

## INEXPENSIVE 3-D LASER SCANNER SYSTEM BASED ON A GALVANOMETER SCAN HEAD

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### ABSTRACT:

This paper deals with a 3-D scanning system based on relatively inexpensive, off-the-shelf products. Although there exist many techniques for obtaining information about object position, size and form, it is still possible to find specific applications where none of the conventional methods seem to satisfy the requirements. Such applications are encountered in challenging environments where one has to simultaneously gather information quickly, with high accuracy and without interaction with the object of interest. The instruments also need to be kept simple, cost effective and robust. In this paper, we propose and investigate a system that angles a beam from a laser rangefinder along the object of interest, in order to determine the object's geometrical properties. The beam is angled by means of a galvanometer scan head. The scanned pattern is conditioned by the assumed object form and position. The pattern is adjusted during the measurement in an appropriate way so that the scanning time is minimized. The object form assumed is a series of concentric pipes of relatively small and varying diameter (10 – 50 cm). The system is designed to determine the position of the joints and the diameters of the pipe sections. This article specifies the characteristics of the system and discusses the various parameters limiting the system performance. Although the system components were not optimal with respect to the measurement requirements, the system's performance is designated as satisfactory. The system can easily be improved by exchanging the components with more suitable units.

### 1. INTRODUCTION

Obtaining information about the position, size and form of an object is a common problem in industrial settings. There exist many solutions to this problem ranging from photogrammetry, via LIDAR scanning, to range imaging cameras (Pfeifer & Briese, 2007; Blais, 2004; Moller, Kraft, Frey, Albrecht, & Lange, 2005; Stettner, Baily, & Richmond, 2004). Each of these techniques has its own application areas. However, there are specific applications where none of the above techniques seem to fully satisfy the right combination of demands. For example, in the challenging offshore environment there is a need for gathering information quickly, with high accuracy and without interaction with the object of interest. At the same time, the instruments need to be kept simple and robust. They need to be inexpensive, tolerate the harsh environment and require minimal maintenance. They must not interfere with the rest of the equipment and, last but not least, have no negative EH&S implications.

Keeping these kinds of applications in mind, we will make an effort to address the problem of close range imaging of diffusely reflecting objects. Commercially available 3-D laser scanners have the disadvantage of high cost and/or low accuracy and low sampling rate. Alternatively, 2-D laser line scanners can be incorporated into inexpensive systems and used for 3-D scanning if they are tilted with the help of mechanical devices. Unfortunately, scanning in the third dimension must occur relatively slowly. In addition, many of the commercial 2-D line scanners have either low accuracy, relatively low sampling rate and/or do not work well enough on targets with low remission coefficient.

This paper will look into the possibility of assembling a cost effective 3-D scanning system based on a laser rangefinder that can acquire 3-D information about an object placed 4-7 meters away quickly and accurately. In order to meet the requirement for a low-cost system, the solution considered will be based on commercial, off-the-shelf products. The focus is set on designing and characterizing a system based on an inexpensive and accurate 1-D laser rangefinder and a galvanometer scan head. Galvanometers and galvanometer scan heads are well-developed, highly accurate and reasonably priced systems readily used in a wide variety of applications, for example in laser shows and welding. Galvanometer scan heads can position the laser beam with extreme accuracy, precision and speed. They offer more degrees of freedom by allowing scanning of the beam either in a continuous manner with raster positioning, in a step-and-hold positioning, or by vector positioning. However, to the best of our knowledge, there have been a very few attempts to use a galvanometer scan head to angle the beam from a laser rangefinder (Kobayashi, Akiyama, Suzuki, & Yoshizawa, 1989; Wang, Hu, Liu, & Liang, 2000; Zexiao, Jianguo, & Ming, 2007).

The system that will be described is well-suited to scan an area where the number of points needs to be minimized because of the demand for a high response time. The fact that the system can be used to measure independent points, and not necessarily whole lines, offers an advantage compared to commercial scanners, since it potentially reduces the time used to scan the object. Based on these points, and some prior knowledge of the shape of the object, different line and curve fitting algorithms can be used to find the size, the position, etc of the measured object.

