# Towards the development of a Digital Twin: A comparative study of 3D data acquisition methods for mechanical and electrical assets

P. Linka[1], T. Kettle[1], M. Leon[2] and R. Laing[2]
[1]Return to Scene Ltd, City Wharf, Shiprow, Aberdeen, AB11 5BY, United Kingdom
[2]Scott Sutherland School of Architecture and the Built Environment Robert Gordon University, Aberdeen, UK
*email: m.leon@rgu.ac.uk

## Abstract

Point clouds and photogrammetry are becoming a quasi-standard as representation tools for capturing existing assets condition and for monitoring the progress and development of new assets. This is apparent to several industries related to construction and manufacturing, including among other infrastructure and energy sectors. These industries face immense pressures to develop the Digital Twin, with significant momentum and extensive research and development being currently undertaken on this topic, focusing on technologies, processes and projects' requirements.

Existing software and online systems and platforms are currently available that can host and integrate the 3D collected data with cloud-based database applications, allowing projects' sharing, viewing, delivery and operation of the assets; these systems are being defined as Visual Asset Management (VAM) solutions. VAM systems can also provide a platform that integrates multiple visual data sources, including Building Information Modelling data, associated asset documentation and photographic records of the assets. Commercial projects that aim to develop a digital twin, focusing primarily on small scale mechanical and electrical assets reverse engineering processes, often utilize faster approaches to 3D data acquisition, like photogrammetry, for cost control and efficiency. However, these types of projects frequently require advanced levels of accuracy that is not often achieved with conventional 3D data acquisition methods.

The research contribution and innovative aspects of this research are focused on conducting a comparative study between the application of multi-image spherical photogrammetry (MISP), a process not typically utilised in 3D data collection, 3D scanning and total station data for very high-accuracy 3D data collection of small scale assets, thus gaining in speed of data collection. The case study involves an Oil and Gas Training Facility, in Aberdeenshire UK, where both a qualitative and quantitative analysis will be undertaken for comparing the 3D collected data. Based on this comparison, an evaluation of the 3D data collection techniques and methods is compiled, followed by the analysis of the developed point clouds. According to that, indicators are proposed to support decision making in terms of accuracy, level of detail and suitability for smaller scale and highly technical projects.

The findings demonstrate that spherical photogrammetry and 3D laser scanning can be used independently or in combination, depending on the project specifics, for ensuring assets accuracy and reliability of information for operations and maintenance, with the parameters of clients' requirements, quality, time and cost having a significant impact on the level of detail that can be provided.

This project proposes a step change in how we consider 3D data acquisition for technical and small-scale projects with a broader impact on developing reverse engineering processes for achieving the Digital Twin.

**Keywords:** Digital Twin, Multi-Image Spherical Photogrammetry, 3D data collection, M&E.

# 1. Introduction

The 4th Industrial Revolution claims to deliver the much-desired continuum between digital and physical spaces while blurring the boundaries between real and virtual environments, thus bringing a paradigm shift in the ways we work, manage and operate assets (Leon et al., 2017; Laing 2019). Achieving this digital revolution for existing assets requires advanced reverse engineering methodologies, employing three-dimensional data capturing processes (Cataluci, 2018; Hanza, 2015; Altuntas, 2015; Pagani, 2011). Factors which influence the choice of 3D capturing methods including the scale of the asset, the type of use, the space complexity and end users' requirements (Altuntas 2015).

This research explored the initial stages of developing a Digital Twin, by investigating three different 3D data capture techniques, within the context of a complex mechanical and electrical (M&E) facility. The data capture methodologies compared within this case study include photogrammetry, HD laser scanning and total station data, where a comparative analysis is implemented.

Previous research indicates that terrestrial laser scanners are not necessarily the most appropriate method when the assets include complex details, due to surfaces being blocked by other items (Altuntas, 2015), where photogrammetry was suggested as the best method to record any obscured areas. As a result, both 3D scanned, and photogrammetric point clouds are merged and integrated into a common coordinate system. This research expands on that in the literature and examines the accuracy and applicability of following data capture methods: 3D laser scanning, spherical photogrammetry and still images for the M&E assets. The significance of this research pinpoints the importance of an accurate 3D data collection for developing a Digital Twin of an asset, especially when it comes to applying reverse engineering processes for M&E facilities.

