INVESTIGATION ON LASER SCANNERS *

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1. INTRODUCTION

The study and choice of a three-dimensional laser scanner for a number of diverse metrology tasks at SLAC (Stanford Linear Accelerator Center) are covered. Specifications including range, accuracy, scan density, resolution, and field of view are discussed in relation to anticipated department requirements. Potential vendors were asked to perform three unique tests ranging from scanning of accelerator components in a non-operating ring, creating a floor-plan of our alignment shop, and accuracy tests in our alignment laboratory. The scope of these tests will be described and some examples of the vendor's results will be included. Details will be presented on the final chosen laser scanner including the assessed ability for the instrument to meet our requirements.

2. TESTING NEEDS AND PROCEDURES

2.1. Overview

Laser scanners can have numerous uses at an accelerator facility like SLAC. Although they are presently not accurate enough for precise alignment of accelerator magnets, laser scanners can be used for component placement and especially for as-built surveys. In this case, mechanical engineers or designers often request a "map" of an area where repair or retrofitting will take place. Using a total station or even a laser tracker requires a significantly higher degree of effort to eventually gather a very limited number of points representing components or the walls in the area. A laser scanner on the other hand can gather positional data on everything visible in the area not only capturing the requested information but also additional objects that invariably can surface as being needed by the engineer or designer.

To reflect the anticipated needs of the laboratory, various tests were developed to help decide which laser scanner should be purchased. The scanner must offer a rapid survey of the entire spatial region of interest (accelerator section or building section) and the scans should be obtainable using a

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grid of variable and selectable density allowing a fine or coarse 1:1 spatial digitization. Each point generated in this process would possess a set of four dimensional data including the position (*x, y, z*) and the intensity (*i*) of the returning signal. The desired scanner would meet the following requirements:

- optimal range of up to 50 m for large structures including buildings or long tunnel sections
- minimum range of 1 m or less to capture regions that are close to the laser scanner such as an accelerator magnets in a narrow tunnel
- user selectable scan density so that only regions of special interest need the highest resolution, saving time and disk space
- resolution < 350 μrad
- minimum accuracy of better than 5 mm at a 50 m range
- measure minimum of 5000 points every second; significantly larger rate desired
- field of view 360º horizontal and at least 60º vertical; full panoramic view desired

The device needs to be a self-contained system with control software that can be upgraded as necessary and communicates with a notebook or pocket PC. Both indoor and outdoor scans are required and operational ambient temperatures need to range from 0ºC to 40ºC to encompass these different surveys.

The scanner software must meet both surveying and Geographic Information System (GIS) requirements. As-built scans of existing structures have to be completed in a timely manner with an ability to capture a majority of the structure in only a few set-ups. The generated point clouds must be rotatable and scaleable allowing superfluous points to be eliminated while also allowing in-situ measurements of point features for geometrical quality control.

Creation of best-fitting surfaces that are compatible with CAD objects in systems such as AutoCAD or MicroStation will have to be easily implemented allowing timely reverse engineering results for complete structures to be obtained. Second order plane surfaces such as cylinders or spheres as well as known profiles and standard dimensions need to be automatically incorporated into the CAD translation. Additionally, extension of modelled regions through a growing function but also allowing for clipping at the intersection of adjoining elements is necessary. Characteristic object parameters including object identification and material composition are important allowing adaptive structural planning contributing to a construction information system that supports a wide range of computational needs.

2.2. Field Evaluation and Test Area

2.2.1. Scope

During the past summer a series of field evaluations on the technical performance of candidate laser scanners was completed. The instruments were tested in an actual field setting closely matching the typical operational use expected by the surveying personnel at the site. The vendors were asked to visit SLAC and conduct a full 3D laser scan. A team of the Alignment Engineering Group's (AEG) surveying personnel oversaw this testing and considered the performance in light of the necessary requirements such as accuracy and speed. The evaluation covered the whole spectrum of project phases from data acquisition, data treatment and visualization. The balance between ease-of-use and meeting the above requirements was paramount in this consideration.

