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Quality of laser scanning in paper mill environment

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Quality of laser scanning in paper mill environment

Till this date laser scanning is preeminent method for mapping large scale objects of interest with high accuracy.

Research methods of this thesis consist of literature review and applied field study. Former focuses on the influencing factors of scanning quality and latter examines the influence of parameters and working methods during data acquisition.

Recommendable workflows of laser scanning have been well documented literature and studies over the years, however all of them refer to laboratory-like conditions, which differ significantly from conditions of a paper mill. Thus, data in the field study of this thesis is being collected just as it would in an actual Client’s project. Consequently, point cloud acquiring process is being optimized by finding a balance between point cloud quality, scanning time, processing time and overall process fluency.

Based on the field study it was concluded that scanning parameters have massive impact on the quality of resulting point clouds and the overall fluency of registration process. Also, it became clear that utility of artificial scanning targets (spheres and checkerboards) is very limited.

Keywords:

Laser scanning, 3D-scan, point cloud, Quality

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Jaakko Leppänen

Laserkeilausprosessin laatu paperitehdasolosuhteissa

Laserkeilaus on menetelmänä omaa luokkaansa suurten kokonaisuuksien kartoittamisessa hyvällä tarkkuudella.

Tämän opinnäytetyön tutkimusmenetelmä koostuu kirjallisuuskatsauksesta, jossa selvitetään pistepilvien laatuun vaikuttavia tekijöitä, sekä kenttätutkimuksesta, jossa tutkitaan skannaus- ja prosessointiparametrien vaikutusta lopputuloksen laatuun.

Suositeltavat skannausmenetelmät on dokumentoitu kirjallisuudessa kattavasti, mutta edeltävät tutkimukset ovat suoritettu laboratorio-olosuhteissa, jotka poikkeavat merkittävästi paperitehtaiden olosuhteista. Näin ollen, kenttätutkimuksen skannaukset suoritetaan vastaavin rajoituksin, kuin toimeksiantajan projekteissa yleensäkin ja optimoidaan datan keruuprosessi skannausajan, prosessointiajan sekä yleisen sujuvuuden suhteen.

Kenttätutkimuksen tulosten perusteella on ilmeistä, että skannaus- ja rekisteröintiparametreilla on valtava vaikutus lopputuloksen laatuun ja dataprosessoinnin sujuvuuteen. Myös skannaustähysten käytön hyödyllisyyden havaittiin olevan rajallinen.

Asiasanat:

Laserkeilaus, 3D-skannaus, pistepilvi, laatu

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List of abbreviations and symbols

c	Speed of light (299792458 meters/second)
RH	Relative humidity (%)
n	Quantity of full waves
r	Radial distance
α	Incidence angle (angular degrees)
λ	Wavelength
Φ	Phase difference
θ	Polar angle
φ	Azimuthal angle
Cluster	A set of scans within a registration project
Delta	Total divergence
dX	Divergence from reference in x-axis direction
dY	Divergence from reference in y-axis direction
dZ	Divergence from reference in z-axis direction
BM	Commonly used abbreviation of Board Machine
Drive side	Back side of machine, location of most equipment
Front side	Operating side of paper or board machine
High	Dataset scanned with high resolution (chapter 11)

Low	Dataset scanned with low resolution (chapter 11)
Scan	Individual point cloud scanned in one location
Scanner	In this thesis used as synonym for TLS
Station	Individual point cloud scanned in one location
TLS	Terrestrial Laser Scanner or Terrestrial Laser Scanning
TOF	Time-Of-Flight

1 Introduction

The basic principle of 3D-scanning dates back to mid-20th century but only the recent decades it has gained more popularity (Vosselman & Maas 2010). Increasing computation power combined with more affordable prices have made 3D-scanning reachable for wider range of companies operating in engineering, construction and architecture (Cheng et al. 2018, 1).

3D-scanners have gone through a similar path as many other technological advances such as lower weight, faster operation, cheaper, easier usage etc. Therefore, in recent years, laser scanning technology has also become available to consumer market with very reasonable prices. Gaming console Xbox’s Kinect controller being a good example of this (Miles 2012). However, this thesis is focused on industrial scale terrestrial laser scanning which is until this day superior way of mapping large industrial objects of interest.

The benefits of laser scanning of complex objects of interest compared to conventional measurements are uncountable, even in contrast to tacheometric measurements as they lack the 3-dimensional aspect that comes naturally with laser scanning. Instead of one highly accurate point by total station, laser scanner captures millions of points with decent accuracy in the same time, making laser scanning far more versatile (Soudarissanane et al. 2009). Not to mention manual drafting of complex geometry by a ruler and a notebook, that was the dominant method not so long ago.

In this thesis takes a wider look into the different technologies which all fall under category “3D scanning” and also digs deeper into the scientific foundation of this revolutionary measuring method, gradually narrowing down to the specific subject of this thesis; terrestrial laser scanning and the data post-processing called “registration” which is necessary to make the raw scan data usable for engineering applications.

This thesis is a part of wider internal study conducted within the Client – Runtech Systems. However, analysis of mobile mapping systems and handheld scanners are entirely excluded from this thesis.

1.1 Research problems

The basic science behind laser scanning and recommendable workflows have been well documented in literature and studies over the years, however an applied study in (extreme) conditions of a paper/board mill are nonexistent.

Research problems are numerous, ranging from scanning issues on-site to off-site data processing, both of which are known to have impact on resulting point clouds.

As any other system when complexity is introduced, there are uncountable number of combinations resulting in different and unpredictable outcome. These influencing factors include selection of scanner equipment, scanner settings, execution of scanning, registration software and used parameters, just to name a few.

By far the most significant factor that cannot be influenced is the operating condition on site, which in this case, includes thermal expansion, vibrations, mist, humidity, mirroring surfaces, nonreflecting surfaces, airborne impurities etc. (chapter 6), all of which are undesirable for any optical measurement. Since these conditions cannot be changed it is necessary to find a workflow that produces acceptable results without requiring overwhelming input from the operator on-site or during data processing, despite the suboptimal scanning conditions and other restrictions.

In Client’s projects it is not often possible to plan scanning route according to theoretical recommendations. In fact, this hardly ever happens. Instead scanning takes place wherever and whenever it is possible to perform.

The word “quality”, as common as it is, can be considered meaningless without further definition. In this thesis it is mainly used to describe dimensional and geometrical accuracy, uniformity of point cloud surfaces and minimal number of outliers. In other words, how well a point cloud reflects the scenery in which it was captured.

Verification of dimensional accuracy of a point cloud is a cumbersome issue because of error propagation in registration connections (presented more detailed in chapter 4.6). Despite the importance, error propagation is an issue that usually can’t be derived from quality reports provided by registration software (Wujanz 2012). In addition, it cannot be deduced from the corresponding standard of optical instruments ISO 17123, which focuses merely to verification of scanner unit accuracy (Gottwald 2008; ISO 107123 2014), thus disregarding one of the key components of uncertainty of a scanning project.

Therefore, the only way of being sure of point cloud accuracy would be always using control points measured by superior accuracy system. This would require bringing a total station or laser tracker alongside with scanner for control point measurement and it wouldn’t be economically reasonable.

When accepting the fact that total error budget of point clouds will remain unknown, still there can be some level of predictability of outcome if certain routines are being followed. Thus, acceptable limits for accuracy can be achieved based on point cloud acquisition process optimization.

1.2 Research questions

All the terrestrial laser scanners on the market today are expensive by any metric (ranging up from approximately 50000 €) but when considering the investment, price is only one factor among many other and is not necessarily even the most important ones.

Just like any other tool of choice, the circumstances and intended usage define the criteria that truly matter. No doubt the scanner with highest point density combined with highest single point accuracy is superior according to numbers. - However, suitability of the instrument in extreme conditions of board mill cannot be determined by numbers on technical specifications. Another issue is that fluency of data registration, which is known to be great cause of result uncertainty, cannot be determined based on (sales oriented) material provided by the software vendor.

The downside of performance is often reduced portability, higher scanning time and prolonged processing time, none of which are acceptable tradeoffs for the Client since time is the factor that has the highest magnitude when working on site against in a densely scheduled shutdown.

The purpose of this study is to optimize quality and consequently increase productivity of point cloud acquiring process by finding a balance between point cloud quality, scanning time, processing time, equipment mobility and overall process fluency.

Main research questions are:

a) *What is the theoretical framework of laser scanning and how can this knowledge be used to improve quality of Client's laser scanning process?* Especially, *what are the main influencing factors causing uncertainty?*
b) Since operating condition is a factor that can't be affected, *what is the magnitude of scanning method and registration parameters into uncertainty of the whole workflow* and *can quality of point cloud be determined by the numbers shown in registration reports?*

Based on knowledge acquired in this study, the Client will be able to determine preferred scanning and registration parameters in any given scenario through their product portfolio.

2 The Client - Runtech Systems

The Client of this study is Runtech Systems Oy (later “Runtech” or “Client”) which is part of multinational Ingersoll Rand corporation. Runtech is a global provider of engineered systems tailored to the pulp and paper industries and it works with customers to better understand and control their operational conditions to maximize efficiency and cost effectiveness.

Runtech’s patented solutions include energy efficient vacuum system and heat recovery optimization, runnability optimization, dewatering, doctoring and cleanliness optimization as well as ropeless tail threading, including related services, spare parts and paper machine audits and consulting.

Many companies are committed to reducing their carbon dioxide (CO_2) emissions before 2030. Saving 1.5 Megawatts in the vacuum system equals a 4,000 metric ton CO_2 savings per year on average. Runtech looks at energy-saving projects from a wide perspective. It is not only about the vacuum pump or the Turbo Blower in the basement. Runtech’s target is to understand what happens at the machine levels and what might be wrong or causing problems with the paper machine.

Understanding the dewatering process is the key to a well-functioning vacuum system. Combining the dewatering measurement system, press section doctoring and heat recovery with a vacuum system rebuild project will shorten the payback time. With the experience of thousands of vacuum system audits and dewatering studies at paper mills, Runtech is able to benchmark the effectiveness of existing vacuum systems, dewatering equipment, suction elements, fabrics and felts. All information often comes together in a step-by-step rebuild or upgrade plan that results in minimized operational expenses coupled with a production increase and runnability improvements.

3 Research methods

The research method is based on two components, literature review and field study. Further on, field study is divided into on-site (scanning) and off-site (data processing and results analysis).

3.1 Literature review

A thorough literature review was conducted to find answers regarding theoretical background of laser scanning. Following main principles were followed throughout the process: Original source has been used whenever possible. A secondary source was used if original source wasn’t available or couldn’t be used for some other technical reason. Also, if language of original source was unknown to the author of this thesis, a secondary source was cited instead.

In literature review conversations from Laserscanningforum.com and Laserscanningeurope.com were also included as secondary sources because a dedicated discussion forum gives insight into hot topics and latest information of recent development in the rapidly evolving industry. Any information received from discussion forums have been given low impact value because of credibility issue, even though all discussion is between geospatial specialists globally, including active representation from all the major hardware and software producers.

References were given an impact factor according to how widely cited they are and also based on how well they support the topic of this thesis. Therefore, their impact factor value is somewhat subjective. The ranking of references was made, and a table created accordingly (Appendix 1).

Literature review consisted total of 109 references, of which 51 were cited.

3.2 Field study and results analysis

As literature review shows, wide variety of high-quality studies have been made over the years about laser scanning with different focuses spanning from physical properties of light to registration algorithm applications and everything in between. However, data of research conducted in extreme conditions of a paper mill is nowhere to be found (more detailed description of the working conditions can be found in chapter 6). Any laser scanning experiments conducted in laboratory conditions bring no further value to the Client so it was necessary to arrange a comprehensive field study to test how theory and practice would align.

4 Literature review and the science of laser scanning

Laser scanning is a remote sensing technique that is based on reflerctorless rangefinder (Vosselman & Maas 2010, 11; Wujanz 2016, 5–6).

4.1 Classification of laser scanning technologies

According to Vosselman and Maas (2010) optical measurement systems can be classified according to Figure 1, where terrestrial laser scanners are highlighted on gray. These systems are based on either Time-Of-Flight (TOF) or phase shift techniques. Since triangulation methods are not relevant to the subject of this thesis, they are entirely excluded

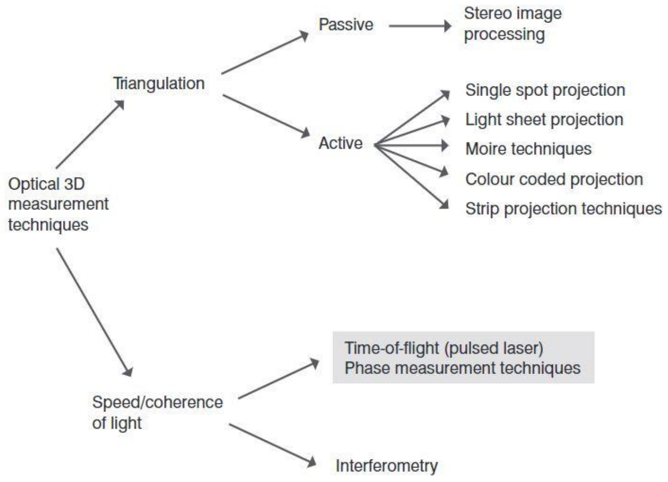


Figure 1. Classification of optical measurement systems (Vosselman & Maas 2010, 2).

Typically, in TLS (Terrestrial Laser Scanner or Terrestrial Laser Scanning) applications laser light is being used because it is more spatially coherent and bright in comparison to multichromatic light sources (Vosselman & Maas 2010, 12).

4.2 Measurement techniques of terrestrial laser scanners

There are two slightly different measurement techniques which both have pros and cons on technical level. However, from a user's perspective, the applied measurement techniques play a less significant role than commercial application.