# 2. Literature Review

Construction and Infrastructure industries are nowadays focusing more and more on the application of Building Information Modelling (BIM) technologies and processes with numerous publications presenting the impact and benefits on projects life cycle (Arayici, 2008; Volk, Stengel, & Schultmann, 2014; Edirisinghe, London, Kalutara, & Aranda-Mena, 2017). Arguably, this research showcases that BIM is still widely underutilised (Hosseini, Roelvink, Papadonikolaki, Edwards, & Pärn, 2018; Orr, Shen, K Juneja, Snodgrass, & Kim, 2014) as it requires a substantial paradigm shift in the ways we approach projects, starting with the end in mind (Re Cecconi, Maltese, & Dejaco, 2017). Nevertheless, other industries, including Manufacturing and Energy sectors, are very well aware of this concept, which is highlighted with the application of reverse engineering processes (Herráez, Martínez, Coll, Martín, & Rodríguez, 2016). The epicentre of reverse engineering lies in recreating a product or asset based on real-life data, where models can be created by utilising 3D data capturing methods followed by 3D reconstruction (Bénière, Subsol, Gesquière, Le Breton, & Puech, 2013). With the current speed of technological developments and Internet of Things, it is only a matter of time to have smart digital “copies” of any scale of assets, including entire cities (Schamp, Hoedt, Claeys, Aghezzaf, & Cottyn, 2018; Rosendahl, Schmidt, Luder, & Ryashentseva, 2015).

## 2.1 Gap in knowledge

The use of laser scanning and photogrammetry as a method for reality capture has been well documented in the literature (Altuntas, 2015; Fadli, Barki, Boguslawski, & Mahdjoubi, 2015; Faltýnová, Matoušková, Šedina, & Pavelka, 2016; Pejic, Krasic, Krstic, Dragovic, & Akbiyik, 2017; Ostrowski, Pilarska, Charyton, & Bakuła, 2018; Daneshmand et al., 2018). Despite an extensive previous research on 3D data capturing techniques, a significant research gap still exists in establishing the accuracy of the methods (Randall & Philp, 2013; Dai, Feng, & Hough, 2014), especially in relation to the multi-image spherical photogrammetry (Fangi 2007; Pagani 2011), an approach not typically utilised for 3D data collection, and their suitability for specific types of projects and environments (Daneshmand et al., 2018).

## 2.2 Total station, 3D laser scanning and photogrammetry

Prior to comparing the 3D data acquisition methods, it was necessary to define two major terms and factors influencing the data capture process of an asset, that is resolution and accuracy. The definitions below are applicable during this research:

- Resolution is a measure intrinsic to the capture device, as it measures the minimal distance between two distinct data samples; these samples consist of points in the case of laser scanning and pixels in the case of photogrammetry (Fadli et al., 2015).
- Accuracy is the difference between the measured sample coordinates and the real physical coordinates of that sample in the captured scene (Fadli et al., 2015).

These factors cannot be separated, as the data resolution and accuracy of a 3D captured sample depends on the range or the distance of the corresponding physical sample from the capture device.

Regarding the various technologies currently utilized for data capture and measurement, these typically include 3D laser scanning, photogrammetry and the use of total station. Total station for example, is recording individual points by measuring the inclined (slope) distance to the object, as well as two angles (horizontal and vertical), which ultimately makes it possible to calculate individual point coordinates. Nevertheless, the quality and accuracy of measurements of modern electronic surveying instruments such as total station may be affected by capacity of the instrument battery, surface material, colour and variations in light conditions (Beshr & Abo Elnaga, 2011).