2.2.2. Data Acquisition

The region of interest was scanned in one or more setups and the resulting series of point clouds were requested to be combined into one "global" coordinate system. This registration process utilized existing or placed tie points.

2.2.3. Data Treatment

Reflections from unavoidable environmental obstructions such as vehicles or people passing through the scanning scene can create either missing regions of data or virtual objects that should be removed. Once these points are eliminated if they are in the way, the following operations are completed:

- Computation of object geometry such as cylinders, spheres, etc. from a subset of the point clouds. Primarily our concern was to have our standard 1.5" retroreflector spheres modelled including a determined center point
- Intersections of objects such as two walls
- Regularization of actual repeating objects from non-regular point clouds
- Orthophoto creation from digital images combined with scans are interesting but with the high resolution of the raw scans, these were found not to be absolutely necessary
- Exporting of point cloud and/or geometrical elements into other programs

2.2.4. Visualization

Data that has been processed and treated can then be visualized:

- Preliminary visual inspection of point clouds in three-dimensions using color intensity representation. The method of displaying the scanned area is important since it will be the main conduit through which all the analysis will begin
- Combining derived objects with point clouds
- Realization of the amalgamation of digital images with registered information to create orthophotos if available
- Three-dimensional modelling and contour generation would be desireable
- Fully mobile point-of-view representation of the scene allowing virtual fly-bys

Test 1: Tunnel Test

The field testing and evaluation of the laser scanner included a scan of an area at SLAC in which magnets and other typical components are present. The scan included measurements of control points that had a common datum with existing AEG control monuments. This would ensure that the laser scans could be integrated into existing and new surveying control data for a positional tie to an existing network datum. The three-dimensional scans should have the ability to be overlapped and connected due to the unique geometry of the tunnel having a limited width but substantial length.

More specifically, the location of the test was at a section of the beamline in the South Final Focus of the Stanford Linear Collider (SLC). It was a section of tunnel about 10 meters long and had unique magnets plus a BPM (Beam Position Monitor) and a collimator (Fig. 1). Scanner coverage also included the existing pipes, wires and hoses as well as the walls in the region.

Fig. 1 - SLC Accelerator Tunnel and Magnets to Test Laser Scanner

To tie the laser scans to the SLAC system the device must be able to accurately measure our retroreflectors. The classical tooling used at SLAC consists of a series of 1½" diameter steel spheres. They are placed on a nest (also known as a Hubbs Cup) that itself fits into a ¼" hole located on a component. With this setting, the center of the sphere is straight over the axis of the ¼" hole at a height offset of exactly 1". For use with the laser scanner, the steel spheres were painted and some bead-blasted for optimal scanning reflectivity. SLAC supplied these for the test although some vendors did prepare their own. The steel spheres were mounted on all accessible ¼" holes for each magnet as well as on the tunnel walls (Fig. 2). The tunnel is approximately 3 meters in width and height and the walls are made of shotcrete. The beamline is located closer to one wall and is on a girder approximately 1 meter wide and 1.5 meters high. Testing in this area was necessary to ensure that this typical tunnel geometry—including the minimum range requirements—can be adequately covered with the candidate laser scanner.

