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Geometric inspection of 3D production parts in shipbuilding – comparison and assessment of current optical measuring methods

Master thesis

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Declaration for the Master's Thesis

I confirm that this Master's thesis is my own work and I have documented all sources and material used. This thesis was not previously presented to another examination board and has not been published.

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ANNOTATION

Ivan Brusak

This master thesis considers the comparison and assessment of current optical measuring methods for the geometric inspection of 3D production parts in shipbuilding.

Studiengang Geodäsie und Geoinformatik

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Lviv 2018

The master thesis includes the following sections:

1. Introduction;
2. Laser Tracker Measurements;
3. Laser Scanning;
4. Photo-based Scanning;
5. Handheld Scanning;
6. Comparison and assessment of optical measuring methods;
7. References

This work presents the use of current optical three dimensional measuring methods, such as laser tracker measurements and laser, photo-based and handheld scanning. The recommendations for optimal settings of using equipment and software products in this research are included. The results of accuracy comparison for the geometric inspection of 3D production parts in shipbuilding and assessment of the cost and time spending are added as well.

The master thesis contains 6 tables and 40 figures.

Keywords: optical measurements, non-contact methods, 3D, geometric inspection, laser tracker systems, laser scanning, close-range photogrammetry, shipbuilding.

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ABSTRACT

Trends of the optical three dimensional measurements are, nowadays, regarding to the high accuracy, small price, real-time processing and equipment portability. In connection with the improvement of old methods and appearance of new one, there is a strong need to compare them for finding the best solving a specific task. The master thesis includes implementation, recommendations and optimal settings, current optical three dimensional measuring methods such as laser tracker measurements and laser, photo-based and handheld scanning for the geometric inspection of production parts in shipbuilding.

The main objective is to find out if the accuracy of 3D mesurments with laser scanning with Z+F Imager 5016 and Laser Control software, industrial photogrammetry with Nikon D2Xs camera with the Agisoft PhotoScan software and handheld scanner DPI-7 is enough for the final measurements of the adhesive angle of the ship. The estimate of the metrological and evaluation efforts of each method is also important.

The measurements were made in one of the halls of Ostseestaal company in Stralsund, Germany with a help of co-fellows geodesists and instruments from Engineer Team Nord company (ITN) and Neubrandenburg and Bochum Universities of Applied Sciences.

The comparison of the mesh models in 3dReshaper, based on the point clouds calculated in Laser Control, Agisoft PhotoScan and Phi.3D softwares and the data from laser tracker Leica AT960LR as ideal geometric description of the detail should be analyzed. Time and cost estimates for the four optical surveying methods will be presented.

1. INTRODUCTION

1.1 OPTICAL 3D MEASUREMENTS TRENDS

Through the last decades there has been a transition from two dimensional (2D) to three-dimensional (3D) models as well as the development of new optical methods for 3D measuring increased in a large number. In their work M. R. Shortis and C. S. Fraser (1986) state that "the discipline (3D measurements) has been and will continue to be driven by the requirements of the aerospace, aircraft, ship building and other large-scale manufacturing industries because of the demand to meet stringent measurement accuracy and productivity requirements". Now, almost 30 years after the published article, there is a strong need to consider and compare the precision, reliability and cost aspects of both traditional and young methods with which we get the three-dimensional coordinates of the object. For the real-time work of last decade possibility and portability of the device have been playing a significant role for customers and performers.

In general, the 3D object measurements and reconstruction techniques can be divided into contact methods (non-optical) and non-contact methods (optical) (Remondino F. and El-Hakim S., 2006). The use of coordinate measuring machines, measuring arms, callipers, rulers or bearings can be an example of the contact methods. The contact methods are mostly popular for the small objects or objects with complex construction (motors in cars). This investigation concerns optical measurements, which can be more portable and can be used for the details in the size more that 10m in length and 4m in width, based on light waves for the shipbuilding production parts.

There are a lot of non-contact techniques for industrial needs, such as time-of-flight and phase measurements that can guarantee submillimeter resolution and laser interferometry that determinates distances as precise as 10^{-7} m in stable atmospheric conditions. For close-range measurements the principle of triangulation and related techniques, like light sectioning and projected fringe methods, can be used as well (H.J. Tiziani, 2000). Moire techniques and white-light electronic speckle interferometry, correlation-based stereovision method (D. Garcia, 2001) are accurate enough even for some deformation analysis of the shapes and engineere surfaces (X. Su and Q. Zhang, 2009; F. Chen et al., 1999). Most commercial systems for 3D shape scanning are based on structured light projection or laser stripe projection (Cui Y. et al, 2010).

Remondino F. and El-Hakim S. (2006) say that the all optical methods can also be divided into two groups, based on the use of active or passive sensors (Fig. 1.1). The spatial data collection techniques based on active sensors provide their own energy for spatial information retrieval. They transmit some form of energy. When the transmitted energy meets an object, it is reflected back and the return energy signal is used to determine the objects` spatial information in the scene (Teizer, 2008). Methods which are using active sensors include triangulation (projection of single spot, lines, grids or 2D-patterns) or measuring with time delay / phase shift (interferometry, time-of-flight). Using of the photogrammetry, videogrammetry, focus/defocus, shapes from shading, silhouette, edges or texture relation to methods with passive sensors.

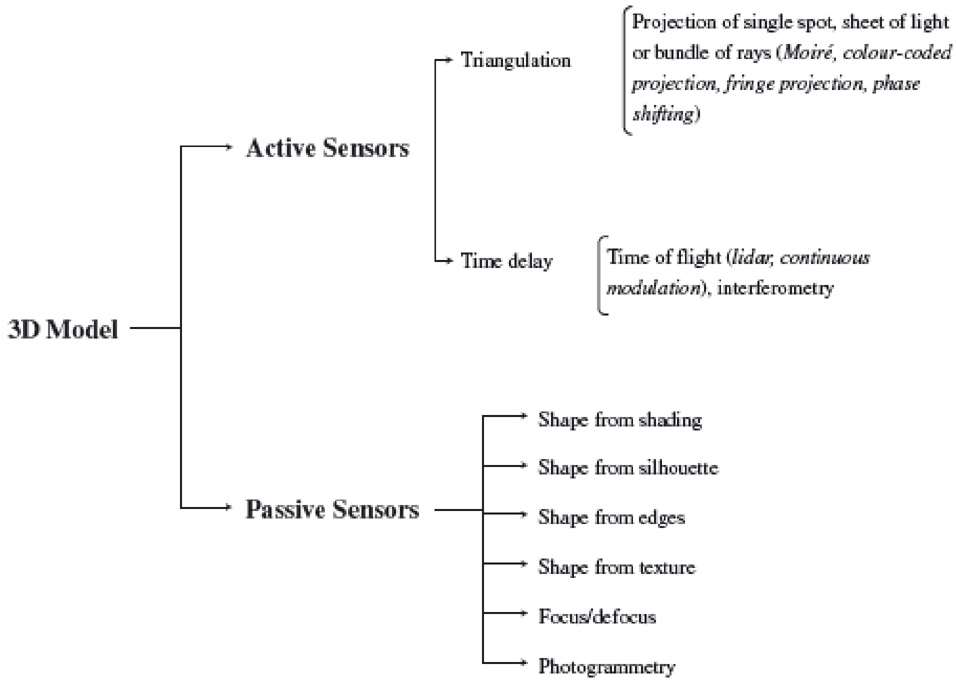


Fig 1.1. *Three-dimensional acquisition systems for 3D object measurements using optical methods based on light waves (Remondino F. and El-Hakim S., 2006).*

This study describes in detail the laser tracker measurements, laser scanning, method of the industrial photogrammetric and handheld 3D scanning for production parts in shipbuilding. A brief overview of other methods for optical 3D measurements is also presented in this section.

Laser tracker measurements are well known and developed from the middle of the last century. Laser tracking is the current trend for precise constructions in shipbuilding, aerospace, automotive, etc. because it provides real-time solutions for determination of the three-dimensional coordinates. (H. Meagher, 2014) However, the instruments and software are still more expensive compared with other techniques. The measuring principle and an example of the workflow with laser scanners are shown in the Section 2.

Nowadays terrestrial laser scanners have a wide use in the engineering applications, for architecture restoration, 3D-mapping, criminalistics, image capturing of road accidents, etc. This optical method gets the information very fast (around 1 million pixels per second) and needs a reliable post processing. Some of the practical aspects of measurements, calculations and work principles are explained in the Section 3.

Industrial or close-range photogrammetry or the photo-based scanning was first employed in the 1970s for non-topographic application and became widespread, particularly for architectural and heritage recording (Shortis M. R. and Fraser C. S. 1991). Nowadays with advanced CCD or CMOS sensors and fully automataised software solutions for processing a big quantity of data, the industrial photogrammetry is more and more popular because it is not expensive equipment and it is simple in its use. The measuring principle and the examples of the close-range photo-based scanning are shown in the Section 4.

Handheld 3D-scanning, e.g. with the new equipment of DOT product, is one of the easiest ways to get a three-dimensional model of the objects for a non experienced surveyor. It's the youngest technique of those listed above and in accordance the least investigated so far. The measuring principle and the results of the handheld 3D scanning are shown in the Section 5.

Pattern projection and moire techniques are also developing for 3D object modeling. The basic moire principle uses two precisely matched pairs of gratings. The projected light is spatially amplituded and modulated by the grating, and the camera grating demodulates the viewed pattern and creates interference fringes whose phases are proportional to the range (Asundi, 1993). Pattern techniques use multiple stripes or patterns projected on the object. Liquid crystal display pattern projection systems create a magnified image of the projector pixel on the object, limiting lateral resolution but providing simultaneous measurements in a single video frame. Depth volume is limited by the defocusing of both projection and detection (Blais F., 2004).

The most popular methods for pattern projection use binary coded or phases shift fringe patterns. Full-field fringe projection techniques are developing nowadays because of the advantages of optical operation, full-field acquisition, precisions, automatic and fast data processing. (Gorthi S. and Rastogi P., 2010). The fringe patterns can be sinusoidal, binary or Ronchi, triangular, trapezoidal, etc. (Zhang Z.H., 2012).

An interesting investigation of the building three-dimensional models of objects was made by (Cui Y. et al, 2010) using time-of-flight cameras. The result is that "3D scans of reasonable quality can also be obtained with a sensor of such low data quality". This example is not demonstrating a millimeter precision, but it shows that there are a lot of established filtering and scan alignment techniques for 3D scanning.

The computer tomography metrology is used for 3D modeling of small objects. Gapinski B. et al. (2013) says that the obtained measurement accuracy of tomography X-ray, optical scanner and coordinate measuring machine are converging (the maximum difference is 0.05mm). Furthermore, X-ray method is better than optical scanner for deep holes in the object, because for the laser technology there is a lack of some part of information.

Finally in the last 5 years mobile phones or tablets have become 3D measuring devices. Project Tango authored by the Advanced Technology and Projects, a skunk works division of Google, initially was released in June 2014. This software works by integrating three types of functionality, such as motion-tracking, area learning and depth perception. First up is motion tracking, which allows the device to understand its position and orientation in a certain environment, using accelerometer and gyroscope sensors. The next step is the depth perception, which examines the shapes around you and gains accurate gesture control and snappy 3D object rendering among other things (for example with Intels' RealSense 3D camera). At the end the area learning, this means that it maps out and remembers the area around it (Mundy J., 2017). Kalyan T.S. et al. (2016) compare Project Tango with the laser scanning and close-range photogrammetry. The conclusion is that "Project Tango has potential to be used, particularly on small size and low budget projects", but the absolute errors up to 0.35 m does not satisfy the level of the accuracy measurements.

In the last years the dynamic optical 3D shape measurement method is discussing. Su X. and Zhang Q. (2010) and Legarda-Saenz R. et al. (2010) demonstrated calculating using the analysis and principles of Fourier transformation to obtain the dynamic phase map from a vibrating object and dynamical changes of the objects shapes. Wujanz D. published the thesis "Terrestrial laser scanning for geodetic deformation monitoring" (2016) that includes methods and models for dynamic scanning.

Summing up there is a lot of optical 3D object measurements methods on the market now and more instrument and software solutions are being developed and improved. Trends are regarding to the high accuracy, small price, real-time processing and equipment portability. In connection with the improvement of old and appearance of new methods there is a strong need to compare them for finding the best solving a specific task.

1.2 Production of the adhesive angle of the ship

The practical part of this master thesis was made in one of the halls of Ostseestaal company in Stralsund, Germany with a help of co-fellows geodesists and instruments from Engineer Team Nord company (ITN). My working contract in Ostseestaal company lasted 6 month from 01.03.2018 to 31.08.2018.

The research of this paper is focused on a comparison of the final measurements of a special part of an adhesive angle of the ship (Germ. *klebewinkel*). This detail was specially made for the investigation. It is an analog of the production part of the ship demonstrated below.

The adhesive angles of the ship are produced in one of the halls of Ostseestaal company in Stralsund, Germany. This detail is 40 meters long, similar to a triangular shape, made of steel and consists of five sections (A,B,C,D,E). Construction of whole detail takes about one month. There are two stands for adhesive angles of the ships in this hall (fig.1.2).

In general, the building plan for every section of the detail comprises of the following stages:

- Orientation and fixing of the base plate on the stand;
- Construction, correction and welding of a metal build table;
- Coating of the metal table with a continuous layer of metal (called hot frame);
- Assembly of a cold frame, that consist of welding metal girders and joists;
- The connection of the cold and hot frame (fig. 1.3);
- Marking pockets and protrusions on the cold frame;

- Final corrections, welding and grinding.

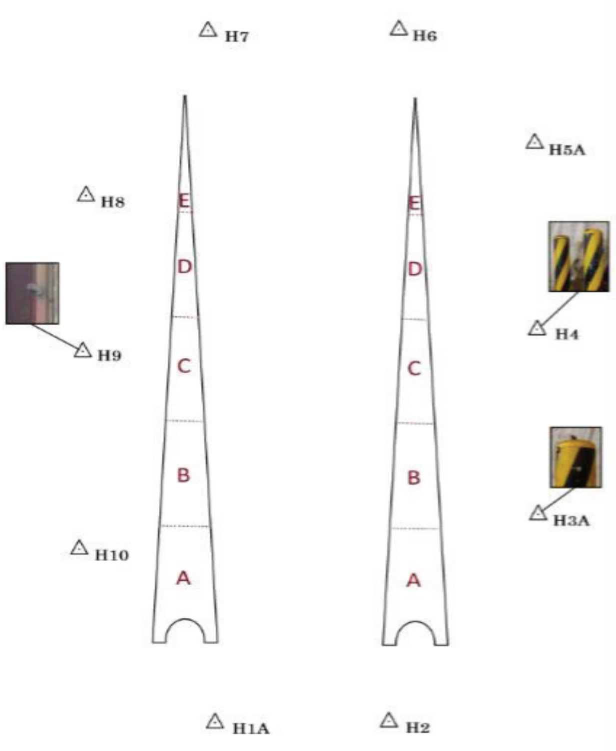


Figure 1.2. *Scheme of the location of the details with sections and ten geodetic rappers in the hall (author, April 2018)*

Figure 1.3. *Connected cold and hot frame of the adhesive angle of the ship. The detail is located between two stands for hot frame. View from the section A (photo author, April 2018)*

The tolerances for the deviation of the theoretical and measured part of the section should not exceed ±2 mm. Such final accuracy requires precise measurements from the beginning of the construction, precision and reliable equipment and good specialists, such as surveyors and workers.