Photogrammetry works with the use of digital still images stitched together (Daneshmand et al., 2018), and spherical photogrammetry with the use of spherical photographs, overlaid and connected from multiple images or lenses images (Fangi 2007). Even though extensive research has investigated the comparison of 3D scanning with traditional photogrammetry, showcasing a good level of accuracy with both methods (Altuntas, 2015; Siebke et al., 2018), little has been done to examine the application of spherical photogrammetry. The critical difference between traditional photogrammetry and spherical one is focused on the time required to collect the data and the number of positions for thorough asset capture. Although both methods use cameras for data collection and the collected images are aligned by use of structure from motion or multi-view stereo algorithms, the processing and information gathering time differs significantly, in favor of spherical photogrammetry (Pagani 2011; Sapirstein 2016).

In terms of data application, the use of photographic surveys and laser scanning can provide the geometry for creation of models such as: building information modelling, digital elevation modelling, digital surface modelling, digital terrain modelling and, most importantly, for the creation of digital twins (Moon et al., 2019; Woodhead, Stephenson, & Morrey, 2018). Importantly, Terrestrial Laser Scanning (TLS) is often used in addition to photogrammetry, offering high accuracy geometric data achieved in fast, accurate and flexible manner (Laing 2019; Daneshmand et al., 2018).

## 2.3 Accuracy issues

Even though the technologies described above include different degrees of accuracy and are typically well-trusted within the construction and infrastructure industries, issues of misalignment and data accuracy are an often encountered, depending on several technical aspects, for example, type of equipment, environmental conditions, quality of lenses, etc. Such errors can cause major issues, especially in assets where high levels of accuracy are required (i.e. M&E equipment).

Moon et al. (2019) conducted an accuracy test for Terrestrial Laser Scanner application with 3D point cloud data collection and photogrammetry application, where the 3D point cloud data were obtained from 2D images. Targets were used to increase the accuracy of the image processing and coherence with the laser scan data. Overlaying data captured by both methods was followed by point matching registration to increase the data coherence. Findings of this study recommended accuracy improvement by combining the scan data with photogrammetry-based point cloud data by creation of the hybrid point cloud where the data distribution below 10 cm was found to have improved from 82.723% to 86.604% (Moon et al., 2019). This research also indicated that where the data distances were large, error arose due to blind spot that occurred during the laser scanner data acquisition.

Another approach to the creation of 3D models by applying surface reconstruction has been presented by Barazzetti et al., (2018). Their experiment involved spherical photogrammetry and use of low cost 360° cameras for asset capture. Automatic generation of 3D model via image-based modelling algorithms was performed using Agisoft PhotoScan (Agisoft Photoscan Pro, 2019) and Pix4Dmapper software (Pix4Dmapper, 2019). Using the ground sampling distance, 6 targets were measured with Total Station and compared to the obtained photographs. The results show 2.5mm discrepancy with the 360° images being three times worse. Despite the findings, Barazzetti et al. (2018) suggest that spherical photogrammetry is beneficial and more suitable in regard to the field of view and image overlap as well as for the use in limited space or where the prompt documentation is required. This paper is re-examining the spherical photogrammetry (Fangi, 2007), which is not yet widely utilized to date, due to limited data processing software available on the market, and proposes an innovative approach in relation to data capture constrains.

# 3. Methodology

As part of this comparative study, we conducted a series of field tests to identify the differences between three different 3D data acquisition methods used to create a digital twin of an asset; these included total station data, terrestrial laser scanning (LS) and multi-image spherical photogrammetry (MISP). The comparative methodology utilized to test the accuracy of different 3D data acquisition methods was adapted from Sapirstein (2016) who applied a similar approach to evaluate traditional photogrammetry over terrestrial laser scanning.

Regarding the study context, the surveyed site is an Oil and Gas Training Facility, in Aberdeenshire, UK, which is representative of a highly technical infrastructure and M&E environment. Following the data collection, the data were compared and evaluated with the application of a number of parameters, including survey time, image quality, point cloud quality and most importantly, data accuracy.