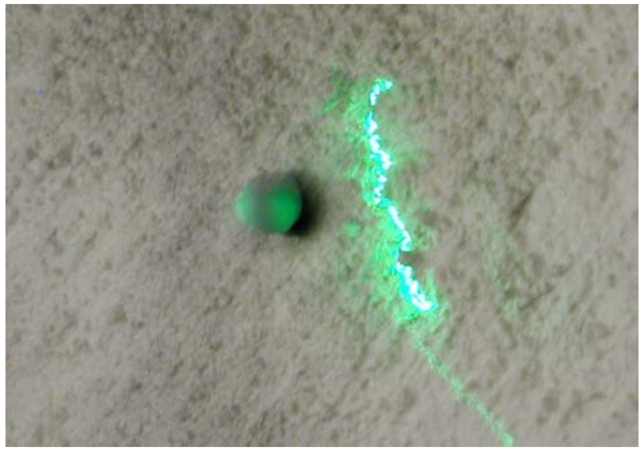


Fig. 2 – Scanning a 1.5” Retroreflector on Tunnel Wall

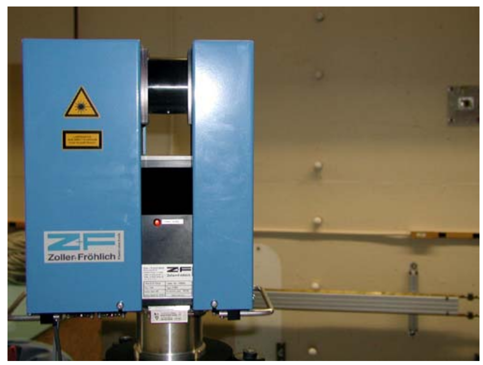
Test 2: Building Test

Another field test was conducted to identify the “as-built” abilities of the scanner. This consisted of a three-dimensional scan of one façade and the inside of our laboratory to create a floor plan (Fig. 3). The geometric integration of this range of data with existing control monumentation was demonstrated by each vendor.

Fig. 3 – Scanning the Alignment Laboratory

Test 3: Accuracy and Resolution Tests

The third test was conducted in our Sector 10 alignment laboratory. A series of spherical targets were to be placed in a row along a portion of the bench at various spacings. The positions of these targets are measured by each scanner and then compared to laser tracker measured coordinates. The horizontal test utilized one wall in the laboratory where, in one setup, the laser scanner was placed almost in-line with the targets near the wall and measurements made (Fig. 4). This was desired primarily to determine the accuracy of the distance measurements of the scanner since the angular field of view would be very small. In the next setup the laser scanner was placed off to one side of the line of targets approximately 2 or 3 meters in distance. The targets were scanned again but this time angular accuracy was the primary concern since the overall angular coverage was relatively large. A vertical test was also designed to determine the accuracy of the potential instrument (Fig. 5).



Figs. 4 and 5 – Horizontal and Vertical Testing of Laser Scanner

A resolution test used a target as shown below in Fig. 6. The front panel had slots which were about 30 mm wide at the perimeter becoming narrower towards the center [1]. For a scanner with a high resolution (small angular increments and a small laser spot) there should be reflections not only from the front panel but also from the solid surface approximately 60 mm behind. With a high resolution scanner the reflections from the bottom surface should not only be present in the wider slotted areas near the perimeter, but also close to the center where the slots are narrow. This target was scanned to detect resolution information from three different distances, 3 m, 12 m, and 25 m.

Fig. 6 – Resolution Test Structure

In Fig. 7 the results of the scans by each vendor are shown. Fig. 7a from Leica's HDS 4500 shows a filtered image due to no intermediate points appearing between the box planes. In such a difficult test the perturbations of mixed pixels, “comet” tails, total reflections, multipath, and more are expected. A clipping filter was used since the scene was well known although in reality prior geometrical information is usually not known. The second pair of images (Fig. 7b) from iQvolution’s iQsun 880 shows very high levels of noise. The third pair (Fig. 7c) from Trimble’s GS 200 has missing data in the middle area and high noise between the planes. In Fig. 7d Z+F’s Imager 5003 generates very few points between the two planes indicating that a very practical “on-the-fly” filter was used. The middle “star” area with the tightest openings is clearly visible indicating good resolution and low noise.

