Possibilities and challenges of measuring small fibre composite system structures using terrestrial laser scanning

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Key words: terrestrial laser scanning, lightweight fibres, quality assessment, scanning spray

SUMMARY

Due to the rapidly increasing demand for living space, the way in which buildings are constructed must change. This topic is the focus of the Cluster of Excellence "Integrative Computational Design and Construction for Architecture" (IntCDC) at the University of Stuttgart. The development of new construction methods also poses new challenges for surveying and quality assurance. One of the construction systems developed involves coreless filament winding of fibre composite systems. The components are developed to be lightweight and with low material consumption, which is the reason that the design is based on the fibre-fibre interaction. The particular challenge here is that the position, diameter and shape of the fibres have an enormous impact on the structural properties. For this reason, the measurement of the fibres is of major importance. In this work, the possibility of measuring coreless fibre composite system components using terrestrial laser scanning will be investigated. Therefore, measurements of the laser scanners Leica HDS7000, Riegl VZ2000 and Trimble X7 are compared. The influence of a scanning spray is also considered. The analysis shows that for this application, time-of-flight scanners are better suited for measuring small structures than phase-shift scanners as these enable a more complete detection of the measurement object. It has also been shown that a better coverage of the object is possible with larger angles of incidence, if the footprint size is smaller. Furthermore, it becomes clear that the intensities, as well as the device-internal limit values for these, are decisive for the geometric representation of the object. as these enable a more complete detection of the measurement object.

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1. INTRODUCTION

The expansion of the global population represents a significant challenge for the construction industry, as it must meet the growing demand for living space. The latest projections indicate that the global population will reach 9.7 billion by 2050 (UNE 2017). If these numbers are taken as the basis for the required living space, it becomes evident that the available living space will have to double within the next 30 years. It is challenging to achieve this with conventional construction processes, as the construction industry is already responsible for 40% of global resource consumption, 40% of global energy consumption, and 50% of global waste production (UNE 2017). Furthermore, the construction industry has the lowest level of digitalization of all industries, which makes such an enormous increase in productivity almost impossible (Barbaroa et al. 2017). In order to address this challenge, the Cluster of Excellence "Integrative Computational Design and Construction for Architecture" (IntCDC) was established at the University of Stuttgart in 2019. Its objective is to rethink architecture and harnessing the full potential of digital technologies. In order to achieve this, both the building materials utilized and the requisite manufacturing processes are taken into account, thereby enabling a comprehensive view of the building systems (Knippers et al. 2021). One of the cluster's central research objectives is the further development of the design and production process for coreless fibre composite components. Fibre composite systems have been employed in the automotive and aerospace industries for several decades due to their favourable material properties, including low thermal expansion and corrosion resistance (Fetzer 1985). Technical developments in coreless production also made it easier to manufacture individual components, as expensive formwork was no longer required for each prototype component and components could therefore be manufactured more individually. In recent years this yields to a notable increase in the use of these materials in architectural applications (Menges and Knippers, 2015).

Figure 1: La Maison Fibre for the Architecture Biennale in Venice, Italy 2021 (left), BUGA Fibre Pavillion at the German Federal Gardenshow in Heilbronn (2019) (right).

Exemplary building demonstrators such as the 'Maison Fibre' at the Architecture Biennale in Venice, Italy 2021 (Dambrosio et al. 2021) or the fibre pavilion at the German Federal Garden Show in Heilbronn, Germany 2019 (Dambrosio et al. 2019) (see Figure 1) showed the potential of this building type.

The fibre structures consist of carbon fibres, which are impregnated with an epoxy resin and then wrapped around a frame construction using a 6-axis industrial robot. The structures themselves are based on the interaction of the individual fibre bundles, which is the reason why the geometry of the fibre bundles and the position of the fibre intersections are of crucial importance for the final components (Balangé et al. 2022, Gil Pérez et al. 2022).