## 3.1 3D data collection

This research is evaluating the levels of accuracy between different 3D data collection methods and for that purpose, it was essential to set up a control coordinate system that both data collection methods could be registered to and quantified against. The "true" 3D coordinates that we would compare both the laser scanning and PG were set out using a total station. The control network that was set out using the Total Station consisted of 25 targets transformed into a site coordinate system. Five of the targets from this were then used as Ground Control Points (GCP) to register both surveys methods to the same coordinate system, leaving 20 targets that were used to compare the recorded 3D position from each survey (Figure: 1). These targets would not be used during the process of registration and alignment to simulate a simple capture done without more advanced survey techniques (Sapirstein 2016).

On the day of the survey, the targets were set out first in a geometric design to create an optimum control network for the site. Two surveyors then conducted the Total Station survey of these targets while a third one started the multi-image spherical capture. The Laser 3D Scanning capture started after the total station survey, and it was followed by the Multi-Image Spherical Photogrammetry (MISP) survey. We also created a grid for positioning the equipment for optimal results. The details of how each method was applied are presented in Table 1.

The laser scanning survey was conducted using a Faro Focus x150, which has an internal accuracy of 3mm up to a distance of 70m away (Faro Focus x150 Tech Sheet). Twenty-two positions were scanned over the site, each with a panoramic spherical image (Figure: 1). These were then registered in Faro Scene software (Faro, 2019) using the Top View-Based and Cloud to Cloud automatic techniques.

The software registration report recorded a mean point error of 2.1mm and a maximum point error of 4.1mm. After the registration was completed, the project was transformed into the coordinate system set out using the 5 GCP. The location of the other targets was automatically detected by the software, which was recorded for comparison. The automatic detection was used to reduce manual error. A final project point cloud was also exported to PTS file format for comparison purposes afterwards.

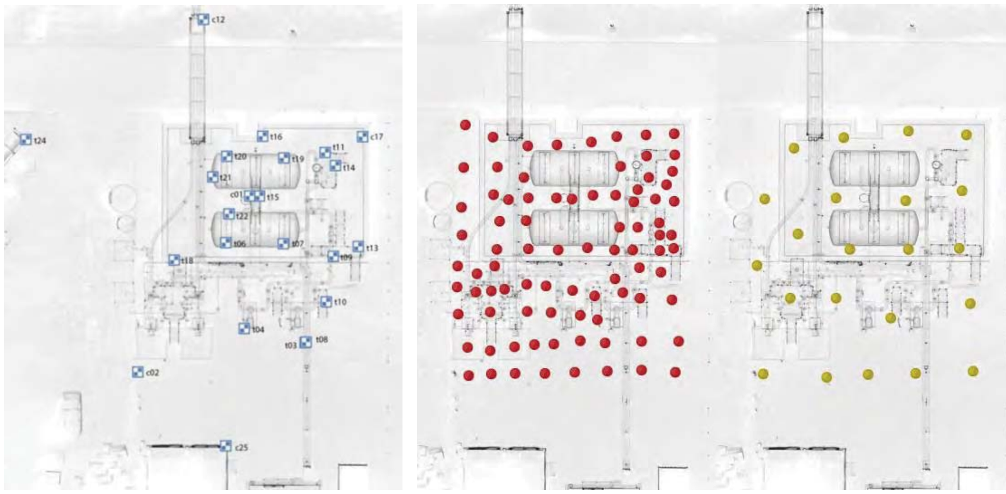

*Figure 1: Location of the targets placed at the survey site and location of positions captured by the MISP and laser scanning survey techniques*

*Table 1: Details of the survey using both techniques, Laser Scan & Multi Image Spherical Photogrammetry*

| | *laser scanning* | *MISP* |
|---|---|---|
| *Survey time (Hr)* | *05:03* | *04:04* |
| *Positions* | *22* | *87* |
| *Spherical Images* | *22* | *172* |
| *Spherical Image size (pixels)* | *10142 x 5071* | *15840 x 7920* |
| *Avg time per position* | *8-15 min* | *2-3 min* |
| *3D points in final point cloud* | *29243077* | *226870132* |

