Laser Triangulation Profilometer for Inner Surface Inspection of 100 millimeters (4”) Nominal Diameter

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Abstract. A new axis-symmetrical system was developed for inner surface pipe measurement focused in the Oil & Gas industry, aiming the quantification of corrosion and others inner surface anomalies. The measurement principle, calibration, analysis of the measurement errors and laboratory and field results are described.

1. Introduction

Inner pipe inspection is of high interest especially for sewer lines and Oil & Gas (O&G) industry [1] [2] [3]. The inner pipe surface is generally measured to detect anomalies like corrosion and deformations. For the inspection of pipes in the O&G industry, sophisticated equipment, named Pipe Inspection Gauge or PIGs, are used. The most common measurement principles used by PIGs are magnetic flux leakage (MFL) [4], ultrasound [5] and mechanical probing [6]. Those devices are very robust, can measure several kilometers of pipes and usually are pushed by the own pipe-line oil or gas flow. PIGs are ideal for long-range pipe measurements, but they are not able to obtain very detailed inner surface information. On the other hand, optical systems are ideal when high density and accurate measurements are needed. Although, the pipe must be empty and clean or filled with a homogenous and transparent fluid.

Inner pipe laser inspection using a conical mirror was described by Inari; et al. (1994) [7]. A laser emitter and a conical mirror are used to generate a conical light sheet for measurement of small heat exchanger pipes (inner diameter range of 14.5 – 25.0 mm). Other systems using similar approaches were described in [8] [9] [10].

The group of Yoshizawa; et al (2006, 2007, 2012) [11] [12] [13] and ours (2007, 2012) [14] [15] independently developed an approach to measure the inner geometry of pipes from a single image using the so called “ring beam” or “radial light sheet” laser system. In previous works we have described a system for the inspection of 152 mm (6”) nominal diameter pipes [16] [15]. In the present paper, we describe the measurement principle, calibration, analysis of the measurement errors and laboratory and field results of a new system³ for smaller (100 mm) diameter pipes.

³ From now on, the laser profilometers for inner measurement of pipes of nominal diameter of 100 mm and 152 mm will be cited on text, respectively, as 4-inch profilometer and 6-inch profilometer.
2. Optical Measuring Principle

In order to measure a full (360°) inner pipe section per acquired image, our system uses a 45° (half angle) conical mirror to project a laser plane perpendicular to the cone axis. The laser source must be tightly aligned to the tip of the mirror. A camera looks at the resulting laser line formed by the intersection of the light plane and the inner pipe wall. The system optical configuration is shown in figure 1. If everything is well aligned and the pipe section is circular, the resulting image viewed by the camera will be a circle.

![Figure 1.](image1.png)

Figure 1. Measurement principle of the optical profilometer [15].

1.1. Image processing

To extract the laser line coordinates the image is analyzed in polar coordinates (see left image at figure 2) and discretized in angle steps $\Delta \theta$. A threshold filter is applied and the center position of the laser line is calculated (center of mass approach) for each discretized line. For our system, the image is discretized in 1440 angles (0.25° angular resolution) and the center is defined as the center of the image. The image processing result is an array of radius indexed by its angle. In order to reduce the processing time, a region of interest is delimited by a minimum and maximum searching radius. Also, the image is processed in a graphic card processor using CUDA parallel computing technique. The typical processing time in GPU is about 2 ms for the whole image (time measured in a Laptop with a GTX 285m graphic board). More details of the image processing can be found at [16].

The measurement is referenced in cylindrical coordinates, as shown in figure 2. For each acquired image, the actual system axial position ($Z$ axis) and rotation (around $Z$ axis) are measured by an odometer and an inclinometer, respectively.

![Figure 2.](image2.png)

Figure 2. Image discretization (left) [16] and cylindrical coordinate system (right).
1.2. Optical Calibration

There is a relationship between the radius in pixel of the laser line image and the actual radius of the pipe in real world coordinates. Ideally, this relationship would be linear, and equal for all angles. Although, due to imperfections, there are significant non-idealities, which can be divided into two main contribution groups: 1) the wide lens distortion plus the refraction on the acrylic wall results in a nonlinear radius relationship; and 2) the misalignment and imperfections of the components results in an uneven behavior for different angles. Besides those effects, the laser line viewed by the camera is not homogeneous, due to laser speckle. This effect is the main responsible for random errors of the system, and cannot be compensated during calibration. As a result, any laser line position is obtained with a ±0.5 pixel repeatability.