That's why the adhesive angle of the ship is a good example for the inspection and comparison of 3D elements, with different measuring methods.

The final measurements, which include the control of the top and two sides of the special analog sample part (fig. 1.4), are the task which should be done and compared with different equipment. The size of this detail is 2.027 m length, 1.950 m wide and 1.045 m high. The metal table is constructed of seven ribs. There are 14 marked points, two points on each of the edge, in the center of the upper side of the sample part. The part of the detail that is shown on the left side of the figure 1.4 is milled and includes the special pocket.

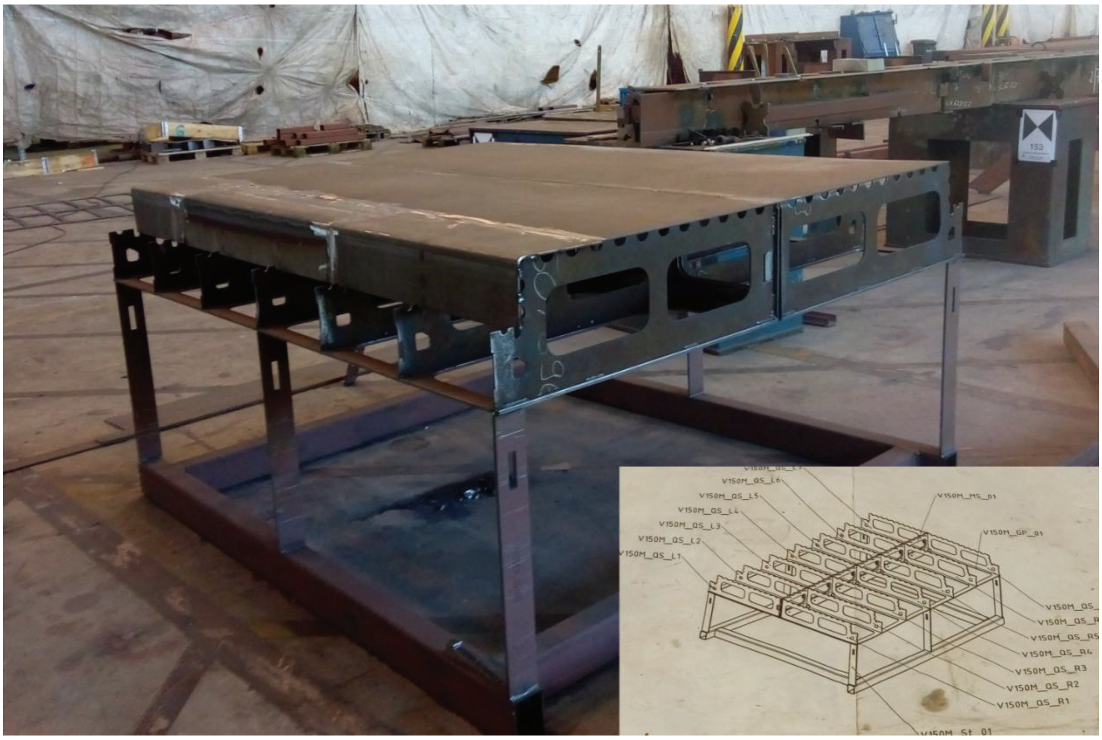


Figure 1.4. *The special analog of the adhesive angle of the ship for the measurements with different optical methods (photo author, May 2018)*

1.3 Study and its Contribution

As the use of different methods for three dimensional measurements grows, the need to analyze their advantages and disadvantages increases as well. The preference of suitable equipment usually can save work and process time, money and number of workers.

The aim of this thesis was to inspect 3D production parts in shipbuilding with different methods, such as laser tracker measurements method, handheld, laser and photo-based scanning methods. The accuracy of the results of metrological and evaluation efforts is also important.

Recommendations for optimal settings of equipment and software products for four current methods are included.

2. Laser Tracker Measurements

2.1. General concept of laser tracker measurements

Nowadays laser trackers are extremely popular as equipment for precise measurements in a wide range of industries, such as automotive, shipbuilding, aerospace, energy, etc (H. Meagher, 2014). This fact is connected to the ability of laser trackers to capture large volumes of 3-dimensional coordinates in real-time with a high accuracy of point positions, and of course portability due to the small size of the instruments.

Laser trackers use a spherical coordinate system (fig.2.1). So every measuring point has three specific numbers:

1. The radial distance *d* between the point and the laser tracker;
2. The zenith angle φ, which means elevation;
3. The azimuth angle θ, means on a reference plane that passes through the tracker and is orthogonal to the zenith.

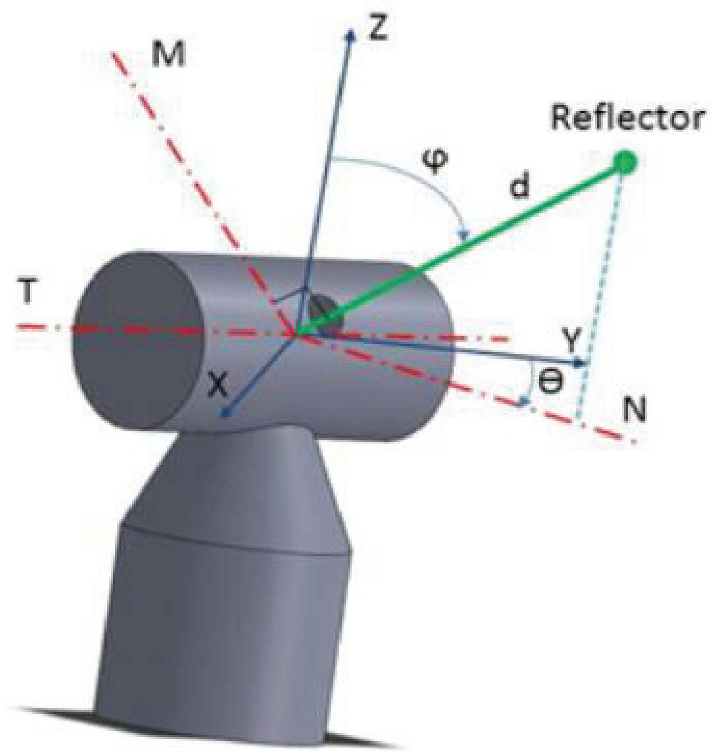


Figure 2.1. *Laser Tracker measuring principle* (Conte J. et al., 2013)

The radial distance *d* is determined by an interferometer, an absolute distance meter or a combination of the two. The absolute distance meter means, that the radial distance *d* is measured with a modulated infrared laser by using time-of-flight and phase measurements. This method is less accurate than the interferometer method, does not require a known starting point to calculate the radial distance. With the interferometer the laser tracker uses its internal displacement measuring interferometer to calculate the distance that the reflector moves from a known location to its current location by counting interference fringes.

The numbers for the zenith and azimuth angles are determined by means of two angular encoders which measure the orientation in the tracker's gimbals along its mechanical axes. A laser trackers` ability to measure angles is less accurate than its ability to measure the radial distance. The angular accuracy is limited by the tracker's intrinsic measurement accuracy and by refraction of the beam due to temperature variations and air turbulence in the measurement environment (Gassner G. and Ruland R., (2009). The turbulence causes small changes in the refractive index n, resulting in small errors in the measured radial distance d but significant deviations in the laser beam direction. T. Zobrist (2009) declares, that the three dimensional accuracy of measuring the position of the reflector is typically limited by these angular errors.

For a deeper understanding of work principles of laser tracker the schematic representation of the internal processes is shown on the figure 2.2.

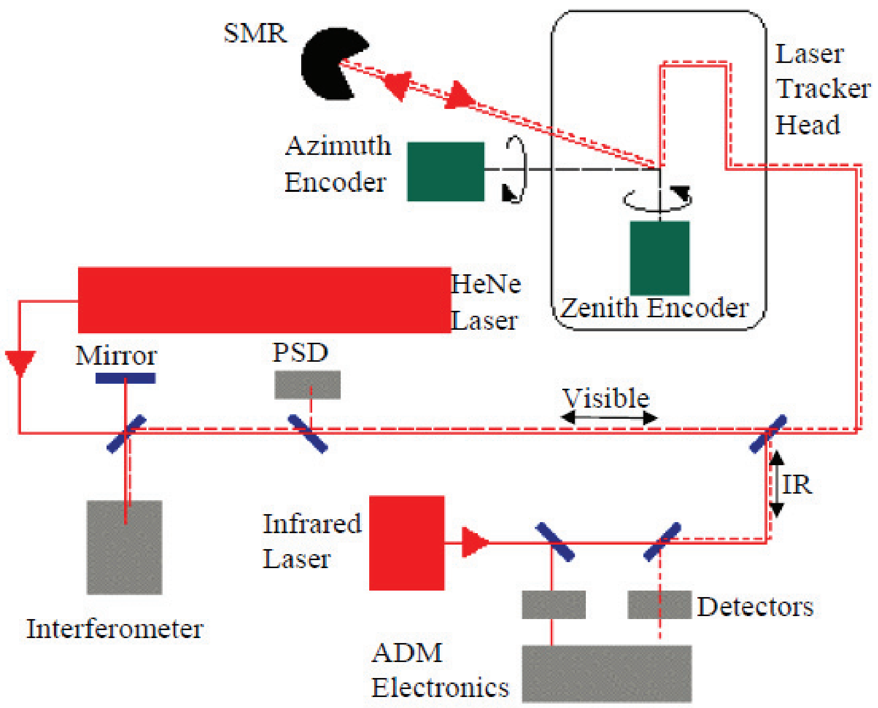


Figure 2.2 *Schematic representation of work principles of a laser tracker* (Zobrist T., 2009)

In a typical measurement sequence, the metrology engineer moves the reflector (e.g. a corner cube prisma) to the desired location on the production part and the laser tracker optics follows with the "laser beam" remaining fixed to the center of the reflector. As the reflector is moved, the laser tracker records the distance, azimuth and elevation. Using elementary matrix mathematic it is possible to transform the measured spherical coordinates (d, θ, φ) to other coordinate systems like cylindrical (ρ, θ, z) or Cartesian (x, y, z) for further processing. Cartesian coordinates are sent to a metrology software application to process (J. Conte et al., 2013).

There are a number of good 3D metrology software solutions available for laser trackers. In this work, Leica Tracker Pilot and Spatial Analyzer are considered in detail. With the use of any of the software solutions, collected data of coordinates can be converted to geometrical features such as points, planes, spheres or cylinders. These features can then be referenced to define datums for position, form, parallelism, perpendicularity, concentricity, circularity and cylindricity. Typically, the data can be presented sufficiently fast instantly – enabling CAD-to-part comparison in real-time (H. Meagher, 2014).

2.2. Leica Absolute Tracker AT960-LR

In the summer 2018 the Leica Absolute Tracker AT960 is a flagship laser tracker of Hexagon Manufacturing Intelligence. This precise and all-in-one portable metrology of a laser tracker offers high-speed dynamic measurement. It is, overall, a solution for different types of 3D measurements, such as probing, scanning and automated inspection.

The Leica Absolute Tracker AT960-LR (fig. 2.3) is a long-range laser tracker model of the AT960 series. With a 3D measurement volume of up to 160 meters in diameter and a 6DoF measuring volume of up to 40 meters in diameter, this model is designed to deliver high-performance speed and accuracy to users taking measurements across a large volume of measurements.

Figure 2.3. *Leica Absolute Tracker AT960-LR in the work process* (photo author, March 2018)

The AT960-LR delivers features such as:

- **Power Lock function** – an automatic measurement-point detection function of tracking in a +/-5 degree field of view with no user interaction required for ease of use and exceptional performance.

- **Data collection at up to 1000 points per second** with real-time architecture and dynamic performance.
- **All-in-one design** – a possibility of this the compact and easy transportable unit to do measurement to a reflector, Leica T-Probe, Leica T-Scan or Leica T-Mac.
- **Built-in Wi-Fi** enables simple setup and communication with the PC for wireless operations, also providing remote control options via laptops, tablets or smartphones, so the tracker can be operated by a single user.
- **High-resolution overview camera** enables operators to remotely view the tracker's field of vision and locating targets to measure to fixed reflectors.
- **Integrated MeteoStation** monitors environmental units conditions including temperature, pressure and humidity to compensate for changes and ensure accurate measurements inside the operating conditions.
- **Absolute Interferometer** (AIFM) combines the accuracy of an absolute distance meter and the speed of an interferometer to give readings quickly and accurately with no need for a home point.
- **The Orient to gravity function** enables users to measure with the Z-axis aligned to gravity, ideal for levelling and alignment tasks such as build and inspect of tool and jig fixturing.
- **Integrated mini variozoom**, that enables to provide 6DoF measurement capabilities for accurate probing, scanning and machine control applications in any light conditions.
- Full **IP54** environmental protection.
- System weight of **14 kilograms**.
- Optional **hot-swappable battery power** capability.

AIFM technology allows high accuracy across a range of measurement modes. There are some published datasheets with mean square error (MSE) values and other data about accuracy of Leica Absolute Tracker AT960. E.g.:

- The MPE for interferometer accuracy equals ± 0.4 μm + 0.3 μm/m.
- Maximum distance uncertainty of 10 microns.
- The MSE for angular accuracy equals ± 15 μm + 6 μm/m.
- Measurements to the classical reflector or sphere mounted reflector (SMR) accurate to within 15 microns.
- Measurements with Leica T-Probe accurate to within 35 microns.

It is to be noted, that these are isolated manufacturer accuracies, and that the overall system chain accuracy for a specific measurement task needs to be determined in a field check.

On the figure 2.4 the example of the instruments connection is shown. Laser tracker should be fixed on a tripod. The sensor of the air temperature should be as possible near the instrument.

