. (2019). Energy Function Algorithm for Detection of Openings in Indoor Point Clouds. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLII-2/W13, 747–752.

Bassier, M. & Vergauwen, M. (2020). Unsupervised reconstruction of building information modeling wall objects from point cloud data. *Automation in Construction*, 120, 103338.

Bosché, F., Haas, C. T. & Akinci, B. (2009). Automated recognition of 3D CAD objects in site laser scans for project 3D status visualization and performance control, *Journal of Computing in Civil Engineering* 23(6), 311–318.

Bosché, F. & Guenet, E. (2014). Automating surface flatness control using terrestrial laser scanning and building information models, *Automation in Construction* 44, 212–226.

Bosché, F., Guillemet, A., Turkan, Y., Haas, C. T. & Haas, R. (2014). Tracking the built status of MEP works: Assessing the value of a scan-vs-BIM system', *Journal of Computing in Civil Engineering* 28(4), 05014004.

Braun, A., Tuttas, S., Borrmann, A. & Stilla, U. (2020). Improving progress monitoring by fusing point clouds, semantic data and computer vision, *Automation in Construction* 116, 103210.

Bueno, M., Frédéric Bosché, González-Jorge, H., Martínez-Sánchez, J., & Arias, P. (2018). 4-plane congruent sets for automatic registration of as-is 3d point clouds with 3D BIM models. *Automation in Construction*, 89:120-134.

Cadena, C., Carlone, L., Carrillo, H., Latif, Y., Scaramuzza, D., Neira, J., Reid, I. & Leonard, J. J. (2016). Past, present, and future of simultaneous localization and mapping: Toward the robust-perception age, *IEEE Transactions on Robotics* 32(6), 1309–1332.

Campanelli, V., Howell, S. M. & Hull, M. L. (2016). Accuracy evaluation of a lower-cost and four higher-cost laser scanners, Journal of Biomechanics 49 (1), 127-131.

Chapman, P., Mitchell, D., McGregor, C., Wilson, L. & Rawlinson, A. (2017). Art of the Point Cloud, Wild Harbour Books.

Chen, M., Koc, E., Shi, Z. & Soibelman, L. (2018). Proactive 2D model-based scan planning for existing buildings. *Automation in Construction*, 93, 165-177.

Cheng, D., Zhao, D., Zhang, J., Wei, C. & Tian, D. (2021). PCA-Based Denoising Algorithm for Outdoor Lidar Point Cloud Data. *Sensors* 21, 3703.

Díaz-Vilariño, L., Khoshelham, K., Martínez-Sánchez, J., & Arias, P. (2015). 3D modeling of building indoor spaces and closed doors from imagery and point clouds. *Sensors* 15(2), 3491–3512.

Dimitrov, A. & Golparvar-Fard, M. (2015). Segmentation of building point cloud models including detailed architectural/structural features and MEP systems, *Automation in Construction* 51, 32–45.

Faro (2020). *Focus Laser Scanner*, Faro Focus s150 Scanner Technical sheet, Faro.

Förstner, W. & Khoshelham, K. (2017). Efficient and accurate registration of point clouds with plane to plane correspondences. *2017 IEEE International Conference on Computer Vision Workshops (ICCVW)*, 2165-2173.

Gao, R., Li, M., Yang, S.-J. & Cho, K. (2022) Reflective Noise Filtering of Large-Scale Point Cloud Using Transformer. *Remote Sensing,* 14(3), 577.

Huang, S., Gojcic, Z., Usvyatsov, M., Wieser, A. & Schindler, K. (2021). PREDATOR: Registration of 3D Point Clouds with Low Overlap, *IEEE Conference on Computer Vision and Pattern Recognition, CVPR,* 4267-4276.

ISO (1994). Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definitions, Standard, International Organization for Standardization (ISO), Geneva, CH.

Käshammer, P.-F & Nuchter, A. (2015). Mirror identification and correction of 3D point clouds. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-5/W4. 109-114.

Kim, M.-K., Wang, Q., Park, J.W., Cheng, J.C.P., Sohn, H. & Chang, C.-C. (2016). Automated dimensional quality assurance of full-scale precast concrete elements using laser scanning and BIM. *Automation in Construction*, 72(2), 102-114.