In order to calibrate the system, we acquire images of an inner stepped cylindrical gauge (SCG) with rings diameters previously calibrated in a coordinate measuring machine (CMM). The SCG has 28 different cylindrical regions with nominal diameter steps of 4 mm. The profilometer is able to measure from the 2nd to the 13th ring, with respective calibrated diameter of 87.897 mm to 131.896 mm. The obtained mean radius in pixel are 327 and 509, which define the profilometer measuring range. Although, those values can be extrapolated a bit (about 10 pixels). The resulting mean resolution is of 0.121 mm/pixel (sensitivity of 8.27 pixel/mm).

Figure 3 shows the system measuring one of the rings of the SCG. The SCG is assembled on our calibration bench and carefully aligned with the profilometer. The bench allows a controlled displacement of the SCG (X, Y and Z axis) using linear translation stages. By moving the stepped cylindrical gauge along the system axis (Z axis) it is possible to submit the profilometer to different and well-known diameters. A third degree polynomial is fitted to relate image radius to ring radius. A different polynomial is fitted for each discretized angle.

Figure 3. Profilometer on the calibration bench. Laser is illuminating one of the rings of the stepped cylindrical gauge. LEDs are turned on just for demonstration.

3. Prototype

The 4-inch profilometer uses a gigabit Ethernet (GigE) CCD camera capable of acquiring images of 1024x1024 pixels at a frequency of 60 Hz (frames per second). The square shape of the sensor is appropriate for the system, since its measuring range is circular and extra borders would be of no use. The theoretical system maximum speed is limited by the camera maximum frequency. A photo of the 4-inch profilometer is shown in figure 4. The laser source (660 nm; 30 mW) is powered through an enameled AWG 40 (~0.1 mm diameter) cooper wire (see figure 5). As it can be seen in figure 6, the
wires did not affect the measurement (right image) and can be barely noticed on a normal camera image (left image). The previously developed profilometer [15] uses batteries to power the laser, thus, no wires pass through the field of view. The wired version makes possible remote laser on/off switch, control its power and enable size reduction.

The 4-inch profilometer has a minimum passage diameter of 85 mm (3.3”); a diameter measuring range of 88 to 132 mm (3.5” to 5.2”); total length of 605 mm and mass of 3 kg.

To measure the displacement along the pipe, a mini optical encoder (1440 pulses per revolution) is attached to one of the prototypes wheels. Also, an accelerometer is used as inclinometer to measure and compensate undesirable rotation along the pipe axis. It must be noticed that the inclinometer will not operate correctly in pipes with axis close to vertical (aligned to the gravity).

Figure 4. Photo of the 4-inch profilometer before insertion into a refinery pipe for inspection.

Figure 5. Detailed view of the AWG 40 wires for powering the laser.

A microcontroller counts the wheel encoder pulses and triggers the camera acquisition for each $p$ number of pulses. Since it is almost impossible to maintain the system displacement at an enough constant speed, the displacement triggered acquisition keeps the Z spacing constant even with displacement speed variations. However, there is a maximum speed that cannot be exceeded, which could result in a frame rate request faster than the camera can handle, resulting in a section lost. In order to avoid that, we evaluated that a considerable safe speed to operate is limited by the acquisition frequency of about 45 Hz (75% of the maximum). Since different axial resolutions can be configured, the displacement speed can be calculated by multiplying the desired resolution ($dz$) by the safe maximum frequency ($dz \times 45$). In our experiments, we use a nominal resolution of 1 mm, which results in 45 mm/s. The real displacement resolution is a multiple (number of pulses) of the odometer resolution (millimeters per pulse), achieved by calibration.
Figure 6. Photos taken by the 4-inch profilometer inside a plastic tube with the LEDs turned on (left) and with the laser turned on (right). The arrows points to the laser power wires (left) and to a pipe heat created imperfection (left and right).

