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COMPARISON OF TERRESTRIAL LASER SCANNING SYSTEMS IN INDUSTRIAL AS-BUILT-DOCUMENTATION APPLICATIONS

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Abstract: In this paper investigations into the practical performance of a complete terrestrial laser scanning system, consisting of scanner hardware and its related software for data processing, are described and compared for different laser scanners. To facilitate this, two projects were conducted to test four and two different laser scanning systems, respectively, in two different industrial as-built-documentation applications (transformer station and water conduits of a waste water treatment plant). In conjunction with the project workflow, the important aspects of precision/accuracy and efficiency of both projects are discussed in this paper.

1. Introduction

Terrestrial laser scanners are frequently used for various applications, which have different requirements for hardware and subsequent data processing via software. The spectrum of products required ranges from simple visualisation of objects using just point clouds, to approximation of objects in simple 3D models via detailed 2D facade plans and complex deformation measurements. On one hand terrestrial laser scanners should be tested from the instrumental point of view using investigations to check whether the instruments meet the accuracy specifications given by their manufacturers. Previous comprehensive investigations of laser scanning systems refer frequently only to the hardware components as presented in [2] and in [5]. On the other hand the overall system performance of a laser scanning system should be tested in comparison with other laser scanning systems, in order to see, if the system fulfils the user requirements for specific applications. The first investigations of the HafenCity University in terrestrial laser scanning for as-built-documentation of an industrial application are described in [6], while their first comparison tests of Trimble GS100 and IMAGER 5003 scanners for an indoor cultural heritage application are summarised in [3].

Therefore, to invest more into the practical performance of an overall system, consisting of scanner hardware and its related software for data processing, two projects were conducted to test four and two different laser scanning systems, respectively, in two different industrial as-built-documentation applications (transformer station and water conduits of a waste water treatment plant). The investigations of the two projects are focused on scanning speed and scanning behaviour, control point signalisation, precision/accuracy aspects, level of detail in the scans, and the efficiency of the work- and dataflow from scanning to 3D object modelling.

2. Object sites

The first test object (project 1) was a transformer station of one of the major power suppliers in Hamburg, which was established in 1958 and extended steadily in subsequent years. The data acquisition of the associated transmission lines was regularly conducted by means of airborne laser scanning using helicopters. However, the transformer station was usually not scanned from the helicopter. A continuous actualization of the old inventory plans of the transformer station could not previously be ensured due to many local changes; in particular height data for the overhead clearance is not available in the plans. Therefore, a recording of the transformer station from the ground with an efficient procedure was requested.

In a second project (project 2), which is an indoor application, the water conduit of the waste water treatment plant in Hetlingen, Schleswig-Holstein, Germany was scanned with two different laser scanning systems to derive inventory plans of the plant.

3. The terrestrial laser scanning systems used

3.1. Hardware

For the scanning of the two object sites the following terrestrial laser scanning systems (Fig. 1) were used: (a) transformer station: Trimble GS101 (upgraded from GS100), Leica HDS3000, IMAGER 5003 from Zoller & Fröhlich, Faro LS 880HE, and (b) water conduit of the waste water treatment plant: Trimble GS101 and IMAGER 5003. The first two laser scanners (GS101 & HDS3000) use the time-of-flight method for scanning, while the other two systems (IMAGER & LS 880) scan with the phase difference method. The technical specifications of the four used laser scanners are summarised in Table 1.

Additionally, it must be noticed that the HDS3000 is also applicable for direct geodetic measuring tasks, i.e. for example by forced centering on tripods and subsequent measurement of the instrument height. The FARO laser scanner is characterised by its arrangement into four system modules: the PC module, laser unit, mirror, and basis module. Thus, the user has the possibility to exchange modules and, relatively simply, to change the scanning distance of the laser system. Moreover, this laser scanner can optionally be used by an internal PC instead of an additional notebook.