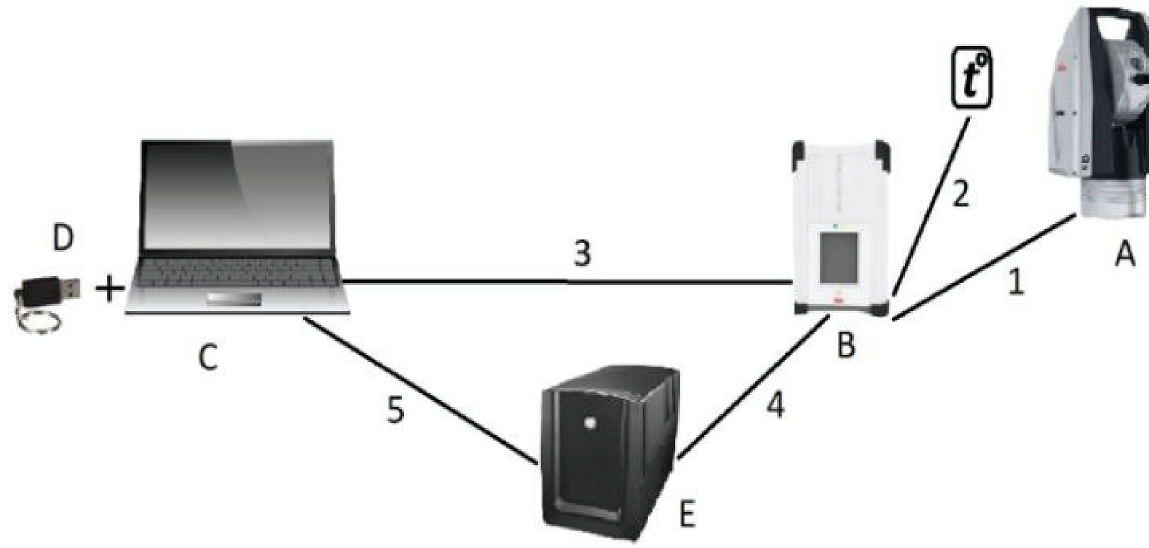


Figure 2.4. *Schematic representation of the instruments connection for laser tracker measurements*

(author, March 2018)

A – laser tracker, B – controller, C – laptop, D – flash drive with software license, E - uninterruptible power supply (UPS), 1 – power and data connection 2 –sensor for the air temperature , 3 – LAN-connection for data transmission, 4 – power connection of the instrument, power connection of the computer.

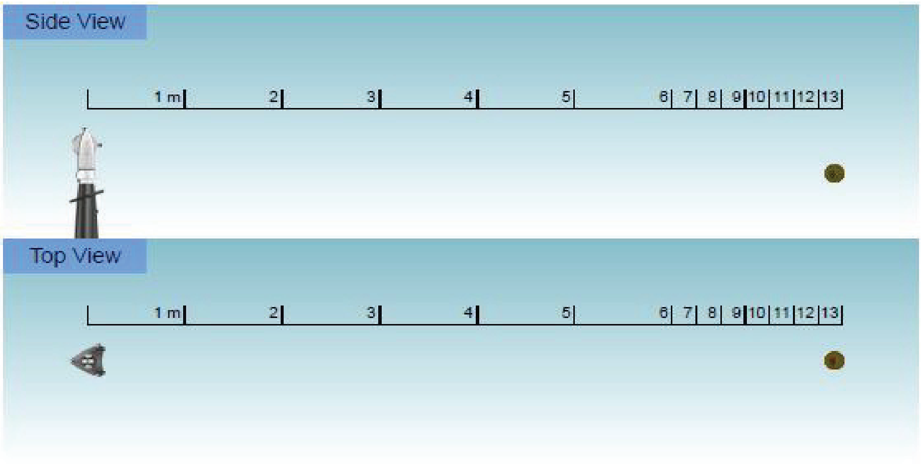
2.3 Workflow in Leica Tracker Pilot Software

The Leica Tracker Pilot provides a graphic user interface to the Leica Absolute Tracker AT930/AT960 for checks, compensations, system maintenance processes and for making reports of those processes.

Before taking measurements it's important to make different checks of the instrument including a field check. The field check enables to find out which accuracy can be achieved under the current environmental conditions with desired settings of a user-specific workflow.

For the measurements of this thesis a Leica Absolute tracker and Red Ring Reflector 1.5 Inch as active target chose were used. After starting Leica Tracker Pilot on the computer an initialization of the laser tracker and the choice of a reflector were made. It is possible that the program takes some time in order for the laser in the instrument to warm up. When the reflector was installed on a pylon and found with the overview camera, the two face field check was made.

The two face field check verifies the angular performance in the current environment using application specific settings. A free setup of two face measurements covering the intended measurement volume is recommended. For the field check there is a need for at least 5-times measurements in two faces, to be valid. The report on 23.05.2018 from Tracker Pilot for working on the detail is shown on the figure 2.5.



Id	U(95) [mm]	3D Deviation [mm]	Target
1	0,014	0,072	BRR 1.5in
2	0,032	0,094	BRR 1.5in
3	0,018	0,099	BRR 1.5in
4	0,017	0,113	BRR 1.5in
5	0,017	0,073	BRR 1.5in

Figure 2.5. *The report of two face field check on 23.05.2018 from Tracker Pilot*

In this case the tolerance for 5 measurements is 124%. The Meteo data is included in the report: temperature was 18.3°C, pressure was 1023 hPa, humidity was 59%.

In case a two face check is "Not OK", that means that the 3D deviation tolerance of at least one measured reflector position is exceeded, it is recommended to assure stable environmental conditions and to check the quality of the used hardware accessories. Then repeat the Two Face Check. Based on practice the acceptable result cannot be often achieved even after the repetition, and then the engineer can confirm the last one.

2.4 Workflow in Spatial Analyzer Software

Spatial Analyzer is a large and complex application with a wide range of measurement applications and has the possibility to work with laser trackers, total stations, laser scanners, etc. This advanced metrology software made by New River Kinematics Company, Virginia, USA that from 2012 is the subsidiary of Hexagon Manufacturing Intelligence.

For starting work with Leica Absolute Tracker AT960 the instrument should be initialized. The next step is positioning – fixing position of the instrument to the measuring detail or to the pylons with known coordinates. For this purpose SMR 1.5 inch and standard measuring mode can be chosen.

After measuring ten stable points on the pylons it is possible to automatically change their names and recalculate them with best-fit transformation (fig. 2.6). If the maximum error is less than 0.3 mm, best-fit transformation can be accepted for final measurements process.

In the case of including CAD model of the section the next actions can be made. We worked in dynamic mode with measuring interval in length direction of 50 mm. For saving new data two collections "Detail-top" and "Detail-side" were created. The top part and the near side to the instrument were measured with SMR 1.5" and the far side – with T-probe stylus 100mm on 0.5".

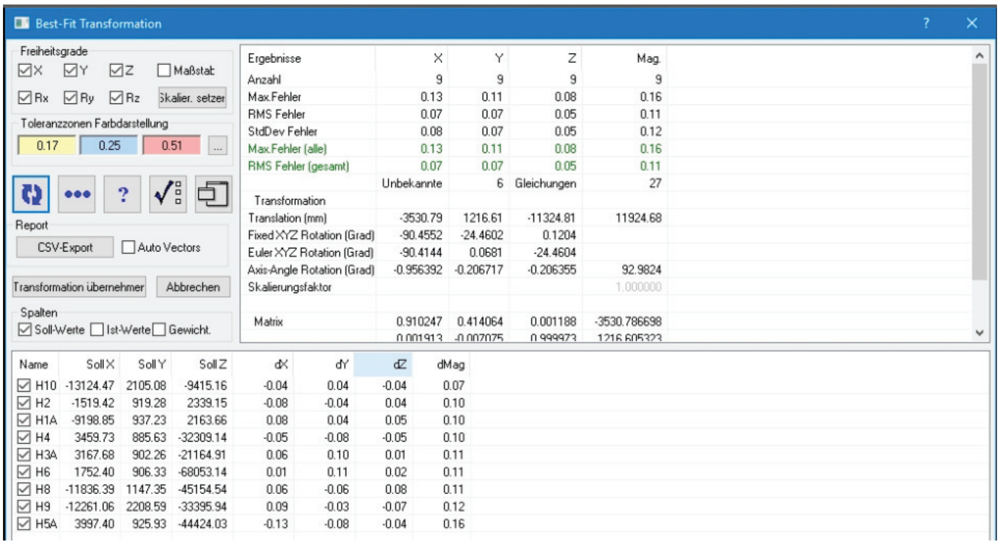


Figure 2.6. *Example of the Best-Fit Transformation in Spatial Analyzer*

For gathering measurements and CAD, as theoretical model of the detail the function group of an object in the menu relationships was used. The model of the vectors for the section A between them is shown on the figure 2.7. As it was mentioned before the tolerances for final measurements of the section are ± 2 mm, therefore the scale bar was limited by these sizes. In practice it is possible to make final measurements of the top and two sides for two sections of the detail using the T-Prome, the SMR and Spatial Analyzer Software just from the one station of the laser tracker.

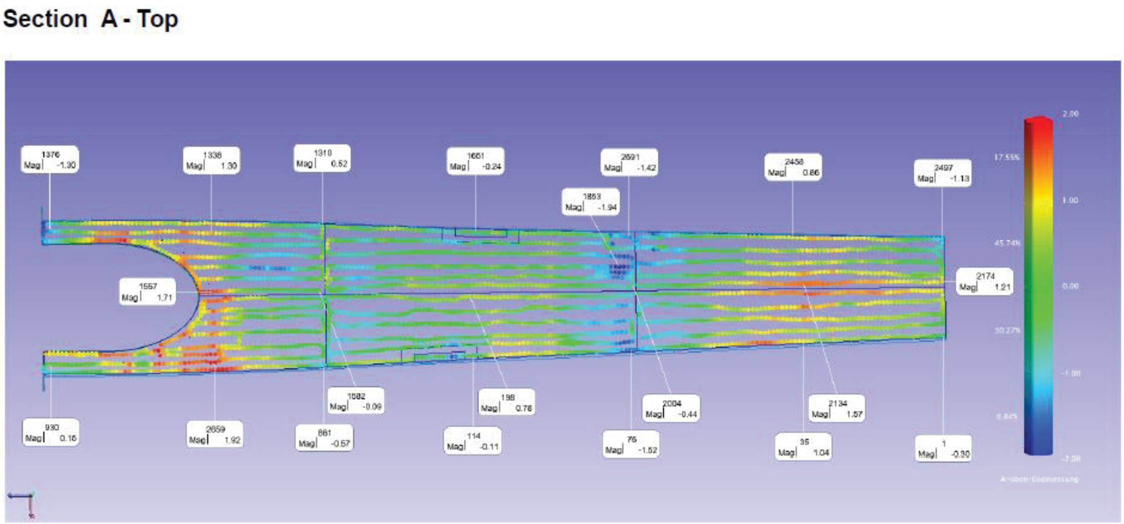


Figure 2.7. *Example of the vectors between measurements and theoretical model for A section*

The special sample part of the adhesive angle of the ship as decribed in the Section 1.2 has no CAD model. The tracker measurements should take the place of geometric description of the detail. So the model of the detail based on the laser tracker measurements. This method was chosen for the adhesive angle of the ship considered in the investigation. The special component is not the ideal form and the model bulding with the laser tracker is a reference one for other methods of measurement considered in this master's thesis.

The implementation of the construction the model of the special component of the adhesive angle of the ship included the next stages:

1. Tracker's orientation – best-fit transformation (fig. 2.6);
2. Measurements of the top and sides of the component;
3. Exporting of the data in .txt format;
4. Building the mesh model in Software 3DReshaper.

The installation and orientation of the tracker was described before. Measurements of the top and side of the detail were made with the SMR and T-probe. The data was taken in dynamic mode and saved in the appropriate groups. In the result 782 points with number and XYZ coordinates for the top of the detail and 261 for the sides were measured and exported. The building of the mesh model is shown in the Section 6.

3. Laser Scanning

3.1. General concept of Laser Scanning

During the last years terrestrial laser scanning has become one of the most important methods of quickly getting the three-dimensional coordinates of objects. This technology is widely implemented both indoors and outdoors. Likewise the point cloud for the whole structure is a result of laser scanning that can include axes, edges, cross sections, surface areas, etc. The problem for laser scanning is usually not the lack of data, but its surplus. Modeling for the entire structure is often not required, or sometimes it is too complex. Then it can be reduced to an approximation of the desired elements of the structure or the selected information is extracted directly from the cloud (G.Lenda et al., 2016).

On one hand, there is a big amount of the companies specialized on laser scanning. On the other hand, the needs to process a lot of data contributed to the emergence of different software products for recalculating data, such as 3DReshaper, ShapeGrabber 3D, Spatial Analyzer, Scene 3D, etc. Wide alternative of devices and software for processing enables the user to easily perform data acquisition, processing and visualization of the results.

Laser scanner digitize the area of interest with a frequency of 10000 Hz or higher. This instrument operates in a spheric coordinate system, so each point has one specific distance (d) and two orthogonal angles (φ, θ). First one is the zenith angle φ, which means elevation and second — azimuth angle θ, which means rotation in Y axes (fig. 3.1).

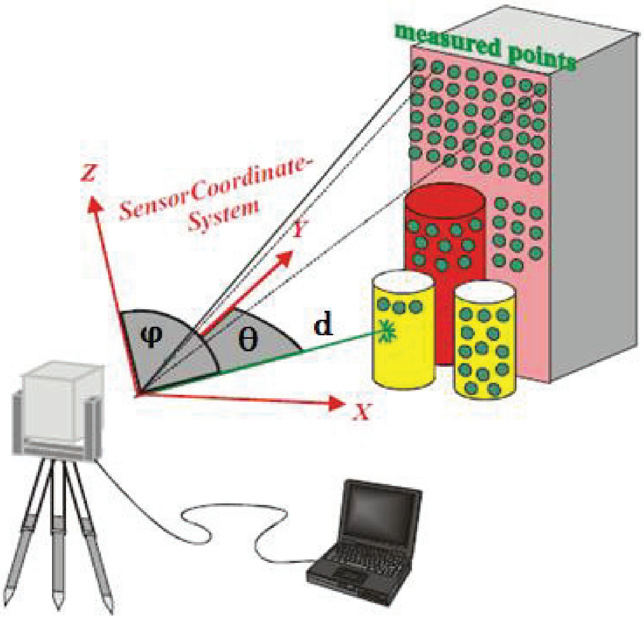


Figure 3.1. *The principle of tacheometric Laser Scanning* (Staiger, 2003)

According to T. Schulz (2007) the laser scanners can measure distances with different methods (fig.3.2). In general there are interferometry time-of-flight methods and triangulation.