4.2.1 Time-Of-Flight

In the time-of-flight (TOF) technique distance is being calculated based on the time delay of a laser pulse returning from target surface (Fabritius 2009, 15; Vosselman & Maas 2010, 3–5). Distance *d* is then calculated by **Error! Reference source not found.**:

$$d = \frac{c \cdot t}{2}$$

Equation 1. Time-Of-Flight measurement.

In the equation above *c* is speed of light and *t* is measured time for laser traveling from scanner's transmitter to reflective target and back to scanner's receiver.

Scanning speed of a TOF-based scanner is relative to frequency of short repetitive pulses. In some cases, scenery might result in multiple echoes that can be interpreted as separate surfaces (for instance vegetation and ground level in airborne scanning). (Vosselman & Maas 2010, 3–5.)

An example of Time-Of-Flight -based terrestrial laser scanner is Leica RTC360 (Figure 2), which can capture up to 2 million points per second at full resolution (Leica Geosystems 2018).

Figure 2. Time-Of-Flight -based Leica RTC360 (Leica Geosystems 2018).

4.2.2 Phase shift

Instead of single frequency pulsed laser, phase shift-based laser scanners use continuously emitted laser signal which can be either amplitude or frequency modulated as illustrated in Figure 3 (Bannister et al. 1992, 126–132; Fabritius 2009, 18–20; Vosselman & Maas 2010, 5–8).

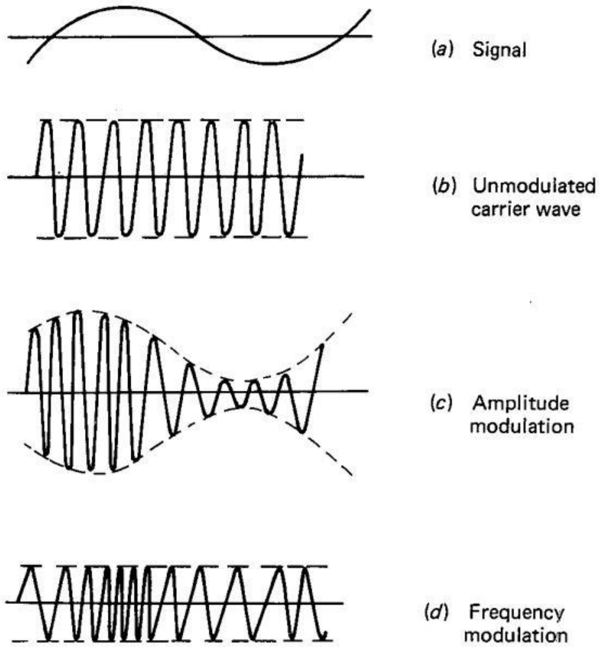


Figure 3. Modulated carrier signal (Bannister et al. 1992, 129).

Based on the phase difference (Figure 4) of transmitted and receiving signals, distance is calculated by **Error! Reference source not found.**.

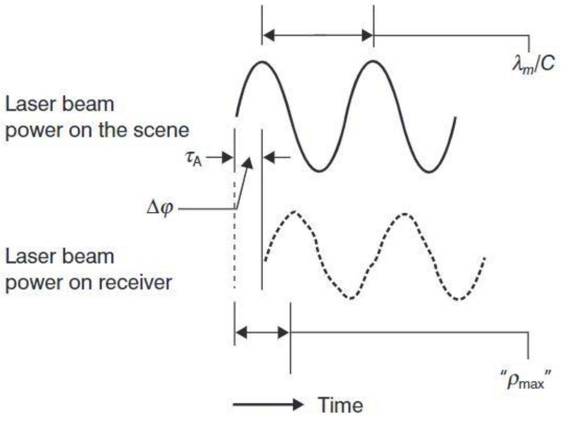


Figure 4. Measurement principle of phase difference (Vosselman & Maas 2010, 6).

$$d = n \cdot \lambda + \frac{\Phi \cdot \lambda}{2 \cdot \pi}$$

Equation 2. Phase shift measurement.

In equation above *n* is quantity of full waves, *λ* wavelength of signal and *Φ* is phase difference of original and returning signal (Bannister et al. 1992, 126–132; Fabritius 2009, 18–20; Vosselman & Maas 2010, 5–8; Heinonen 2020, 7).

Scanning speed of phase shift-based scanners is function of sampling interval (Vosselman & Maas 2010, 5–8). Faro Focus (Figure 5), the laser scanner used in chapter 9 of this thesis is based on phase shift method and it is capable of capturing up to 976000 points per second (Faro 2021, 3).

Figure 5. Faro Focus S (Faro 2021, 2).

4.3 Laser scanner field of view and coordinate system

Figure 6 is presents a typical field of view of a terrestrial laser scanner. There might be some variance on the vertical angle depending on which commercial system is at hand, however basic principle remains the same. Blue rays in Figure 6 represent laser emitted via rotating mirror simultaneously as the scanner is rotating around its own vertical axis, thus capturing 360º horizontal and 300º vertical field of view of the scenery.

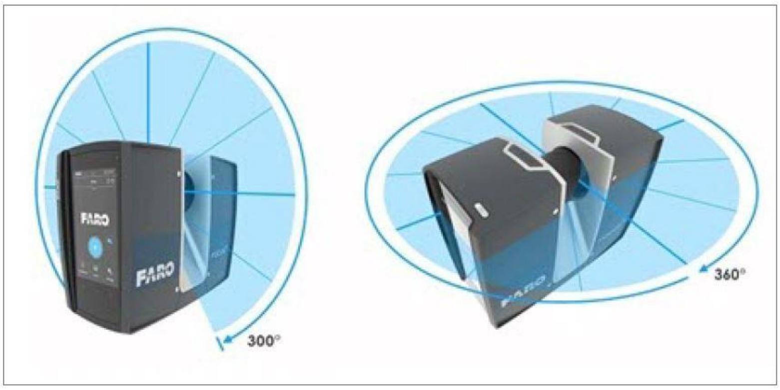


Figure 6. Faro Focus field of view (Faro 2021, 4).

Points captured by terrestrial laser scanners are in spherical coordinate system where scanner is regarded as origin point. A spherical coordinate system is illustrated in Figure 7, where *r* is radial distance, *θ* (theta) polar angle and *φ* (phi) azimuthal angle (Soudarissanane et al. 2009, 1; Spherical coordinates - Encyclopedia of Mathematics, n.d.).

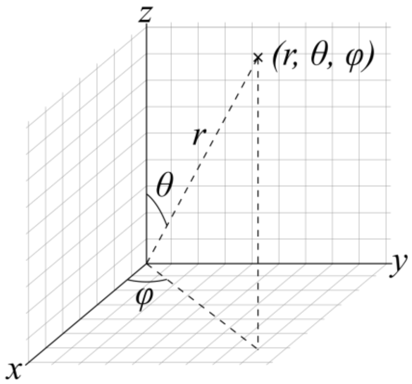


Figure 7. Spherical coordinate system.

Spherical coordinate system then needs to be converted into cartesian coordinate system which can be done by equation **Error! Reference source not found.** (Soudarissanane et al. 2009, 2; Heinonen 2020, 7; Spherical coordinates - Encyclopedia of Mathematics n.d.).

$$x = r \cdot \sin\theta \cdot \cos\phi$$

$$y = r \cdot \sin\theta \cdot \sin\phi$$

$$z = r \cdot \cos\theta$$

Equation 3. Conversion of coordinate system (Heinonen 2020, 7).

Coordinate system conversion results all points of a cloud to be x, y, z coordinates, which are more convenient and commonly used in engineering applications (Heinonen 2020, 7).

4.4 Laser beam properties

In literature laser beam is often presented as a ray with no physical dimensions (Vosselman & Maas 2010, 12), however this is merely a simplification to represent the basic idea. Instead, the beam does have transmitter-dependent diameter, which in case of Faro Focus is 2,12 millimeters (mm) and beam divergence of 0,024 º (angular degrees) (Faro 2021, 147). To put that into perspective, size of the 2,12 mm laser beam increases over distance so that spot diameter at 50 m (meters) is almost 15 mm and at 100 m around 30 mm.

4.4.1 Edge effect and stray points

At smaller distances beam diameter defines the smallest possible features that can be scanned. At greater distances increase of spot size causes sharp corners to seem as rounded in resulting point cloud because laser signal echoes are creating readings mostly from adjacent surfaces of the corner instead of the sharp edge. Furthermore, at greater distances there is a tendency of increased stray points (Figure 8), which occur when the laser only partially hits the edge of an artifact causing the signal to receive false readings outside the artifact. (Boehler & Marbs 2003, 3; Jacobs 2006; Mechelke et al. 2007, 9; Fabritius, 2009 23–24.)

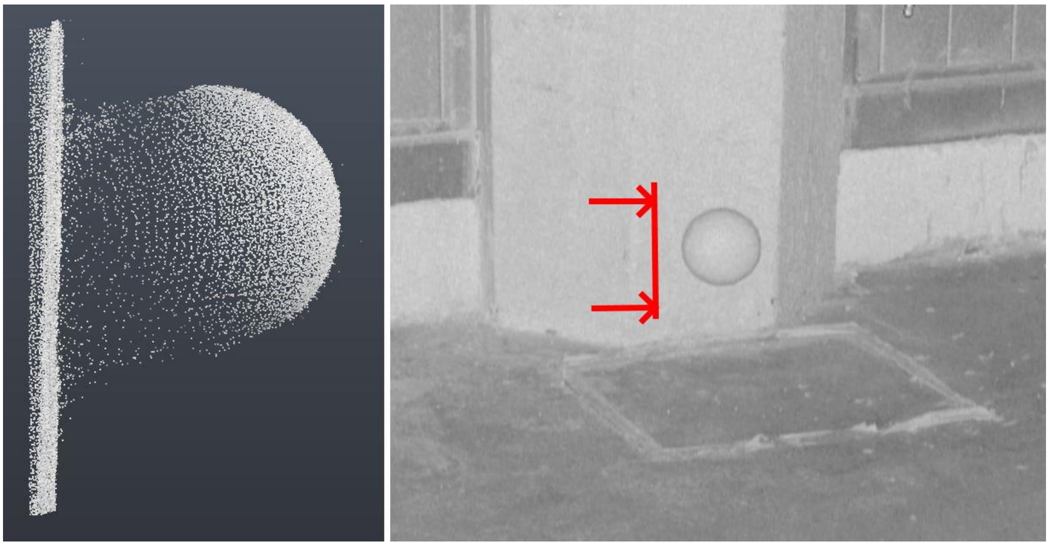


Figure 8. Example of stray points on a 145 mm sphere and corresponding intensity image.

4.4.2 Intensity

One of the variables that most scanners capture among the point coordinates is the intensity of signal. In literature intensity of laser signal is defined as the strength of returning signal, which indicates the relative reflectivity of target (Vain 2012, 10–13; Wujanz et al. 2018, 3; Joala 2006). Most modern scanners create images based on intensity values, which are commonly used as preview pictures of the scan. These resemble black and white images, however darker tones indicate lower reflectivity on specific wavelength instead of object color in visible spectrum of light (Vosselman & Maas 2010, 14–15).

On the left side of Figure 9 there is an example of point cloud scanned in light rain condition, where all intensity values below 20 % have been filtered off. Green color indicates intensity of rain droplets to be approximately 30–40 %. On the right side of Figure 9 is corresponding intensity image, where sky has been filtered and thus it seems black.

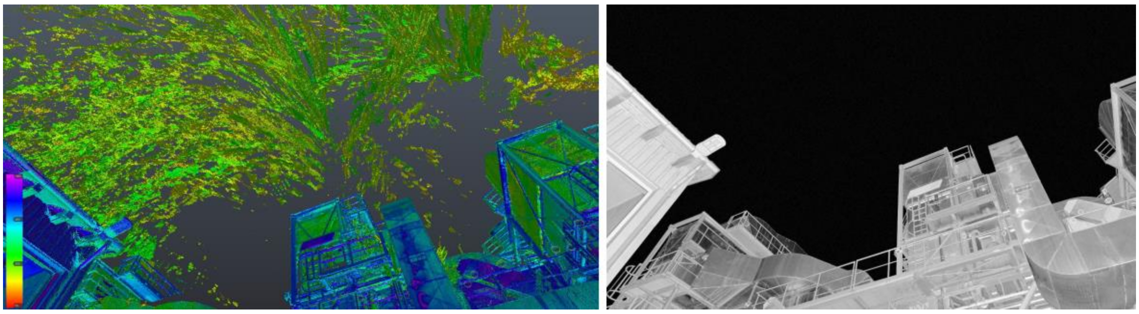


Figure 9. Point cloud view of light rain and corresponding intensity image.

Based on intensity even some textures, such as text can be detected from the point cloud, if relative reflectivity of the text differs from base paint (Joala 2006).

4.4.3 Laser safety

Laser wavelength of Faro Focus is 1550 nanometers, which is in the infrared spectrum and thus invisible to human eye (Hecht 2022.). Faro Focus is declared as laser class 1 product, which is considered to be inherently safe (Stuk 2019).

4.5 Registration and geo-referencing

Usually more than one scan is required to capture the whole object or area of interest. To illustrate the basic principle of registration, Figure 10 shows object of interest in the center and different viewpoints with unique colors around it. These three viewpoints represent individual scan stations which contain almost all the features that are needed to replicate the object of interest. (Wujanz & Neitzel 2016.)

Figure 10. Scanning of object of interest from different viewpoints (Wujanz & Neitzel 2016, 6).

As described in chapter 4.3, terrestrial laser scanners measure points in the scanners local coordinate system. Therefore, in order to assemble all individual scans into a scanning project, coordinate systems of individual point clouds must be transformed into a common coordinate system (Tao et al. 2020, 1; Alsadik 2020, 2; Gruner et al. 2022, 1). Therefore, capturing the object of interest from selected perspectives alone is not adequate since there must also be sufficient amount of overlap between two adjacent scans with recognizable features (Wujanz & Neitzel 2016, 5–7; Pavan et al. 2020; Tao et al. 2020, 1).