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## 2. INSTRUMENTATION AND METHODS

### 2.1 System design

The proposed system consists of a galvanometer scan head from Cambridge Technology and a laser rangefinder based on phase shift comparison measurement principle from Acuity Laser Measurement Systems. The laser beam is scanned over the target in two dimensions, by two galvanometer mirrors. The light scattered from the target is sent back into detector through the same system of mirrors, see Figure 1.

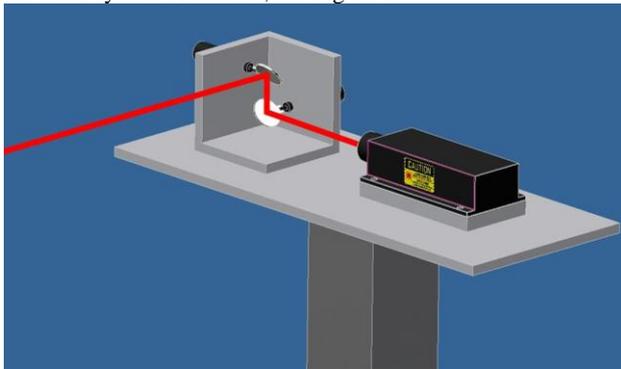


Figure 1. Angling of laser beam by galvanometer mirrors

The aim of this study is to investigate the potential of such a measurement system. The hardware/software components of the system used in experiments for this paper do not represent the optimal choice and introduce several obvious limitations. The components are, however, easy to replace, leading toward an optimal hardware/software system. Optimal hardware setup denotes here a system consisting of inexpensive, commercially available components that will give best possible speed and accuracy of measurements. Improvement of the measurement result can be done in software as well, through the use of signal filtering and algorithms.

Some prior knowledge of the placement and the shape of the object are assumed. Thus, different line and curve fitting algorithms can be used to find the form of the measured object. In this study, the assumed shape is a series of concentric pipes with relatively small and varying diameters, ranging between 10 and 50 cm. This form can be designated as challenging for most of the commercially available scanners and yet quite common in industrial applications. The given position is vertical and somewhat centred with respect to the scanned area.

The surface properties are assumed to be diffusely reflecting. Handling of the eventual specular reflection (wet or oily surface) depends on the properties of the chosen rangefinder. The commercially available ones cannot handle both types of surfaces at the same time. However, by using the galvanometer scan head setup, it is possible to combine the two types of laser rangefinder devices into one system that can work on both specular and diffusely reflecting surfaces.

The 3D measurement presented in this paper locates joints and determines diameters along the pipe from a fixed remote distance of 4-7 m, see Figure 2. The measurement requirements are listed in Table 1.

Requirements	
Measurement area	$1.8 \times 0.5 \text{ m}^2$
Point sample speed	100ms
Accuracy	Joint < 10mm, diameter < 10mm

Table 1. Measurement requirements

Based on these requirements and the above mentioned assumptions, the scanning can be performed in a controlled and systematic manner and in the shortest time possible.

In this particular case, the algorithm begins with a horizontal scan at the bottom of the scanning area. The exact positions of the pipe in the  $x$  direction and the pipe diameter are determined by a circle fitting the measured data (Chernov). The laser beam is thus scanned vertically in the  $y$  direction along the pipe. The measured data is used to reproduce the profile of the pipe. Based on this measurement and the previously measured position of the center of the pipe, all diameters can be calculated. However, to reduce the uncertainty of the measurement subsequent scans in the  $x$  direction are made as well, at the given  $y$  positions of interest. The pipe diameters at these positions are then determined by circle-fitting.