Fig. 1: The used terrestrial laser scanning systems for the comparison tests: Trimble GS101, Leica Scan-Station, IMAGER 5003 from Zoller & Fröhlich, Faro LS 880HE.

Manufacturer/Scanner		Trimble GS101	Leica HDS3000	Z+F Imager 5003	FARO LS 880 HE
Scan method		Time-of-flight		Phase difference	
Field of view [°]		360 x 60	360 x 270	360 x 310	360 x 320
Scan distance [m]		2 - 100	1 – 100	1 – 53,5	< 78
Scanning speed [Pts/'']		up to 5000	up to 4000	500000	120000
Angular resolution [°]	Vertical	0,0017	0,0034	0,018	0,009
	Horizontal	0,0017	0,0034	0,01	0,00076
Scan precision		6mm	4mm	6mm	± 3mm/10m
Scanner guidance		Notebook or Pocket PC	Notebook	Notebook	Notebook or internal PC
Camera		integrated video camera	integrated digital camera	Optional add-on	Optional add-on

Table 1**:** Summary of technical specifications of the laser scanning systems used

3.2. Software

The following software packages were used for the project transformer station together with the respective laser scanners covering functionalities of both system control and data post processing: Z+F LaserControl (version 6.8.0.8), Leica Cyclone (version 5.4.1) and FARO Scene (version 3.0.11.23). However, for the Trimble laser scanning system three software packages were used: program PointScape (version 3.1.4.1) for system control, and RealWorks Survey (version 5.0.3.0) and 3Dipsos (version 3.0.5) for the subsequent data processing. All modelling results of the post processing software packages were exported to DXF, in order to continue the construction work in AutoCAD 2004.

For the second project of the waste water treatment plant the following software packages were used: Z+F LaserControl for scanning with the IMAGER 5003 and Light Form Modeller (LFM) for modelling; PointScape for scanning with the GS101 and RealWorks Survey and 3Dipsos for 3D modelling.

4. Scanning

The scanning of the transformer station was conducted on different measuring days. For better comparability of the results of the four different scanners a local control point network was established as a first step using the high precision Leica total station TCRP1201. The obtained standard deviation of the control point coordinates was better than 3 mm using the software PANDA from GeoTEC, Laatzen for geodetic network adjustment. With reference to this control point network the different spheres/targets of each individual scanner were determined afterwards by free stationing with better than 6 mm accuracy for the residuals of the targets.

The scanning with the four laser scanners was performed with the related specific program. Practically the scanning was essentially influenced by the respective distance measurement principles. The two systems with phase difference method realized very fast individual scanning within 10 minutes per scan station with a measuring range of 360°, however these scanners needed more scan stations and more tie points for the registration/geo-referencing due to their reduced scanning range. In comparison, the scanners with the time-of-flight method needed significantly less scan stations. Nevertheless, an average scanning time of up to two hours was achieved per scan station using time-of-flight scanners.

Spheres as control and/or tie points can be used by all laser scanning systems. For the instruments of Trimble and Leica special expensive targets are available (Fig. 2), which allow semi and/or fully automatic target recognition in the point clouds. Figure 2 also illustrates the simple paper targets used by the other two scanning systems, which can be printed as required. The scanning conditions are summarised in Table 2. For all scanners the same pixel spacing of approximately 16–20mm at 25m distance was selected. Furthermore, it was realised in a later stage, that the number of 30 targets was not sufficient for the registration of the Z+F scans. Therefore, six additional natural tie points had to be manually identified in the point clouds for registration. The subsequent additional measurement of these natural tie points is also available in all other post processing software packages.