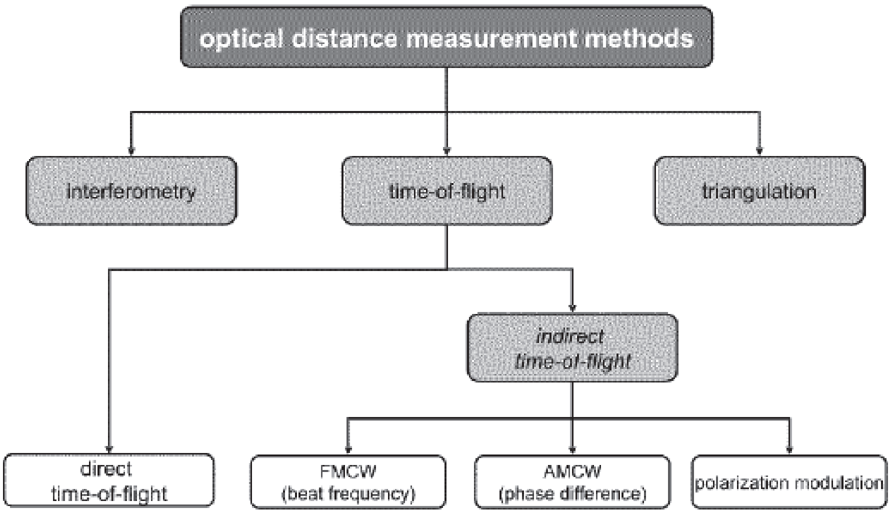


Figure 3.2. *Optical distance measurement methods in terrestrial laser scanners* (Schults, 2007)

Terrestrial laser scanners usually work with direct or indirect time-of-flight methods. The work principle is based on measuring the time it takes for a pulse or pattern of energy emitted by the laser scanner to travel and strike a surface and to return. This measurement method leads to some systematic scale errors, which depend on the reflective surface and material (W. Boehler and A. Marbs, 2003). The error will influence distances between two points which are located in different directions as seen from the scanner. It is clear that this error will change depending on the surface and can be maximized when angle between two points is 200 gon (e.g. when scanning two opposites walls in the room from one station). This is the main reason why a generally acceptade calibration and certification of lasers in laser scanners is not possible.

The angle measurements are determinated electro-optically by encoders with respect to a horizontal and a vertical direction. This method is based on transmission or on reflected light. The photodiodes convert the light energy that is thrown as a pattern on the glass arc, into electrical energy. In the end this signal changes from an analog to a digital output.

The angle measurements are less accurate when determined with distance, that's why the errors of rotation in tilting and collimation axises (fig. 3.3) have a big influence to the final value of the three dimensional coordinates of the points. Moreover T. Schulz (2007) presents facts in such a way that, the results can be improved by applying calibration values to correct systematic errors in the post processing. Because of the measurement principle of laser scanners the very same point cloud cannot be taken from the two repeated surveys. So deviations can only be noticed after objects have been extracted from the point clouds and made up into a model. However, if the geometric properties of the objects are known, the deviation of single points from the object's surface may be an indication for the accuracy.

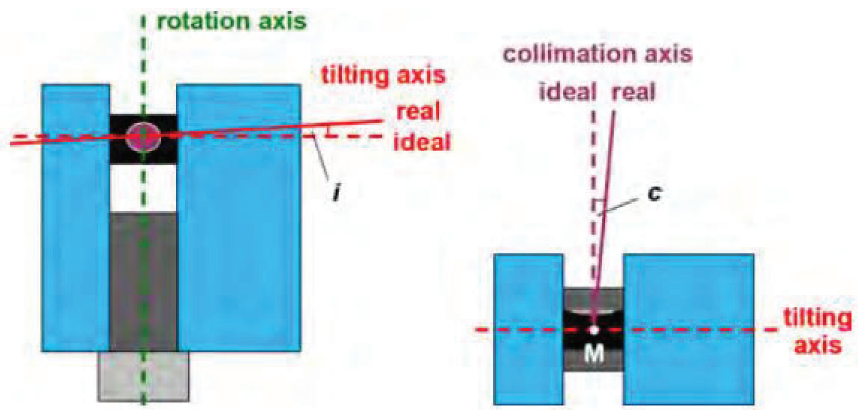
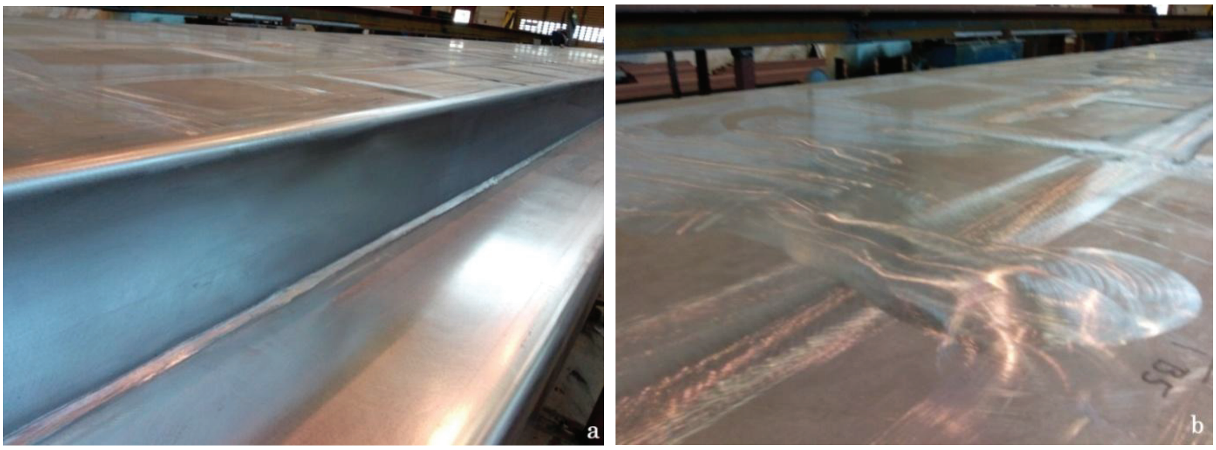


Figure 3.3. *Occurrence of a tilting axis error and collimation error* (Neitzel, 2006)

As was mentioned before, the kind of objects material is important for laser scanning because of the time-to-flight measurement principle some of the points can have big errors of the final position. Selected steel detail, such as the adhesive angle of the ship, has some grinded metal surfaces, which can act as a mirror for laser beams (fig.3.4). Therefore the reflection may change the understanding of the shape by the program.



Figures 3.4 (a,b). *Well-polished piece of detail (a) and grinding surface that looks like a mirror for laser scanning* (photos author, April 2018)

As mentioned in the work of T. Voegtle et al. "Influences of different materials on the measurements of a terrestrial laser scanner" (2008) metal plates induce enormous mean square error (MSE) values much higher than the general range accuracy of the laser scanner. Interestingly, this investigation states that "the measurement accuracy of laser scaning at night-time and on bright materials increases for all kinds of surfaces". On the other side, Y. Reshetyuk (2004) in similar research states, that indoor illumination does not exert any tangible effect on the recorded range and intensity. However results of his investigation as the results of T. Voegtle et al. (2008) also show the higher MSE for metal parts in comparison with other surfaces.

3.2. TECHNIQUE FOR LASER SCANNING

3.2.1. Laserscanner Z+F Imager 5010

The Z+F Imager 5010 (fig. 3.5a) is the highly precise and reliable instrument for the laser scanning in close and far distances, cause it can scan up from 0.3 to 187 m with up to 1 million pixels/sec. The extended field-of-view of this device is wide – with 320° vertically and 360° horizontally.

The stand-alone concept guarantees easy storing of the data on an internal hard disk or two integrated and removable USB sticks. It is possible to see a panorama view on the devices display and make some corrections for the mode of measurements with no need of special computer controller.

The time needed for measurements in one station is very important characteristic for the laser scanners. In the Z+F Imager 5010 it depends on two variable settings, such as the resolution and the quality. Seven different levels of resolution and four levels of quality can be chosen. As noted in the datasheet for the Z+F Imager 5010 the "ultra high" and the "extremely high" resolutions are recommended only for scan selections because of the enormous amount of data.

Figures 3.5 (a,b). *Devices for laser scanning: Laserscanner Z+F Imager 5010 (a) and Leica Total Station TS-15 (b)* (photos author, April 2018)

The test laser scaning of the adhesive angle of the ship was conducted to find optimal settings for satisfactory final accuracy at minimum scan time. These recommendations are presented in part 3.3. “Configuration of Laser Scanning Measurements”.

3.2.2. Leica Total Station TS-15

Leica Total Station TS-15 (fig. 3.5b) is an instrument for measuring, calculating and capturing geometric data. In this case this device was used without GNSS system and without remote controller. The user interface is basic for all Leica’s tachometers. Therefore it was easy to work with it. This instrument also can make automatic target aiming that is based on digital image processing method.

As published in the datasheet for Leica Total Station TS-15 the linear accuracy in the standard mode for prism is 1 mm + 1.5 ppm and 2 mm + 2 ppm for any surfaces. Angular accuracy of horizontal and vertical measurements is 3’’ (1 mgon).

Downloading of the data from Leica Total Station TS-15 to the computer is possible by the use of a USB stick Leica in .gsi, .pkt and .txt formats.

3.3. Configuration of the test laser scanning measurements

The testing scanning of the adhesive angle of the ship was made with the Laserscanner Z+F Imager 5010 and Leica Total Station TS-15. The measurements of the two sections were carried out in the following stages:

1. Choosing the configuration of measurements and fixing the special marks;
2. Work with the Leica Total Station TS-15 – orientation, measurements of the geodetic points with prism and measurements of the special marks in none-prism mode;
3. Work with the Laserscanner Z+F Imager 5010 – general scanning and measurements of the special marks with higher accuracy.

The configuration of the test laser scanning measurements includes 1 station of the Total Station TS-15, 5 stations of the Z+F Imager 5010, fixing of the 8 special marks.

There are some important comments for this workflow. Primarily all of the special marks and most of the geodetic points should be seen from the station with TS-15. It should be noticed that from every measurement with scanner should be seen at least 3 special marks in satisfactorily resolution (1 per 1 mm). This is necessary for future processing in the L+F Scan Control and 3DReshaper software. It is possible also to make scan selections with higher quality and resolution for some special marks.

3.4. Processing of the test laser scanning data

Scans (.zfs) with project (.zfprj) for Z+F Laser Control Software, tachymeter data (.txt) as the result of the laser scanning and coordinates of control points in the hall (.txt) as additional data for the testing measurements.

It is possible to process the measured data in Z+F LaserControl and work in real time with Laserscanner Z+F Imager as well. In general, the workflow in this software includes scanner control, capturing, analysis, processing and outputpf the data. We were interested in analysis, processing and output of the data.

First task is a review of the scans after opening the project. The next is to change approximately the laser scanner positions. The manual preregistration of the scan positions in 2D is possible in the edit mode (fig 3.7).

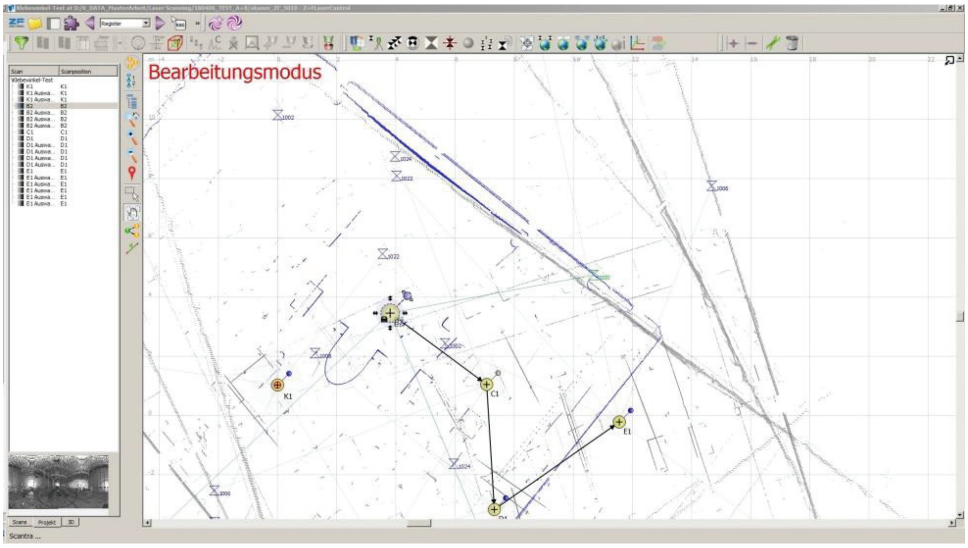
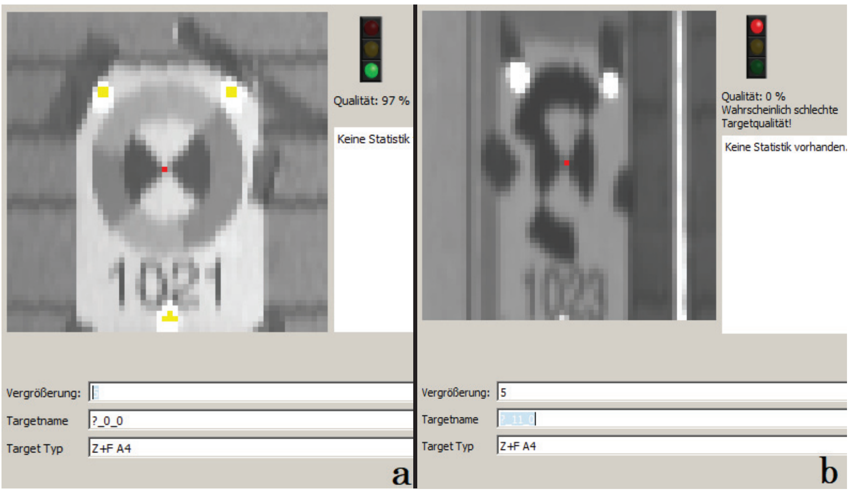


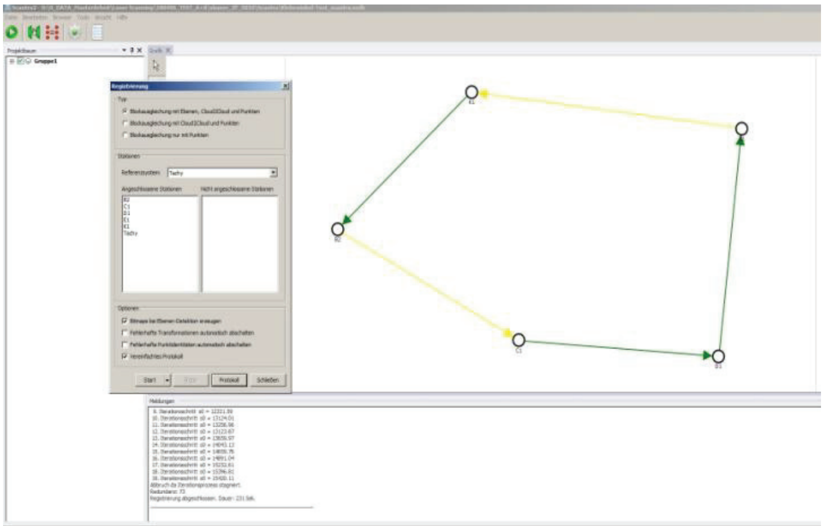
Figure 3.7. *The manual preregister the scan positions in Z+F LaserControl Software*

The next steps are to add coordinates of known targets from TXT file, to find targets automatically and filter them (fig.3.8), and make registration of the scan positions.