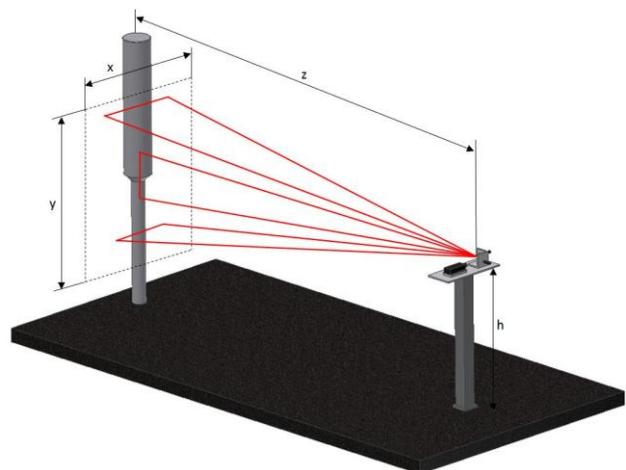


Figure 2. Measuring system with scan area

### 2.2 Setup

The setup consisted of off-the-shelf parts, a galvanometer scan head from Cambridge Technology and a laser rangefinder from Acuity Laser Measurement Systems. A dedicated microprocessor based controller and application software was used to process all signals in the system and evaluate measurement results using sophisticated algorithms; see Figure 3 and Table 2. Specifications for the laser rangefinder and the galvanometer are listed in Table 3 and 4 respectively.

The zero position of the galvanometer mirrors is located, by definition, in the center of the scanning window. The scanning area depends upon the distance between the system and the target as well as the maximum permissible angle of the galvanometer mirrors. The GSI 10 mm galvanometer has an optical angle of  $\pm 20^\circ$  in each direction. At a distance of 4 m, this gives a theoretical scanning window of  $2.9 \times 2.9 \text{ m}^2$ . The galvanometer mirrors used in these experiments are undersized with respect to the AR1000 receiver lens. At large angles, the

amount of light reflected back into the receiver is not sufficient for the rangefinder to make an accurate distance measurement. Thus, only a part of the theoretical window can be used.

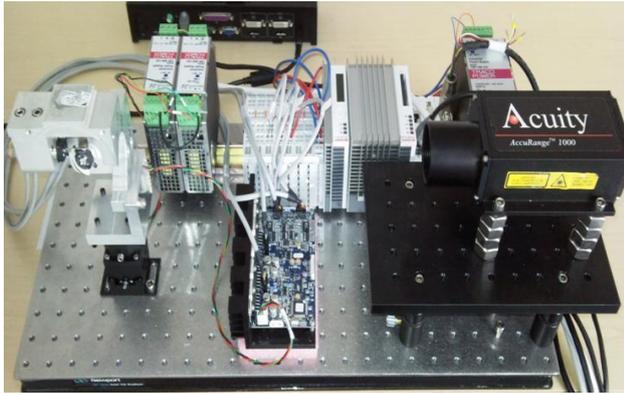


Figure 3. System setup

	Component	Type	Data
<b>Hardware</b>	Optical table	Newport	
	Power supplies	TRACO	24V, 4A/7.5A
	Embedded-controller	Beckhoff	CX1030-w/EtherCAT
	Laser	Acuity	AR1000
	Galvo scan head	Cambridge	6220H
	Galvo driver board	Cambridge	Digital lightning
<b>Software</b>	Application SW	Beckhoff	TwinCAT
	Graphical user interface		VB.NET
	Tunemaster	GSI	Config. of galvanometer

Table 2. Main measurement system components

<b>Acuity AR1000 rangefinder</b>	
Laser type	650nm, 1mW, visible red
Span	0.1-30m (at 85% diffuse reflectance)
Accuracy	± 3mm
Resolution	0.1mm
Laser Spot	5.1mm
Output	4-20mA

Table 3. Laser specifications

<b>GSI 10mm galvanometer</b>	
Galvanometer type	6220H'
Mirror size	10 mm
Step response	200µs
Repeatability	8 µrad
Linearity	99.9%

Table 4. Galvanometer specifications

### 3. EXPERIMENTS AND RESULTS

#### 3.1 Calibration

An example of a distance measurement plot is shown in Figure 4. The left-hand side of the plot is the initial, horizontal scan, as explained in the section 2.1. The right-hand side of the plot shows the subsequent vertical scan.

A linear offset in the measurement with respect to the angle was observed. A simple angle adjustment was done manually, but could be incorporated into the software as an automated calibration routine in the future. A vertical line scan of a flat surface was performed with the  $x$  mirror in zero position. The data from the scan were fitted to a linear model, and this model was used to correct further measurements with respect to the  $y$  mirror angle. Figure 5 shows the scan with correction.