In the example case of the statue, there must be significantly more scan stations to achieve enough information so that transformation parameters can be computed. Basic principle of sufficient overlap is presented in Figure 11, where ten scan stations are representing object of interest to achieve enough overlap for successful registration. (Wujanz & Neitzel 2016, 5–7; Pavan et al. 2020).

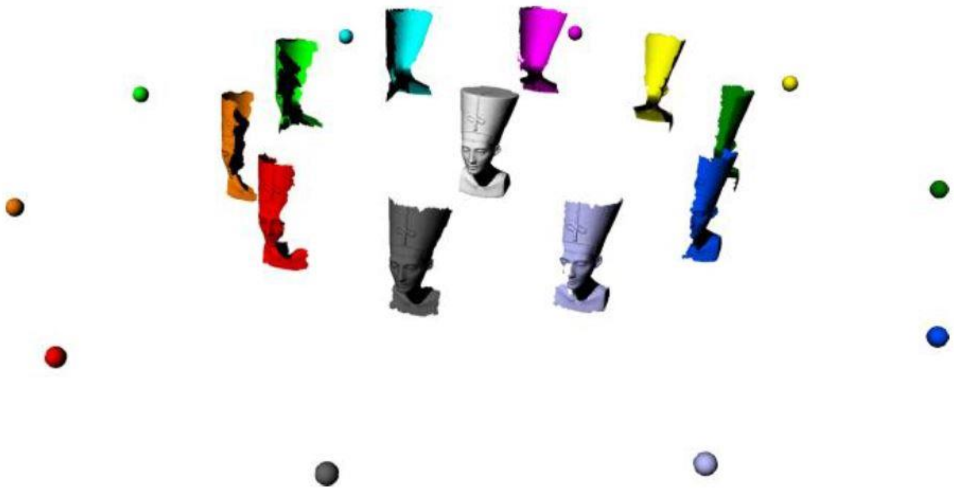


Figure 11. Scanning of object with sufficient overlap (Wujanz & Neitzel 2016, 6).

There are various ways for performing the registration. All of them are based on automatic feature detection. However, the features which are matched define the category of registration. These are presented in following chapters more in detail.

4.5.1 Target based registration

A frequently conducted way of aligning multiple scans into a common coordinate system is to use artificial targets, which are placed within the scanning scene.

In order to align scans, targets must be located within the scene in a way that at least three common targets are visible in two consecutive scans. The usage of scanner's inbuilt inclinometer as one of the three targets is possible if hardware-software combination allows it. To achieve higher accuracy, it recommended to place targets on the outer perimeters of scenery instead of collinear formation. (Chow et al. 2010; Wujanz et al. 2019, 2.)

Two kinds of targets are most commonly used: spheres and checkerboards, which may vary in size. Regardless of the target type, automated alignment of point clouds relies on feature detection, which allows the calculation of center point. After center points have successfully been acquired, point to point correspondences are computed and transformation parameters applied accordingly (Wujanz et al. 2019, 1–2).

There are several practical downsides associated in target-based alignment, which include transporting targets and the required time placing targets into scene. Also, artificial targets tend to have limited usability in other than open spaces or outdoors.

When geo-referencing is a necessity, artificial targets must be used because it is not possible without them (Chow et al. 2010, 2). Target based registration has potential for high precision, however additional measuring equipment with superior accuracy, such as total stations or laser trackers, are inevitably necessary, making this approach economically debatable (Gruner et al. 2022, 1; Wujanz et al. 2016, 2).

Checkerboard targets

Planar targets such as checkerboards, are a low-cost solution, which are commonly sold as stickers (1–2 € per unit), plates with magnetic back side (15–20 € per unit) or as boards with magnetic base (80–110 € per unit). They can even be fabricated simply by printing the checkerboard pattern on regular paper.

The center of checkerboards can be pinpointed accurately based on the intensity value of the pattern in the target, which potentially result in high accuracy. Checkerboards can be used for registration and geo-referencing, however incidence angle (chapter 4.6.1) limits their usability significantly. (Chow et al. 2010; Gruner et al. 2022, 1; Alsadik 2020, 2.)

Target spheres

Spherical targets provide 360-degree field of sight, which increases their usability. However, center point of sphere must be calculated through the average of the significant amount of scanning points on the sphere’s surface making the result less accurate and not suitable for geo-referencing. (Chow et al. 2010; Alsadik 2020, 2; Gruner et al. 2022, 1.) There are also few a practical downside of using spherical targets. The transportation of spheres is known to be troublesome, and their unit price is high (120-150 € per unit). Furthermore, since spheres protrude out of the entity they are mounted on, there is higher risk of being unstable throughout the survey (Wujanz et al. 2019, 2).

4.5.2 Targetless registration

Targetless registration can be performed according to two following methods (or their variants): (i) point-to-point or (ii) according to geometric primitives. It is common for all the methods to use a vast amount of redundancy within the point clouds, which basically means that registration feature correspondences are mostly acquired outside of object of interest (Chow et al. 2010, 2; Wujanz et al. 2019, 2).

Point-to-point registration

Point-to-point matching of feature correspondences is based on Iterative Closest Point algorithm (ICP) or its variants and it is the most commonly used method for point cloud alignment today (Chow et al. 2010, 2; Alsadik 2020, 1;Tao et al. 2020, 1). It was originally presented by Besl and McKay (1992) in the early nineties. The basic principle of ICP is illustrated in Figure 12, where 2-dimensional representations of a shark are aligned.

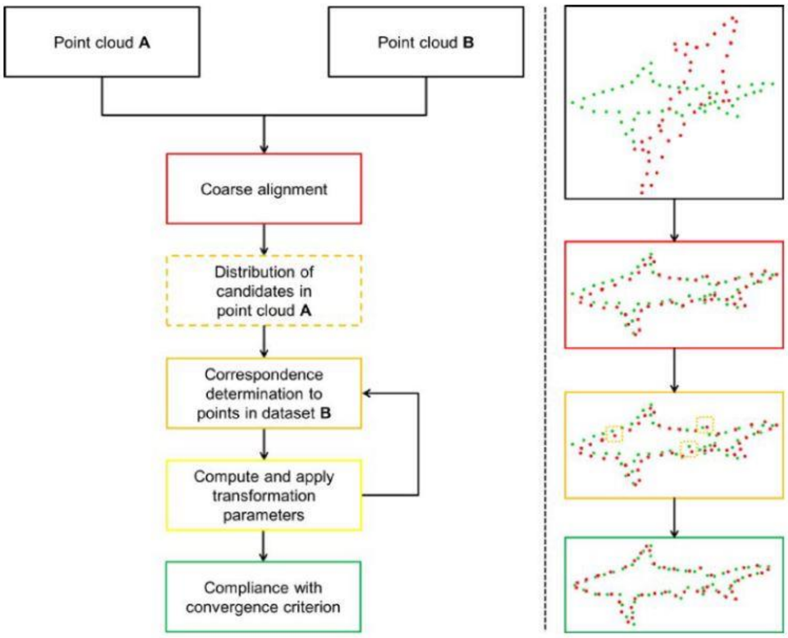


Figure 12. Schematic visualization of point matching process (Wujanz 2016, 20).

Despite its versatility, there are some drawbacks of using ICP. Feature recognition requires high computational power and often manual pre-alignment of point clouds is necessary making the workflow time consuming. Also point matching methods are known to produce erroneous results if there are not enough overlapping geometric primitives (for example flat wall) or too many repetitive features, especially on sparse point clouds. (Chow et al. 2010, 2; Wujanz et al. 2019, 2; Tao et al. 2020, 2; Pavan et al. 2020, 2.)

Registration based on geometric primitives

Instead of point-to-point correspondence matching, registration can also be carried out by using geometric primitives (such as planes, cylinders and spheres). These features are automatically extracted from point clouds, correspondences are searched and alignment parameters are applied based on them. Figure 13 illustrates a plane-to-plane matching process. (Vosselman et al. 2004; Wujanz 2016, 21–24).

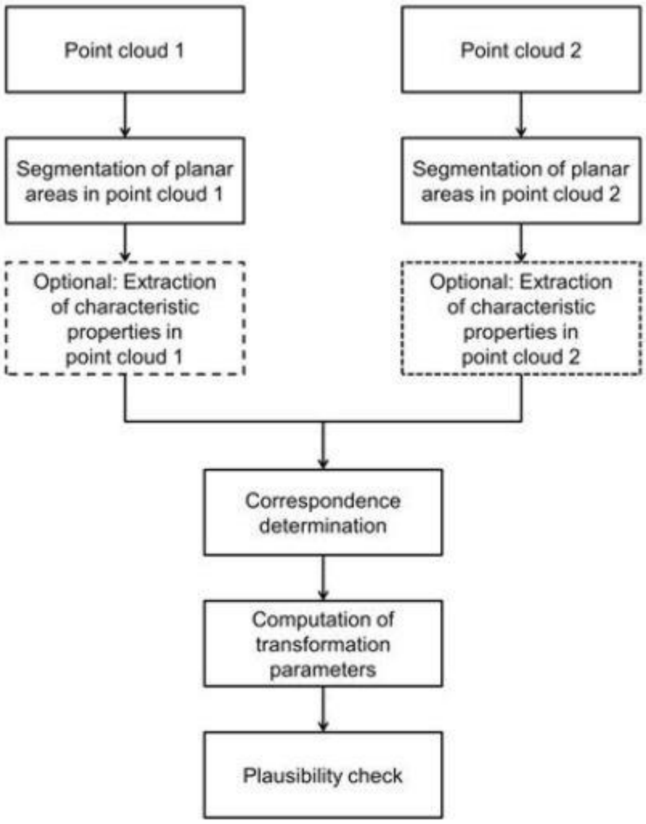


Figure 13. Schematic illustration of plane-based alignment (Wujanz 2016, 24).

Registration based on geometric primitives has higher potential for accuracy than point based methods, especially in human made environments, where planes and cylinders are common. Also, geometric primitives-based methods are more tolerant to noise and point density variation. A downside of such methods is the fact that extracting of features is time consuming. (Wujanz 2016 21–24; Tao et al. 2020, 2.)

4.6 Accuracy of laser scanning and process total error budged

The precision of laser scanning is a combination of uncertainty in distance and angular measurement of the scanner, and the correctness of computational algorithm that produces the point cloud. Therefore, their effect cannot be determined separately (Mechelke et al. 2007, 4).

4.6.1 Accuracy of laser scanners

There are four major factors influencing quality of point cloud. These are (i) instrument calibration, (ii) atmospheric conditions, (iii) object properties and (iv) scanning geometry (Soudarissanane et al. 2009).

Instrument calibration

Boehler and Marbs (2003) have stated that industrial scale laser scanners are built in small series which has an impact on their quality so that announced measuring accuracies are a matter of doubt. Single point accuracy may vary depending on how the device has been calibrated and treated after it was fabricated (Boehler & Marbs 2003, 2). According to specifications Faro Focus S, which is used in the field study of this thesis, has accuracy of distance ±1 mm and angle measurement 19 arcseconds for both horizontal and vertical angles, if correctly calibrated (Faro 2021, 147).

Atmospheric conditions

Atmospheric conditions are known to influence significantly into quality of resulting point clouds. High humidity combined with low temperature will cause atmospheric turbulence or even fog to appear which will attenuate amplitude of returning signal and thus reduce point density especially on longer distances. Also mist and airborne impurities are known to decrease signal to noise ratio, thus resulting lower quality point clouds. (Hejbudzka et al. 2010; Soudarissanane et al. 2011, 2.)

Temperature of the atmosphere has no direct affect to operation of laser scanner, as long as it is within limits defined by manufacturer, however changes in temperature will cause thermal expansion within scanner mechanics, resulting in increased uncertainty. Even though laser scanner operates on specific wavelengths of radiation, other sources of light, natural or artificial, have negative impact on laser scanners signal to noise ratio as they are captured by scanners photodetector. (Boehler & Marbs 2003; Mechelke et al. 2007, 10–11; Voegtle et al. 2008; Vosselman & Maas 2010, 15; Hejbudzka et al. 2010.)

Object properties

The properties of scanning subject are known to have a significant influence on the resulting point cloud.

Reflective characteristics define the strength (intensity) of a returning laser signal. Rough finish materials tend to diffuse the signal and thus result in weakened echo but on the other hand, mirroring or otherwise non-retroreflective surfaces are known to be difficult to scan. Wet surface absorbs the laser light, which reduces reflectiveness. (Lichti & Harvey 2002; Boehler & Marbs 2003, 4; Voegtle et al. 2008.)

Also, object shape has influence on the resulting point cloud. If object of interest contains plenty of sharp edges, it is inevitable for edge effects to appear (chapter 4.4.1) but on the other hand, registration is difficult if object doesn’t contain enough recognizable features. (Boehler & Marbs 2003, 3–4; Kersten et al. 2009.)

Even object color is known to have influence into point cloud quality in some cases, however it is depending mostly on commercial application (Mechelke et al. 2007, 9; Voegtle et al. 2008).

Scanning geometry

One of the major factors of point cloud quality is scanning geometry, especially incidence angle of the laser beam (Soudarissanane et al. 2009; Kersten et al. 2009, 11).

Influence of incidence angle is illustrated in Figure 14, where reflection of laser beam into perpendicular surface creates round spot and a clear sinusoidal signal. As incidence angle *α* increases, footprint of laser becomes increasingly elongated and wider in time, thus lowering signal to noise ratio (Soudarissanane et al. 2009; Vosselman & Maas 2010, 15).