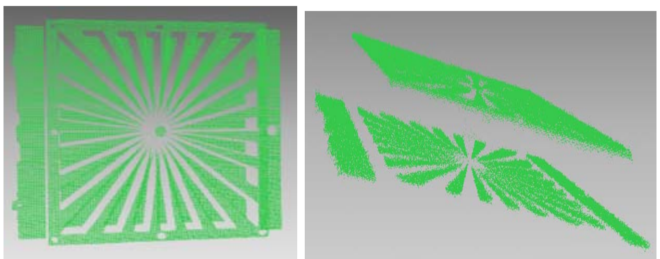


Fig. 7a – HDS 4500

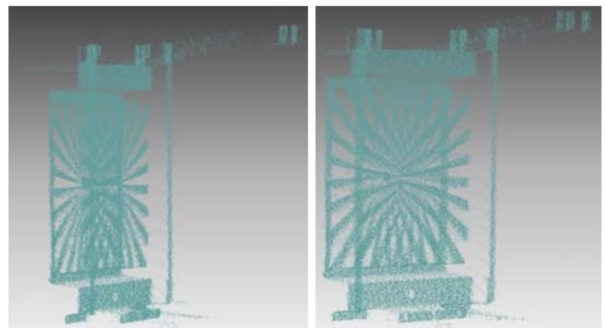


Fig. 7b – iQsun 880

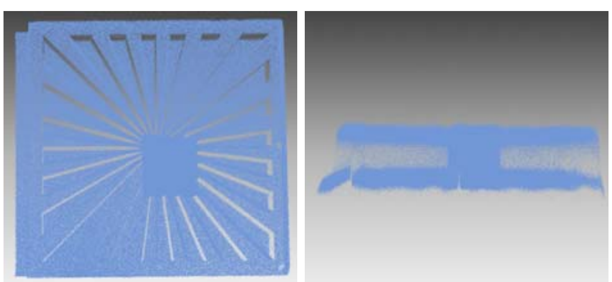


Fig. 7c – GS 200

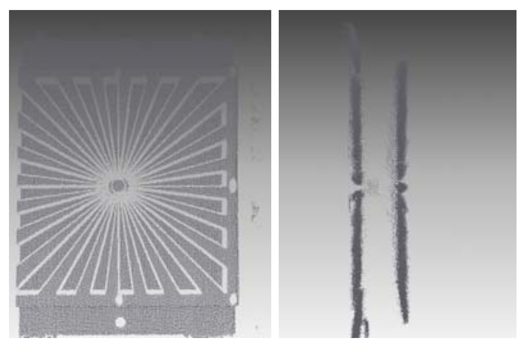


Fig. 7d – Imager 5003

3. THE SELECTED LASER SCANNER

3.1. Overview

The Imager 5003 manufactured by Zoller+Fröhlich (Z+F) was chosen for its overall ability to meet the requirements specified earlier and for its openness to future hardware upgrades. Details on this can be found in the poster “Laser Scanner Demonstration” by Fuss et. al [2]. The existing software from Z+F was not adequate for the needs of the laboratory and thus Cyclone software from Leica was chosen. In this section details on the Z+F Imager 5003 are presented based on supplied technical specifications and the paper "Understanding Imager 5003 Accuracy Specifications" by Z+F [3]. Some technical results are presented on why the Imager 5003 was chosen.

3.2. Specifications

3.2.1. General Specifications and Error Sources

The Z+F long range Imager 5003 meets the specifications necessary for SLAC. The range limitations from 1 m to 50 m are adequate. Resolution can be varied from a 1/16 density preview mode, a 1/4 middle resolution mode, a 1/2 high resolution mode to the full Super High Resolution mode. This allows for fast and less dense surveys when time is a limiting factor or alternatively scanning in the highest resolution for the best results. With a typical data acquisition rate of 125,000 pixels per second, time will not be as limiting a factor as is disk storage space. Gathering this much data is possible due to the fine increments of the mirror or scanner body. The horizontal resolution is 0.01º (~175 µrad) and the vertical resolution is 0.02º (~350 µrad). The vertical field of view is a large 310º while the horizontal field of view is the full 360º.

The Imager 5003 has a LAser RAdar system (LARA) and a mechanical deflection system [3]. LARA works by measuring the travel time of the laser beam through phase differences and consists of two errors: linearity and range noise. The mechanical deflection system consists of a rotating mirror for vertical deflection of the beam and also a rotation of the entire unit for the horizontal coverage. Together these provide the necessary polar coordinates of one unique scanned object point. Errors in reading these angles contribute to the total error of the system.