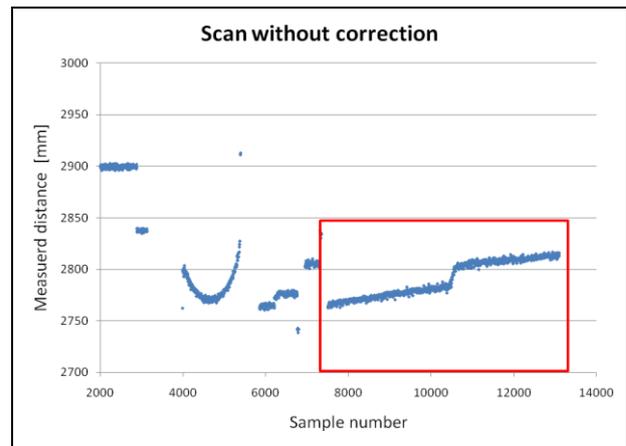


Figure 4. Scan used for correction calculation. Marked area shows the profile scan over the pipe. In this uncorrected scan, the detection of change in diameter failed and next diameter was not scanned

#### 3.2 Experiment - design

The system is programmed to scan a pipe, detect a set of parameters (including diameters at different heights of the pipe), and map the profile of the pipe. The profile indicates the changes in the diameter.

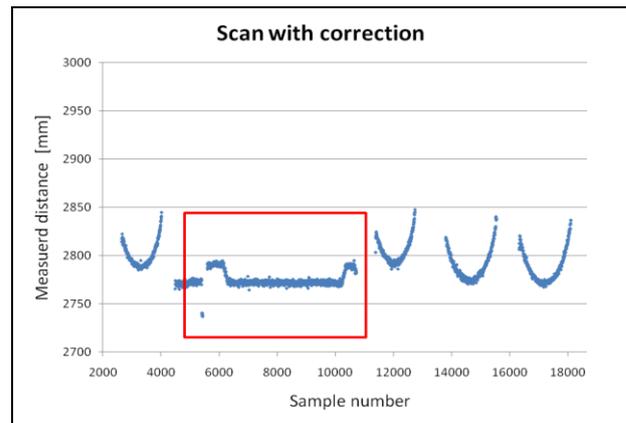


Figure 5. Scan with correction. Marked area shows the profile scan along the pipe, with correction. In this scan, the change in diameter was detected. All diameters were scanned. During a line scan, the galvanometer moves at a constant speed. The AR1000 rangefinder is set to register a measurement every

100 ms. Nonetheless, the controller updates the signal from the laser every 2 ms; see Figure 6. Every five consecutively received signals were observed to be equal. The rangefinder takes one of the 10 received signals of different value to make a sample. This sample is thus used for the computation of the diameter and the profile mapping.

The fact that the laser receives a unique signal every 10 ms implies the possibility to try and decrease the sampling speed to 10 ms and increase the speed of the system 10 times. However, experiments show that this causes poor measurements.

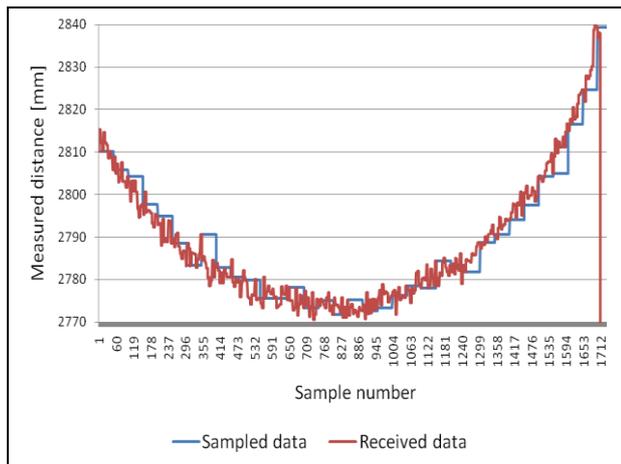


Figure 6. Laser sample and signal received by controller

Evenly spaced horizontal measurements over the pipe were used as input for determining the diameters, using circle fitting. In some experiments, the data were filtered beforehand by removing the significant outliers.

Experiments were performed with different sampling speeds and different velocities of the mirror in order to study the performance and limitations of the system. The settings that were used during testing are presented in Table 5.

