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High-Precision Oil Processing Applications Using 3D Terrestrial Laser Scanning

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Abstract: Terrestrial Laser Scanning (TLS) has been emerging as a revolutionary surveying and geomatics technology in the past decade. Currently, 3D TLS is being used as a standard tool for several applications that require high accuracy in position and 3D modeling, high resolution with dense data points and high efficiency that includes all aspects of data collection and data processing in a timely manner scenario. These applications cover the whole spectrum of engineering disciplines such as geomatics, civil, architecture, environmental, industrial, petroleum and oil processing. Several TLS systems are currently available in the market that differ in size, used laser (in terms of power, class and wavelength), range accuracy, scan acquisition rate and available sampling resolution. In this paper, the application of 3D TLS in a petroleum and oil processing project will be shown and discussed. In this project, one of the major objectives is to create a 3D model of an existing Treater located in the Oil Processing Building on SAIT (South Alberta Institute of Technology, Calgary, Alberta, Canada) campus that is to be replaced by a new Treater with a different design. Piping attached to and surrounding the existing Treater needs to be removed and redesigned to install the new Treater. Thus, building a replicate 3D model of the existing Treater is used to aid the design of the new piping. In addition, such created 3D model will function as an as-built documentation for the existing Treater. To accomplish this, the Leica ScanStation C10 3D Scanner was used and the data was processed by the Leica Cyclone software and then the created 3D model is presented in CAD using the AutoCAD Civil 3D software. In the paper, the work performed as well as the procedures followed will be presented and the obtained results will be shown. In addition, data analysis and accuracy assessment with respect to the industry requirements for the project will be presented and discussed.

Key words: Terrestrial Laser Scanning · 3D Modeling · High-Precision Oil Processing Applications · Point Cloud Processing

INTRODUCTION

The last decade has shown an increasing trend in the use of advanced surveying technologies and techniques in several applications. The most commonly noticed of these technologies is the 3D Terrestrial Laser Scanning (TLS) and the accompanied techniques for the data processing and representation. LASER, as an acronym, refers to Light Amplification by the Stimulated Emission of Radiation. Laser scanning is used in terrestrial applications (TLS) and in Airborne Laser Scanning (ALS) applications as well. The ALS is usually known by the acronym LiDAR (Light Detection and Ranging). The concept of both TLS and ALS is the same; however there are several differences such as geometry aspects, data georeferencing tools and the power and wavelength of the used laser [1]. Although the ALS (or LiDAR) systems have been used in the late 1970s, the utilization was limited due to the complexity of the system and the lack of cost efficiency. In the mid-1990s and after the advanced direct georeferencing systems implementing the Inertial Navigation System (INS) and the Global Positioning System (GPS) were used, LiDAR has become a standard tool for obtaining accurate measurements to generate Digital Elevation Models (DEMs) and Digital Terrain Models (DTMs), see for instance [2, 3] for early discussions and results on INS/GPS direct georeferencing for ALS applications.

Since its early development and utilization in the early 2000's until its fully developed and operational platforms used nowadays, 3D TLS has been implemented in several different applications. These include tunneling [4, 5], deformation surveys [6, 7, 8], classification of complex natural scenes [9], heritage and historic recordings [10, 11, 12], as-built documentation of industrial sites and engineering projects [13, 14, 15]

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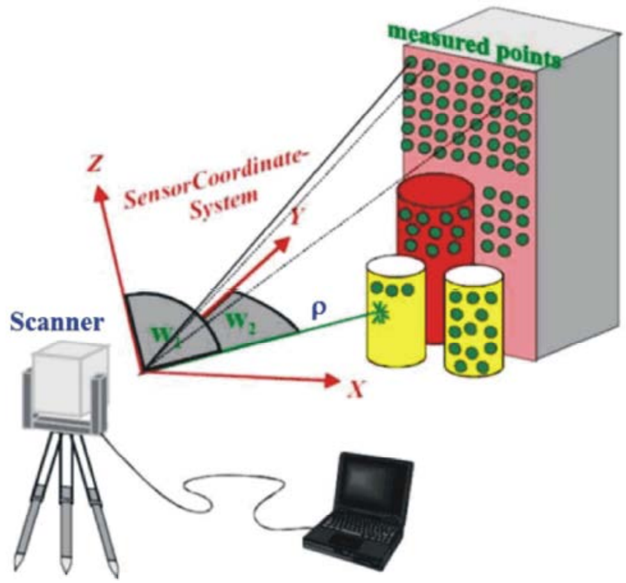