3.2.2. Ranging Errors

Calibration of the Imager 5003 involves the laser beam being pointed onto a target plate having a defined reflectivity. Using a calibration fixture allows a set of known target distances to be compared to a mean range value measured with the scanner using 10,000 samples. The error between these is modelled into a correction function and stored. Thus only random errors consisting of linearity errors and range noise remain for the overall range error.

Linearity errors are specified as non-gaussian and are found to be constant over the entire range of the scanner. Empirical usage indicates a linearity error ranging from ±5 mm. Range noise, the second random component, is caused by object distance and reflectivity. For an instrument that scans as fast as the Imager 5003, range noise can not be "averaged out" as can be done with slower laser scanners. Range noise spans from about 1.0 to 2.5 mm rms for lighter to darker objects at around 10 m and up to about 6.5 mm rms for dark objects (20% reflectivity) at around 25 meters. It is important to consider the normalized range noise value for an instrument since this factor considers the sample rate in the assessment. Thus at 25 meters for dark objects the normalized range noise is around 0.018 mm rms for the Imager 5003 where a pulsed-based scanner at 1000 samples per second would be worse at 0.047 mm rms [3].

3.2.3. Mechanical Deflection System Errors

Discrepancies between the actual deflection angles for the scanning laser beam and the measured angles of the mirror create angular errors. These errors consist of both the horizontal and vertical components and through calibration with known object distances they can be reduced to less than 0.02º (<350 µrad) at one sigma.

3.2.4. Total Error

The total error computes to the values indicated in Table 1 [3]. Note that the range noise is negated since it becomes less significant due to numerous object points.

Distance (m)	50	30	20	10
Abs. Error (mm rms)	25.2	15.7	11.1	7.0

Table 1: Long Range Imager 5003 Specifications

These values represent a “worst-case” assessment for single observations and do not consider the benefit of using known targets. To relate the scanner system to a known local coordinate system, a registration process is initiated whereby at least four checkerboard targets are scanned that have been surveyed with a total station and assigned local coordinates.

Practically it should be noted that objects that have been scanned and modelled for CAD applications actually “average” the above errors leading to as good as 3 mm of error for regions less than about 15 m in span [3]. Test 3 described above with the Imager 5003 had most deviations less than 3 mm. Standard deviations of the differences were about 1.3 mm for distance measurements and 0.6 to 1.3 mm for both horizontal and vertical angles depending on the distance to the target. These corroborate with the specifications provided by Z+F.

3.3. Selecting the Imager 5003

Detailed analysis of the Imager 5003 was made by the fourth author who compared it to three other instruments that were demonstrated at SLAC. One of these was actually constructed with the same hardware as the Imager 5003 but using significantly different software. Weighting the criteria described above for each candidate instrument gave a clear advantage to the Imager 5003 (see ref. [3] for further details):

- Accuracy (15%)

- Data acquisition speed (15%)
- Price (15%)
  - Initial Acquisition
  - Hardware Upgrades
- Customer References (15%)
- Field evaluation results (40%)
  - Software
  - Test 1: Tunnel Test
  - Test 2: Building Test
  - Test 3: Accuracy Test

Although the software that was demonstrated with the Imager 5003 was not exceptional, the remaining criteria including accuracy, speed, customer references and overall field performance was considered to be excellent. Upgradeability was prominent since Z+F specified that SLAC will receive upgrades to the hardware system. The new system is expected to include numerous improvements.

4. SUMMARY

Zoller+Fröhlich’s Imager 5003 will be a useful addition to the available alignment tools used by SLAC. It provides a reasonable balance between speed and accuracy for many non-precise surveying tasks and promises to grow in relation to the needs of the laboratory.

References

[1] Boehler et. al., “Investigating Laser Scanner Accuracy”; CIPA Symposium, Turkey; October 2003.
[2] Fuss et. al., “Laser Scanner Demonstration”; Poster IWAA2004, CERN; October 2004.
[3] Zoller+Fröhlich, “Understanding Imager 5003 Accuracy Specifications”; Zoller+Fröhlich; July 2004.