Figures 3.8 (a,b). *Example of the manual filtering of the targets automatically recognized: a – good quality (97%), b – bad quality (0%)*

The register plane to plane the program Scantra was used (fig.3.9). As mentioned in the manual for the program this process uses automatic generated planes for registrations with bundleadjustment and is optimal for indoor registration. For the plane to plane registration targets are necessary for transformation in a superior coordinate system, but also can help to improve the result. If the registration is finished the protocol of the global block adjustment can be displayed (tables 3.1-3).



Figures 3.9 (a,b). *The plane to plane registration: green arrow is a very good matching result and yellow is good.*

Table 3.1. Adjusted Translation Parameters of Stations

№	Station	Tx	Ty	Tz	sigma_x	sigma_y	sigma_z	sigma_t
1	B2	6.851	2.329	0.000	0.0001	0.0001	0.0007	0.0008
2	C1	-3.383	5.759	-0.002	0.0002	0.0003	0.0014	0.0014
3	D1	-9.594	6.587	-0.004	0.0006	0.0004	0.0017	0.0018
4	E1	-1.551	9.789	-0.001	0.0006	0.0016	0.0011	0.0020
5	K3	0	0	0	0	0	0	0

Table 3.2. Adjusted Global Point Coordinates

№	Point	X, m	Y, m	Z, m	sigma_x	sigma_y	sigma_z	sigma_p
1	1000	11.584	-2.837	-0.264	0.001	0.001	0.0011	0.0018
2	1006	-5.872	-1.255	-0.274	0.0011	0.0012	0.0012	0.0021
3	1021	1.759	-4.78	0.032	0.001	0.001	0.001	0.0017
4	1024	-11.547	7.251	-1.034	0.001	0.001	0.0012	0.0018
5	1023	-6.299	1.06	-0.275	0.0015	0.0017	0.0017	0.0028

Table 3.3. Residuals of Transformation Parameters

№	from Station	to Station	Vt, m
1	B2	C1	0.0002
2	C1	D1	0.0000
3	E1	K3	0.0001
4	K3	B2	0.0000

The next step is to display all scans in 3D. For this purpose the dialog “View all registered scans in 3D” was used. There are some important parameters for building of the point cloud, such as a subsample and a minimum pixel distance. We chose the subsample equals 2 and 0.0500 m for the minimum pixel distance.

It is also necessary to filter the data. The 3D volume selection can be used to select a 3D volume and cut off the date inside or outside this box.

Different formats can be chosen for the export of 3D point cloud data, such as a BMP, JPG or GIF picture, a 3D PDF file and a 3D data files in the .ai and .ask as well. The result data was exported in .ask-format with the XYZ and RGB information.

The testing measurements of the adhesive angle of the ship were made in April 2018. It was suggested to work in different modes to check the final accuracy of 3D model. As a result we have chosen the “high” resolution and the “normal” quality for further research. The lowest mode parameters for the scanning the adhesive angle of the ship are not satisfactory for the mm accuracy. Having examined the collected information in 3DReshaper, we came to the conclusion that for the further analysis of the sample part of the adhesive angle of the ship 4 stations measurements are enough.

3.5. Laser scanner measurements without post processing

The final measurements of the special component with laser scanner were made in cooperation with Techner Company from Berlin and Bochum University of Applied Sciences in May. The more modern Z+F IMAGER 5016 and software products Scantra and Z+F LaserControl installed on the laptop in the time of measurements were used. That technique offers the option to orientate all the scans in the field automatically. The exported in the field data does not need a post processing accept of clipping of the point cloud of detail and comparison with the other data that was made in the 3DReshaper software.

The orienting of the 4 scans in the “high” resolution and the “normal” quality in software products Scantra and Z+F LaserControl is the same as in the post processing mode in Section 3.4 but works fully automaticaly. The connection between Z+F IMAGER 5016 and software is realized with WiFi in the frequency range of 2.4GHz / 5GHz.

On the one hand the Z+F IMAGER 5016 has similar characteristics compared to the 5010 version, such as the high-speed mode up to 1 million pixels/sec, guarantee eye safe class 1, possibility of the field-of-view 320° x 360° etc. On the other hand the possible scanning distance increases from 187 m to 360 m as well as quality of the final point cloud (fig.3.10). Interesting fact is that the quality between the test measurements with model 5010 and 5016 differs noticeable in the grinding surfaces (fig.3.4). It can be seen from the final measurements that there is no problem for new scanner to fix real points of the object even in not well polished places. The point cloud was exported in .pts-format.

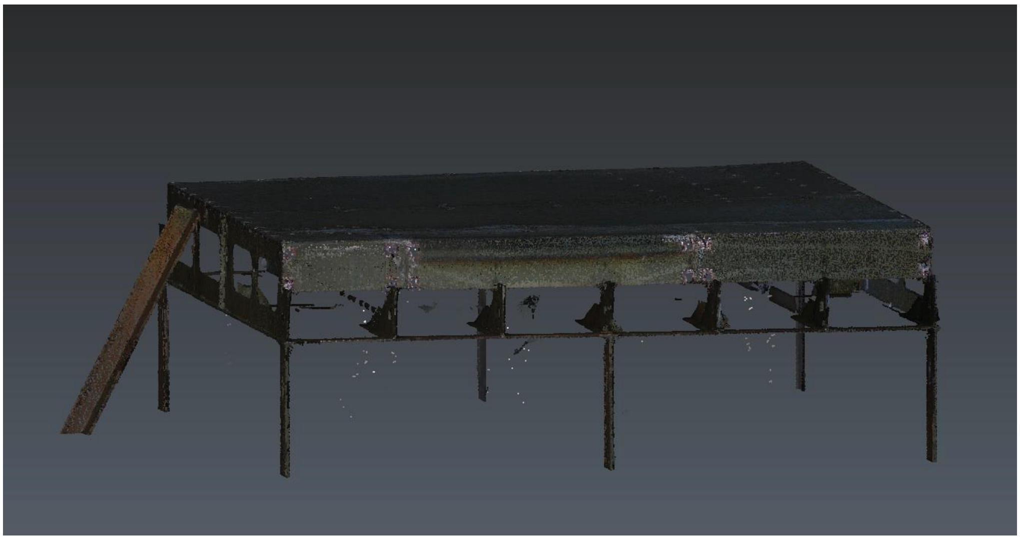


Figure 3.10. *The point cloud data of the special analog of the adhesive angle of the ship*

4. Photo-based Scanning

4.1 General Concept of Photo-based Scanning

Photo-based scanning or industrial (close-range) photogrammetry is based in general on well-known and well-studied principles of classical photogrammetry. Close-range photogrammetry developed from the 1960s and became technically and economically successful in industry in the 1980s, with a first breakthrough in automated and high accurate 3D measurements (Fraser C.S. and Brown D.C., 1986; Karara, 1989; Atkinson K. B., 1996).

Reconstructing 3D objects from overlapping converging 2D photographic images is one of the fundamental tasks of photogrammetry. The calculation of the three dimentional coordinates of the objects include two main steps: first the orientation of the images in a common 3D coordinate frame; and second the subsequent generation of a dense point cloud or surface model. The general concept from the real object to the photogrammetric model is shown on the figure 4.1.

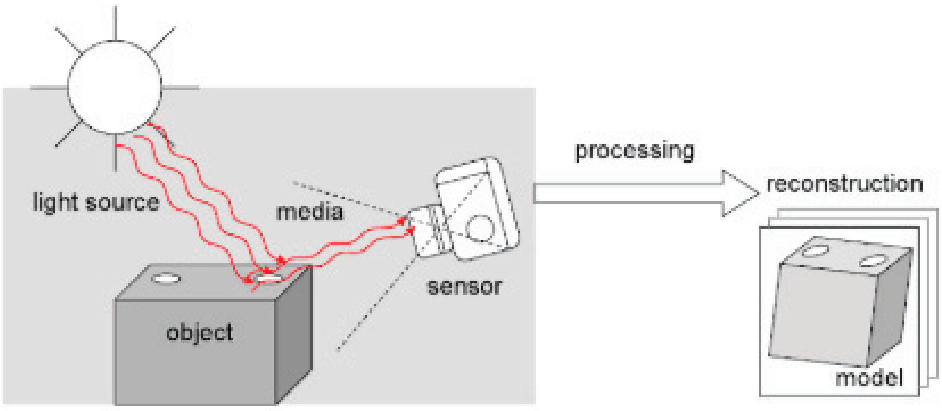


Figure 4.1. *General concept from object to model (Luhmann et al., 2014)*

The photos can be recorded with either a single mobile camera and fixed reference points or few cameras fixed relative to a common axis, a known distance apart. The model for 2D transformation presented by Gomercic and Jecic (2000), for reconstruction of a light rays uses two sets of coordinates, where coordinates (x, y) represents the position of an observed point projection in an image (fig.4.2).

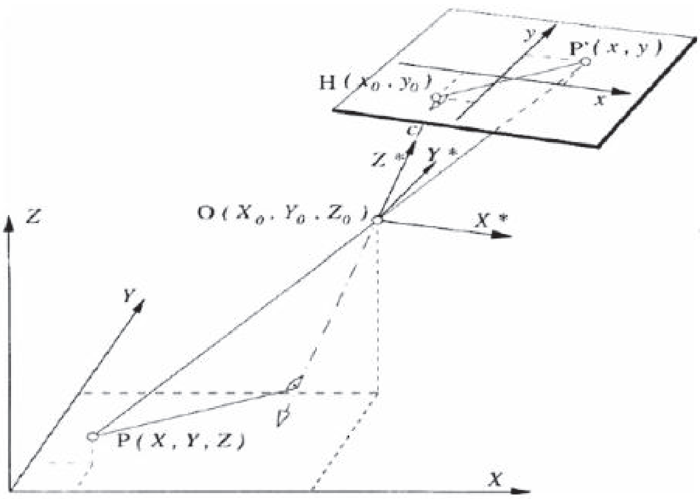


***Figure 4.2**. The relationship between object and photograph point (Gomercic M. and Jecic S.,2000)*

The relationship between those two systems can be calculated using two equations of image coordinates (x,y). Common specific points on the object, are identified in each image. The additional equations are necessary for determination the object coordinates X, Y, Z. The specific point has to be recorded from another photograph, which gives two additional equations. This system of the equations is predefined. The optical measurement techniques for determination of a object point position are based on stereoscopic effect. The three dementional coordinates of a point is found by triangulation with intersection of straight lines (fig. 4.3) (Atkinson K. B., 1996).

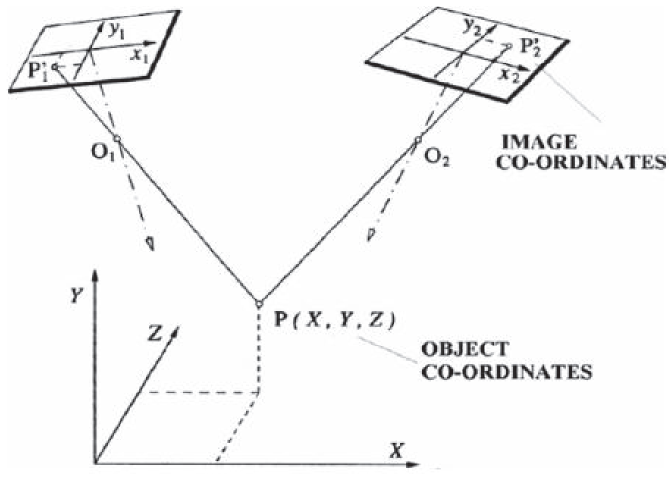


***Figure 4.3.** Triangulation principle (Chen B.Q. et al., 2011)*

The point P has projections points P_1' and P_2' on photographs. A sufficient amount of the equations should be added from the different camera positions for making a redefinition of the system. There are a lot of mathematic methods for calculating this system of nonlinear equations. The most suitable method for machines is iterative with an error minimization. The results are three dimentional coordinates of object points and other parameters of the mathematical model, like camera calibration and data about reliability and accuracy.

Important also is that the same object points in the photos can be used for system calibration. In general the accuracy of photogrammetric method is based on size of object, quality and resolution of photos. The final accuracy of the positions of the object points was near 1 mm on the start of this centuary (Mikhail E. M. et al., 2001) and now this method demonstrates submillimeter accuracy in 3D (Junga S. H., 2008; Boesemann W., 2016).

Luhmann T. (2010) divides the current industrial photogrammetry into 2 types, such as off-line and on-line systems (fig.4.4).

Usually on-line photogrammetry systems include few calibrated and oriented cameras located on special places. The data is transmitted with a direct link and in real-time to the server. 3D information about object is directly generated in order to control a connected process with respect to an external reference frame. The online close range photogrammetic systems can be useful for the tube measurements – cameras set-up on a tube bending machine; robot calibration – cameras determine the robot trajectory in space; sensor navigation or tactile probing – the device or probe tracked by cameras (Luhmann T. et al., 2014; Boesemann W., 2016).

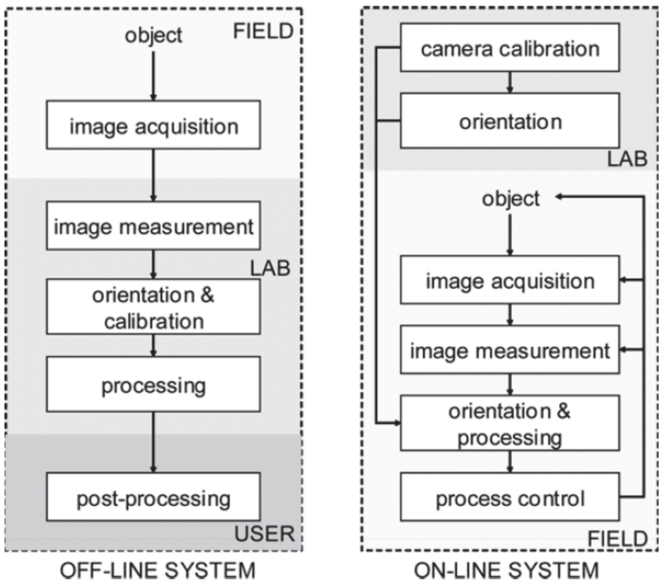


Figure 4.4. *General operational stages for off-line and on-line systems in the industrial photogrammetry (Luhmann, 2010)*

The off-line system was used for the industrial photogrammetry. So the scheme of the measurements include preparation, image acquisition, image measurements, orientation and calibration of the cameras, processing and post processing of the data.