	Laser sampling time [ms]	Mirror speed [cm/sample]	Comment
Setting 1	100	0.5	Filtering data.
Setting 2	10	0.5	No filtering
Setting 3	100	1	No filtering
Setting 4	100	0.5	No filtering. Used the average of the 10 unique signals.

Table 5. Settings used during the testing

For the settings 2 and 3 no filtering of the data was done before the data were used as input to the circle fitting algorithm, while setting 1 is tested both with and without filtering. In addition, to increase the performance of the system with setting 1, the calculations were based on an average of the 10 unique signals that are registered for each sample.

### 3.3 Results

Profile scanning always gives a satisfactory result after calibration, and when the galvanometer mirrors are not angled more than  $\pm 10^\circ$ . The scan fails in the outer part of the theoretical window. The accuracy of the measurements is given in Table 6.

	Diameter [cm]	Joints [cm]
Setting 1	+3, -1	$\pm 0.5$
Setting 4	+1, -0.5	$\pm 0.5$

Table 6. Measurement accuracy

There was also a clear difference in the measurement accuracy in experiments performed with the different settings. Calculations with data collected with setting 4 give a more stable and more accurate result than using setting 1 with filtering only. Setting 2 gives more inaccurate results than setting 1, and the results are also far more unstable, see Figure 7 and Figure 8. Setting 3 completely fails for some scans and the measurements are otherwise far too inaccurate.

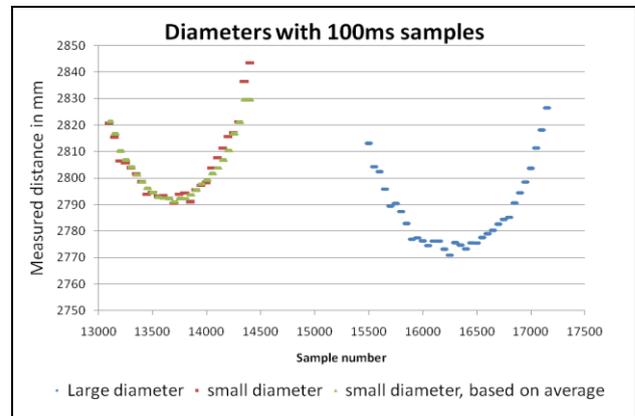


Figure 7. Scan with setting 1

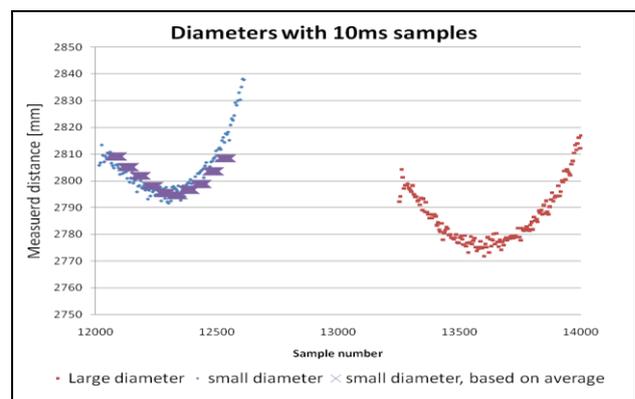


Figure 8. Scan with setting 2. Notice that the samples vary more than for the scan with setting 1.

#### 4. DISCUSSION

The specifications of the hardware components limit the measurement system performance with respect to accuracy and speed.

The speed of the galvanometer system is high and the sampling speed is limited to 50Hz by the sampling speed of the AR1000 rangefinder. Even though the rangefinder updates itself every 10 ms rather than every 100 ms, performing the scan more quickly fails (setting 3), probably due to the fact that the laser fails when the measured distance changes too quickly (maximum velocity of the moving target is specified as 4 m/s).

The accuracy of the measurement system is more complex and depends on a range of factors, including the size of the galvanometer mirrors, the distance between the laser and the galvanometer, angular resolution of the galvanometer and the accuracy of the laser. Greater inaccuracy was observed for the measured diameter than for the determined joint position. This is probably due to the fact that the diameter is calculated by a non-optimal circle fitting algorithm, while the data for the profile was used directly.