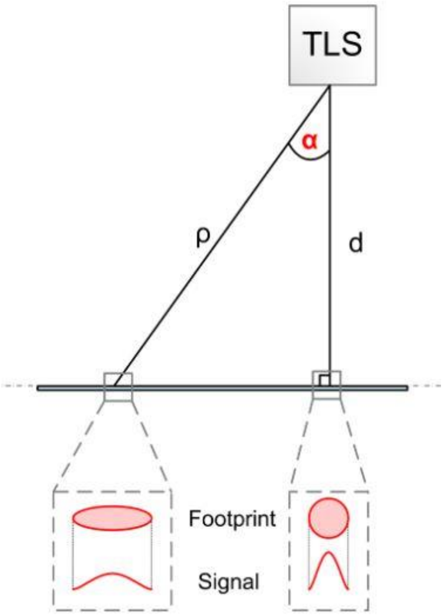


Figure 14. Effect of incidence angle to signal (Soudarissanane et al. 2009, 2).

When scanning a planar feature, density of points decreases significantly over distance, as illustrated in Figure 15, where *x* is distance from scanner.

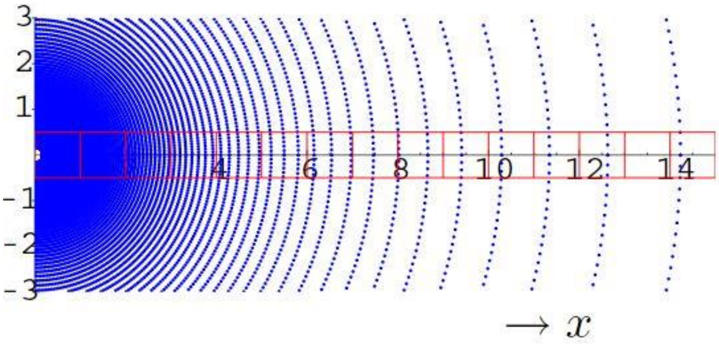


Figure 15. Scanning points distribution over distance (Lindenbergh et al. 2005, 2).

Combination of incidence angle and point distribution over distance causes scanning points contribution to be dominated by incidence angles above 70 º as illustrated in Figure 16 (Lindenbergh et al. 2005; Soudarissanane et al. 2009).

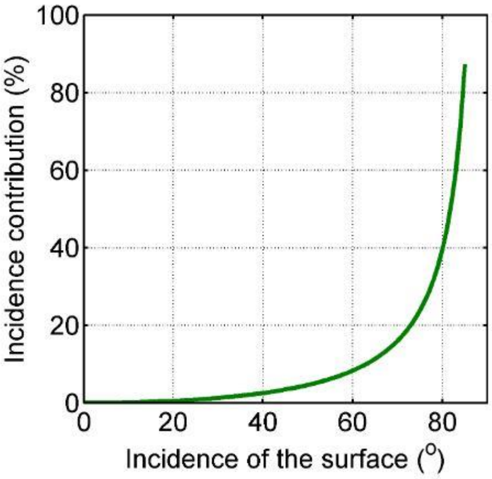


Figure 16. Incidence angle contribution (Soudarissanane et al. 2009, 3).

4.6.2 Influence of registration into process uncertainty

As stated in beginning of chapter 4.6, global accuracy of laser scanning process can be divided into accuracy of the scanner and accuracy of registration. In following headings are presented factors that are known to have high level of influence into registration process uncertainty.

Quality of scanning data

Quality of captured data has significant effect on outcome of point cloud alignment algorithm. There are five common artifacts that have the highest impact to registration: (i) non-uniform sampling, (ii) noisy data, (iii), outliers, (iv) misalignment and (v) missing data. These are illustrated in Figure 17 by a two-dimensional shape. (Berger et al. 2017.)

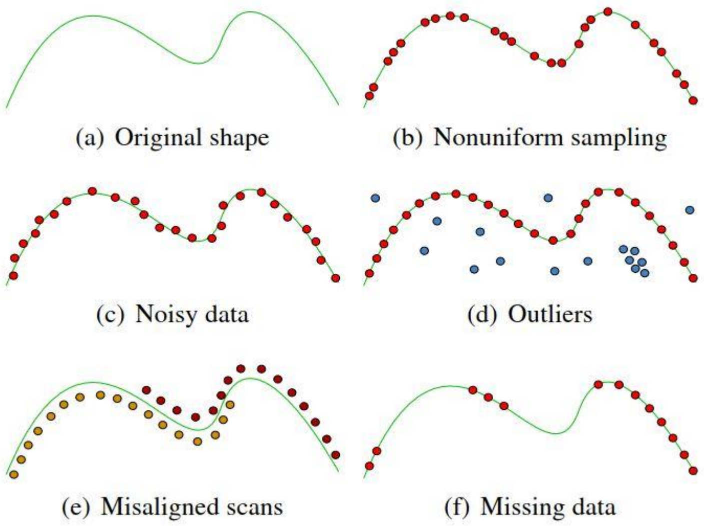


Figure 17. Different forms of artifacts (Berger et al. 2017, 7).

Influence of noisy data, outliers, misalignment and missing data are quite self-explanatory, however impact of Non-uniform sampling requires further review.

Non-uniform sampling causes inevitably aliasing, which is illustrated in Figure 18, where each color represents different scans and on the right effect of aliasing as a cross section.

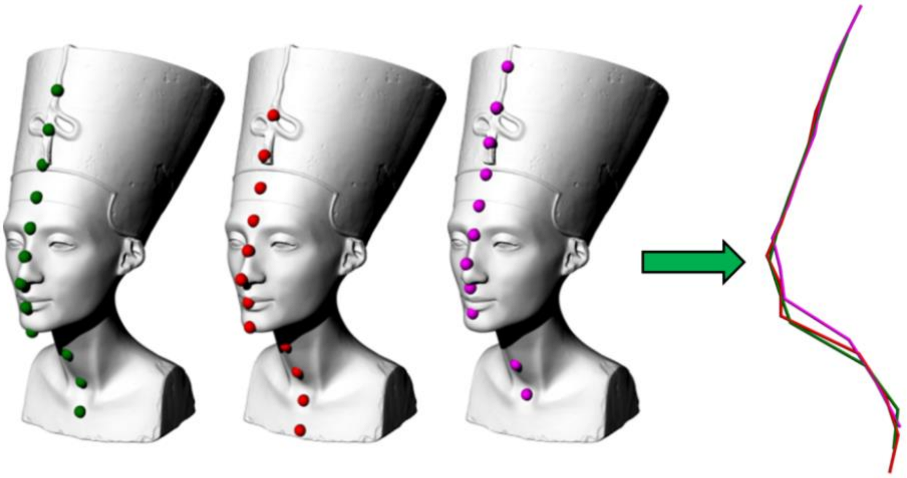


Figure 18. Aliasing due to non-uniform sampling (Wujanz n.d.).

Aliasing is unsolvable problem in laser scanning, which always causes a slight misalignment even in optimal conditions. Due to sequential data acquiring process of terrestrial laser scanning these small misalignments are repeated hundreds or thousands times and as a consequence, they can cause massive error propagation over distance. (Wujanz 2012; Berger et al. 2017, 6–7.)

In Figure 19 error propagation has been illustrated by a puzzle, where each piece represents one scan and connections between pieces represent registration alignment. Even slight misalignment in each connection causes error to accumulate over distance with unpredictable outcome. Effect of drift can be minimized by a planning the scanning route to form an interconnected network. (Koski 2012, 35–38; Wujanz 2016, 11–13; Wujanz et al. 2019.)

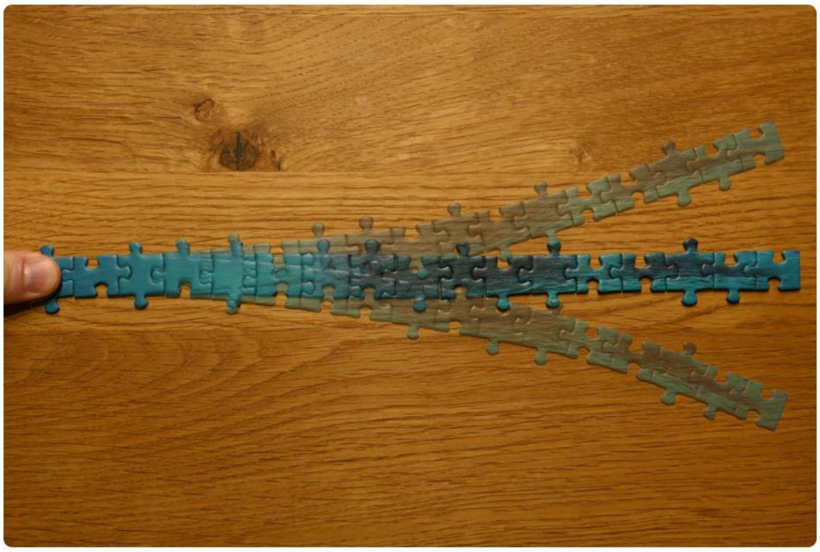


Figure 19. Illustration of error propagation (Wujanz 2019).

4.6.3 Registration reports

Once registration of a scanning project is finished, there is always a software-dependent quality report available, which contains some key figures of the alignment computations. There are significant differences within contents of these reports between commercial applications.

Registration reports should always be doubted because most registration processes are based on minimizing Root Mean Square (RMS) of alignment parameters. Thus, the quality metrics within the reports are most commonly based on computation of alignment residuals, which are not able to detect error propagation (Wujanz 2012; Wujanz et.al 2019, 1–4; Weisstein 2022).

5 Laser scanning workflow

Regardless of the used hardware or technology driving it, the terrestrial laser scanning workflow always follows the same path. From site visit to engineering software there are steps are: planning, data acquisition (scanning), data processing and finally export to CAD (Wujanz et al. 2019). There might be some variance depending on hardware-software-CAD combination, but the basic principle remains the same.

On an economic perspective, possible factors that might cause negative impact on quality should be identified in the early stages of project because cost of influencing quality of outcome rises significantly over time, as illustrated in Figure 20 (Wujanz et al. 2019, 1).

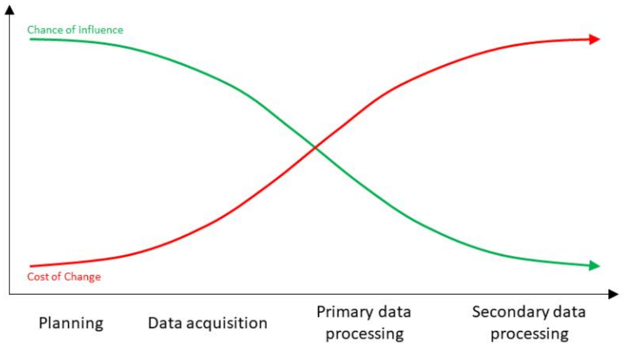


Figure 20. Cost of changes over time (Wujanz et al. 2019, 1).

After registration of a complex scanning project is finished, changing the outcome might be extremely difficult and time consuming. In some cases, it might be more cost-effective to start registration from beginning instead of changing the once finished project. Both of these scenarios consist solely out of unproductive work, which wouldn’t be needed at all if quality issues were noticed in the early stages.

6 Description of operating conditions

Instead of clean, stable and predictable laboratory-like conditions, Client’s projects always take place quite in the opposite conditions. Below are listed some of the common factors, presented in no particular order.

When machine is running temperatures inside drying hood are typically reaching up 90°C and during a short shutdown there’s not enough time to cool down, resulting in operating temperature around 70 °C. Laser scanner can withstand these temperatures for a short time when specially equipped (Figure 21), not to mention the human limits of the operator. In perspective, temperature change from 20 °C to 90 °C (or vice versa) on a 100 meters long drying section causes approximately 9 centimeters of thermal expansion, which will definitely show in in point cloud if it was scanned at uneven temperature.

Figure 21. Faro Focus equipped with cooling elements.

Sudden changes in temperature are also common within the mill. For instance, outside temperature could be around -20 °C (dry air) and inside +40 °C (wet air), so when a door is held open, significant amount of turbulence is inevitable and humidity will condensate.

In the wire section (also known as wet-end), atmospheric conditions are dreadful for any electro-optical device. Air is humid and temperatures are relatively low causing condensate to form everywhere. Commonly there are also some misaligned washers that are spraying outside the machine making the whole wire section area soaking wet. Furthermore, in some cases, mist and steam are forming condensate into ceiling structures and slowly dropping down like rain. Typically, all surfaces are more or less wet causing (class 1) laser beam of the scanner to lose its reflective characteristics (Voegtle et al. 2008, 5–6; Hecht 2022).

Figure 22 shows an example of a scanned wire section, where intensity values below 20 % have been filtered off. The scene included tremendous amount of visible mist and all surfaces were wet, causing intensity values to be mostly between 50–80 %. Only in few spots intensity reaches above 90 %, even though scanning distances were only few meters. False echoes caused by mist are highlighted by red eclipses.

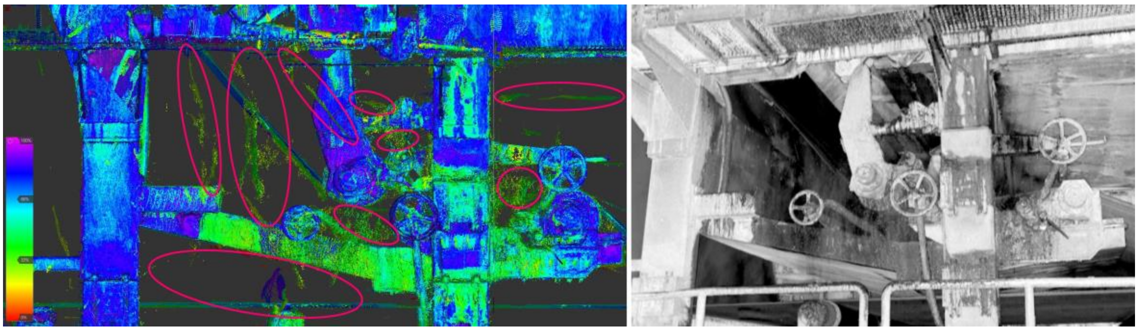


Figure 22. Example of mist on wire section and corresponding intensity image.