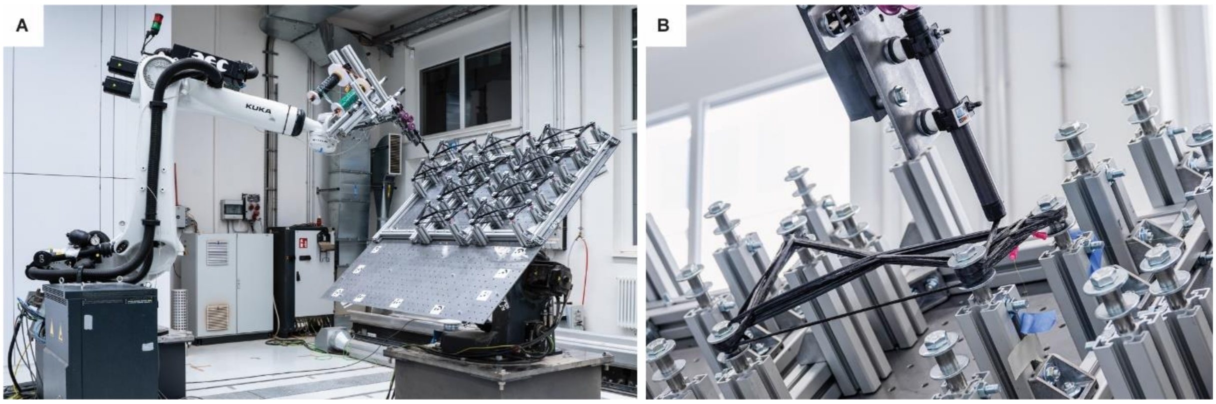

Fig. 2. a) Fabrication set-up with KUKA robot b) exemplary element (Gil Pérez et al. 2022).

For such complex building components, quality modelling and quality assurance are of crucial importance. One method for this was developed as part of a holistic quality model that models the quality requirements of different disciplines (Zhang et al. 2020, Haag et al. 2024). This model is based on the identification and evaluation of certain control and decision points for the production process as well as for the fabricated components. In this work, the focus is on geometric quality and, in particular, the control point after the measurements are carried out,so that the quality of the measurements can be assessed.

In geometric quality assurance in construction, laser scanners are frequently used to capture the objects in order to compare the measured point cloud with a model derived from the original planning (Tang et al. 2022). This is typically the case with larger components that have a closed surface structure. However, the objects under consideration in this study comprise a network of fibre bundles (see Figure 2) for which no 3D planning model is available. The diameter of the fibre bundles is approximately one centimetre, which presents a significant challenge in terms of accurate measurement (Balangé et al. 2022, Gil Pérez et al. 2022). With the aim of generating 3D point clouds of the fibre objects, both photogrammetric approaches and acquisition using terrestrial laser scanners represent a possibility. However, the photogrammetric approaches proved to be impractical in this specific scenario due to external disturbances like the lightning conditions in the fabrication area.

In this work, the possibilities and limitations of different terrestrial laser scanners will be analysed. The measurements are carried out under real-life conditions. The aim is to take into account both the influence of the small object size and the surface properties of the object.

2. THEORETICAL BASICS

In order to be able to take a closer look at the effects occurring during the measurement process, with regard to the characteristic scanner properties, the relevant measurement methods and the thereby caused effects are explained in this section. The focus hereby will be on the different methods of distance measurement, the behaviour when measuring small objects or edge points, as well as the intensities.

2.1 Distance Measurements for Terrestrial Laserscanning

As with classic total stations, the time-of-flight and phase-shift methods are used to measure distances with terrestrial laser scanners. The time-of-flight method sends out the signal, reflected by the object and sent back. The time required for this can then be used to determine the distance travelled. In the phase-shift method, the laser beams of different wavelengths are compared with each other and the distance is determined from the phase shift. Both methods have different advantages and disadvantages due to the respective measuring principle. In general, longer ranges can be achieved with the time-of-flight method, but the method is considered to be less accurate and more time-consuming than the phase-shift method (Kuhlmann & Holst 2017). Another difference is the possibility of multi-point detection. With the time-of-flight method, it is possible to detect multiple objects in the beam path, depending on the instrument and the software used (Schäfer 2017).

2.2 Resolution, footprint size and intensity

Two of the key characteristics of laser scanning is the resolution and the footprint size. The resolution, or more specific the scan density, indicates the distance between two measuring points and is therefore decisive for determining the limits of the detectable objects (Kuhlmann and Holst 2017). Figure 3 (left) shows an example of a narrow object. With the resolution 1 used, one measuring point still falls on the object to be measured, while with resolution 2 the object falls between two measured points and therefore cannot be detected. However, the laser spot that hits the object is not point-shaped, but describes a circle or an ellipse depending on the angle of incidence. These footprints typically have a diameter of several millimetres up to the centimetre scale at a respective distance. Here, the footprint size increases with increasing distance from the scanner. An overview of the different footprint sizes of the scanners used in this work can be found in Table 1. In combination with the scan density, this results in the pattern shown in Figure 3 on the right. In addition to the coordinates of a measured point, most laser scanners also provide an intensity or, in some cases, a reflectance value. These values provide information about the intensity of the reflected laser pulse. This intensity depends on the respective material, the incidence angle and, depending on the scanner, also on the distance from the object (Wujanz et al. 2017). The measured intensities thus represent an average over the entire laser spot and not the value of the directly represented measured point (Chaudhry 2021).

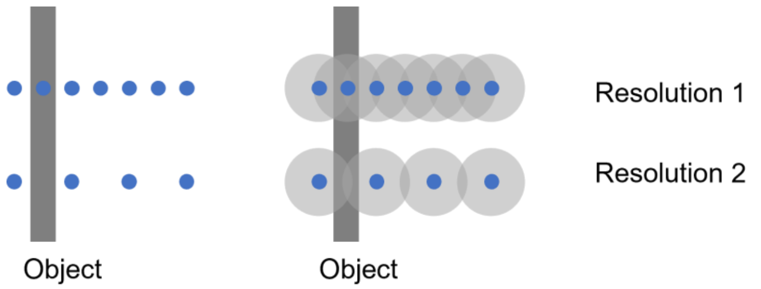

Figure 3: Small measurement object and the measured points in 2 different resolutions. The point centres are shown in blue, while the entire laser spot is shown in grey.