Fig. 1: 3D TLS Data Acquisition [18]

and engineering construction surveys [16, 17]. The remarkable advantage of using 3D TLS in the above applications shows in the ability of obtaining millions of accurate 3D points. Moreover, laser scanners are capable of obtaining such accurate data in harsh or difficult field conditions such as environmentally hazardous areas (due to chemicals or high temperature for example) or inaccessible areas. Performing surveys in such areas will be extremely difficult and inaccurate in the same time if classical surveying techniques such as total stations are implemented. Using TLS, easy and fast acquisition of complex geometric data from objects can be obtained where the scanner records the range, the intensity (as a grey level or digital number) of the returning signal and the scan angle of each measurement. Thus, each point is described in a 3D local (sensor or scanner) spherical coordinate system with the scanner in the origin. Then, the scanner internally transforms the spherical coordinates into a Cartesian (X, Y, Z) coordinate system (Fig. 1) [18]. In the figure, ρ represents the range where w_1 and w_2 represent two orthogonal angles (zenith angle and horizontal direction), respectively.

Instead of obtaining a single measurement as performed by a regular laser range finder, 3D TLS devices have rotating mirrors that allow millions of measurements to be made over a single scene (setup) in a few seconds or minutes (depending on the type of scanner). The output of such process is known as a point cloud which consists of the local coordinates as well as the corresponding intensity for each data point (Fig. 1). In other words, a point cloud contains two types of information. The first type is metric information that describes the object geometry and shows spatial relationships between objects in the scene while the second type is visual (or thematic) information that is used to describe the properties of the object surface and to obtain the reliability of the range data for each point [19]. The area of interest is usually scanned in more than one scene. The merging of several point clouds from different scenes in one single common coordinate system is known as the registration process. After registration, the X, Y and Z directions are usually set to east, north and up, respectively [16]. In addition, the intensity for each point will have a value between 0 (for black) and 255 (for white).

TLS systems used in surveying applications can be categorized into two major types. The first type is called Time-Of-Flight (TOF) scanners, sometimes referred to as Pulse-Based (PB) scanners or simply laser range finders while the second type is called Phase-Shift (PS) scanners. The PB scanners have a laser diode that sends a pulsed laser beam which is reflected off the scanned object. Using accurate timing, a sensor measures the time (i.e. the TOF) for the optical pulse to travel to and from the reflected surface. Knowing the speed of light c and the measured TOF t, the range ρ can be calculated as: $\rho = c * t/2$ (Fig. 2). This principle is similar to that used in total stations; however the PB scanners provide much higher scan acquisition rates [20].

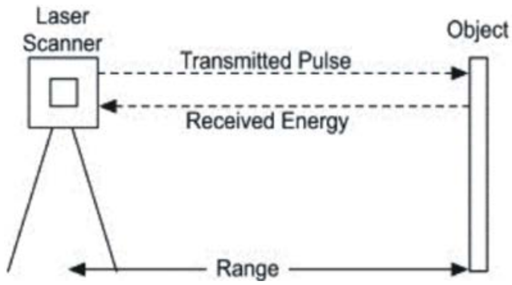

Fig. 2a: (after [21])

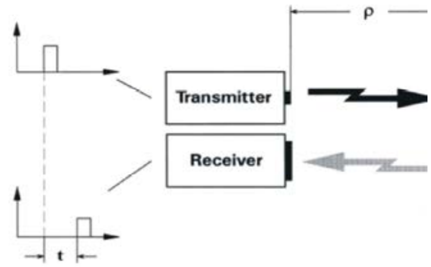

Fig. 2b: (after [22])