There are a lot of cases of the automatic modelling method for steel structures using photogrammetry. Junga S. H. et al. (2008) demonstrate an automatic 3D modelling procedure using calibration target and auto modelling system with the measurement accuracy in three dimension less then 0.05 mm in the each axes. Chen B.Q. et al. (2011) show "a good ability of the photogrammetric approach to provide high resolution 3D models of deformed surfaces and demonstrated its effectiveness". Valenca J. et al (2008) concluded that photo-based scanning can be used in structural monitoring without loosing accuracy. There are also some advantages in relation to traditional methods, such as that a big quantity of points can be considered and automatically processed and easy positioning of the system, as in the case of bridges.

4.2. Equipment for Photo-Based Scanning

4.2.1. Camera Nikon D2Xs

The quality and chosen parameters for work of the camera are as well important for the industrial photogrammetry as the accuracy of total station for classical geodesy measurements. That is why the camera Nikon D2Xs was0 chosen (fig.4.5). This camera was released on July 2006. The integration of a 12.4 megapixel CMOS image sensor allows making up to five frames per second in continuous shooting mode. Work with 11-area autofocus system, producing JPEG or RAW images, new LCD with a 170-degree wide viewing angle are the characteristics of the Nikon D2Xs that can also be mentioned.

Important parts of the camera for industrial photogrammetry are the flash and the data transmission. The best for the photo-based scanning is the flash located around the objective. This location guarantees the necessary uniform lighting from the objective's side. It is possible to realize online data transmission during the measurements with the Wireless Transmitter WT-2/2A connected to the Nikon D2Xs to a computer with Camera Control Pro software installed on.

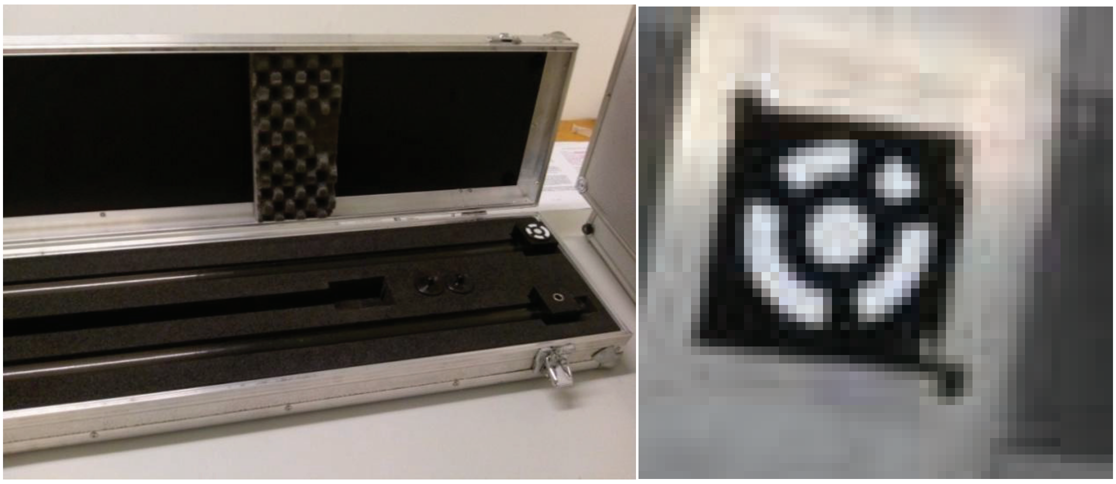
Figure 4.5. *Camera Nikon D2Xs used for the industrial photogrammetry* [nikonusa.com]

For the Nikon D2Xs such parameters for measuring as ISO 300, f-number – f 8.0 and flash sync 1:250 were fixed. The ISO parameter regulates the level of cameras' sensitivity to available light. The f-number of an optical system is the ratio of the system's focal length to the diameter of the entrance pupil. It is a dimensionless number that is a quantitative measure of lens speed, and an important concept in photography.

4.2.2. AICON`s scale bars and special marks

The use of the AICON`s scale bars and special marks (fig. 4.6) is necessary for the precision results and the automatical calculations in the software products. The special marks are 8-bit coded. The number less than 100 of unique coded marks is usually enough to the industrial photogrammetric project.

AICON`s scale bars are necessary for the control and providing correct measurement of distances in the photos. AICON`s cross can also be used for the determination of the relative orientation of the images. In these studies we used the scale bars for test measurements.



Figures 4.6. *AICON`s scale bars and the special coded marks used in the investigation (photos author, April 2018)*

Dosil R. et al. (2013) demonstrate the automatic target decoding process (fig.4.7). The first step is the detection of the 8-bit target by the software. It is realized with the best fitting of the elliptical model of inner white circle and photos regions. This process is automatically controlled by the location of the outer circle, because of this radius is known by the software. The next step is a normalizing coded ring region. The outer circle can be read by the program as the binary code based on the taking the maximum in the radial dimension. In this example decoded binary profile corresponds to code #5 in the LUT of the 8-bit codification scheme. The last step for the software is to determine the correlation coefficient between the synthetic and real ring.

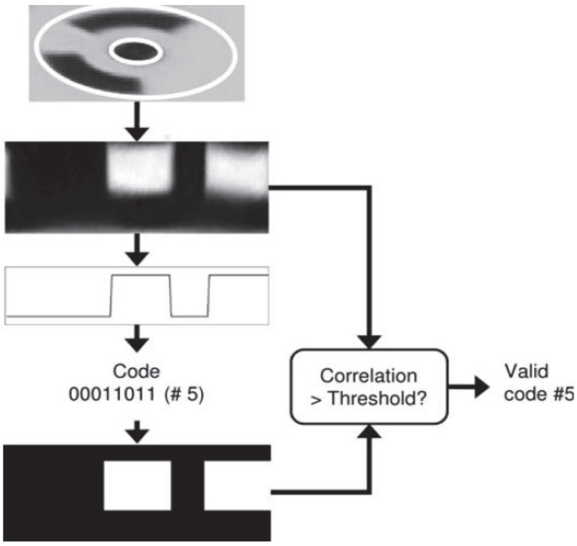


Figure 4.*7 Target decoding process (Dosil R. et al., 2013)*

4.3. Calibration of the Camera and AICON`s scale bars

Actually there is not a strong need to make the calibration of the camera and special scale bars before every set of the measurements. The data from the manuals can be taken. The calibration of the equipment can be made once on the season or less often accordance to the frequency of the equipment use and required measurement precision. The calibration of the camera and special scale bars was made in the end of April 2018 in Neubrandenburg University of applied sciences with the purpose for the new rectification of the basic parameters.

The horizontal comparator with the interferometer was used for the scale bar comparison (fig.4.8). The specified measuring point distances are mean values from in each case 5 individual measurements of the left and right edge of the measuring marks.

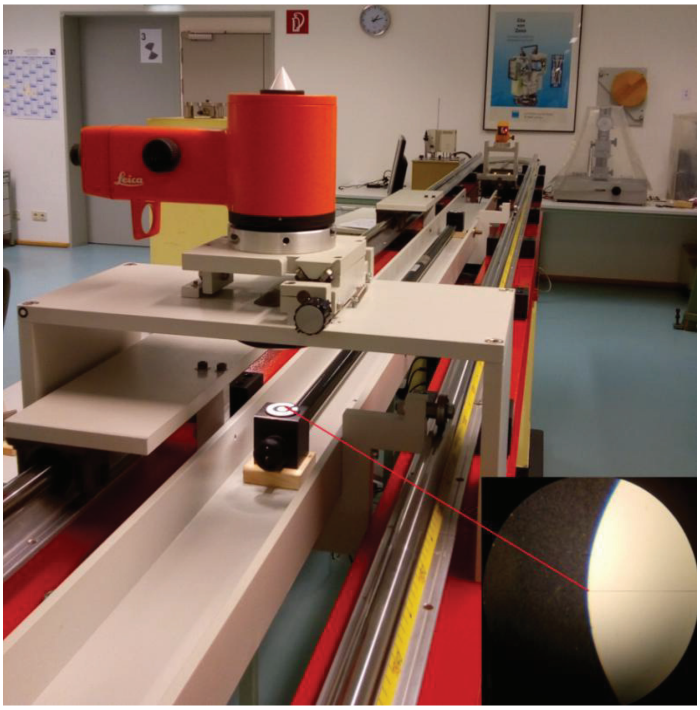


Figure 4.8. *Horizontal comparator in Neubrandenburg University of applied sciences with the example of left side measurement of the special mark (photo author, April 2018)*

The length of the scale bars in the manual is defined to hundredths of a millimeter. The horizontal comparator with the interferometer can guarantee this precision. The stated length measuring accuracy of the laser interferometer is 0.0003 mm. The setting accuracy of the measuring mark edge is approx. 0.005 mm. We increase the amount of the individual measurements from standard 3 to 5 for the control of the setting of the measuring mark edge. The standard deviations were less than 0.004 mm between related distances.

The results of the AICON`s scale bars calibration on 27.04.2018 as well as the previous calibration on 21.05.2013 made by Dipl.-Ing. Martin Kiskemper are shown in the table 4.1. The Schema of the connected scale bars is demonstrated in the figure 4.9.

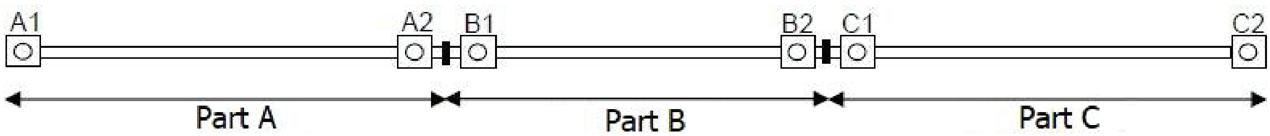


Figure 4.9. *The Schema of the connected scale bars*

Table 4.1. The results of the AICON`s scale bars calibration

Distances of the individual measuring marks	New values (27.04.2018) [mm]	Old values (21.05.2013) [mm]	Change [mm]
A1 - A2	**2000,65**	2000,58	0,06
B1 - B2	**1499,02**	1499,00	0,02
C1 - C2	**2000,63**	2000,61	0,02
A1 - B2	**3579,31**	3579,74	-0,43
B1 - C2	**3579,36**	3579,84	-0,48
A1 - C2	**5660,45**	5660,41	0,04

The calibration of the Nikon D2Xs camera was done by student of Neubrandenburg University of applied sciences Tetiana Nasadyk as a part of her Master thesis with the help of Dipl.-Ing. Olena Lisnyk. The camera calibration was made in the laboratory of Neubrandenburg University of applied sciences with fixed special marks in the walls and ceiling of the room.

In this investigation the unknowns are object points, the interior orientations and the exterior orientations of the camera. The translation, the rotation and the scale are the constraints. The image coordinates and distances are measured on the photos.

The data was calculating in Aicon 3D Studio software from the two sets of measurements. It is possible to see the stable parameters between the results of two independent sets, for example the sigma value in the first case is equal 0.00037 mm as well as 0.00039 mm in the next, the median and RMS values are also close. The most important parameter for further work is the new value of the focal length that equal 24.188 mm.

In summary, the Nikon D2Xs camera and the calibrated scale bars are suitable equipment for the precise photo based scanning.

4.4. Configuration of the photo-based Scanning

4.4.1. Preparations and Image Acquisition

Preparations for the industrial photogrammetry include fixing of the special coded marks and scale bars near or on the object (fig.4.10). There are some requirements for this process:

- The marks and scale bars should be stable during the time of the image acquisition;
- The special marks should be well-distributed over the whole object;
- For the purpose of the validating the scale changes across the entire project it is recommend to place the scale bars as far away from each other as possible.

Image Acquisition is a very important part of the photo-based scanning. Because the non-focused images as well as photos made from incorrect positions cannot give a satisfy result. Transparent, shiny and very thin objects, as well as movements and crisscrossing of the objects have negative effect (Brandon Blizard, 2014). For the example if an aspect of the object is very thin, the software is not able to place enough dots across that component to figure out its shape. The other problem of transparent and shiny objects is that current photogrammetric software solutions cannot distinguish between a white dot on object and the reflection of light. If there are very plain featureless textures, there are not enough features to be tracked by the software.

Figure 4.10. *Location of the scale bars and the special coded marks fixed with the magnet to the steel detail for test measurements (photo author, May 2018)*

There are some special requirements for the ability to self-calibrate the camera in the post processing, that refer to the image acquisition. First of all, there should be at least four photographs for the three-dimensional object. Secondly there is the roll diversity - at least one picture must be rolled approximately 90° differently than the others. The third requirement is that you must have a minimum number (e.g. twenty) of well-distributed points on each photograph and for the entire measurement. The distribution of the points throughout the picture is important for the further calculations.

4.4.2. Workflow in Agisoft PhotoScan Software

For the construction of the three dimensional model of the adhesive angle of the ship the software Agisoft PhotoScan was chosen. It is an image-based 3D modeling solution aimed at creating professional quality 3D content from still photographs. Both image alignment and 3D model reconstruction are fully automated. Agisoft PhotoScan is easy-to-use software solution for photogrammetry made in St. Petersburg, Russia with possibility to take a trial version for learning up to 30 days.

According to the manual the processing procedure in the Agisoft PhotoScan includes several stages, such as camera alignment, calculation of the dense point cloud, generation of a surface.

After the downloading of the photographs the focal length parameter was changed. According to the camera comparison it equals 24.188 mm.

For the final measurements only 20 special non-coded marks were fixed on the sample part of the adhesive angle of the ship and manually measured with the tracker. It's possible to minimize the calculation process if the same points are manually chosen on the photos. It was used four well distributed markers. The MSE of the location equals 1.8 mm or 0.054 pix. Two scale bars between four points based on the coordinates from the tracker for the scaling of the model were chosen. Total MSE of the scale bars equals 1.0 mm.

The next step is to make the camera alignment. For this purpose the most precision mode “highest” was chosen. At this stage PhotoScan searches for common points on photographs and matches them, as well as it finds the position of the camera for each picture and refines camera calibration parameters. As a result a sparse point cloud and a set of camera positions are formed. (fig. 4.11).