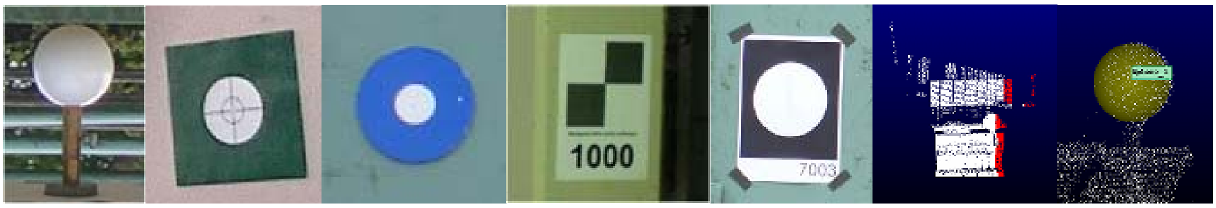

Fig. 2: Targets for semi-automatic registration of scans: Trimble sphere and target, Leica HDS target, paper targets of Z+F and FARO, scan and identification of a Trimble sphere

Scanner	**GS101**	**HDS3000**	**Imager 5003**	**LS880 HE**
Scan software	PointScape	Cyclone	LaserControl	FARO Scene
Pixel spacing (25 m dist.)	16,7mm	20,8mm	15,7mm	15,5mm
Scanning time / station	1,5h	2h	7min	7min
# scan stations	4	5	16	15
Type of target	Sphere	HDS, sphere, paper	Paper, sphere	Paper, sphere
# Targets	9	23	30 (+ 6)	41

Table 2: Scanning statistics with four different laser scanning systems in project 1

The second indoor object was scanned with IMAGER 5003 and Trimble GS101 with the following conditions: (a) nine IMAGER 5003 scan stations with a scan resolution of 6mm at 10m using 16 targets and 9 spheres, which resulted in 20-30 min per station, (b) eight Trimble GS101 scan stations with a scan resolution of 30mm/10m using 4 targets and 9 spheres, with an elapsed time of 45-75 minutes per station, which correspondents to 7.5 hours scan time in total.

5. Registration/Geo-referencing

Differences in the laser scanning systems regarding the procedures for scan registration and geo-referencing are essentially justified by the respective distance measurement principle of the assigned laser scanning systems. The registration was carried out for each data set with the related software of each system, but as an exception, the scans of the IMAGER 5003 were registered and geo-referenced with both related software, Z+F LaserControl and Cyclone. The systems with phase difference method usually generate scans with substantially larger data volume and more scans of an object. The available computer performance often does not allow a registration of all scans at once. Consequently, only the geo-referencing of individual scans was carried out to avoid large data volumes.

The results of the precision analysis for registration and geo-referencing of the scans of the transformer station are summarized in Table 3. It can be seen that the precision is always better than one centimetre, but it varies slightly, by some millimetres, in the range. It can be indicated that the laser scanning system of Leica obtained the best results. Furthermore, the time required for registration and geo-referencing is summarized, which shows clearly that the disadvantage of longer scanning time could be balanced by significantly faster registration and geo-referencing.

	Scanner	Trimble GS101	Leica HDS3000	Zoller & Fröhlich IMAGER 5003	FARO LS880 HE
Precision	**Software used**	RealWorks Survey	Cyclone	ZF LaserControl Cyclone	FaroScene
	Average deviat. registration	6mm	4mm	- - - ZF 6mm Cyclone	- - -
	Average deviat. geo-referencing	9mm	5mm	10mm ZF 8mm Cyclone	7mm
Time used	**Target definition**	- - -	2h	3h ZF, 5h Cyclone	3h
	Registration / Geo-Referencing	0,5h / 1h	1h / 0,5h	8h ZF, 3,5h Cyclone	6h
	Time in total	**1,5h**	**3,5h**	**11h ZF, 8,5h Cyclone**	**9h**

Table 3: Precision for registration & geo-referencing and required time in project 1

Although the phase difference scanners are much faster in the field than the time-of-flight scanners, increased data processing in the office is needed resulting in additional expenditure, which is partially caused by the clearly higher number of necessary targets and by the different scanning and recognition method of the targets. Thus, these targets are measured individually with the time-of-flight systems and already recognized in the field as spheres, while for the other systems no such separate scanning of spheres/targets is performed. Instead, the spheres/targets are usually included in the scans and measured manually in each scan in the office afterwards.