Fig. 2: Pulse-Based (PB) TLS Principle

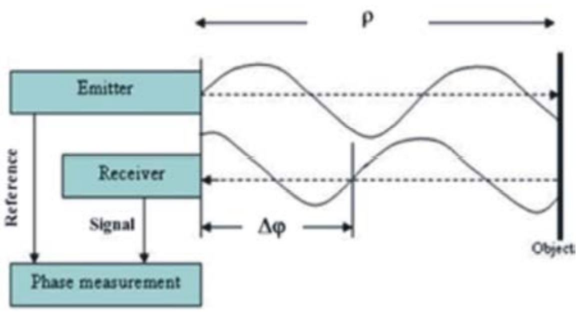

Fig. 3a: (after [20])

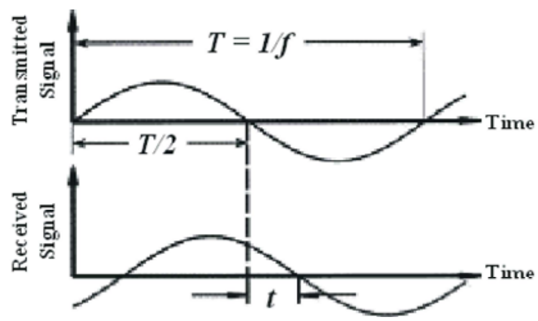

Fig. 3b: (after [22])

Fig. 3: Phase-Shift (PS) TLS Principle

On the other hand, the PS scanners implement a constant (continuous) laser beam with sinusoidal modulated optical power (with modulation frequency f) that is emitted from the scanner and reflected off an object. The reflected light is then detected and compared with the emitted laser beam to determine the phase shift (or difference) $\Delta\varphi$ and hence the TOF t can be obtained as: $t=(\Delta\varphi/2\pi + N)*1/f$, where N is the integer number of wavelengths. Then, the range can obtain as shown earlier (Fig. 3). It should be noted that several modulation frequencies are usually used in a single scan for accurate estimation of the TOF.

PB scanners are capable of capturing data at a longer range than PS scanners. The PB scanners have a scan distance of up to 2000 m (with a typical range of 200-700 m), while the PS scanners have scan distances up to 120 m (with a typical range of 10-70 m). However, PB scanners can only collect up to 50,000 points per second while PS scanners can collect at a much higher speed with up to 1 million points per second [4]. Therefore, PB scanners are usually used for exterior applications while the PS scanners are typically used in industrial applications. Hence, for the project discussed in this paper that requires creating a 3D model of an existing Treater located in the Oil Processing Building at SAIT, a PS scanner would be preferred. This is due to the nature of the project that requires providing details of the piping attached to and surrounding the existing Treater, which in turn will aid in the design of the new piping and will serve as an as-built documentation for the existing Treater. For this project, the only available scanner at the time was the Leica ScanStation C10, which is a PB scanner. The test results showed that using such scanner provided the required accuracy and was more than sufficient to perform the task. However, in a future continuing work, other different scanners (PB and PS) will be available and a constructive comparison will be carried out.

Project Description: The current Treater located in the Oil Processing Building at SAIT (South Alberta Institute of Technology, Calgary, Alberta, Canada) is out of date and is to be replaced by a new prototype model. As mentioned earlier, one of the major objectives of this project is to create an as-built documentation for such Treater including its surroundings and pipe attachments using 3D TLS. As-built documentations is extremely necessary in several industries especially oil and gas.