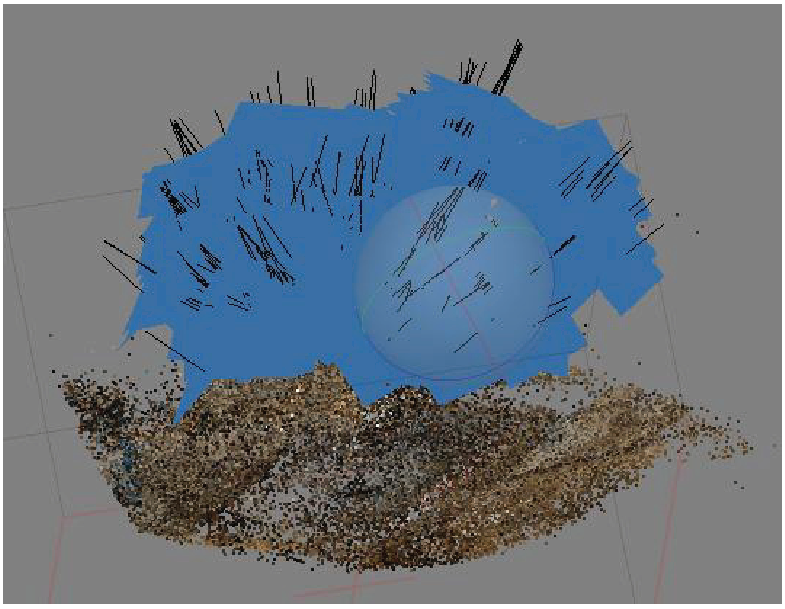


Figure 4.11. *Camera alignment in Agisoft PhotoScan software*

The next step is generating a dense point cloud that is built by PhotoScan based on the estimated camera positions and pictures themselves. Usually this is the long calculating process because of the big quantity of the points, especially when the “high” processing mode is chosen. The dense point cloud may be edited before proceeding to the next stage (fig. 4.12).

Figure 4.12. *Generated dense point cloud in Agisoft PhotoScan software*

It was not necessary to generate the mesh model because of the future work in 3DReshaper. It is possible to clean unnecessary points from the model with the deleting of the manual chosen free form selections. In the result only it was export the point cloud of the top and sides in ASTM E57 format.

5. Handheld Scanning

5.1. General concept of the handheld scanners

Handheld scanners are the type of scanners moved by hand over the object being captured. They are smaller and cheaper that laser scanners or trackers and can be optimal supplement to making the 3D models. Liscio (2014) mentioned that handheld scanners have an important role in forensics, because of the greater capture speed, satisfactorily accuracy and quality of the final model. However, developing of the new 3D sensors, software solutions, easy in use process of handheld measurements and the favorable price make handheld scanners competitive equipment for engineering tasks.

Nowadays there are many types of handheld scanners for the industrial objects from the size of 1cm to some meters size. The most popular companies, such as Artec, DotProduct, FARO, Craform, Shining, Thor, etc. use laser triangulations or different types of structured light technologies as work principle for the handheld scanners. On the Aniwaa.com site you can find the prices for the equipment from the 1000 $ to 100 000$ based on the possible size of the scanned object, accuracy of measurements, country of invention and positive feedback from the community. For example the FARO handheld scanners typically have a sensor developed in-house and software that improves on the typical structured light devices by using a stereo pair of infrared cameras to accurately triangulate the structured light pattern. The Artec Eva handheld scanner uses the structured light technology to 3D scan a wide variety of subjects and their textures: objects, mechanical parts, people, vehicles and environments.

Handheld scanner DPI-7 of DotProduct Company (fig. 5.1), a manufacturer based in the USA, was chosen for this investigation because of the technical characteristics for this type of object and availability of this device in Techner Company from Berlin as well. The DotProduct DPI-7 is the clever combination of an Android tablet, a sensor from PrimeSense 3D and Phi.3D software from DotProduct.

The simple understanding of the working principle can be described as videogrammetric measurements with structured light technology. In the case of PrimeSense 3D sensor, a type of pattern in the NIR is projected onto the object and recorded by two cameras (in the same spectrum and RGB). The general concept of videogrammetric measurements was developed after the implementation of close range photogrammetry for the industrial objects. This is the logic consequence of the development of the optic measurements that is supported by the technical progress in the last decades. Therefore the basis understanding of principles of close range photogrammetry, which shown in Section 4.1, are necessary for the concept videogrammetric measurements. Gruen (1997) says that the videogrammetric measurements is a subcategory of both photogrammetry and machine vision. Important issue is that in the videogrammetry the object coordinates are captured by two or more video frames. A stereo model of the 3-D object cannot be mathematically reconstructed only with the one video frame. The principle of passive and active mode of optical triangulation is used as well. It should be mentioned that the camcorders can capture numerous video frames in a given time span. In the work process the current captured video frame is built upon the previous one in the real time and it can be full automation procedure. So the object points from the 2D locations can be tracked and matched in 3D (Brilakis et al., 2011).

5.2. The DotProduct scanner DPI-7

The DPI-7 equipment consists of an android table computer with handle attachment, license of DotProduct Phi.3D software, a 3D sensor made up of a near infra-red (NIR) projector, a NIR camera and a RGB color camera, 3 USB to micro USB connectors for connecting camera to tablet (fig.5.1). The measuring principle includes two stages. In the first step the infrared projector projects a pseudo-random pattern on the object. On the second stage this pattern and the changes of the shape are measured with NIR and RGB camera. The point cloud is converted from the range images. The coordinates are compensated to gravity, using the internal accelerometer and gyroscope sensors in the tablet (Jahraus et al., 2015).

Figure 5.1. *Handheld scanner from DotProduct (photo author, May 2018)*

Light weight and low power requirements of the PrimeSense sensor makes it a perfect for the handheld scanning. There are a lot of calibrations for the PrimeSense devices. Burrus (2012) estimates the important parameters of both the NIR and RGB cameras using OpenCV procedures. Jahraus et al. (2015) check the work of the DPI-7 with this sensor and state that the errors in the depth dimension of the scanner are proportional to the square of the depth. The DPI-7 has a specification in use. The implementation of the sensor technology will show better results indoor in dark places than outdoor in sunny places since the sun interferes with the infrared pattern of the sensor.

The most powerful part of the DotProducts' handheld equipment is the Phi.3D software on the tablet, that gives an opportunity to intelligently register and process detailed point cloud on the fly (Ahern and Spring, 2015). T. P. Kersten et al. (2016) state that the iterative closest point (ICP) algorithm performs a preregistration of scans. The ICP algorithm for six degrees of freedom requires a procedure to find the closest point on a geometric entity to a given point. "This algorithm always converges monotonically to the nearest local minimum of a mean-square distance metric, and the rate of convergence is rapid during the first few iterations" (Besl and McKay, 1992). This mathematical apparatus is used for the reinstating sensed data from the objects with an ideal geometric model, prior to shape inspection. After captured and ICP algorithm, the registration is optimized by eliminating incorrect points. Advantage at work for the user as is also in that the Phi.3D software gives real-time feedback to the user on the tablet during the measuring process. This fact is important because in the moment of the capturing the user can understand success or falling of the section.

The measuring range of the DPI-7 scanner is between 0.6m and 3.3m. The weight of the instrument is less that 1 kg, the dimensions are $20 \times 24 \times 6 cm^3$. Summing up the DPI-7 is a satisfactory equipment for the small projects of the indoor scanning.

5.3. The measurements configuration for the handheld scanning

First step after the overview of scanned object is to connect the sensor with the USB cables to the tablet and fix handle to the table as well. Then start the Phi.3D software on the tablet. The software is easy to use. The menu consists of such parts as File, Scan, Append, Targets, Opt, Coords, Measure, Session, Settings. If the folder for file and based settings are chosen the user can press measure menu. The system needs approximate 2 minutes preheating time for the sensor after the starting.

The measurements were made walking through the area around the special analog of the adhesive angle of the sheep with the range of 1.5m. So the creation of the registered color point cloud was made in few minutes on the tablet in the field. At first there was a plan to make the model with the special photogrammetric marks for the future comparison, but it was not possible because of the strong reflection ability of these marks. The DPI-7 turned the error after 10-20 seconds of session of scanning. Eventually the model was made on the first measurement session after all the marks were taking away.

The result of the measurements (fig. 5.2) was exported in the suitable for the 3DReshaper .ptx- format.

Figure 5.2. *The result of the scanning with the DPI-7 from DotProduct*

6. Comparison and assessment of optical measuring methods

6.1. Workflow in 3DReshaper Software

3DReshaper is a software solution dedicated to processing any type of point clouds in a wide array of applications as well as do the comparison between two CAD mesh models. So, it is a multi-purpose solution for the surveying, civil engineering, mining, etc. 3DReshaper software has no software caused limit concerning the point clouds or mesh size. The limit is the memory of a computer.

There are a lot of videos and practical exercises as support from the 3DReshapers' software on the official webpage. The price for the license for 3DReshaper depends on the options and the type and cost from US $3,800 to $15,000.

There are near 30 possible import formats for the point clouds supported by 3DReshaper, such as Zoller and Fröhlich (*.zfs, *.zfc), fichiers ASCII (*.asc, *.csv, *.xyz, *.yxz), 3DReshaper binary file (*.nsd), DOT Products (*.dpl,*.ptx), etc. as well as IGES, STEP and DWG for CAD models. So this software can be useful in this investigation according to the work import formats and comparison functions. The 3DReschaper software version 2016 year with license and the trial version 2018 were used.

6.1.1. Best-fit comparison of laser tracker data and handheld videogrammetry

The initial data for the comparison of laser tracker and handheld videogrammetry came from two point clouds. There are 1043 points with number and XYZ coordinates for the top and sides of the detail in the .txt. The important thing is to be sure that the coordinates are in meter format. On the other side the .ptx data from handheld scanner from DotProduct was not filtered (fig.5.2). It is just the all scan special detail of the adhesive angle of the ship.

After the starting 3DReshaper software the import of the .pts file was made. The mesh model of this point cloud was made. In the result the nets include 62087 triangles, because of the additional data. The next step is to filter this data and leave only top and sides parts. After this, the final mesh model includes 9564 points and 18857 triangles.

The data from the tracker was import as points. The mesh model was also built. It includes 1043 points and 1967 triangles. Important is that the points are evenly distributed because we measured the surfaces manually with T-probe and SMR.

The two point clouds have different coordinate systems. The best-fit function cannot work immediately because of the far distance between points and the turn around the axis. In this case the function 3-2-1 Registration was used. We chose approximately 3 points in the different edges of the two models. In the result mesh models were preorientated up to 0.05 m. In the situation like this the function 'Best-fit' with the option 'All together' can work effectively as well.

In the result of comparison was found that the 80.4% surfaces of the mesh models are less that ± 0.003 m (fig.6.1). The maximum differences are +0.015 and -0.019 m. The upper part of the adhesive angle of the ship has better result that side.

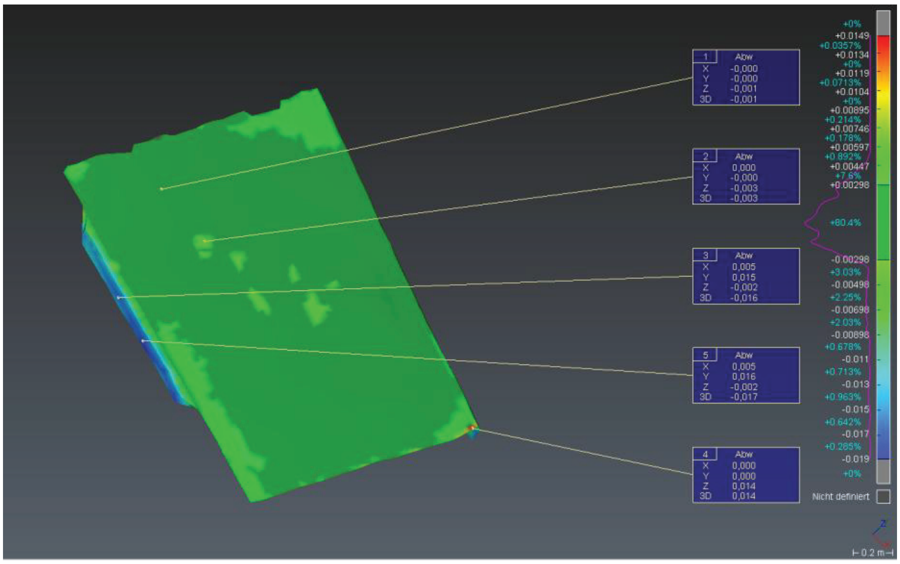


Figure 6.1. *Best-fit comparison of laser tracker data and handheld videogrammetry*

6.1.2. Best-fit comparison of laser tracker measurements and laser scanning

The mesh model based on the laser scanning data includes 10646 points and 21022 triangles. The functions such as 3-2-1 Registration and Best-fit were used. The problem area is near the special marks (e.g. the convexity on the smaller side appears). It regards to the strong reflections of the special marks material. In the result of comparison was found that the 87% surfaces of the mesh models are less that ± 0.0015 m (fig.6.2). The maximum differences are +0.007 and -0.009 m. The upper part of the sample part has better result that side.

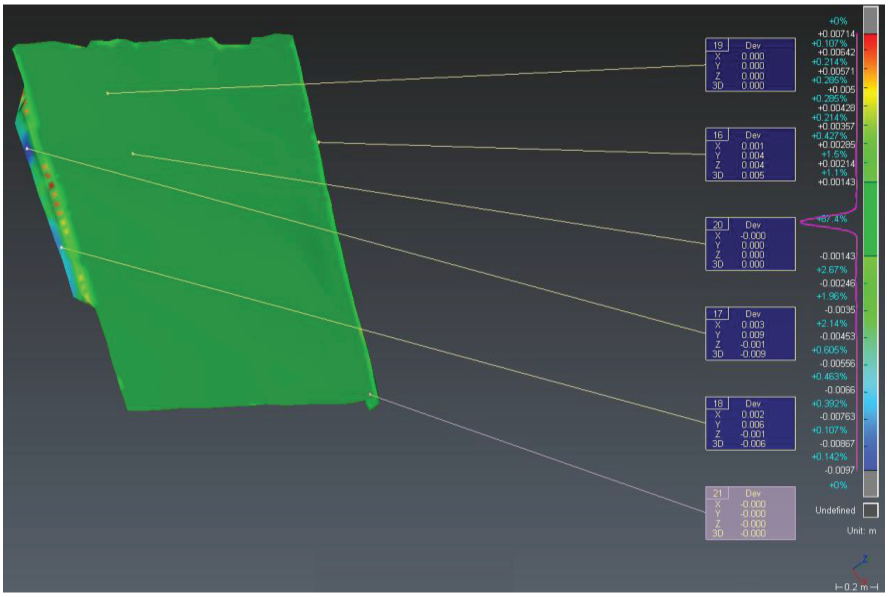


Figure. 6.2. *Best-fit comparison of laser tracker data and laser scanning*

6.1.3. Best-fit comparison of laser tracker measurements and photo-based scanning

The mesh model based on the photos data includes 16297 points and 31953 triangles after the filtering. The functions such as 3-2-1 Registration and Best-fit were used. The problem area is the smaller side of the sample part. It regards to the strong reflections of that area and insufficient amount of the photos. In the result of comparison was found that the 93% surfaces of the mesh models are less that ± 0.003 m (fig.6.3). The maximum differences are +0.016 and -0.021 m.