The photogrammetric survey was conducted using the Multi-Image Spherical Photogrammetry (MISP) technique, due to its key advantages compared to traditional photogrammetry, including the speed at which the site could be covered, completeness of the documentation and correction of image distortion by merging the images together, thus making it an ideal technique (Fangi, 2007). A Nikon D800 with a 16mm fisheye lens was used on a panoramic head to capture 360 high definition equirectangular images in 87 positions around the site (Figure: 1). The multiple exposure and directional images were merged to create a spherical image using PTGui panoramic photography software (PTGui, 2019) at a high pixel resolution to increase the possible accuracy (Fangi, 2007). The equirectangular images were then aligned together using Agisoft Photoscan Pro photogrammetric software. After alignment, the targets were automatically detected by the software and the 5 GCP used to transform to the same coordinate system. Once again, the position of the other targets was then recorded for comparison and a dense point cloud produced and exported to PTS file format.

# 4. Data analysis, evaluation and findings

## 4.1 Data Analysis

As stated at the beginning of the paper, we analysed the collected data with two separate aims: 1. to calculate the precision of points in space as recorded by laser scan and multi-image spherical photogrammetry (MISP) and 2. to calculate the precision and accuracy of measurements taken from the recorded data.

The error difference for each target form both techniques in comparison to the total station was calculated using, and subsequently, RMS (Root, Mean, Squared) error of 0.003m for the laser scan and 0.016m for the photogrammetry was recorded.

To calculate the accuracy of measurements for each technique, the distance between targets was calculated for total station, laser scanning and MISP using the same method as aim 1. The distances calculated from the laser scanning and MISP were then compared to the results from TS using it as a control to establish the error in measurement recorded in both techniques (Table 2).

*Table 2: Observed Error in measurements (m) for Laser Scan and Multi Image Spherical Photogrammetry measurements*

| | *laser scanning* | *MISP* |
|---|---|---|
| *MIN Error* | *0.000* | *0.000* |
| *MAX Error* | *0.005* | *0.023* |
| *Standard Deviation* | *0.001* | *0.005* |
| *RMS* | *0.002* | *0.009* |
| *95.5% confidence level (±m)* | *0.002* | *0.008* |
| *Precision 1:k* | *n/a* | *1:3526* |

Following the calculation of error for each measurement, the standard deviation, RMS and 95.5% confidence level (that measurement taken will be within the calculated error), was determined. Result of ± 0.002m for the laser scanning and ± 0.008m for MISP at 95.5% confidence level have been observed. Subsequently, the precision for the MISP was calculated in line with previous research (Sapirstein 2016), to estimate the possible error within the captured scene while removing scale. This is calculated as 1: k, where k is the size of the scene divided by the standard error. For example, a precision of 1:1000 would produce an estimated error of 1mm in the scene that is 1m long, however, would produce an estimated error of 10mm in the 10m long scene. The precision recorded for the MISP capture is 1:3526 so a scene that was 10m would expect to have an error of 0.0028m.

## 4.2 3D data evaluation

On inspection of the results, we identified benefits and challenges for each survey technique. MISP method allowed the capture of significantly more positions than laser scanning technique (Figure: 1), due to less time required to capture each position as presented in Table 1. Following the data processing within a visualization software, it also became apparent that the addition of more set up positions required by MISP significantly reduced the blind spots in the reality capture of the site. The MISP technique employed in the study also produced images with a greater level of detail than those recorded by laser scanning. The MISP recorded images of a 125MP compared to 52MP by the laser scanning (Figure 2).

The point clouds exported from each technique differed significantly in the number of points they had generated (Table 1) due to several factors including, the number of positions captured, the quality setting of the laser scanner and the number of features identified in the photogrammetric software. For achieving the same level of detail with the 3D points captured, the survey time would have to be significantly extended when applying 3D laser scanning. Furthermore, point clouds generated from each survey technique were reviewed in a point could visualization software (Autodesk Recap), and several differences have been identified as described below.