One of the main problems with working on operational machines is the shutdown scheduling. Duration of shut down is typically only a few hours and annual shut is planned to last approximately one week. During a planned shutdown, surroundings of the machine are always crowded of workers because of all the maintenance works that must be done during the shutdown.

When working around a paper machine (especially on the drive side), there is always a risk of being soaked wet by machine operators. This is due to the fact that machine wet-end and press sections are being washed regularly with water hoses. Water spray might come from any direction without warning and there’s not much that can be done to prevent it. Thus, any equipment being used must withstand occasional spray without breaking.

On Drying section shreds of paper or board are typically cleaned by blowing compressed air into machine. That raises tremendous amounts of airborne dust and fibers into atmosphere of the machine hall. This combined with condensate forming onto optics causes impurities to accumulate, thus leading the scanner to lose laser emitting and receiving properties and finally resulting in corrupted point clouds.

In a mill, walls are typically either rough finish concrete or masonry, both of which are known to be challenging for laser scanners due to low quotient of reflection (Boehler & Marbs 2003, 4; Křemen et al. 2006; Wujanz, 2018 14–16). Additionally, most surfaces are more or less covered with dirt and fiber sludge causing them to lose their planarity and therefore making feature recognition of registration software to fail.

Without exception fabrics in the wire- and press-sections are closed loop construction. In order to have them installed and replaced, paper and board machines are built by using cantilevered (Törmänen 1989) structure, where machine front side is hanging during fabric installation. As a scanning subject, a cantilevered machine is unstable because geometry changes dramatically when cantilever locks are opened.

In a machine hall there are significant amount of repetitive features, such as building columns, machine frames and drying cylinders, which are identical as geometrical primitives and therefore known to confuse the feature recognition algorithms.

Quite commonly there is no way around area of interest to create a closed loop, which is advisable to ensure minimal error propagation. Instead, usually scanning route forms a straight line, as it was in case of the field study on Tako Board Machine 2 (BM2) (chapter 9).

Vibration is a very typical problem that comes in all shapes and sizes. In the most ultimate cases the whole machine hall might vibrate according to frequency determined by misbalanced rotating drying cylinders. Additionally, raised platforms tend to vibrate due of any equipment mounted on them. An example of vibration in point cloud is shown in Figure 23. Influence of vibration seen on a checkerboard targetFigure 23, where left side image is scanned on steady concrete and right side on a vibrating platform.

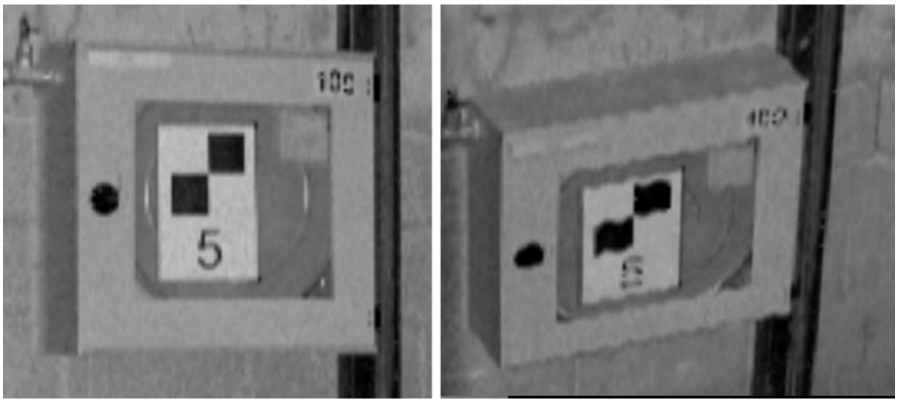


Figure 23. Influence of vibration seen on a checkerboard target.

7 Hardware description

Instead of ranking hardware according to only one factor it was necessary to find optimal hardware for laser scanning under conditions described in chapter 6. Only handful of terrestrial scanners fulfill Client’s requirements so finally two of them were chosen to the field study: time-of-flight based Leica RTC360 and phase shift-based Faro Focus S. These two scanners are similar in many ways, however Faro Focus is compatible with most registration software, while RTC360 is restricted only to Leica’s own software based “RTC 360 workflow” (Biasion et al. 2019).

Even though Leica RTC360 is the most recent rival of terrestrial laser scanners with outstanding performance, due to lack of any software compatibility, the subject of this thesis was chosen to be solely a few years earlier released phase shift-based Faro Focus S-series.

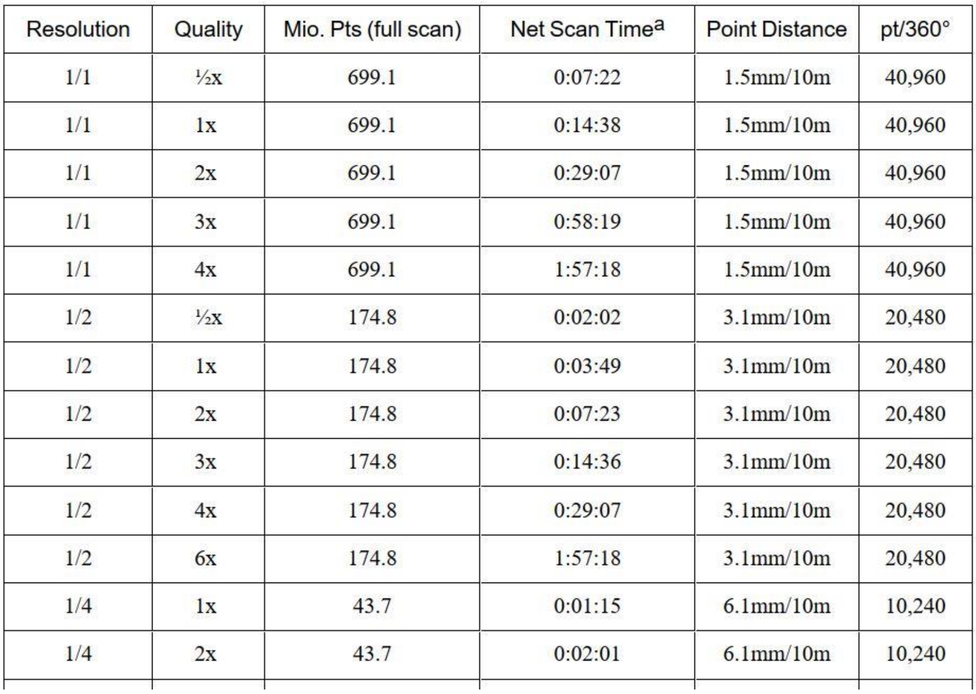
In addition to the aforementioned terrestrial scanners also mobile and handheld scanners were used in the field study, however analysis of their results are excluded from this thesis.

Reference points

Reference points around area of interest were measured with Leica AT 401 laser tracker. According to manufacturer it has angular measurement accuracy of 0,5 arcseconds and maximum uncertainty of 10 micrometers on distance measurement (Leica Geosystems 2019).

Faro Focus S Terrestrial Laser Scanner

Faro Focus S is a phase shift based terrestrial laser scanner that is capable of capturing (at highest resolution) 1,5 mm point spacing at distance of ten meters (Figure 24. Example of Faro Focus resolution settingsFigure 24).



Resolution	Quality	Mio. Pts (full scan)	Net Scan Time[a]	Point Distance	pt/360°
1/1	½x	699.1	0:07:22	1.5mm/10m	40,960
1/1	1x	699.1	0:14:38	1.5mm/10m	40,960
1/1	2x	699.1	0:29:07	1.5mm/10m	40,960
1/1	3x	699.1	0:58:19	1.5mm/10m	40,960
1/1	4x	699.1	1:57:18	1.5mm/10m	40,960
1/2	½x	174.8	0:02:02	3.1mm/10m	20,480
1/2	1x	174.8	0:03:49	3.1mm/10m	20,480
1/2	2x	174.8	0:07:23	3.1mm/10m	20,480
1/2	3x	174.8	0:14:36	3.1mm/10m	20,480
1/2	4x	174.8	0:29:07	3.1mm/10m	20,480
1/2	6x	174.8	1:57:18	3.1mm/10m	20,480
1/4	1x	43.7	0:01:15	6.1mm/10m	10,240
1/4	2x	43.7	0:02:01	6.1mm/10m	10,240

Figure 24. Example of Faro Focus resolution settings (Faro 2021, 46).

Resolution is presented by unit of spacing between two points scanned at distance of ten meters. Quality setting is a parameter that influences on how many times each point is being measured (Faro 2021, 40). By these two variables it is possible to balance between point cloud quality and speed.

8 Software description

There are wide variety of software that could have been included into the study. Every hardware provider has their own dedicated software but there are also dozens of independent software with various benefits and disadvantages.

Compatibility of data is a major issue in laser scanning, which causes difficulties in multi-software workflow. Data conversion is time consuming and unproductive, which should be avoided whenever possible. However, in a case of applied study certain amount of conversion, mostly from registration software to analysis software was accepted.

Main software used in results analysis Faro Scene, Pointcab Origins, Polyworks, Recap Pro and CloudCompare. There were also some additional software involved that had so minimal impact to the overall study process that they are not worth mentioning in this thesis.

9 Field study at Metsä Board Tako BM2

To make field study worth the effort, it needed to simulate real project conditions as well as possible. Since it would be nearly impossible to imitate paper mill conditions anywhere outside an actual mill site, search for a suitable site was conducted and soon found from Tampere City, Finland. As a sign of goodwill, personnel of Metsä Board Tako were kind enough to let the research team to use their premises for the field study.

9.1 The scanning site

Field study was carried out between November 29 and December 4, 2021, in board mill Metsäboard Tako, Board Machine 2, located in the center of Tampere city Finland.

9.2 Subject of study - Tako Board Machine 2

Board production on Tako BM2 was terminated in 2007 (Puunjalostusinsinöörit Ry 2011) but only a small fraction of the machine has been dismantled ever since. Therefore, as a laser scanning subject, BM2 doesn’t differ from an operational machine. Furthermore, BM2 is located in the same machine hall, only few meters apart from operational Board Machine 1, causing the conditions around BM2 to equivalent to operational machine.

By construction, BM2 (Figure 25) is a non-typical machine; mezzanine level is located above drying section with concrete floor in between and drying hood protrudes partially through mezzanine level floor so that upmost elements of the machine (top of MG-Yankee cylinder and infrared dryers) lay on the mezzanine level. Wire section consists of three wires as in any board machine, however top- and filler-wires are up in the mezzanine level and bottom-wire down at machine level.

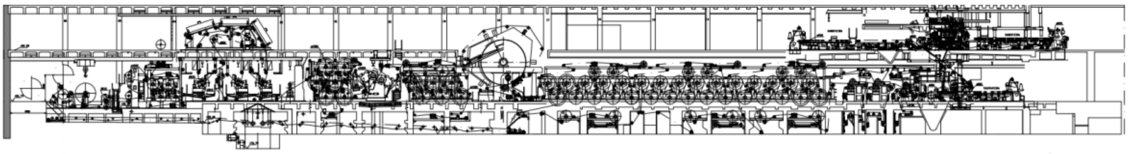


Figure 25. Front Side view of BM2.

Length of machine from bottom-wire headbox to pope-reel is approximately 100 m and web width is 3,6 m.

It is a common phrase among people in industry that Tako BM1 and BM2 are board machines assembled into an apartment building. That said, it is easy to see that BM2 is built in extremely tight space and surroundings of machine, stuffed with vital equipment, are making the machine hall notoriously crowded and thus very demanding subject for thorough laser scanning.

All the things listed above make BM2 a perfect subject for the study.

9.3 Rules and guidelines for the field study

Some rules were applied to simulate real life project conditions. These rules and guidelines are based on years of working experience in Client’s projects. All the projects have some common restrictive elements which were applied to the field study as follows:

- On-site scanning time was limited to 5 days (with two optional days simulating weekend)
- Length of each working day was limited to 16 hours but preferably closer to 12 hours
- Optional days to be used only in force majeure conditions
- Not allowed to intervene in production in any way
- Requested by the mill personnel, only BM2 drive side was allowed to be scanned on machine level

To be able to scan the planned route, it was calculated that scanning time of one individual scan must not exceed 90 seconds. Faro Focus S provides multiple resolution options that meet the duration criteria. Eventually three settings were chosen:

- 1/4x1, which has point spacing 6,1 mm and duration 75 s
- 1/8x2, which has point spacing 12,3 mm and duration 48 s
- 1/16x3, which has point spacing 24,5 mm and duration 34 s

To meet the scientific criteria following exceptions to the rules were implemented; preparation of the experiment site was carried out one week before scanning. This included planning the scanning routes, marking scan locations into floor, placing the targets and performing laser tracker measurements for reference.

9.4 Theory and practice (and the difference)

Preparations of the study were made to meet all scientific criteria and therefore a system was created to track the whole scanning process, capturing supplementary information that scanner does not provide.

The tracking system (Figure 26) consists of a GoPro Max camera mounted into scanner tripod and a secondary camera that is mounted into scanner operators' helmet, thus catching different point of view into same scene. The camera setup was designed so that Max's 360-degree field of view would capture experiment identification code, atmospheric and lighting conditions, scanner settings, and possible operator mistakes. Only a fraction of Max's field of view was aimed at scanner, thermo-humidity meter or identification badge, so most of it was recording what was happening within the scanning site. Both cameras were set-up to record time-lapse video with 0,5 second interval and they were launched with a remote controller causing both videos to have identical timestamp.