The odometer calibration was done using a three meter reference straight guide and a laser interferometer with negligible uncertainty. The number of pulses obtained for a known distance of about 3 meters was acquired five times. The obtained mean relation in pulses per millimeters is of 0.072600 (sensitivity of about 13.7 pulses per millimeter), with a standard deviation of 7.2E-06. After calibration, the system was displaced several times by a set of known distances. The resulting error curve is displayed in the graph of figure 7. It can be noticed that the error increases with the distance, probably due to drift.

Imperfection on the pipe wall will affect the displacement measurement, since variations in the pipe radius will result in a larger displacement measurement than the actual displacement in the pipe axis. Changes in the odometer wheel diameter (due to abrasion or due to adhesion of material) will also increase the error, e.g.: a variation in the odometer wheel diameter of 0.1 mm results in an error increase of 0.3%.

Figure 7. Odometer error curve for five different ranges. Mean error (points), confidence range and fitted line using least squares method (LSM). Vertical and horizontal axis represents, respectively, the error and the distance. Values in millimeters.

4. Results
The profilometer was tested and evaluated in laboratory and in onsite conditions. These experiments are described next.
4.1. Optical Calibration Evaluation

Two different procedures were used to take the calibration images: A) the SCG was aligned to ring 8th; B) the SCG was re-aligned for each ring.

To align the SCG, it is moved until a fitted circle center X and Y coordinates are less or equal 0.03 pixels apart of the processing polar coordinate center. The circle fitting is done using least absolute deviation (LAD) method, which is more robust to outliers then the least square method [17].

To reduce the speckle random error, a median and a mean filter were applied to the radii data of all calibrations. The filter size was set to 11 elements and it was repeated 10 times (11x10). Figure 8 shows radius data obtained for the 8th ring before and after filtering. We observed that taking more than one image per ring did not improve the calibration, because the difference in radius in pixels is very low and mainly due to speckle effects.

![Figure 8](image)

**Figure 8.** Radius data (raw and after filtered using a mean and median filter of e elements and applied t times exj). Data obtained from an image of the 8th ring.

4.1.1 Polynomials Comparison. The mean radii for each image used during calibration ‘A’ were calculated. Those mean values were used as input of the calibration polynomials. The plot result is shown in figure 9. Only part of the 1440 polynomials are plotted (for every 30°). As can be noticed, the resulting polynomials for different angles are almost close to straight lines and not very much different to each other.

To evaluate the differences between the obtained polynomials, the resultant radii in millimeters were subtracted from the obtained with the mean polynomial. The result is shown at figure 10. As one can see, for the same radius in pixel, there are a difference of about ±0.3 mm. This can be due to two main reasons: 1) uneven behavior for different angles; 2) misalignment in the trajectory of the SCG during calibration. It is impossible to tell which one is the main influence just by looking to the profilometer and calibration bench assembly. Although, if the uneven behavior for different angles is the main factor, the calibration ‘A’ (alignment only in one ring) must have a smaller measurement error. On the other hand, if the misalignment in the trajectory of the SCG is the main factor, calibration ‘B’ (realignment in all rings) must have a smaller measurement error.

![Figure 9](image)

**Figure 9.** Calibration using method ‘A’ (alignment in only one ring) polynomials plot. The polynomials for different angles almost overlaps.
4.1.2 Measurement Error for Displaced SCG. In order to evaluate the measurement error using the different calibrations (A and B), we captured images of the SCG displaced in the X and Y axis for different rings and positions. Figure 11 shows a photo of the setup and the acquired image of the 10th ring of the SCG displaced to the left. A circle was fitted to the measurement result in millimeters and the center of coordinate of the data displace to its center. The error was calculated subtracting the obtained moved radii from the respective calibrated radius of the SCG. The resultant errors using calibration ‘A’ and ‘B’, are shown, respectively, in figures 12 and 13. In figure 12, we also show the error using a mean polynomial for all angles for calibration ‘A’. For calibration ‘B’ mean polynomial, the error plot was almost the same. The legends show the fitted circle X and Y displacement in millimeters, the values were obtained using the mean polynomial.