Due to the area-like spots, it is often the case that a spot does not lie completely on the object to be measured. The handling of these spots depends on the distance measurement method used. For time-of-flight scanners, the distinction between the first pulse and the last pulse is particularly important. The first-pulse method is mainly used by terrestrial laser scanners, as the object that the laser spot hits first is usually the object of interest. The last pulse is more common in airborne laser scanning when the ground is to be scanned and pulses from trees, for example, are not considered. This behaviour is also shown in Figure 4 on the left. The laser spot (blue) hits the edge of the object, part of the spot is now reflected by the front surface and part by the rear surface. This results in the two red measuring points. However, it should be noted that a separation between the first and the last pulse is only possible if the distance between the two objects is large enough compared to the length of the pulse. Otherwise, the pulses overlap and separation is not possible. Depending on the method and device, the corresponding pulse is now used as the final measured point. In most terrestrial laser scanners, a defined limit value for the required intensity is required. For the first pulse, the intensity has to exceed this limit value is then used as the measured point (in Figure 4 left, this corresponds to the front red dot). However, this limit value is not known for most scanners. If the intensity value is not exceeded the next pulse is regarded as the first pulse (cf. Figure 4 left, rear red dot). In addition to the first and last pulses, some scanners can also provide all pulses that exceed a defined limit value so that several distance measurements can be assigned to one angle measurement. This is for example possible with the Riegl VZ2000 (Riegl Laser Measurement Systems GmbH 2015).

Figure 4: Behaviour of a laser spot on an edge for a time-of-flight scanner (left) and a phase-shift scanner (right).

In comparison, the phase-shift method results in mixed reflections in the edge area. As a result, averaged distance measurements are carried out and measuring points can be located not only on the foreground or background, but also in the area in between. This is shown in Figure 4 on the right. The laser spot (blue) is divided here by the edge, with the red dots representing the measured points. Points are either located on the object or the background, which is shown by the two red points on the edge, or, most likely, they are located between the object and the background due to mixed reflection (centre red point). This effect is usually referred to as the mixed-pixel effect.

3. CASE STUDY

The aim of this work is to investigate how different scanners behave with regard to the possibilities of completeness of geometry detection. The test specimen utilized in this work is an element that was manufactured as part of the research presented in Gil Pérez et al. (2021). This is an object manufactured from carbon fibre bundles that were pre-impregnated with epoxy resin prior to production. The object has a size of 400 x 315 x 32.5 mm and has a curved structure. As the object has already been used for a load test, there are some gaps in the structure, which are not relevant for the analyses carried out here. The measurements were carried out with 3 different scanners: the Leica HDS7000, the Riegel VZ2000 and the Trimble X7. The scanners used are scanners that are generally intended for use in different areas of application. The Trimble X7 is intended for shorter distances, up to 80 m (Trimble 2020), whereas the Riegl VZ2000 with a range of up to 2 km is intended for use in longer distances (Riegl Laser Measurement Systems GmbH 2015). With a distance of 187 m, the Leica HDS7000 lies between the other two (Leica Geosystems AG 2011). The instrument settings and the measurement setup are illustrated in the following sections.

3.1 Instrument characteristics

To ensure the comparability of the measurements, comparable scan settings were selected for all scanners. However, due to the limited number of available settings, it was not possible to apply identical settings to all devices. An additional crucial parameter at this point is the resolution, which primarily determines the portion of the spot that lies on the object or background. The point spacing at a distance of 3 m and the respective resolution are shown in Table 1. Taking into account the resolution and the footprint size, it is possible to make an approximate estimation of the number of points in the fibre cross section. A distinction is made between the number of points whose centre is on the object and the number of points with a spot that partially hits the object. This estimation is also shown in Table 1. In addition to the scan settings and characteristics, the measuring principle for the distance measurement of the scanners used must also be mentioned at this point. The Leica HDS7000 measures with a phase-shift method, while the Riegl VZ2000 and the Trimble X7 use the time-of flight method.
In addition to the measured coordinates, all scanners also provide intensity values for each measured point. These are normalised values in the range between 0 and 1. However, the scanners' internal settings for these scalings are not known. For this reason, these values are only used for comparison within a scan and cannot be directly compared numerically between

different scans or scanners. For the Riegl VZ2000, it is also possible to directly analyse the reflectance values for which a distance-dependent correction has already been performed and information on the interpretation of the values obtained is also available. However, as this option is not available for the other two devices, only the intensities are analysed in more detail in this work.