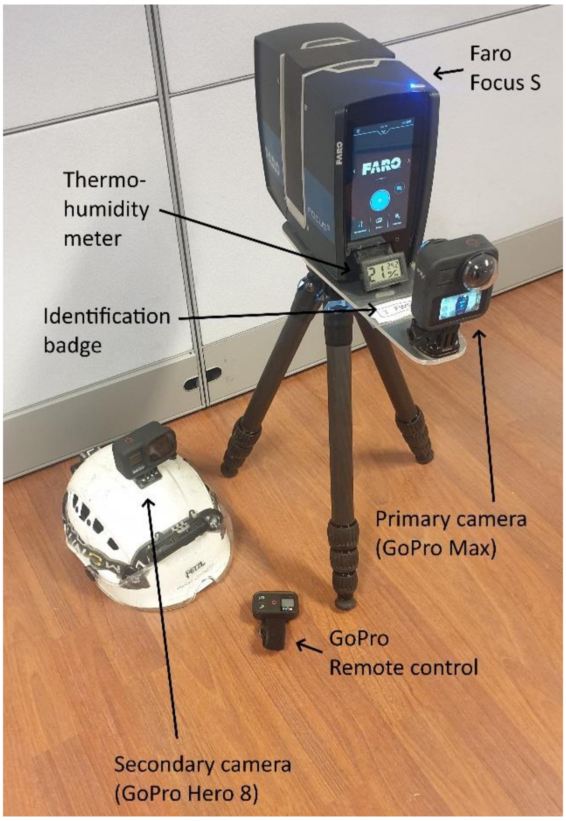


Figure 26. Tracking system.

What was described above was the theory. In practice, the bracket holding GoPro Max blocked Faro’s cooling air inlet partially, which led to scanner overheating when operating temperature reached approximately 30 ºC. As the system failed and there was no time nor tools to modify or rebuild the tracking system, secondary solution had to be improvised. This consisted simply of pen, notebook and a camera.

Another unexpected issue was that during the week between site preparation and scanning, some of the checkerboard target stickers had fell off and some, due to high temperatures, were peeling the reflective surface layer causing the checkerboards to lose their geometric characteristics. Also, during scanning especially non-fixed targets were dislocated several times due to an unexpected external force. In other words, someone or something had bumped target out of place.

9.5 Scanning of BM2

Scanning was mostly performed according to planned route with only small exceptions as something unexpected happened along the way. A good example of this is a sudden steam pipe leakage that occurred at planned route caused need for re-planning the leakage area.

During scanning remarks were made that resulting point clouds would contain significant amount of moving objects blocking the scanners sight to artificial targets. Typical moving objects were mill personnel or forklifts but most commonly the scanner operator. For example, once a web break occurred at BM1 causing all machine operators to rush into machine hall resulting overwhelming amount of moving obstacles into scanning scene.

Along the way significant changes in temperature and humidity were recorded ranging from 21 ºC, RH 59 % to 43 ºC, RH 39 %. Especially on the mezzanine level, where temperature and humidity was at highest (Figure 27), it became overwhelmingly difficult for operator to focus on the scanning subject in adequate level of detail and simultaneously to place scanner in a way that required minimum three targets would be visible. Thus, a hypothesis was made that target based registration would fail, especially checkerboard based.

Figure 27. Atmospheric conditions at mezzanine level.

10 Point cloud registration, first phase

Registration was done in two phases so that in the first phase the entire site of interest illustrated in Figure 28 and Figure 29 was registered with each resolution setting, software and registration parameters multiple times. This phase consisted of 133 individual scan stations, which are represented in pictures below as colored dots.

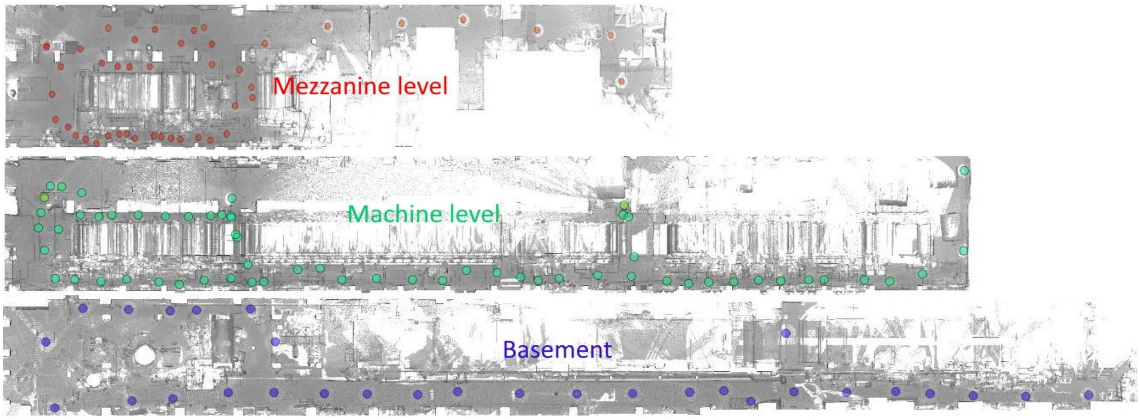


Figure 28. Plan view of the scanning site.

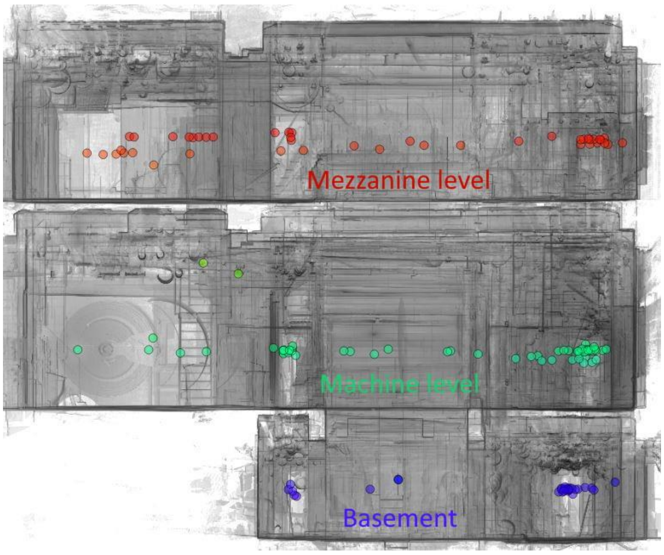


Figure 29. Wet-end view of the scanning site.

10.1 Target-based registration

Target-based registration was performed to all datasets according to following methods.

10.1.1 Registration with checkerboard targets

First target-based registration was restricted to checkerboards only. Automatic target acquisition seemed to work just fine, however there was only few occasions (out of 133 instances) when all required three targets were visible without interference, thus resulting into fatal failure of the registration. Same result was achieved with every software and all resolution settings.

10.1.2 Registration with spherical targets

Second registration set was restricted into spherical targets only. Automatic feature detection worked fluently with only small differences between the software and most pairwise connections were finished successfully. As the algorithm bumped into incomputable connection, a cluster was automatically created, resulting into a handful of clusters with correct internal connections.

Furthermore, connections between clusters were seemingly erroneous, as illustrated in Figure 30, which can be best described as chaotic mess. The remaining connections could have been added or corrected manually but as study subject the result was no doubt clear.

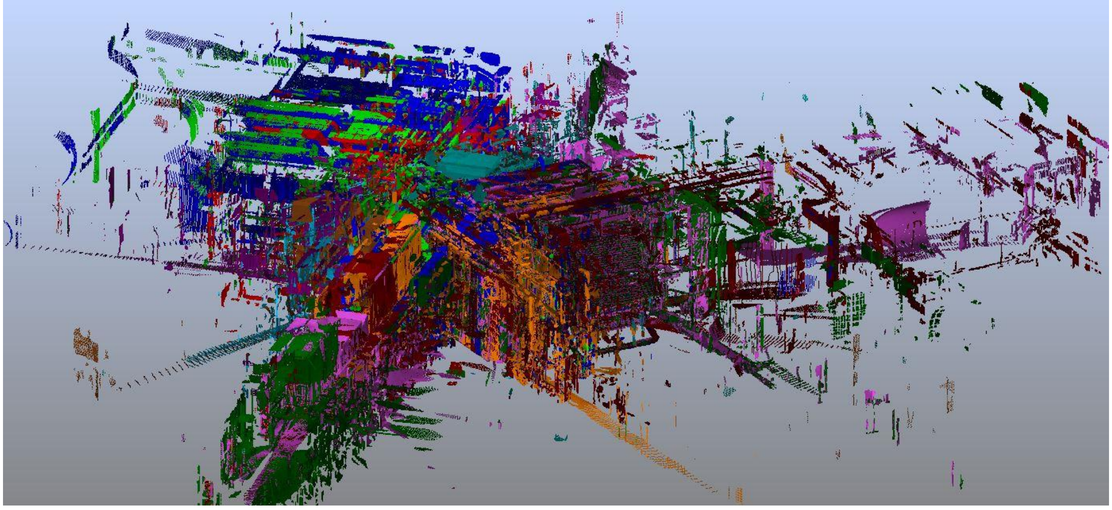


Figure 30. Result of sphere-based registration.

10.1.3 Registration with checkerboards and spheres

Third set of target-based registration was based on both, checkerboards and spheres. This time the registration was able to finish without significant action required by the operator. Visual inspection of the resulting point clouds showed nothing unusual, so reference points were introduced.

The comparison revealed remarkable difference between reference points and scans. Greatest deviation 1,4 meters (Figure 31) was found from reference point number 40, located on machine level dry-end back wall. Distance of the reference point is approximately 130 meters from project point of origin.

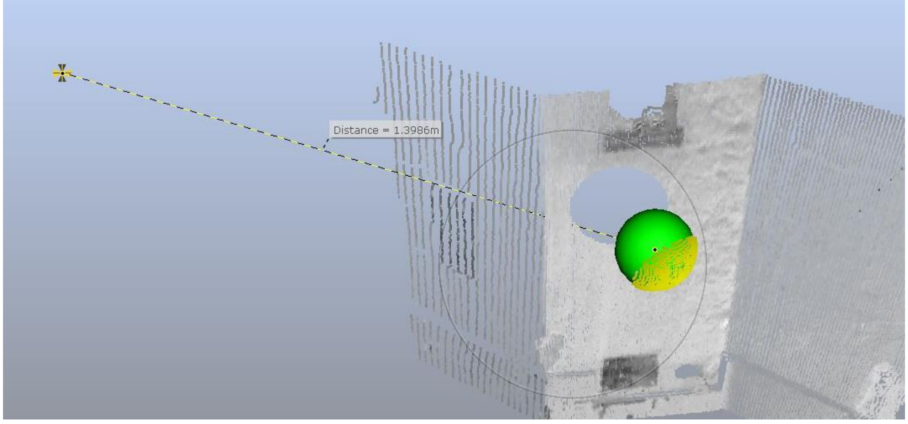


Figure 31. Target-based registration - deviation from reference point number 40.

Since error propagation had been far greater than expected and registration report showed nothing out of ordinary, a more thorough visual inspection was conducted. Used targets were inspected one by one and was discovered that computational residuals could be found hiding all over the point cloud. In Figure 32Figure 32. Collage of misaligned standard 145 mm spheres are four examples of clearly detectable misalignment, all of which are redundant targets according to registration report. Also, it was noted that error budget was smaller in higher resolutions by notable margin.

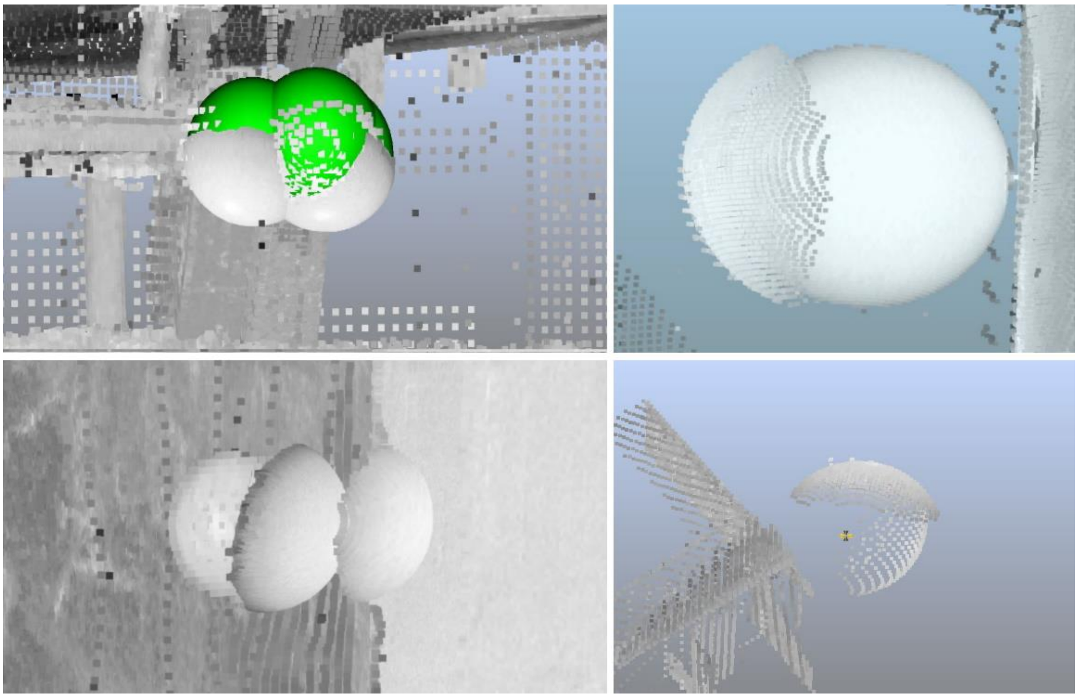


Figure 32. Collage of misaligned standard 145 mm spheres.

10.2 Targetless registration

Targetless registration was run to all data sets with enough repetition that a pattern started to emerge. Registration parameters were adjusted accordingly until optimal combination for each resolution data set was found.