Smaller errors were obtained using the calibration B. This result supports that the main factor of the differences of the polynomials was the misalignment of the trajectory of the SCG during calibration. In addition, the error using the mean polynomial for both calibrations were practically the same. This shows that the system has a small uneven behavior for different angles, except for regions around 220°, 275° and 330°. For each ring measured, the sum of the tendency plus two times the standard deviation was evaluated, the maximum value obtained is $E_{\text{max}}$. Table 1 shows an error comparison of the calibrations. In conclusion, a unique mean polynomial can be used in the cost of a small increase in the error. Also, an alternative solution would be to use an intermediate number of polynomials, since the polynomials don’t vary significantly for close angles.
Figure 11. Photo of the profilometer measuring the 10\textsuperscript{th} ring of the SCG displaced (left) and the resulting detected laser line (in red) at the measuring software (right). Concentric circles represent the radius measuring range.

Figure 12. Error plot for different positions and rings. The calibration images were taken aligning the SCG for only ring 8\textsuperscript{th}. Polynomials fitted for each angle (top) and a unique mean polynomial for all angles (bottom).
Figure 13. Error plot for different positions and rings. The calibration images were taken realigning the SCG for each ring. Polynomials fitted for each angle.

Table 1. Calibrations maximum error of the measurement of the SCG in various position comparison.

| Calibration | Procedure                        | $E_{\text{max}}$ [mm] |
|-------------|----------------------------------|-----------------------|
| A           | Alignment on the 8th ring         | 0.20                  |
| B           | Re-alignment in all rings         | 0.15                  |

4.2. Outside Laboratory Refinery Pipe Measurement

Two refinery pipes were measured in field environment. Figure 14 shows a photo of the setup. Figure 15 shows the profilometer been inserted in one of the pipes. Figure 16 shows two pictures taken by the profilometer, with the laser and LEDs on (left) and a typical measurement image (right).

Figure 14. Refinery pipes measurement setup. Two 4” pipes can be seen on the right part of the photo.
The measurement results are displayed in three different forms: 1) as a colored 2D radii map, where the horizontal and the vertical axis represent, respectively, the Z axis, or the length, in millimeters and the angle in degrees; 2) as a graph of the mean diameter change in percent and 3) in 3D. The colors in the 2D and 3D images represent radii values.

The first pipe measured ‘A’ has a length of 2.2 m. The 2D analysis is shown in figure 17. The pipe did not present any localized corrosion or weld joint. Although it was detect a conical shape with very small diameter change of 0.35 % per meter.

Figure 18 shows the 2D analysis of the pipe ‘B’. Also in this pipe, no corrosion was detected, but a pipe welded joint can be clearly seen around the middle of the graph. The inner diameter reduction in the welding is of about 1.5%. The 3D view of pipe ‘A’ and ‘B’ is shown in figure 19.
Figure 17. Pipe ‘A’ measurement result. Radius map and color scale (top); mean radius graph (bottom). Radius color range: 45.4 to 45.9 mm.

Figure 18. Pipe ‘B’ measurement result. Radius map (top) and mean radius graph (bottom). Pipe union around the middle of the measurement. Radius color range: 41.5 to 42.8 mm.
Conclusion

We described a new measurement system for inner surface inspection of 100 mm (4") nominal diameter pipes that uses a radial laser light sheet emitter and a variation of the laser triangulation principle. Two calibrations procedures were tested and compared. A misalignment between the standard step cylindrical gauge and the profilometer was found to be the main factor of the differences in the polynomials for different angles. We evaluated that the radius measurement error in laboratory tests was of about ±0.2 mm.

The system was able to measure the inner surface of two refinery pipes with high resolution. On the first pipe, a variation in diameter of 0.35 % per meter was detected. On the second pipe, a welded union was measured, where the diameter is reduced by 1.5 %.

In future work, we will perform a deeper analysis of the profilometer error including a 3D measurement comparison. Also, different calibration approaches and the effects of the misalignment of the laser and the conical mirror must be investigated.

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