In project 2 the targets and spheres were used just for registration of the scans, i.e. a geodetic 3D network for the determination of the control point coordinates and the geo-referencing was not necessary. The results of the registration are summarised in Table 4.

6. Modelling

After registration and geo-referencing the structural components of the transformer station were modelled using the point clouds. For the 3D modelling two different software packages were used. Due to the strategic partnership between Leica and Zoller & Fröhlich, and between Trimble and Faro, the point clouds of the scanners with phase difference measurements could be transferred to the corresponding software of the partner Cyclone and 3Dipsos, respectively. Therefore, the programs Cyclone and 3Dipsos were exclusively used for 3D modelling in the first project, while LFM and 3Dipsos were used in the second project. One practical outcome was that the data conversion between the individual data formats can be very time consuming, approx. 20 minutes per scan (Z+F scans into Cyclone). For modelling the objects were approximated by geometric primitives. The degree of complexity can be chosen to be quite simple if, in particular, the attention is focussed on the meaning and/or symbolism than on the geometrical correctness. Thus, if necessary, a polyline can sufficiently represent an electric power line or a cylinder an isolator.

Therefore, besides simple geometrical primitives (e.g. line, cylinder, plane, box, etc.) more complex construction parts should also be considered for modelling in this investigation. As a multi-layered model H-carriers were used from a library, compound elements as well as 3D meshes were constructed and also partially replicated using a copying function. For example, the large isolators (Fig. 3 left) were constructed using cylinders and boxes as geometric primitives. In order to work as efficiently as possible, the copy & paste function was used in AutoCAD for the same elements. In Figure 3 (centre) the copied elements are represented in AutoCAD as a superimposition in comparison with the constructed results. Although the copy & paste function works efficiently it was not always operational for this transformer station due to the fact that the objects (e.g. isolators) are manufactured manually and differ significantly.

A partial model of the transformer station was constructed in the point clouds of the respective scanners using different primitives described above within the evaluation software. In Fig. 3 (right) a part of a constructed model is presented, which was generated from Trimble GS101 data in 3Dipsos. More detailed results of this project are summarised in [1].

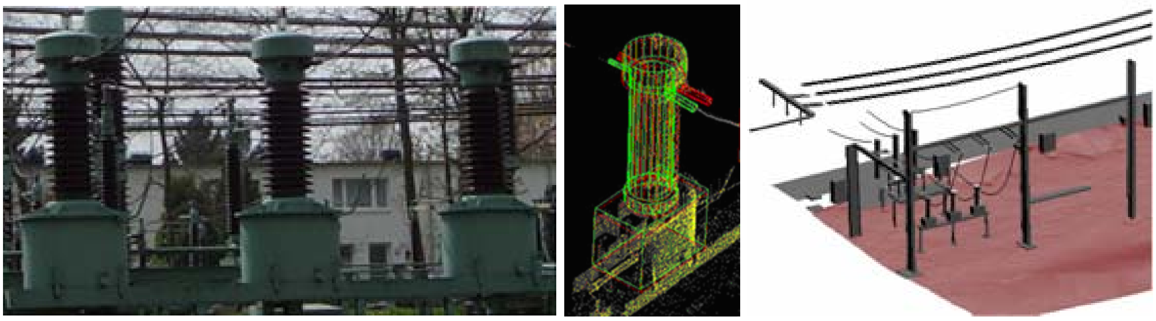

Fig. 3: Isolators (photo left) constructed in Cyclone including a superimposed copy (centre), part of the 3D model (transformer station), constructed in 3Dipsos from Trimble GS101 data (right)