Kim, P., Chen, J. & Cho, Y. K. (2018). Automated point cloud registration using visual and planar features for construction environments. *Journal of Computing in Civil Engineering*, 32(2).

Li, F. & Kim, M.-K. (2021). Mirror-aided registration-free geometric quality inspection of planar-type prefabricated elements using terrestrial laser scanning. *Automation in Construction*, 121, 103442.

Li, J., Qian, F. & Chen, X. (2020). Point Cloud Registration Algorithm Based on Overlapping Region Extraction, *Journal of Physics: Conference Series*, 1634, 012012.

Li, S., Lu, R., Liu, J. & Guo, L. (2021). Super Edge 4-Points Congruent Sets-Based Point Cloud Global Registration. *Remote Sensing,* 13, 3210.

Maalek, R., Lichti, D.D., Walker, R., Bhavnani, A. & Ruwanpura, J.Y. (2019). Extraction of pipes and flanges from point clouds for automated verification of pre-fabricated modules in oil and gas refinery projects. *Automation in Construction*, 103, 150-167.

Mora, R., Martín-Jiménez, J.A., Lagüela, S. & González-Aguilera, D. (2021). Automatic Point-Cloud Registration for Quality Control in Building Works. *Applied Sciences,* 11(4), 1465.

Nikoohemat. S., Peter, M., Oude Elberink, S., Vosselman, G. (2018). Semantic Interpretation of Mobile Laser Scanner Point Clouds in Indoor Scenes Using Trajectories, *Remote Sensing*, 10(11), 1754.

Perez-Perez, Y., Golparvar-Fard, M. & El-Rayes, K. (2021). Segmentation of point clouds via joint semantic and geometric features for 3d modeling of the built environment. *Automation in Construction*, 125, 103584.

Perez-Perez, Y., Golparvar-Fard, M. & El-Rayes, K. (2021). Scan2bim-net: Deep learning method for segmentation of point clouds for scan-to-BIM. *Journal of Construction Engineering and Management*, 147(9).

Porras-Amores, C., Mazarrón, F. R., Cañas, I. & Villoria Sáez, P. (2019). Terrestrial laser scanning digitalization in underground constructions, *Journal of Cultural Heritage,* 38, 213–220.

Quintana, B., Prieto, S.A., Adan, A., Bosché, F. (2018)., "Door Detection in 3D Coloured Point Clouds of Interior Environments", *Automation in Construction*, 85, 146-166.

Ridene, T., Goulette, F. & Chendeb, S. (2013). Feature-based quality evaluation of 3D point clouds -Study of the performance of 3D registration algorithms. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* XL-2/W2. 59-64.

Son, H., Kim, C. & Turkan, Y. (2015). Scan-to-BIM -an overview of the current state of the art and a look ahead, in *Proceedings of the International Symposium on Automation and Robotics in Construction*, Oulu, Finland, 1-8.

Tait, A. (2018). Visual hierarchy and layout (J. P. Wilson, editor), The Geographic Information Science and Technology Body of Knowledge (2nd Quarter 2018 Edition), University Consortium for Geographic Information Science (UCGIS).

Valero, E., Adán, A. & Bosché, F. (2016). Semantic 3D reconstruction of furnished interiors using laser scanning and RFID technology, *Journal of Computing in Civil Engineering* 30(4), 04015053.

Valero, E., Forster, A., Bosché, F., Hyslop, E., Wilson, L. & Turmel, A. (2019). Automated defect detection and classification in ashlar masonry walls using machine learning. *Automation in Construction*, 106, 102846.

Valero, E., Mohanty, D. D., Ceklarz, M., Tao, B., Bosche, F., Giannakis, G. I., Fenz, S., Katsigarakis, K., N. Lilis, G., Rovas, D. & Papanikolaou, A. (2021). An integrated Scan-to-BIM approach for buildings energy performance evaluation and retrofitting, *Proceedings of the 38th International Symposium on Automation and Robotics in Construction (ISARC)*, Dubai, UAE, 204–211.

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