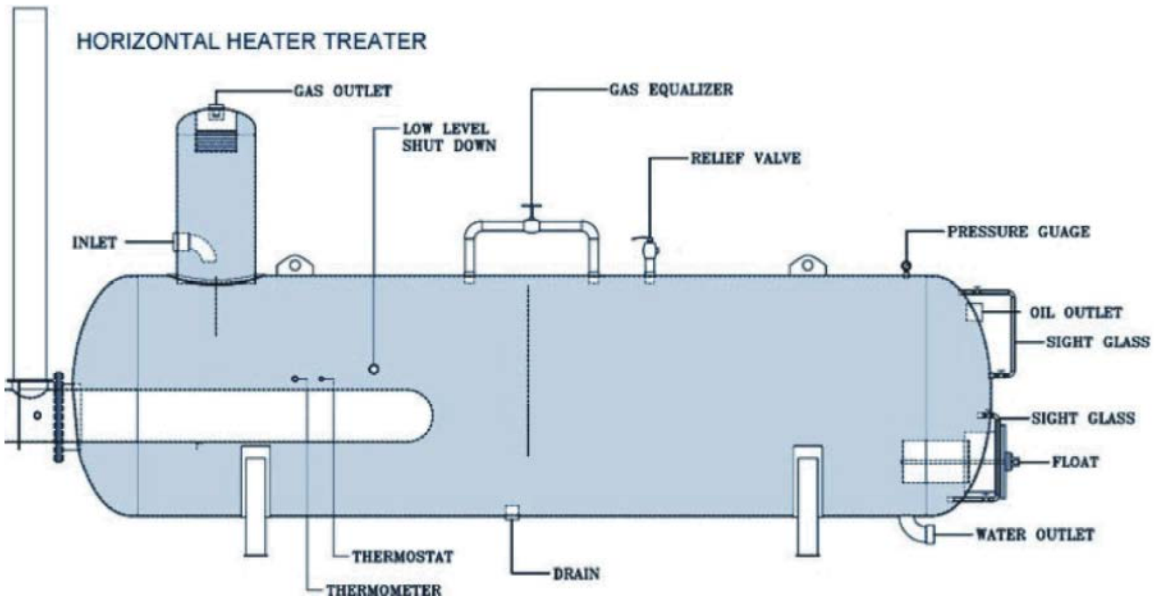

Fig. 4a: Heater Type [24]

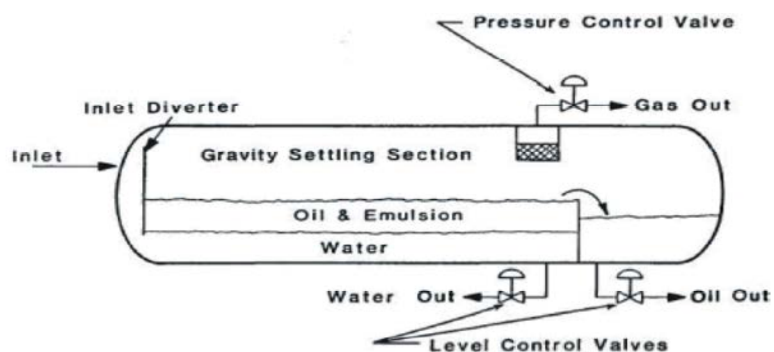

Fig. 4b: Emulsion Type [25]

Fig. 4: Schematic of Horizontal Treaters

They are used to display the details of machinery and piping that physically exist and may differ from original plans. In addition, as-built documentations are useful for modifications or repairs that may need to be done to installed machinery, piping or surrounding area in the future. Before TLS implementation in the past for such applications, engineers relied on outdated facility drawings and equipment information as well as on a limited number of available surveying field measurements that were obtained using handheld laser measuring device or standard metal tapes [14]. For larger site plans, as-built documentation is used to show maneuverability around objects in the area and to provide evacuation plans as well.

In general, a Treater is a piece of oilfield equipment used to separate a raw product of a combination of oil, gas and water. In other words, a Treater (horizontal or vertical) is a vessel used to treat oil-water emulsions so the oil can be accepted by the pipeline or transport. A Treater can use several mechanisms including heat, gravity segregation, chemical additives and electric current to break emulsions [23]. Also, Treaters can be categorized as either heater or emulsion types (Fig. 4) for common schematics of both types horizontal Treaters.

The Treater located at SAIT is an emulsion Treater that uses heat and gravity to separate the gas, water and oil from the emulsion. Fig. 5a shows the existing Treater and the attached piping, while Fig. 5b shows the location of the Treater in the Oil Processing Building at SAIT. The pipes in the figure have the following color codes to represent what fluid they carry: blue (water exiting), green (oil exiting), orange (gas entering), yellow (gas exiting) and brown (raw emulsion entering).