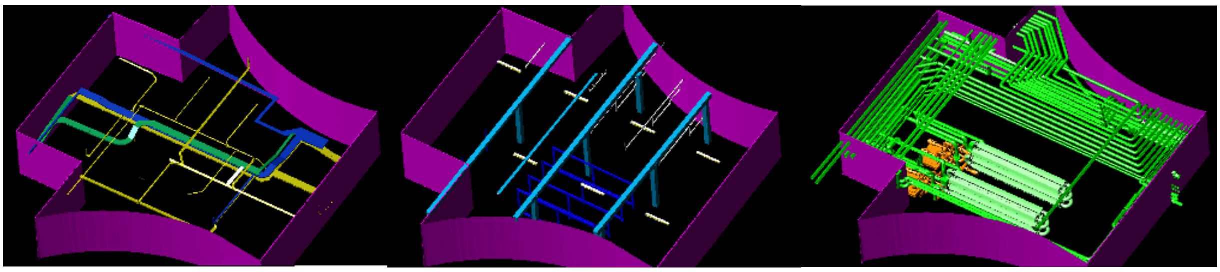

Fig. 4: Overview of three levels of the pipe line system, located in the same room (project 2).

In the second project, a 3D CAD model of the entire industrial pipe line system (Fig. 4) could be generated with a precision of 11mm. For this modelling the point clouds of the Mensi GS101 and the related software RealWorks Survey and 3Dipsos were selected due to the reduced noise of the point cloud and the better software functionality for 3D modelling. Here, it could be realised that additional photographic object documentation could significantly support the 3D modelling. More detailed results of this project are summarised in [4].

7. Comparative investigations

In order to compare the differently generated partial 3D models of the transformer station, identical elements (e.g. cylinders and planes) were selected from each CAD model. Criteria for the comparison were the orientation, the size and the accuracy of the constructed element, i.e. cylinders with different radii as well as different orientation and position in space were compared to each other. In Fig. 5 cylinders and their spatial distribution are illustrated.

Fig. 5: Selected cylinders for comparison in the photo and in the partial model (right)

For most of the modelled elements significant geometric differences could not be discovered, but for some investigated criteria larger differences between the geometric values of the individual elements resulted. The radii match well, but the radii of one cylinder could be determined with a standard deviation between 15 and 30 mm for all four used data sets, but the largest deviation between all four radii (approx. radius is 20 cm) was 9 cm. The difference of the z-direction of one cylinder was 6 gon between the lowest and highest value. In general, on the one hand, obvious systematic deviations could not be seen, but on the other hand small deviations were detected between the models derived from all four laser scanning systems. There is no systematic reason concerning the method of distance measurement (phase difference method in the case of IMAGER 5003 and LS 880 HE) or the modelling software (3Dipsos in case of GS101 and LS 880 HE). Additionally, large planes were compared in the different models. In each case the four normal vectors and the determined standard deviation of the plane agreed very well.

The results of 3D modelling, which could be achieved in a defined time period of 22-26 hours using the point clouds of two different laser scanners (HDS3000 and GS101) in each corresponding modelling software package, are presented in Fig. 6. If one compares the construction results (Fig. 6), which were achieved in the same elapsed time, one recognizes that the modelling with Cyclone was the fastest. Among other things this is due to the easy and straight-forward operation of the software. In partial tasks like meshing or construction of power supply lines 3Dipsos has clear advantages, since the automatic construction of pipe lines was implemented for example. However, in the construction with 3Dipsos, above all, the bounding of the objects was time consuming. The data flow of the systems with phase difference measurement method in the evaluation and modelling programs, which were originally conceived only for the systems with time-of-flight methods, turns out to be difficult, since the large data volumes can be only poorly processed in the programs. In particular functions like meshing routines fail due to large data volumes.