According to visual inspection, point clouds were good quality regardless of resolution and no significant misalignments could be found. In comparison to control points, differences started to show up between registrations done by different software and a clear correlation in favor of higher resolutions regardless of registration software. This can be seen from Figure 33, where left side deviation is approx. 810 mm (low resolution) and right side 300 mm (high resolution). Also, it was noted that low resolution datasets started to cause failure with certain registration parameters.

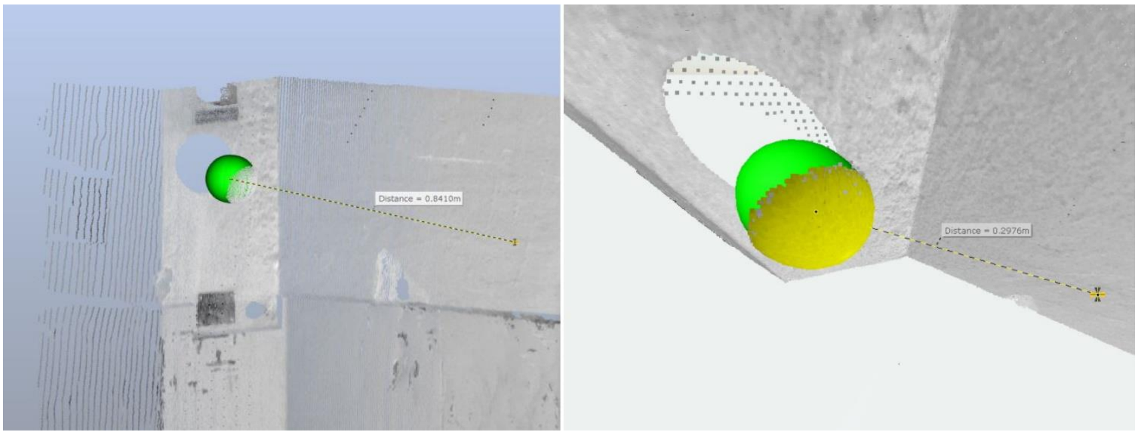


Figure 33. Targetless registration - deviation from reference point number 40.

11 Point cloud registration, second phase

Second phase was required to simulate worst case scenario. For this a specified route was planned that would, according to theory, maximize error propagation. The route contained especially those features that should normally be avoided, such as open loops and long straight lines without possibility of interconnected network design. The route consisted of 73 scan stations as illustrated in Figure 34 and Figure 35. Also 20 reference points were chosen along scanning route for more thorough investigation of error propagation.

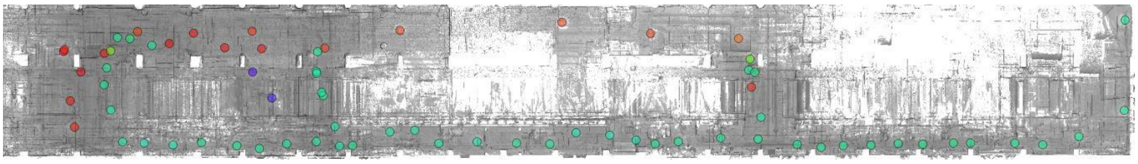


Figure 34. Plan view of second phase registration route.

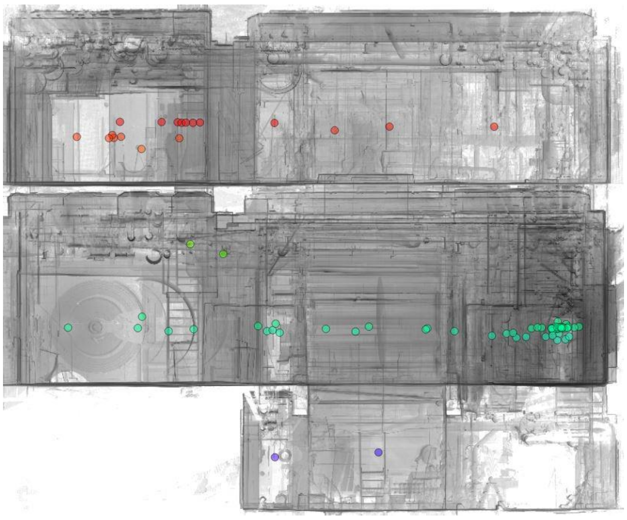


Figure 35. Wet-end view of second phase registration route.

Two dataset-software -combinations were chosen based on results achieved in the first phase. All those datasets that had required significant input from the operator during first phase registration were disqualified regardless of result quality. Also those datasets that had way above average processing times were disqualified, because the they wouldn't meet Client's criteria (chapters 1.1 and 9.3). Finally, two datasets were chosen as follows:

1. The best result based on control points
2. The last in the list of qualified datasets

Not surprisingly first dataset was high and the second low resolution (later referred only as High and Low), both were based on targetless method. The two final datasets were registered 10 times each to gain statistic credibility.

11.1 Visual analysis

None of the resulting point clouds showed anything alarming simply by visual observation. In other words, there was no way of telling if there were even any differences among the point clouds in neither High or Low.

All twenty-point clouds were placed into a single reference frame according to same parameters and each point cloud was colored individually so that comparison could be performed. This was done to High and Low separately.

Figure 36**Error! Reference source not found.** shows significant deformation at ends of an open loop, mostly in y-axis direction. Left side of image are High point clouds each in their unique colors, center is corresponding intensity image with red notations pointing the cross-section location and right side is the same cross-section of a point cloud registered with a closed loop (in the first phase). It is notable that deformations of all datasets are into same direction.

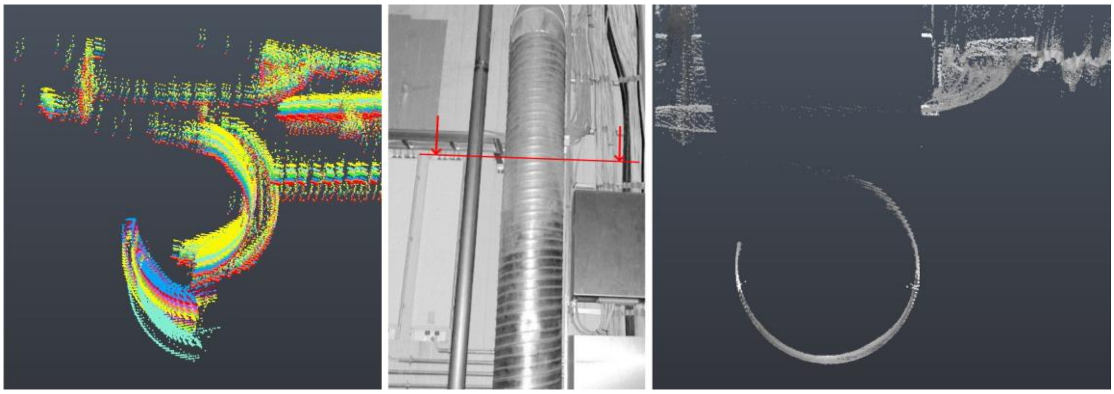


Figure 36. Horizontal cross-sections of a 280 mm diameter air duct and corresponding intensity image.

Comparison also revealed significant error propagation over distance in z-direction. Figure 37 shows a slightly slanted longitudinal cross section of machine hall, where all features except floor has been removed. This way even small changes in vertical shape and alignment can be easily detected. Length of the cross section is approximately 85 meters.

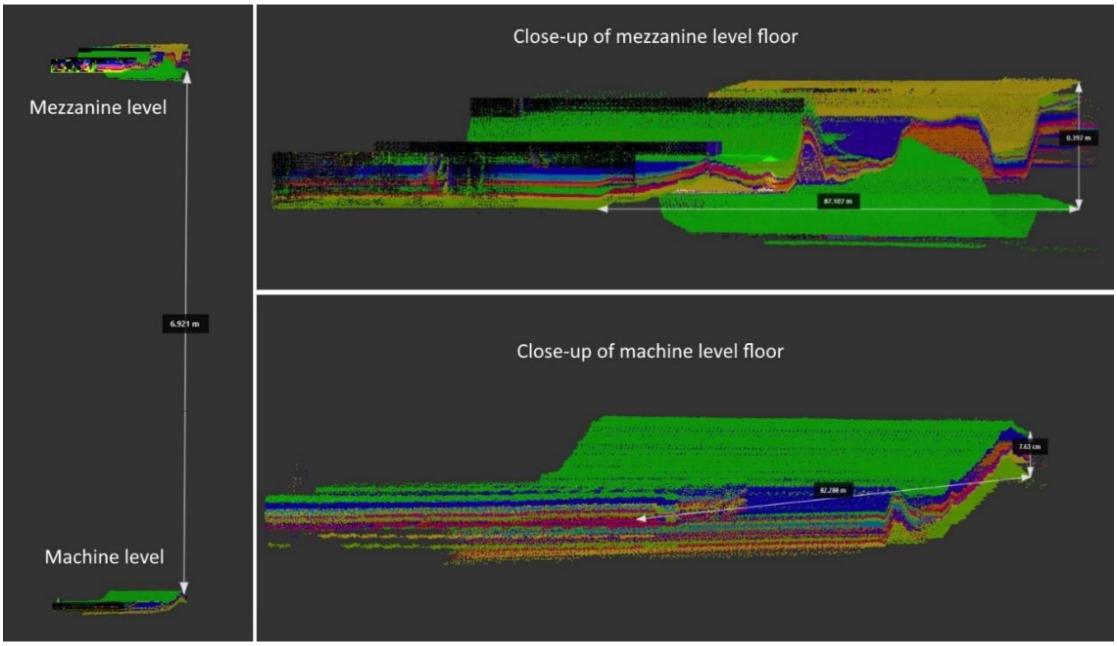


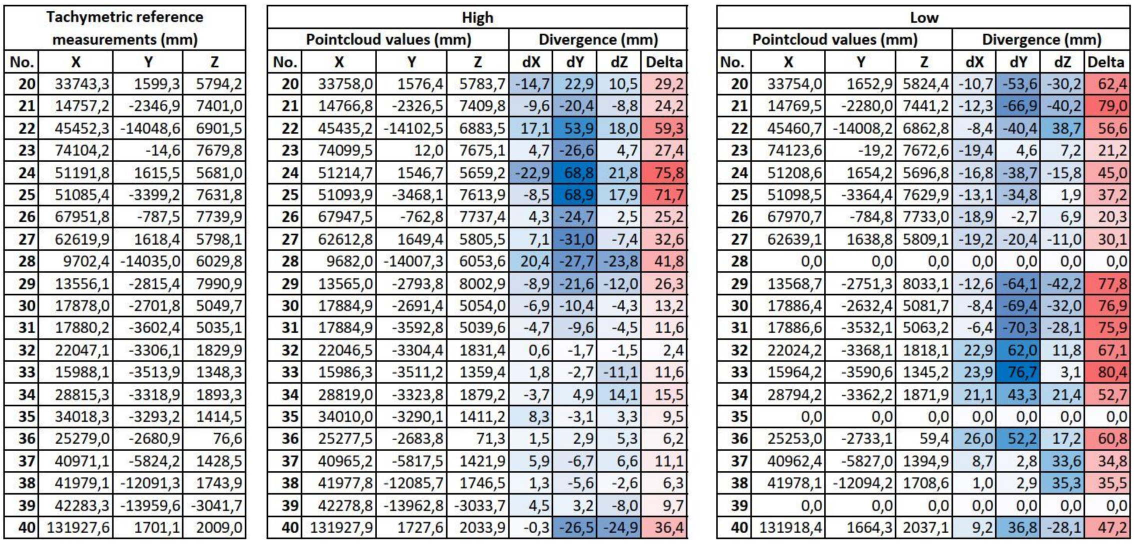
Figure 37. Longitudinal cross-section of machine hall, High dataset.

Most notable in Figure 37 is how light green layer on mezzanine level is starting at topmost on the left and crossing others to become the lowest on the right.

11.2 Numerical analysis

Laser tracker reference points were introduced and a following type of comparison table (Table 1. Reference point comparison tableTable 1) was created for each dataset. In the low datasets points 28, 35, and 39 are set to value zero because points of interest were too far from scanner causing insufficient amount of points on target for reliable feature recognition.

Table 1. Reference point comparison table of two randomly selected datasets.