The mirror size of the x-y galvanometer system used in this test was 10mm, while the diameter of the receiver lens of AR1000 was greater than 30mm. Thus, a substantial part of the returning light was lost and never hit the receiver lens, see Figure 9. Therefore the accuracy of the distance measurement was reduced.

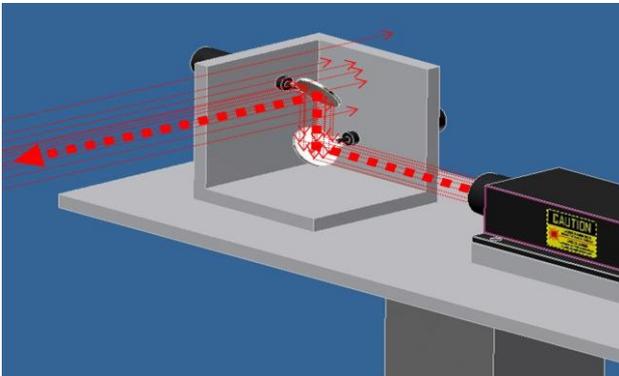


Figure 9. Only a part of the returning light will be reflected into the detector by the mirrors.

In addition to this, the sender and the receiver lens of AR1000 are not centred. This again introduces difficulties and increased measurement errors due to the undersized mirrors of the galvanometer scan head.

Furthermore, the speed and accuracy of the scan depends upon the number of measurement points. The number of points needed must therefore be evaluated for each application according to the set demands.

#### 5. CONCLUSION

A 3D measurement system based on a laser rangefinder and a galvanometer scan head was described and characterised. Only reasonably inexpensive, off-the-shelf products were used as system components. A controlled and systematic scanning approach was investigated in an attempt to reduce the time

needed to perform the desired measurements. Although the components were not optimal with the respect to the measurement requirements, the obtained results were satisfactory with an accuracy within the specified limits. The system is built in such a manner that the components can be easily exchanged with more suitable units. The system can easily be extended to include and coordinate simultaneous use of two rangefinders, one optimized for diffusely reflecting surfaces and one optimized for specular reflection. This will be the subject of our future work.

#### 6. REFERENCES

- Beraldin, J.-A., 2004. Integration of laser scanning and close-range photogrammetry - the last decade and beyond. *XX ISPRS Congress, Commission V*. Istanbul.
- Blais, F., 2004. Review of 20 years of range sensor development. *Journal of Electronic Imaging*, 13 (1), pp. 2314-240.
- Chernov, N., u.d. *The University of Alabama at Birmingham, The department of mathematics*. Fitting ellipses, circles, and lines by least squares. <http://www.math.uab.edu/~chernov/cl/index.html> (accessed 12 Apr. 2010)
- Harding, K., 2008. Hardware based error compensation in 3D optical metrology systems. *Ninth International Symposium on Laser Metrology, Proc. of SPIE*, 7155.
- Kobayashi, K., Akiyama, K., Suzuki, I., & Yoshizawa, I., 1989. Laser-scanning imaging system for real-time measurements of 3-D object profiles. *Optics Communications*, 74 (3,4), pp. 165-170.
- Moller, T., Kraft, H., Frey, J., Albrecht, M., & Lange, R., 2005. Robust 3D Measurement with PMD Sensors. *1st Range Imaging Research Day at ETH*.
- Pfeifer, N., & Briese, C., 2007. Laser scanning - Principles and applications. *Geo-Sibir, III International Scientific Conference*, pp. 93 - 112. Nowosibirsk.
- Stettner, R., Baily, H., & Richmond, R., 2004. Eye-Safe Laser Radar 3-D Imaging. *RTO SCI Symposium on "Sensors and Sensor Denial by Camouflage, Concealment and Deception"*, pp. 23-1 - 23-6. Brussels.
- Wang, J., Hu, Z., Liu, Y., & Liang, J., 2000. Experimental research on laser tracking system with galvanometer scanner for measuring spacial coordinates of moving target. *Optical Measurement and Nondestructive Testing: Techniques and Applications, Proc. of SPIE*, 4221.
- Zexiao, X., Jianguo, W., & Ming, J., 2007. Study on a full field of view laser scanning system. *International Journal of Machine Tools & Manufacture*, 47, pp. 33-43.

#### 7. ACKNOWLEDGEMENTS

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