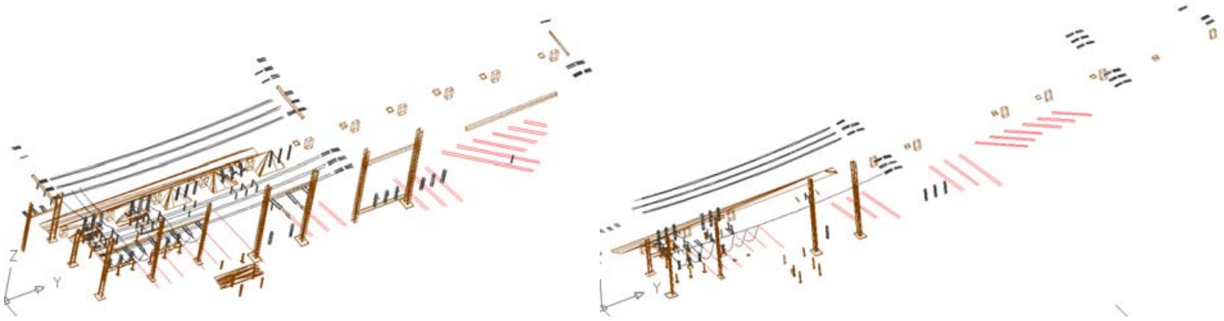

Fig. 6: Comparison of a 3D model (project 1) constructed from HDS3000 data with cyclone (left) and constructed from GS101 data with 3Dipsos (right) in the same elapsed time

In the second project a representative test object (Fig. 7) of the complex indoor environment was selected for a realistic comparison of four possible combinations of data processing: (i) GS101 with Trimble software, (ii) IMAGER 5003 with Z+F software, (iii) GS101 with Z+F software, and (iiii) IMAGER 5003 with Trimble software. As major test criteria for the whole workflow the following aspects were defined: data handling, precision, data integration, and efficiency. The results of the comprehensive precision analysis are summarized in Table 4. It shows that a general precision of one centimetre for the 3D CAD model could be achieved with all four combinations of systems used. These precision values are the result of the workflow from scanning, registration, and modelling.

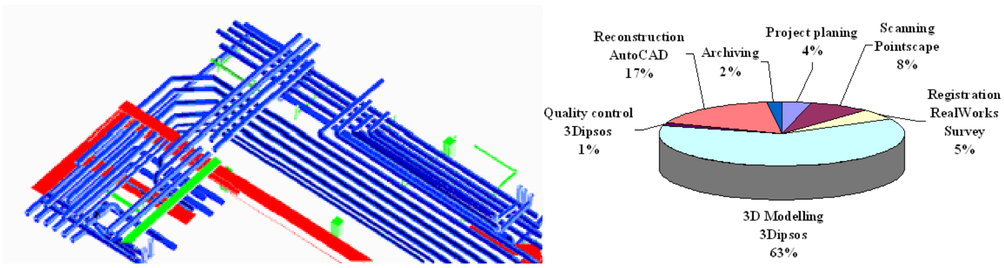

Fig. 7: Selected test area of project 2 for 3D CAD modelling of the pipe line system (left) and expenditure of human labour for the project 2 using Trimble system (right)

Scanner	Precision			
	Scanning (specs)	**Registration**	**Modelling**	**3D CAD model**
GS101	6,0mm / 10m	± 2,4mm	± 3mm - ± 6mm	± 9mm
	PointScape	RealWorks Surv.	3Dipsos	
IMAGER 5003	3,1mm / 10m	± 8,2mm	/	± 11mm
	LaserControl	LaserControl	LFM Modeller	
GS101	6,0mm / 10m	± 2,4mm	/	± 11mm
	PointScape	RealWorks Surv.	LFM Modeller	
IMAGER 5003	3,1mm / 10m	± 8,2mm	± 3mm - ± 5mm	± 10mm
	LaserControl	LaserControl	3Dipsos	

Table 4: Summary of the achieved precision for each step of the workflow of the second project

8. Time and cost aspects

On the basis of time and cost management the projects could be judged with regards economy and efficiency. In order to achieve a time comparison in 3D modelling for the transformer station project, the same time period of 22-26 hours was used for 3D modelling of each data set. Only the FARO data could not be modelled in this way due to lack of time. The other generated 3D models were compared visually after completion. In order to ensure a realistic time comparison in 3D modelling, the operator had received a short introduction into the respective scanning and registration software as well as some short training for the modelling programs 3Dipsos and Cyclone. The elapsed time for the workflow of the project transformer station is summarised in Table 5.