Table 1: Resolution and spot size at the measured distance according to data sheet and personal communication with the manufacturer (Leica Geosystems AG 2011, Trimble Inc 2020, Riegl Laser Measurement Systems GmbH 2015) and the expected number of point on the object.

	Resolution at 3 m	Footprint size	Points on the object	Points with part of the spot on the object
Leica HDS7000	1.8 mm	4.4 mm	5	8
Trimble X7	1.5 mm	4.4 mm	6	9
Riegl VZ2000	2.1 mm	19.8 mm	4	14

3.2 Measurement Setup

In order to be able to compare the different instruments with each other, it was necessary to realize the same test setup for all instruments. Since in reality, especially for large objects, the angle of incidence varies greatly, the influence of this on the measurements should also be investigated. Therefore, the object was mounted on a turntable in order to investigate the influence of the angle of incidence on the possibility of detecting the object. The measurements were then carried out at a distance of approximately 3 m from the object. Furthermore, the scanners were positioned at the same height as the object. The configuration of the measurement setup is illustrated in Figure 5.

Figure 5: Measurement setup with the object in the initial position and the Trimble X7 laserscanner.

The scans were conducted with the object undergoing different degrees of rotation using each of the three scanners. The position of the scanner was maintained fixed, and the object was rotated in 10° increments from 0° to 90°, with the 0° point marking the initial epoch. To additionally examine the repeatability of the scans, the scans were repeated five times in the initial epoch. Given that the object surfaces to be measured are shiny black, the measurements were also carried out using the AESUB scanning spray for comparison purposes. This spray forms a matte white layer on the surface of the object. The layer thickness is specified by the manufacturer as 8-15 µm, which can be considered negligible in comparison with the expected measurement accuracy at this point (AESUB 2023) The scanning spray used in this work is applied to the measured object and sublimates after about 4 hours, depending on the environmental conditions.

3.3 Evaluation

Although the scans of all scanners were taken from the same point of view, the zero direction of the scans of different scanners is not identical. In order to be able to compare the individual scans directly with each other, a registration was carried out using black and white targets which were evenly distributed in the surrounding area. This made it possible to directly compare the individual scans. In order to be able to consider all influences directly, the data was used unfiltered for further processing. For the following evaluations, selected scans were additionally recalculated into the originally measured polar coordinates in order to be able to evaluate the foreground and background in relation to the angle measurement. In order to investigate the influence of the scanning spray on the edge detection of the object in more detail, the background of the object, or more precisely the shadow of the object, was examined in more detail.

4. RESULTS

The measurements carried out in this study are now analysed in terms of the differences between various scanners, the influence of the scanning spray and the influence of the angle of incidence. The focus of the evaluation is on the possibility of complete capturing of the object. In addition, the influence of the intensities on the measurements of the edge area is analysed in more detail.

4.1 Comparison of Laserscanners

When comparing the scanners, the effects caused by the small structures of the measured object are now considered in more detail. The difference between the various distance measurement methods is of particular importance here. The measurements are now first examined with regard to any mixed pixel effects that may occur with the individual scanners, which are to be expected due to the small object size. It turns out that this effect can only be observed with the Leica HDS7000, the only phase-shift scanner. Here, the object can be recognized three more times between the real measurement and the background (compare Figure 6).

Figure 6: Point cloud of the HDS7000 and the additional visible point clouds created by the mixed pixel effect.

This effect cannot be observed with the other two scanners. This confirms the effects described in section 2.2 when dealing with incomplete laser spots on the measurement object. This allows the effects shown in Figure 4 to be displayed directly here as well.
The complete capture of the test object using the three scanners is being investigated in this section. The scans of the zero epoch (0° incidence angle), which represents the geometrically best measurement configuration for this test are shown in Figure 7 in the top row. Here it can be seen that the completeness of the acquisition between the three scanners exhibits greater differences. The comparison of the individual scanners with each other shows that complete detection of the object without using a scanning spray was only possible with the Trimble X7. It is also noticeable that the gaps occurring in the measurements with the HDS and the VZ2000 occur at the same locations on the object as shown in Figure 7. As the measurement setup was identical for all scanners, this indicates that the angle of incidence on the object at this point may lead to problems with both devices.