Tachymetric reference measurements (mm)			
No.	**X**	**Y**	**Z**
20	33743,3	1599,3	5794,2
21	14757,2	-2346,9	7401,0
22	45452,3	-14048,6	6901,5
23	74104,2	-14,6	7679,8
24	51191,8	1615,5	5681,0
25	51085,4	-3399,2	7631,8
26	67951,8	-787,5	7739,9
27	62619,9	1618,4	5798,1
28	9702,4	-14035,0	6029,8
29	13556,1	-2815,4	7990,9
30	17878,0	-2701,8	5049,7
31	17880,2	-3602,4	5035,1
32	22047,1	-3306,1	1829,9
33	15988,1	-3513,9	1348,3
34	28815,3	-3318,9	1893,3
35	34018,3	-3293,2	1414,5
36	25279,0	-2680,9	76,6
37	40971,1	-5824,2	1428,5
38	41979,1	-12091,3	1743,9
39	42283,3	-13959,6	-3041,7
40	131927,6	1701,1	2009,0

High							
Pointcloud values (mm)				Divergence (mm)			
No.	**X**	**Y**	**Z**	**dX**	**dY**	**dZ**	**Delta**
20	33758,0	1576,4	5783,7	-14,7	22,9	10,5	29,2
21	14766,8	-2326,5	7409,8	-9,6	-20,4	-8,8	24,2
22	45435,2	-14102,5	6883,5	17,1	53,9	18,0	59,3
23	74099,5	12,0	7675,1	4,7	-26,6	4,7	27,4
24	51214,7	1546,7	5659,2	-22,9	68,8	21,8	75,8
25	51093,9	-3468,1	7613,9	-8,5	68,9	17,9	71,7
26	67947,5	-762,8	7737,4	4,3	-24,7	2,5	25,2
27	62612,8	1649,4	5805,5	7,1	-31,0	-7,4	32,6
28	9682,0	-14007,3	6053,6	20,4	-27,7	-23,8	41,8
29	13565,0	-2793,8	8002,9	-8,9	-21,6	-12,0	26,3
30	17884,9	-2691,4	5054,0	-6,9	-10,4	-4,3	13,2
31	17884,9	-3592,8	5039,6	-4,7	-9,6	-4,5	11,6
32	22046,5	-3304,4	1831,4	0,6	-1,7	-1,5	2,4
33	15986,3	-3511,2	1359,4	1,8	-2,7	-11,1	11,6
34	28819,0	-3323,8	1879,2	-3,7	4,9	14,1	15,5
35	34010,0	-3290,1	1411,2	8,3	-3,1	3,3	9,5
36	25277,5	-2683,8	71,3	1,5	2,9	5,3	6,2
37	40965,2	-5817,5	1421,9	5,9	-6,7	6,6	11,1
38	41977,8	-12085,7	1746,5	1,3	-5,6	-2,6	6,3
39	42278,8	-13962,8	-3033,7	4,5	3,2	-8,0	9,7
40	131927,9	1727,6	2033,9	-0,3	-26,5	-24,9	36,4

Low							
Pointcloud values (mm)				Divergence (mm)			
No.	**X**	**Y**	**Z**	**dX**	**dY**	**dZ**	**Delta**
20	33754,0	1652,9	5824,4	-10,7	-53,6	-30,2	62,4
21	14769,5	-2280,0	7441,2	-12,3	-66,9	-40,2	79,0
22	45460,7	-14008,2	6862,8	-8,4	-40,4	38,7	56,6
23	74123,6	-19,2	7672,6	-19,4	4,6	7,2	21,2
24	51208,6	1654,2	5696,8	-16,8	-38,7	-15,8	45,0
25	51098,5	-3364,4	7629,9	-13,1	-34,8	1,9	37,2
26	67970,7	-784,8	7733,0	-18,9	-2,7	6,9	20,3
27	62639,1	1638,8	5809,1	-19,2	-20,4	-11,0	30,1
28	0,0	0,0	0,0	0,0	0,0	0,0	0,0
29	13568,7	-2751,3	8033,1	-12,6	-64,1	-42,2	77,8
30	17886,4	-2632,4	5081,7	-8,4	-69,4	-32,0	76,9
31	17886,6	-3532,1	5063,2	-6,4	-70,3	-28,1	75,9
32	22024,2	-3368,1	1818,1	22,9	62,0	11,8	67,1
33	15964,2	-3590,6	1345,2	23,9	76,7	3,1	80,4
34	28794,2	-3362,2	1871,9	21,1	43,3	21,4	52,7
35	0,0	0,0	0,0	0,0	0,0	0,0	0,0
36	25253,0	-2733,1	59,4	26,0	52,2	17,2	60,8
37	40962,4	-5827,0	1394,9	8,7	2,8	33,6	34,8
38	41978,1	-12094,2	1708,6	1,0	2,9	35,3	35,5
39	0,0	0,0	0,0	0,0	0,0	0,0	0,0
40	131918,4	1664,3	2037,1	9,2	36,8	-28,1	47,2

Divergence values were calculated simply by subtracting point cloud values from reference values. Total divergence values (delta) were calculated by **Error! Reference source not found.**:

$$delta = \sqrt{dX^2 + dY^2 + dZ^2}$$

Equation 4. Total divergence.

Divergence values (x, y, z) highlighting in Table 1 is set to blue and delta to red. Intensity of highlighting indicates greater values in darker tone.

Statistics

A brief calculation of statistics was conducted and corresponding graphs were created. Shape of incidence values in Figure 38 clearly indicate normally distributed data for all datasets with only few outliers.

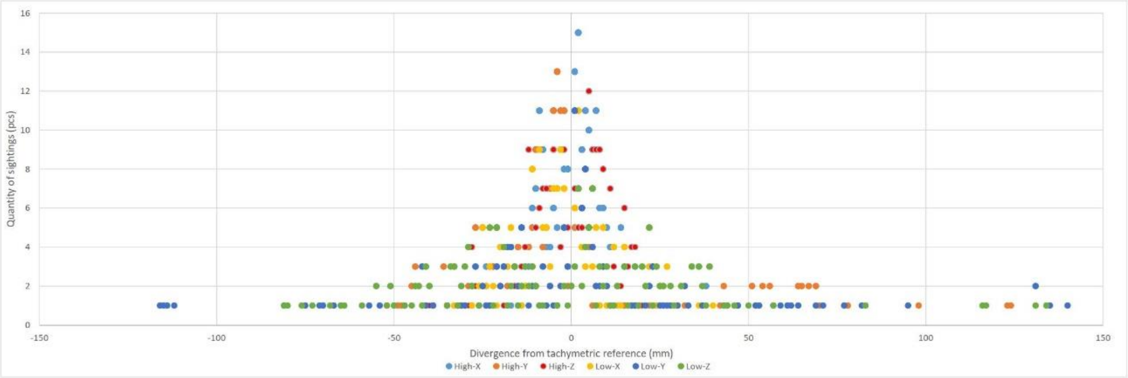


Figure 38. Frequency of divergence values on all datasets.

Summary of statistics were calculated and following Table 2 was created accordingly, which shows clearly greater key figures for Low datasets.

Table 2. Summary of statistics, High vs. Low.

Statistics	High			Low		
	X	Y	Z	X	Y	Z
Minimum	-33,0	1,0	-52,0	-41,0	-116,0	-80,5
Maximum	38,0	15,0	124,0	39,3	139,8	133,3
Median	1,5	7,5	-5,0	-2,6	0,2	1,3
Mean	0,2	7,7	0,1	-2,3	-0,9	-2,4
Variance	106,8	14,9	864,8	200,9	1492,4	1213,2
Deviation	10,3	3,8	29,3	14,1	38,5	34,7
Lower quartile	-8,0	4,8	-15,3	-10,4	-17,7	-27,2
Upper quartile	7,0	11,0	3,0	5,1	8,8	19,2

Box-whisker plots were created for each coordinate direction to visualize the massive difference between High and Low. In Figure 39 is presented pairwise plot of x-direction for reference.

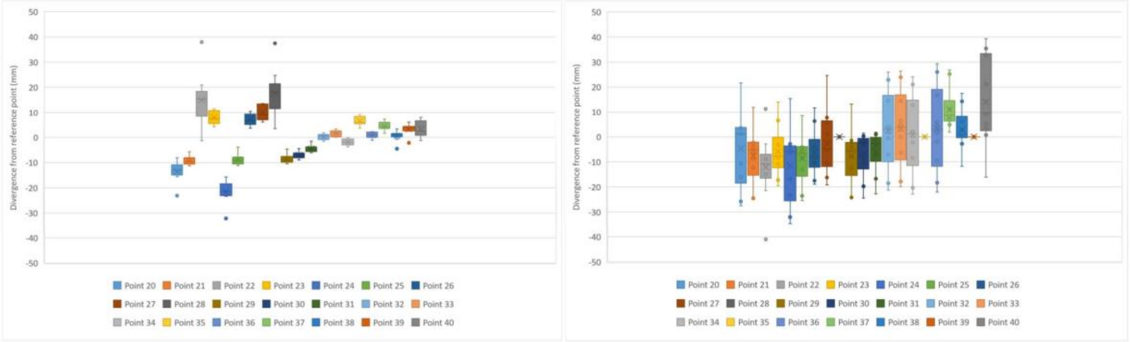


Figure 39. Divergence from reference points in X-direction, High vs. Low.

Registration reports

One of the key questions of this study was to find out if registration reports provide information that can be used to determine quality of point cloud.

All the software used in this study have different tools and metrics for quality analysis. Some have connection matrix indicating pairwise alignment of scan stations, and some offer only a very limited report that contains few numbers indicating alignment confidence. None of the used software provide proper tools for topology or error propagation analysis. As noted in the literature review (chapter 4.6.3), registration reports should always be a matter of doubt (Wujanz 2012, 5–6; Wujanz et al. 2019), which was proven to be true during target-based registration (chapter 10.1).

All the relevant registration reports were analyzed to find out if they provide any useful information or should they always be discarded as misleading.

Looking at red dots highlighted in green eclipse (Figure 40) might seem like well-planned network design (chapter 4.6.2), however registration reports indicate significantly below average alignment confidence around this area. This can be confirmed by comparison to control points as they reveal increased uncertainty.

Figure 40. Area of significant thermal expansion.

Reason for this is that instead of network design, the machine front side wire section on mezzanine level was scanned twice three days apart. First time on cold machine during shutdown and later on hot running machine.

Closer look at point cloud comparison (Figure 41) shows significant deformations within the area of thermal expansion, thus proving that registration reports do indeed provide valuable information of problematic areas.

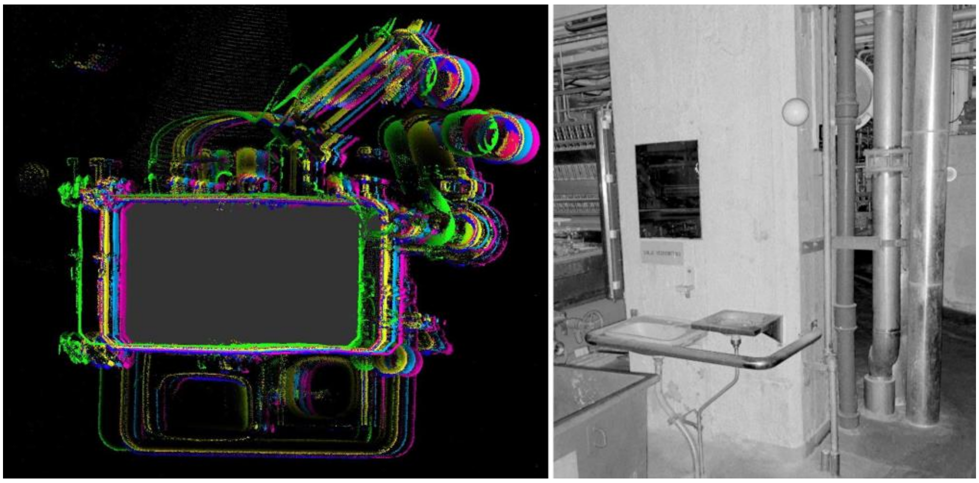


Figure 41. Example of point cloud deformations in area of thermal expansion.

12 Conclusions

Laser scanning is more widely researched issue than it seemed in the beginning of study. Literature provides theoretical answers to many questions regarding influencing factors to quality and error propagation issues, including significance of spot size and laser beam propagation (chapter 4.4). Literature also explains well the nature of aliasing caused by non-uniform sampling, which is inevitable in laser scanning and also how to minimize the effect it has on process overall uncertainty (chapter 4.6.2). All this theoretical knowledge can be well utilized to optimize workflow for any desired scenario.

Extensive field study (chapter 9) was conducted to find answers regarding the impact of scanning method and registration parameters (chapter 1.2). In the aftermath of field study (chapters 10 and 11) it became obvious that scanning parameters have massive impact on the quality of resulting point clouds and the overall fluency of registration process. Also, it was noted that sufficient overlap for alignment of the scans is highly relative to used resolution but also it is software dependent.

Numerical analysis of results revealed that even though higher resolutions are superior in every measured aspect, no doubt, lower resolutions can be used for scanning if schedule requires so. However, it is advisable to always use higher resolutions if possible, unless effect of drift caused by error propagation can be cancelled by working allowances of the final deliverable installation.

One of the most interesting aspects of the field study was the utility of artificial targets. Transporting the targets on site can be troublesome (especially when aviating) and placing them into scenery is laborious, but they can be arranged if there’s a clear benefit for doing so. However, on site there were many problems in placing the targets because checkerboard stickers do not stick in wet or greasy surfaces and magnetic pedestals cannot be mounted onto non-ferrous metal surfaces. Furthermore, a troublesome characteristic of a Class 1 laser turned out to be that even few drops of water on a target will cause laser to lose reflectivity and thus geometric properties of the target (Hecht 2022.) And there are leaking pipes and condensate everywhere in a mill.

None of the target-based registrations were able to be finished regardless of used software and any of the parameters. As hypothesized in chapter 9.5, target-based registration was a failure by any standard. Therefore, it seems obvious that use of artificial targets as a registration method does not provide any benefit when compared to targetless approach (actually quite the contrary). However, targets are very useful if there’s need to revisit the site later because they enable to accurately combine point clouds from different visits. Also, they are very convenient for merging clusters and for scanning staircases etc. which are usually outside of area of interest but necessary for the whole project to be aligned.

Analysis of the registration reports revealed that some issues, for instance, effect of thermal expansion (chapter 11.2) can be detected with high reliability. As a summary, instead of blindly trusting the green lights and small numbers indicating minimal alignment error, registration reports can be useful instrument if known what to search for.

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Besl et.al.	1992	A Method for Registration of 3-D Shapes	Journal Article	3
Bannister et.al.	1992	Surveying, 6th edition	Book	3
Lichti et.al.	2002	THE EFFECTS OF REFLECTING SURFACE MATERIAL PROPERTIES ON	Journal Article	3
Boehler et.al.	2003	Investigating Laser Scanner Accuracy	Report	3
Sithole, George	2003	Comparison of filtering algorithms	Journal Article	3
Vosselman et.al.	2004	Recognising structure in laser scanner point clouds	Journal Article	3
Blais, Franc¸ois	2004	Review of 20 years of range sensor development	Journal Article	3
Rietdorf et.al.	2004	A Concept for the Calibration of Terrestrial Laser Scanners	Report	3
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