Laser scanning quality can appear sharper than MISP as can be seen in figure 4, due to the accuracy of laser scanning point collection and the algorithms to match the features in the spherical images. Furthermore, blind spots were present in both survey techniques; however, more of them were apparent in laser scanning than MISP. Two factors contributing to this are the number of laser scanning positions recorded and the ability for the photogrammetric software to identify features within the spherical images. A lack of line of sight created blind spots when we applied laser scanning survey, thus missing details that have to be recorded. On the other hand, blind spots are occurring with MISP when the detail that needs to be captured cannot be seen in the multiple spherical images, and the features cannot be identified by the photogrammetric process.


*Figure 2: Example of Spherical images from laser scanning (top) and Spherical Photography (bottom).*

Concerning the level of detail, more comprehensive and dense capture can be recorded by MISP where there are features that can be matched, in comparison to the laser scanning, where the level of detail depends on the quality setting of the laser scanner equipment and the number of scanning positions. Additionally, material properties of the surfaces that can be recorded by the previous methods also vary. The recorded properties of different materials in each point cloud also differ significantly due to the capabilities of the techniques used to capture the information. For example, laser scanning has difficulty in capturing matt black materials, where MISP struggles to record the surfaces that have no texture (lack of roughness of material) such as solid colours. When it comes to the infrastructure specifics, for example, the areas of concrete flooring have a higher level of texture, that can be identified as a feature in the photogrammetric software and will produce a higher number of points than recorded by laser scanning.

## 4.3 Constraints model

Overall, to ensure the best possible outcome of a survey, it is necessary to establish the aim, scope and required data quality of the capture. Following the data analysis, it is essential to select a capture method with great caution following a clear identification of priorities, requirements and purposes of the survey. Importantly, achieving a balance between factors and constraints influencing the choice of the method can be proved challenging. Figure 3 represents a proposed Iron Triangle focused on the Reality Capture, where capturing time, quantity (of points and blind spots) and accuracy (Quality of point cloud), must be taken into consideration as they highly depend on each other and can impact the overall outcome, thus representing a constrains model. Any amendments to the original scope of the capture will influence the factors mentioned in Figure 3.


*Figure 3: Iron Triangle of reality capture.*

# 5. Discussion

In order to compare 3D data collection methods and equipment efficiency and accuracy, the same data was used when tested with all the different methods as per previous research (Fadli et al., 2015), with the number of targets utilised and the data collection process impacting the quality of the results. Similarly, Shanbari et al. (2016) suggest that models and point clouds accuracy derived from photogrammetric data collection depend on the image quality; however, they cannot match the millimetre accuracy expected from laser scanners. Nevertheless, this may not be a concern as it depends on the level of accuracy and level of detail that is part of the scope for any given project. Importantly, additional research reported that photogrammetry and laser scanning techniques could be used in combination to enhance the results of the digital surveys (Boehler & Marbs, 2004; El-Omari & Moselhi, 2008; Fadli et al., 2015; Moon et al., 2019).

Moon et al. (2019) specifically, highlighted the significant accuracy improvement in the 3D point cloud data by combining output collected by terrestrial laser scanner and photogrammetry, emphasizing the complementary values of each technique with the combination of the two techniques giving the optimum results. Furthermore, this research suggested the creation of hybrid point clouds can overcome the geographic and physical limitations of laser scanning technology, an output supported by this research as well.

## 5.1 Conclusions

The study presented in this paper focused on establishing the accuracy and precision of the most popular surveying methods: laser scanning and spherical photogrammetry. The knowledge contribution is the use of a multi-image spherical photogrammetry method, instead of traditional photogrammetry, for improving capturing time on projects where time is limited. The study results prove the suitability of the MISP for reality capture, reverse engineering and digital twin creation. When it comes to the comparative analysis of 3D laser scanning and MISP, both methods offer different benefits but also have limitations, like the line of sight issues and surfaces texture. The research proposed a mixed methods approach that would include both MISP and 3D laser scanning, while the Iron Triangle of Reality capture can provide further support and understanding regarding constrains prioritising.

# Acknowledgements

The authors would like to acknowledge the support by Innovate UK and Scottish Funding Council, Grant No. KTP011078.

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