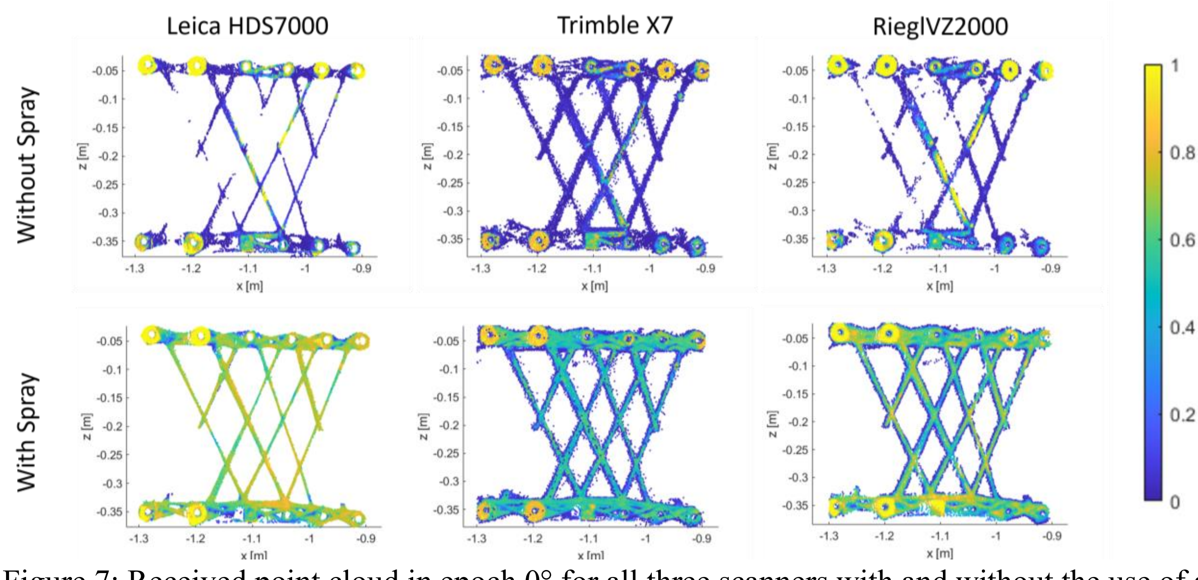

Figure 7: Received point cloud in epoch 0° for all three scanners with and without the use of a scanning spray.

4.2 Comparison of measurements with and without scanning spray

In order to be able to analyse the influence of the surface of the measured object, the measurements without scanning spray are now compared with those with scanning spray. The results for the measurements using the scanning spray are shown in Figure 7 in the bottom row. The measurements with the Riegl VZ2000 in particular show that the intensity decreases sharply towards the edge from 0.5 to 0.1, which indicates that the laser spot is no longer completely on the object at these points. The intensities will be investigated in more detail in section 4.4. In addition, the number of measured object points with and without the use of the scanning spray is now compared. These are shown in the Table 2. This demonstrates that the change in the number of points is smallest in percentage terms for the Trimble X7 measurements with 77% of the points for the measurement without spray. The largest deviation here is seen in the measurements of the Riegl VZ2000 with 62%. This can be explained primarily by the footprint size. The comparison of the measurement data from the Leica HDS7000 shows that a continuous detection of the object is possible with the help of the scanning spray. However, the fibre thickness recorded here is still significantly thinner compared to the other two scanners. In general, a significant increase of the measured points on the object is shown when using the scanning spray.

Table 2: Number of measured points for the measured object in epoch 0° and for the rotated measured object in epoch 50° with and without scanning spray for all three scanners.

Scanner	0° without spray	0° with spray	50° without spray	50° with spray
HDS7000	9031	12148	7757	11272
Trimble X7	23994	31077	17908	25328
Riegl VZ2000	10304	16709	3445	12246

4.3 Influence of the angle of incidence

Since in reality it is not always possible to achieve an ideal measurement configuration for all parts of the object, especially with larger objects, the influence of the angle of incidence is considered in more detail below. In the following, a rotation of the object by 50° is considered, as this corresponds to a frequently occurring measurement configuration in reality. This shows that the Trimble X7 and the Leica HDS7000 still return sufficient measured points on the desired measured object even at worse angles of incidence. However, the measurements with the Riegl VZ2000 show that detection without scanning spray is only possible with very few gaps.