Fig. 5a: Treater and Attached Piping

Fig. 5b: Treater Location in the Production Building

Fig. 5: Existing On-Site Treater and Surroundings

Fig. 6: Leica Scan Station C10 3D Scanner [26]

Accuracy of single measurement	Position[1]:	6 mm
	Distance[1]:	4 mm
	Angle (horizontal/vertical):	12" / 12" (60 μrad / 60 μrad)
Modeled surface precision[2]/noise	2 mm	
Target acquisition[3]	2 mm standard deviation	
Dual-axis compensator[4]	Selectable on/off; Setting accuracy: 1.5" / 7.275 μrad, resolution 1", dynamic range ±5'	

All ± accuracy specifications are one sigma (1 σ) unless otherwise noted.
1 At 1 m - 50 m range, 1 σ
2 Subject to modeling methodology for modeled surface
3 Algorithmic fit to planar HDS targets

Type	Pulsed; proprietary microchip	
Color	Green; visible (wavelength = 532 nm)	
Range	C10:	300 m @ 90%; 134 m @ 18% albedo (minimum range 0.1 m)
	C5:	35 m @ >=18% albedo (upgradeable to full C10 range)
Scan rate	C10:	up to 50'000 points/sec, maximum instantaneous rate
	C5:	25'000 points/sec (upgradable to full C10 speed)
Scan resolution	Spot size:	≤ 7 mm from 0 - 50 m (based on Gaussian definition) ≤ 4.5 mm from 0 -50 m (based on FWHH definition)
	Selectability:	Independently, fully selectable vertical and horizontal point-to-point measurement spacing
	Point spacing:	Fully selectable horizontal & vertical; through full range
Field-of-View (per scan)	Horizontal:	360° (maximum)
	Vertical:	270° (maximum)

Fig. 7: Specifications of the Leica ScanStation C10 Scanner [27]

As mentioned earlier, a new designed Treater will be installed to replace the existing one. The new model has different inlets and outlets for the various piping. The 3D model of the on-site Treater created by the TLS will be used to determine where the old piping will be removed and to design the new piping. For the new piping, it will be designed as efficiently and neatly as possible to allow better access to the equipment and easier modifications to the piping in the future if necessary.

TLS Equipment and Software: The laser scanner used for the project was the Leica ScanStation C10 3D Scanner. The C10 3D Scanner includes scanner, tilt sensor, battery, controller, data storage, auto-adjusting video camera and laser plummet. It is a Pulse-Based (PB) TLS that can collect up to 50,000 points per second and has a field of view of 360° x 270° as shown in Fig. 6. The specifications of the Leica ScanStation C10 Scanner are also given in Fig. 7.

Two types of scanning targets were used in the project. The first type was a magnetic one that would stick to any metallic surface and the other type was a freestanding prism pole target attached to a tripod. The two types of used targets are shown in Fig. 8. The freestanding prism pole target was used in empty areas that could be seen by multiple setups where there was no surface to attach a magnet target to. With the used Leica ScanStation C10 3D high precision scanner, the Leica Cyclone 3D Point Cloud Processing Software is the most compatible engine to work with the collected data. The Cyclone software allows manipulating the obtained data from the scanner in a user friendly environment. In addition, it has a pipe modeling module for data georeferencing as well as distance and volume calculations. The version of the software used in this project was Cyclone 7.2 [28].

Testing and Data Acquisition: Before the actual scanning of the Treater area, several dry tests were performed first to ensure the functionality of the scanner and the accuracy of the data processing including targets and other features in the scenes. Moreover, several scan resolutions were attempted with different scanner-to-object distances. One of these tests was done in a classroom on SAIT campus (Fig. 9) for the obtained point cloud of such test.

As a common practice in TLS projects, some measures need to be taken before the scanning of the site starts. This includes the determination of the required number of scan stations and where these stations should be located. This is largely dependent on the size of the area being scanned and how much detail is needed. Moreover, the location of the scan targets (used as control and/or tie points in data processing as will be discussed later) should be decided and fixed. For this project, three scan stations were utilized and were located on the left, front and right sides of the Treater. The use of multiple setups ensured that the Treater is captured from multiple angles and no information would be lost by being in the shadow of another object. In addition, six targets were used in the test and their locations were fixed for all scan setups. Fig. 10 shows the approximate locations of the scanner setups and the used targets as well.