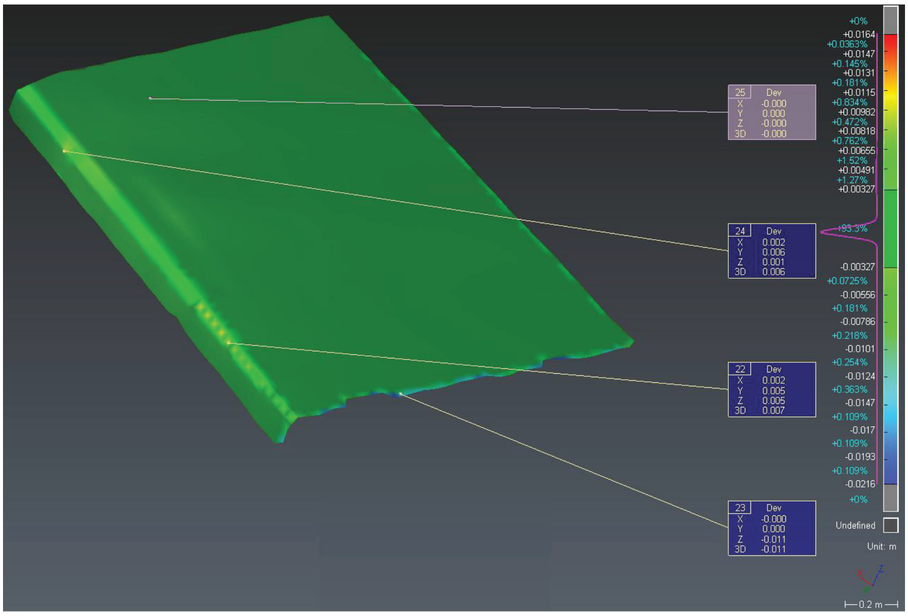
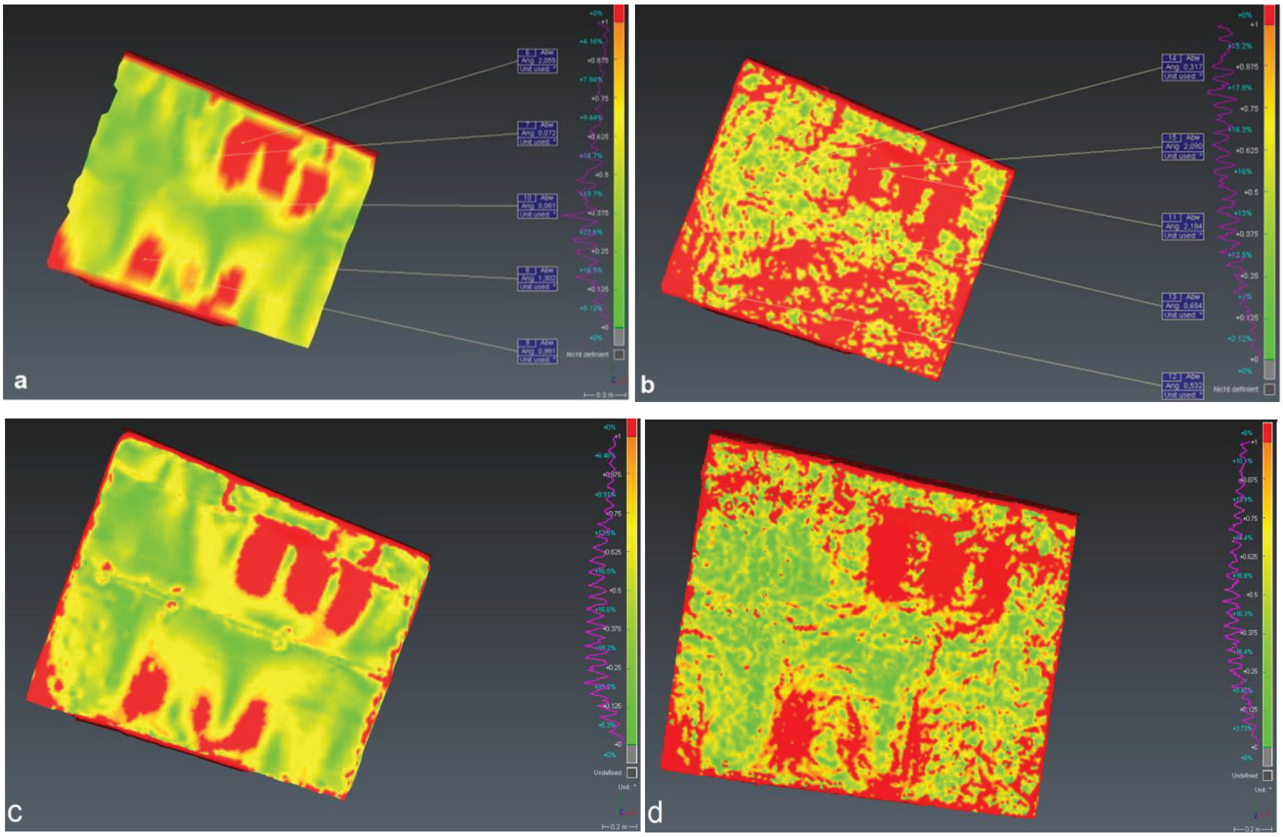


Figure 6.3. *Best-fit comparison of laser tracker data and photo-based scanning*

6.1.3. Slope analysis and the defected data

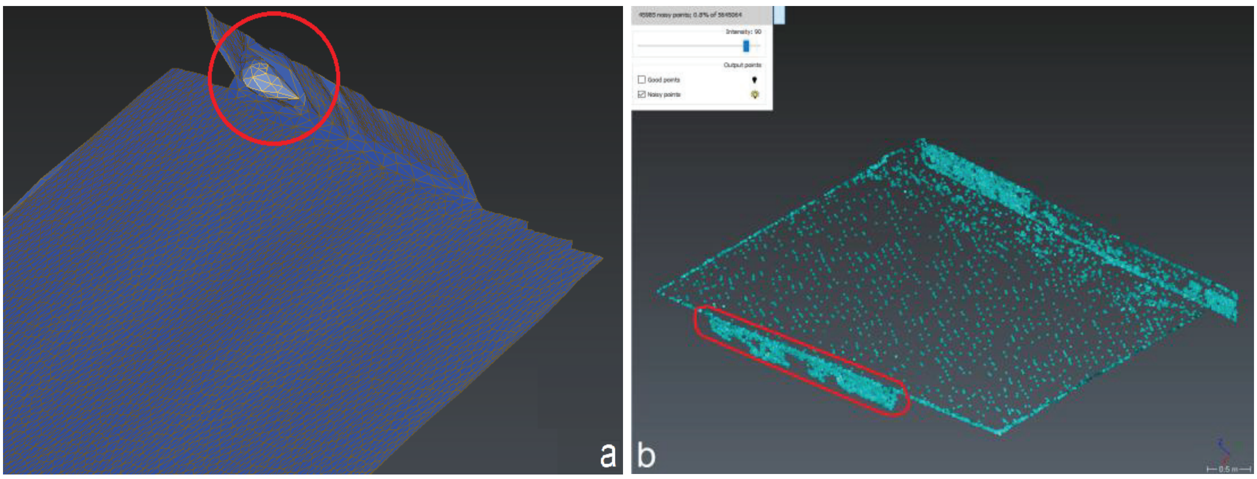
It is also possible in 3DReshaper software to analyze the planes of the mesh models. The slope analysis of all mesh models with the slope 1° is shown on the figures 6.4.



Figures 6.4(a,b,c,d). *Slope analysis for the laser tracker data (a), handheld videogrammetry measurements (b), laser scanning (c) and photo-based scanning (d)*

The slope analysis shows that the models from laser scanning (fig.6.4.c) and laser tracker measurements (fig.6.4.a) are quite similar to each other. The handheld videogrammetry measurements have the biggest slope distortions comparing to the tracker data.

The laser and photo-based scanning characterized with the defected data. The convexity on the smaller side related to the high reflection of the mark in that place. Based on the industrial photogrammetric data all of the points of the smaller side are unsatisfactory quality. It is related to the insufficient amount of the photos of the small side.



Figures 6.5(a,b). *Defected data: convexity on the side for the laser scanning (a), smaller side for the photo-based scanning (b)*

Summing up the table 6.1 include the results and characteristics of the best-fit comparisons with the laser tracker data.

Table 6.1. The results of the of best-fit comparisons different methods and laser tracker data

Method (equipment) that compares with the laser trackers data		Laser scanning (Z+F Imager 5016)	Photo-based scanning (Nikon D2Xs + Agisoft Photoscan)	Handheld scanning (DPI-7)
The percentage of the area with differences less that	1mm	80%	60%	40%
	2mm	89%	80%	60%
	3mm	96%	93%	80%
Max. positive difference, mm		+7	+16	+15
Max. negative difference, mm		-9	-21	-19
Defected data		Convexity on the smaller side	All points of the smaller side	-
Improving of the data		Smoothing	Filtering	-
The area of the detail with the max. difference		Special marks	sides, special marks	Sides and edges

6.2 Comparison of the metrological and evaluation efforts

Based on the current trends of the measurements, which regarding to the high accuracy, small price, real-time processing and equipment portability, there is a strong need to compare accuracy, metrological and evaluation efforts as well.

The time needed for measurements, processing and getting a point cloud data is an important parameter. In this case, the minimum time for measuring the simple analog of adhesive angle of the sheep is demonstrated if the user is only one and familiar with the equipment. The fastest method is the handheld scanning (20 min). It needs 10 minutes for the connection the DPI-7 and switching on the Phi.3D, 5 minutes for measuring including the preheating time for the sensor and 5 minutes for saving and export the point cloud.

The work with laser scanner Z+F Imager 5016 and the Z+F Laser Control on the laptop in the field needs 15 minutes for connecting the equipment and fixing special marks in the hall and 30 minutes of measurements (4 stations, 6 minutes per station and installation at the station) with high accuracy and normal quality and 5 minutes for the data export. If there is important to change the coordinate system of the scans to the coordinate system in the hall the Total Station can be used. It needs near 20 minutes of measurements and 20 minutes more for export and recalculating the point cloud in Z+F Laser Control. Summing up it needs 50 minutes for the laser scanner data and 40 minutes more for the changing of the coordinate system.

The laser tracker measurements with the AT960 need 20-30 minutes for the hardware connection of the system and preheating time for the AIFM, 10 minutes for the field check and positioning to the hall coordinate system, 15 minutes for the dynamic measurements (1000 points with interval 5cm) with SMR and T-probe and 5 minutes for the export of the data. So the process include near 50-60 minutes of working time.

The biggest amount of the time takes the photo-based scanning (6.5 hours): 15 minutes for the fixing of the special photogrammetric marks, 40 minutes for the taking 300 photos, 10 minutes of exporting, 30 min for the photos alignment and 5 hour for the building a dense point cloud in Agisoft Photoscan.

The price of the equipment used in the master thesis varies considerably. The most expensive equipment is one for laser tracker measurements. Leica Absolute Tracker AT960-LR with special tripod, license for Spatial Analyzer and T-probe cost near the 250 000 $. The price for the Laserscanner Z+F Imager 5016, Z+F LaserControl and Scantra software are near 85 000 $. The handheld scanner DPI-7 with Phi.3D software and Camera Nikon D2Xs with the Agisoft Photoscan are much cheaper. The equipment for the handheld scanning and for the industrial photogrammetry cost near 5 000 $ per measuring set.

Eventually the table 6.2 includes price aspect and working time with different equipment.

Table 6.2. Price aspect and working time with different equipment

<table>
<tr><th colspan="2">Method and equipment</th><th>Laser tracker (Leica AT960LR + T-probe + Spatial Analyzer)</th><th>Laser scanning (Z+F Imager 5016)</th><th>Photo-based scanning (Nikon D2Xs + Agisoft Photoscan)</th><th>Handheld scanning (DPI-7)</th></tr>
<tr><td rowspan="4">Time, min.</td><td>preparation</td><td>30-40</td><td>15</td><td>15</td><td>10</td></tr>
<tr><td>measurements</td><td>15</td><td>30</td><td>40</td><td>5</td></tr>
<tr><td>export and processing</td><td>5</td><td>5</td><td>330</td><td>5</td></tr>
<tr><td>sum</td><td>50-60</td><td>50</td><td>385</td><td>20</td></tr>
<tr><td colspan="2">Approximate price for the equipment, $</td><td>250 000</td><td>85 000</td><td>5 000</td><td>5 000</td></tr>
</table>

CONCLUSIONS

The results of accuracy comparison (table 6.1) of the sample part of the adhesive angle of the ship for the laser, photo-based and handheld scanning with laser tracker measurements as well as the assessment of the price and time aspects (table 6.2) of the equipment include the following items:

- Laser scanning with Z+F Imager 5016 is more accurate method compared to the photo-based and handheld scanning. The maximum differences between mesh models based on the laser scanning and laser tracker measurements are +7mm and -9 mm. The 87% of the vectors have the length less that 1.5 mm (fig.6.2). In general laser scanning without special marks can be used for the regular final measurements of the adhesive angle of the ship.
- The fastest method (approximate 20 minutes) for the scanning of the sample part of the adhesive angle of the ship is the handheld with the DPI-7 and Phi.3D from DotProduct company.

The equipment is portable, processes the data in real-time but not enough precise for the final measurements of the adhesive angle of the ship.

- The laser and photo-based scanning characterized with the defected data. The convexity on the smaller side caused by the reflection of the special marks. A bad quality for the smaller side is related to the insufficient amount of the photos. The defected data can be eliminated in the measuring process or postprocessing.
- The handheld scanning with the DPI-7 and photo-based scanning with Nikon D2Xs camera and Agisoft PhotoScan software can be used for the small projects with the tolerances less that ±20 mm. Taking into account the economy of the working time with the handheld scanning and approximate the same the price (5 000$) for both equipment the handheld scanning is more competitive.
- The photo-based scanning with Nikon D2Xs camera and Agisoft PhotoScan is not suitable for the final measurements of the adhesive angle of the ship. It caused of the grinded metal surfaces with big reflection characteristic and non contrast surface that important for calculations in Agisoft PhotoScan. The amount of working time for industrial photogrammetry (6.5 hours) can be minimizing with instantaneous data transfer from camera to computer for calculations.

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