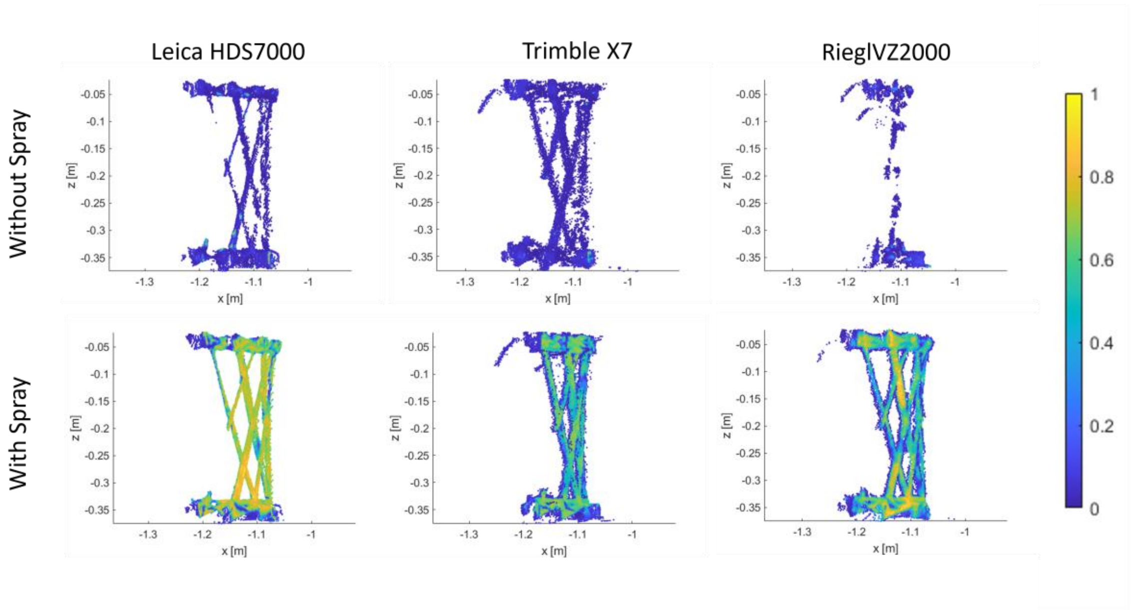

Figure 8: Received point cloud in epoch 50° for all three scanners with and without the use of a scanning spray.

If consideration is again given to the number of points on the object with and without the spray (cf. Table 2), it can be seen that the Trimble X7 still detects the most points on the object in percentage terms with 71%. However, the Leica HDS7000 follows just behind with 69%. This shows that there is only a percentage change of 5-6 % compared to the 0° position. A greater difference can be seen when looking at the Riegl VZ2000 data. Without the use of the spray, only about a quarter of the points can be detected.

In addition to the changes in the number of points on the object using the spray, the change in the number of points in the rotated state can now also be considered. It is noticeable that the number of points changes the least with the Leica HDS7000 and, with a rotation of 50°, 93% of the original number of points is achieved with the spray and 85% without. The Trimble X7 is also in the order of 75% with spray and 71% without the use of scanning spray. The Riegl VZ2000 shows the largest differences here with 33% with spray and 28% without spray. This directly confirms the visual impression that detection with the Riegl VZ2000 is no longer complete in both scenarios as the angle of incidence increases. This behaviour can be observed due to the large footprint size of the Riegel VZ2000. As a result, only a small part of the spot falls on the object. Due to the limit values of the intensities (cf. section 2.2), the measured points are no longer assigned to the object.

4.4 Investigation of the intensities and edge areas of the measurement object

In addition to the completeness of the acquisition, the intensities are now also considered in more detail. It is assumed that the intensities should decrease towards the edge of the object, as only incomplete spots occur at this point. For this purpose, two smaller sections of the point cloud are now examined in more detail. These are spatially at approximately the same height and are mirrored to the axis through the centre of the object. The selected areas are shown in

Figure 9. Due to the curvature of the object, different angles of incidence can be observed through the two sections, which may have an influence on the intensities

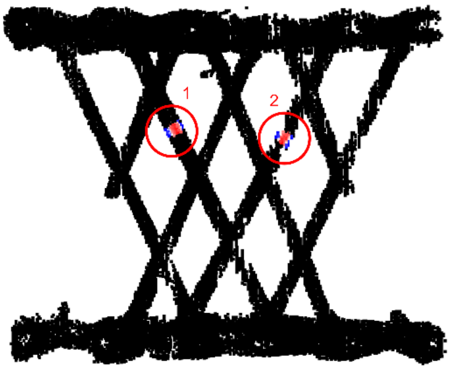

Figure 9: Point cloud of the test object with the two selected sections 1 and 2.

Since capturing with the Leica HDS7000 proved to be difficult in both scenarios (with and without scanning spray), only the Trimble X7 and the Riegl VZ2000 will be considered further in the following. The selected sections are shown in Figure 10. An examination of the point cloud slices for section 1 shows that a rising and falling gradient of intensities is visible in the course of the fibre cross-section, especially in the measurements of the Riegl VZ2000 using the scanning spray. Without the use of the spray, a difference between the edge points and the points in the centre of the fibre bundle is still visible. This difference is also observed with the Trimble X7 using the scanning spray. This clearly shows that there is no smooth transition between the intensity values, but rather a sudden change. Without using the spray, there is no visible difference in the intensities.

The second area shows the strongest intensity in all scans, as the measuring beam hits the object at an almost perpendicular position. A gradient of intensities can be observed here for all four measurement scenarios considered. Here it is particularly noticeable that the intensities without scanning spray are stronger than those with scanning spray. This effect can be observed for both scanners. A possible explanation for this could be that the shiny surfaces of the object are highly reflective when hit perpendicular and therefore a stronger reflection is possible compared to the white matt surfaces using the scanning spray. This effect is additionally strengthened by the fact that more points are measured in this section without the use of the spray than with, which contradicts the general trend over the entire object as shown in Table 2. Another observation in this section is that the edges of the fibre bundle are more clearly defined without using the spray. This is particularly visible with the Riegl VZ2000.