Once the targets are fixed and the locations for the scan stations have been determined, the scanning process was carried out. First, an image of the whole area was scanned where in this case a panoramic view of 360°x70° was selected. The image scan was taken at a full 360° horizontal scan since it was necessary to find all the targets shown in Fig. 10. However, the window for scanning can be adjusted to only include the area of interest (Treater and the surrounding area), which consisted of an approximately 70°x70° window. The resolution for the scan was chosen to be 1cm x 1cm resolution at approximately 6m distance to the intended scan objects. Then, a higher resolution scan was done to accurately select the control targets center. In the latter case, the scan resolution was increased to 1mm x 1mm. As mentioned earlier, the immediate result after each scan is a point cloud in which each point is represented by 3D local coordinates and the intensity of the reflected signal. The process of merging point clouds obtained from different scan stations into a single coordinate system is called point cloud registration. It should be noted here that such registration process simulates a relative orientation process between the scan stations coordinate systems. However, if the objective is to register the point clouds in a global (i.e. geodetic) coordinate system; an absolute orientation has to be performed later (which requires the knowledge of the global coordinates of at least three of the fixed targets). In the sequel, the discussion will be devoted to registration into a local coordinate system, i.e. the scanner coordinate system of one of the scan stations.

Usually, registration in industrial projects (such as the one discussed in this paper) is realized using features for which exact correspondence exists between different scans, i.e. signalized control, tie points, fixed targets, or common features. However, if exact correspondence between the scans is not available (i.e. the object is not

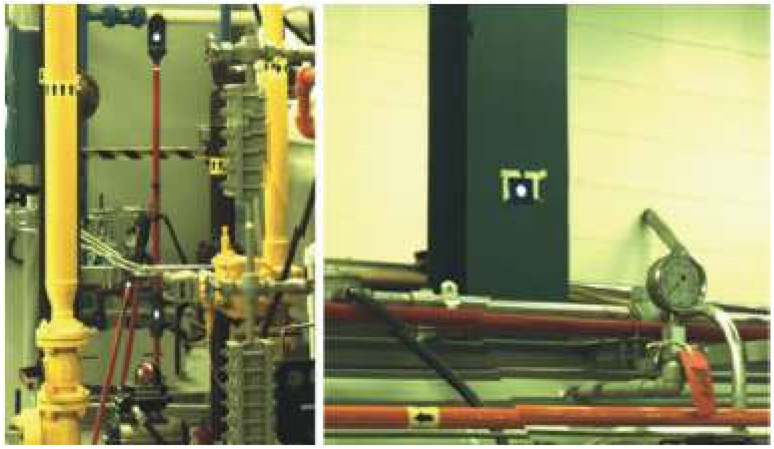

Fig. 8: The Prism Pole Target (left) and the Magnetic Target (right) used in the Project