	GS101	**HDS3000**	**Imager 5003**	**LS 880 HE**
Scanning	5	9	4	4
Definition of targets	- - -	2	3	3
Registration/Geo-referencing	1,5	1,5	8	6
3D Modelling	22-26	22-26	22-26	- - -

Table 5: Comparison of the elapsed time for the entire workflow of project 1 for each system

For the second project it can be seen in Fig. 7 right that the 3D modelling with 3Dipsos and the object construction account for approx. 80% of the entire project. Based on other project experiences a typical ratio of 1:10 can usually be assigned to the time required for object recording in relation to data processing for object modelling and construction; the results in this project 2 were similar. The expenditure of human labour for this project amounted to 101 hours in total. This corresponds to theoretical costs of approx. € 7,000, which were deduced using appropriate current hourly wages for measuring assistant, technician and engineer. However, it seems that these costs are appropriate to European market conditions. In Table 6 the expenditure of human labour for project 2 is summarised in a comparison of the four combinations as described in chapter 7. These results confirm the similar results from project 1, which are summed up in Table 5. It is obvious, that with LFM less construction time was necessary in AutoCAD.

Step of a procedure	Expenditure of time [h]			
	Z+F	**Trimble**	**Trimble/Z+F**	**Z+F/Trimble**
Signalisation	0,5	0,5	0,5	0,5
Scanning	LC 3	PS 7,5	PS 7,5	LC 3
Registration	LC 8,5	RWS 2,5	RWS 2,5	LC 8,5
Data transfer (RWS⇔LFM)	-	-	2,5	9
3D Modelling	LFM 15,5	3Di 16	LFM 14	3Di 14,5
AutoCAD	2	5,5	2	5,5
Elapsed time in total	**37**	**38,5**	**36,5**	**47,5**
LC….LaserControl, PS….PointScape, RWS….RealWorks Survey, 3Di….3Dipsos, LFM….LFModeller				

Tab. 6: Comparison of expenditure of human labour for project 2 for four combinations

9. Conclusions and outlook

In the first project (transformer station) slightly different results could be achieved with all used terrestrial laser scanning systems. All systems showed advantages and disadvantages in the hard- and software components for this specific application. The time gained during data acquisition with the phase difference systems is later lost through the increased post processing time for the target definition and registration / geo-referencing. Here, the differences are most significant between the systems. On the other hand, in the case of modelling, all functionality for the object definition is similar and leads also to a similar construction precision. However, the noise of the point cloud significantly influences the final results. Nevertheless, the data exchange between the systems should be comprehensively improved in future.

In summary, it can be concluded for the second project "waste water treatment plant" that the IMAGER 5003 offers better performance in data acquisition for this indoor application due to its speed and flexibility, but the point clouds, although much more dense, include more noise than the GS101 scans. On the other hand, 3Dipsos offers larger construction functionality for 3D modelling than LFM, although more construction time in AutoCAD could be necessary. It can also be stated, that a combination of both systems (hardware from one system and software from the other system) cannot be recommended due to problems with data transfer and integration. It remains to be proven, whether third party software for 3D modelling could be an alternative in the future.

The statements about the hardware already require change due to the fast revision times of laser scanners. The new generation of laser scanners is already available on the market; for example the new IMAGER 5006 offers a number of characteristics, which were missed or criticized with the predecessor model tested here, such as an increased scanning range and an improved distance measurement capability with reduced scan noise. In summary, systematic investigations are generally necessary to determine the appropriate terrestrial laser scanning system to use for a specific application.

10. References

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