The respective size of the point cloud can now be viewed for both sections. This shows that there is a difference between the scenarios with and without scanning spray, especially in section 1. The crucial point here is the internal handling of the received pulses by the devices. While several pulses can be received and evaluated with the Riegl VZ2000, the Trimble X7 only delivers one measured point at a time. This corresponds to the first pulse received that exceeds a defined limit value described in section 2.2.

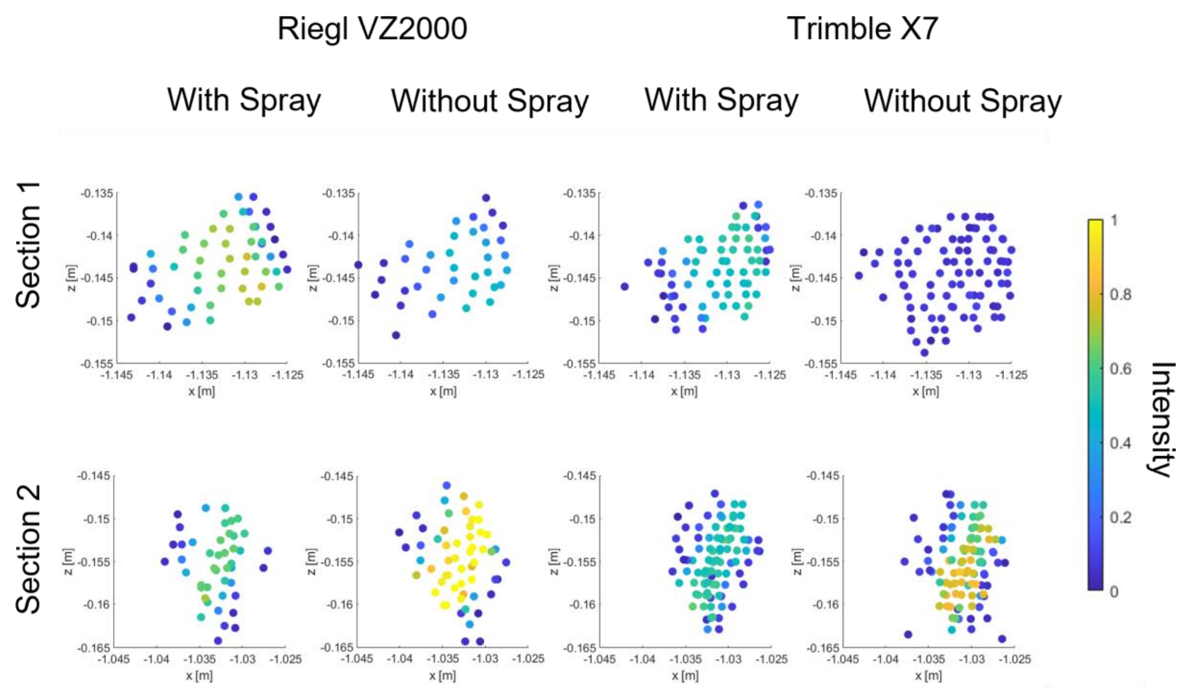

Figure 10: Point clouds with displayed intensities for sections 1 (top) and 2 (bottom) for the measurements with the Riegl VZ2000 and the Trimble X7 with and without scanning array.

As the footprint size is quite large compared to the object size, only a few spots lie completely on the object. Most measurements are therefore mixed reflections. This is also the reason why the intensities decrease towards the edge. Due to the different reflectance properties of the object with and without spray, as well as depending on the angle of incidence of the measuring beam, the geometric conditions change when a point is placed on the object and when the measured point is placed on the background. As the Trimble X7 provided the most promising results for this application in the previous analyses, the shadow of the object is now also examined more closely for the Trimble X7 measurements.

Figure 11 shows the shadow of both point clouds. The boundary areas are of particular interest here, as this makes it possible to determine how many additional points are captured using the spray and thus also the order of magnitude of the change in the captured geometry. A closer look at the shadow shows that the shadow is generally larger when using the spray. This is due to the fact that there are more points on the object in this case, which also confirms the observations from Table 2. However, it also shows that these effects do not occur evenly across the entire object. It is also visible that the smallest differences occur in the area of section 2, where the measuring beam hits the object almost perpendicular. This shows that the angle of incidence on the measurement object increases the influence of the limit value for the intensities and thus results in greater differences between the measurements with and without scanning spray.