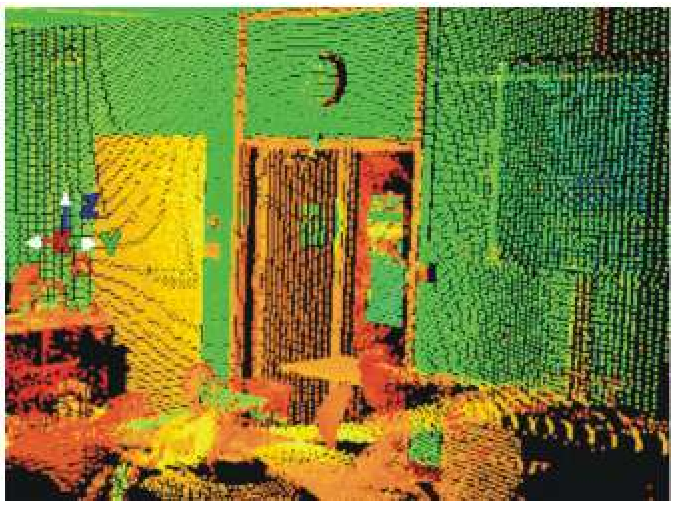

Fig. 9: Example of an Obtained Point Cloud using Leica ScanStation C10 Scanner

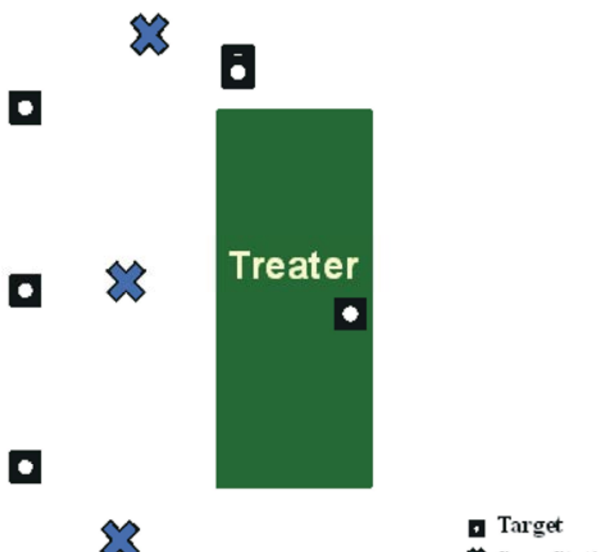

Fig. 10: Locations of the Scan Stations and Used Targets (not to scale)

accessible to fix targets or common features and tie points are hard to identify), the Iterative Closest Point (ICP) registration algorithm or one of its variants is usually used. The ICP algorithms do not require common points and the exact correspondence is replaced by iteratively determined approximate correspondence of points or small surface elements [1]. However, the ICP algorithms require good a priori orientation estimates. For more discussions on ICP algorithms, consult [29-32]. When using common features for registration, these features have to be extracted first. This task becomes accurate if artificial retroreflective targets are fixed in the scene due to the high intensity recorded values of the reflected energy for those targets in the obtained intensity images. In this case, most of the point cloud processing software packages is able to detect those targets automatically. Also, common natural structure elements can be identified in the intensity image but usually with lower accuracy than that obtained from retroreflective targets. In the test carried out in this paper, registration using suitable overlapped areas between scans and then using targets as tie points was implemented as discussed earlier.

Data Processing and 3D Modeling: The point cloud data processing for this project was performed using the Leica Cyclone 7.2 software. Before carrying out the point cloud registration, a visual check on several pieces of piping was done to determine if there are any large differences between point clouds. From the three point clouds, none were found. Registration of point clouds was done using two approaches. The first one was by using overlapped areas between scans where some common (easily definable) features observed from each individual scan were selected. The second approach was by including the targets also in the overlapped areas as tie points. In the test, at least four targets were available in each overlapped area. The first approach was used in the analysis as a preliminary step for quality purposes and to investigate if there were any blunders in the data, however, the final results were based on the second approach. For both approaches, the coordinates of the first scan station was fixed to a local coordinate system. Using the first approach, the largest error residual vector from the Least-Squares-Adjustment (LSA) applied in the software was obtained as 2cm. This indicates that the data from the different scans was merged successfully even without the artificial targets. In addition, this accuracy level is sufficient for most applications including petroleum and oil processing especially with large pipe sizes. In fact, the standards for oil and gas industry states that piping modeling accuracy should be within 2cm. After including the targets in the registration process using the second approach, the largest error residual vector was obtained as 2mm which meets all industry standards even for small piping.

After registration is done where the outcome will be a single point cloud, a filtering process has to be performed on the dataset. This is due to the fact that the point cloud will contain non-relevant Treater points that represent other features surrounding the Treater. In addition, it will contain points that are caused by reflections from obstacles or persons passing the scene during scanning. These non-required points are considered as noise. The filtering process will remove such noise from the dataset as well as unnecessary redundant information. For this project, the majority of noise that had to be removed was points captured beyond the Treater area. Moreover, other noise that had to be removed was points related to personnel walking around during the scanning sessions. Fig. 11 shows the top down view of the entire registered scene. In the figure, it illustrates also a selected area around the Treater where everything outside it was considered as noise and was removed before the 3D modeling of the Treater. This was performed by the filtering module available in the Leica Cyclone 7.2 software.