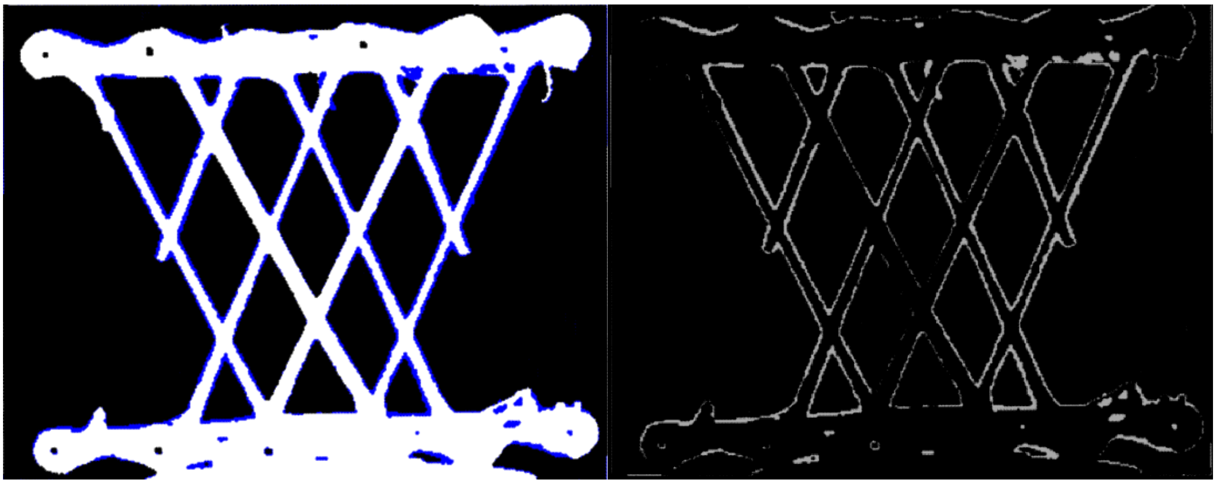

Figure 11: Left: Shadow of both point clouds (Trimble X7 with (black) and without (blue) scanning spray), Right: Difference of the shadow images of both point clouds with the differences in white.

In addition to the occurrence of the differences, the size of the differences is also important. This also allows the differences in the captured geometry of the object to be examined more closely. As previously mentioned, the deviation is not the same across all areas of the object. In most regions, however, differences in the order of magnitude of two measurement points can be determined at the edge of the object. With a point spacing of 1.5 mm at the distance of the object (see Table 1), this means a difference of 3 mm at each object edge. Since this effect must now be considered twice for the total geometry, as the effect occurs on both sides of the fibre bundle and can therefore add up to 6 mm, which has an enormous influence for an object size of 1 cm. The larger influence of the geometry on the detected object size depends on the small object size, the footprint size and the device's internal limit values. If the recorded width of the fibre bundle is compared with mechanical measurement methods such as a calliper it is shown that the Trimble X7 measurements without scanning spray provide the best representation of the geometry of the object.
However, it has to be noted at this point that only measurements from one instrument site are considered here. In addition, as mentioned in section 3.3 the unfiltered data is considered first for better comparability and to analyse the measurement effects.

5. CONCLUSION AND OUTLOOK

The investigations carried out in this work show that it is possible to detect the individual fibre bundles using TLS. However, the quality and completeness of the measurements is highly dependent on the scanner used. It is shown that a time-of-flight scanner provides a more complete detection compared to the phase-shift scanner used. The influence of mixed reflections is given and therefore only an incomplete detection of the object can be achieved. As measurements are carried out at close range, it also became apparent that this corresponds

to the intended measuring range of the Trimble X7 and that the Riegl VZ2000, with its strengths in measuring large distances, is not suitable due to the resulting very large footprint size.
The surfaces of the object can be captured due to the high point density and the close-up range. In contrast to many other applications, the overlapping of the laser spots is desirable in order to obtain as many points as possible on the object and to be able to filter them accordingly later. In addition to the comparison of different scanners, the influence of the scanning spray and thus the change in the reflectance properties of the object was also examined in more detail in this work. This showed that the scanning spray made it possible to detect the object continuously with all three devices, but that the measured fibre width showed clear geometric differences. Obviously, it is visible that a larger fibre width is detected for all scanners in the measurements with spray compared with the measurements without spray. Initial investigations showed that the results without the spray fit the expected dimensions of the object better. In addition, the influence of the angle of incidence on the measurements was investigated. This shows that a smaller footprint size is preferable for larger incident angles, as this ensures a more complete capture of the measurement object.
In conclusion, the comparison of the scanners examined showed that the Trimble X7, of the scanners examined here, is best suited for this application scenario. However, further investigations are necessary in order to be able to make a final statement regarding the differences of the captured geometry.
For further investigations, a complete survey of the object has to be carried out from several points of view. These measurements would also provide different angles of incidence of the measuring beam on the object, which can compensate for inaccurate point measurements due to the high point density. This also makes it necessary to select a suitable filter to eliminate outliers. Another important point for the further work is the creation of a reference of the measurement object in order to carry out an evaluation of the captured point cloud in relation to the real geometry of the object. For this purpose, methods of industrial measurement technology, such as the use of a strip light projector (GOM - Optical Measuring Techniques 2010), could be used to capture a reference geometry and to compare the captured geometry with the reference using TLS (with and without scanning spray).

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