As a final presentation for the project, 3D modeling of the Treater was performed where the registered point clouds are converted into 3D models. These models are not only used to represent the scanned objects in 3D but are also needed to display measurements and different views in 2D. In general, 3D CAD models of industrial sites are required for maintenance, access planning and safety analysis. Usually, industrial sites contain a large percentage of relatively simple geometrical shapes (such as cylinders and planes) and thus, these shapes are accurately described if recorded with the high density point clouds using TLS, see for example [33, 34]. This is the reason that most point cloud processing software (including Leica Cyclone) can perform automatic extraction of standard shapes from the cloud, especially pipes and pipe fittings. For this project, point clouds that were modeled mostly consisted of cylinders (such as piping), planes (such as walls and flooring, elbow piping, flanges and valves. For this project and based on the specifications required to design the new piping, only the 2-inch and larger piping was modeled. This is because such large piping transports the critical raw and separated products to and from the Treater. The smaller piping is less significant for modeling purposes since it is

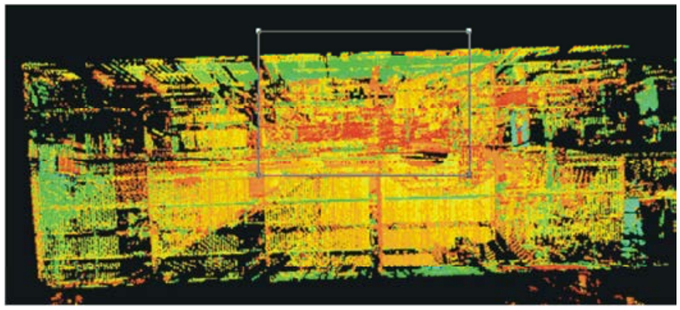

Fig. 11: Point Cloud for the Scanned Scene before Noise Removal

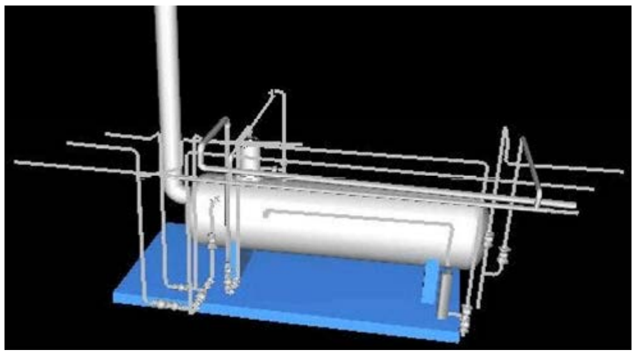

Fig. 12: The Generated 3D Model of the Existing Treater

considered as parts of the Treater and is used mainly to monitor fluid pressure and levels. The smaller piping is also pre-assembled with the Treater and does not need to be attached to any existing pipe located in the building. Using the Cyclone software piping and 3D modeling tools, the completed 3D model for the existing Treater was obtained and is shown in Fig. 12.

SUMMARY AND CONCLUSIONS

In this paper, the concept and potential implementation of accurate 3D Terrestrial Laser Scanning (TLS) in petroleum and oil processing applications was discussed. In such applications, as-built documentations (presented in the format of 3D models) are extremely important since they show the details of existing machinery and piping that may differ from original plans and are useful for modifications or repairs that may need to be done in the future. It will be very difficult and costly as well to obtain the level of detailing required to build these 3D models using traditional surveying techniques such as total stations. Currently, these 3D models can be obtained with high accuracy in a very cost effective way using TLS systems and the corresponding advanced point cloud processing software. In this paper, an overview of the TLS technologies, types, operation procedures and data processing approaches was given first. Then, a detailed description of the project covered in the paper, as an oil and gas application where TLS is implemented, was presented. For this project, the major objective was to create a 3D model of an existing Treater located in the Oil Processing Building on SAIT (South Alberta Institute of Technology, Calgary, Alberta, Canada) campus that is to be replaced by a new Treater with a different design. Piping attached to and surrounding the existing Treater needs to be removed and redesigned to install the new one. To accomplish this task, the Leica ScanStation C10 scanner and the Leica Cyclone data processing software were utilized. Using several retroreflective targets and multiple scan stations, the obtained point clouds were registered in a single point cloud. In such registration process, the largest error residual vector obtained from the lest-squares adjustment applied in the software was 2 mm. This level of accuracy meets all accuracy requirements of the project and all similar projects based on the industry given standards. This was achieved although the Leica ScanStation C10 scanner is a pulse-based type which can collect only up to 50,000 points per second. It is recommended, however, to use phase-shift scanners for similar projects due to the higher available data collection rate with up to 1 million points per second. This will provide more details of the piping attached to and surrounding Treaters located in industrial sites.

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