Rotating optical geometry sensor for inner pipe-surface reconstruction

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ABSTRACT

The inspection of sewer or fresh water pipes is usually carried out by a remotely controlled inspection vehicle equipped with a high resolution camera and a lightning system. This operator-oriented approach based on offline analysis of the recorded images is highly subjective and prone to errors. Beside the subjective classification of pipe defects through the operator standard closed circuit television (CCTV) technology is not suitable for detecting geometrical deformations resulting from e.g. structural mechanical weakness of the pipe, corrosion of e.g. cast-iron material or sedimentations. At Fraunhofer Institute of Optronics, System Technologies and Image Exploitation (IOSB) in Karlsruhe, Germany, a new Rotating Optical Geometry Sensor (ROGS) for pipe inspection has been developed which is capable of measuring the inner pipe geometry very precisely over the whole pipe length.

This paper describes the developed ROGS system and the online adaptation strategy for choosing the optimal system parameters. These parameters are the rotation and traveling speed dependent from the pipe diameter. Furthermore, a practicable calibration methodology is presented which guarantees an identification of the several internal sensor parameters. ROGS has been integrated in two different systems: A rod based system for small fresh water pipes and a standard inspection vehicle based system for large sewer Pipes. These systems have been successfully applied to different pipe systems. With this measurement method the geometric information can be used efficiently for an objective repeatable quality evaluation. Results and experiences in the area of fresh water pipe inspection will be presented.

Keywords: surface reconstruction, pipe inspection, laser triangulation, laser profiling system

1. INTRODUCTION

Today earth-laid fresh water and sewer pipes can are rehabilitated by modern redevelopment procedures without having the pipes to be replaced or reinstalled. With regard to a cost-effective planning and application of such redevelopment measures, the assessment and objective evaluation of the pipe condition is economically and ecologically essential before starting a rehabilitation procedure. Currently the inspection of earth-laid pipes is usually carried out by a remotely controlled inspection vehicle equipped with a high resolution camera and a lightning system. Based on the recorded video images defect assessment is performed by a human operator manually.¹ This operator oriented approach based on offline analysis of the recorded images is highly subjective and prone to errors. Beside the subjective classification of pipe defects through the operator, standard CCTV inspection technology is not suitable for detecting geometrical deformations resulting from e.g. structural mechanical weakness of the pipe, corrosion of the pipe material or strong sedimentations.²³

In order to measure pipe deformations several laser light profiler concepts have been introduced in the last years.¹²³ By overlaying the scenery with structured light in the shape of a ring or a set of hyperbola lines a “scale of light” is added to the viewed scenery and mapped onto e.g. a CCD camera (see figure 1). With the aid of image processing techniques for line extraction and successive trigonometric transformations the 3D coordinates of the projected laser lines can be calculated. In order to reconstruct the inner pipe geometry over the whole pipe length the sensor is moved by an inspection vehicle through the pipe.⁴⁵

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Due to the optical arrangement of the camera axis in parallel to the pipe axis, most of the profiler concepts suffer from their functionality by the so-called "shadowing effect" especially in pipes with strong geometrical defects caused e.g. by sedimentations. In order to overcome these limitations at the Fraunhofer Institute IOSB a new Rotating Optical Geometry Sensor (ROGS) for pipe inspection has been developed which is capable of measuring the inner pipe geometry very precisely.

Organization of the paper: In section 2 the sensor concept is described. Section 3 explains the used calibration method for the sensor. Section 4 gives the integration of the sensor. Experimental results are presented in section 5. Finally, we conclude our work and outline future work in section 6.

2. ROTATING OPTICAL GEOMETRY SENSOR

The basic concept of the developed optical geometry sensor is based on the well known optical triangulation technique. In contrast to available laser triangulation scanners for pipe inspection, which usually consist of a laser projector and a rotating mirror, the developed concept uses at least two triangulation sensors of similar
type which are arranged in parallel, with their laser beam direction in diametrical opposition. By simply rotating the laser triangulation modules around the pipe axis and simultaneous forward motion through the pipe it is possible to scan the inner pipe geometry over the whole pipe length.

In figure 2 the ROGS concept with four laser triangulation modules arranged with 90° angular displacement around a mechanical rotor is illustrated schematically. To calculate the polar coordinates $P(R, \Phi)$ of a single laser measurement with respect to the sensor center following trigonometric transformation has to be applied:

\[ R = \sqrt{(R_{\text{Laser}} + X_{\text{Offset}})^2 + Y_{\text{Offset}}^2} \]  
\[ \Phi = \Phi_{\text{Laser}} - \arcsin \left( \frac{Y_{\text{Offset}}}{\sqrt{(R_{\text{Laser}} + X_{\text{Offset}})^2 + Y_{\text{Offset}}^2}} \right) \]

Due to the mechanical layout of the sensor the inner surface of the pipe is scanned in spirals whereas the number of spirals corresponds to the number of lasers installed. As an example figure 3 illustrates the scanning lines of a sensor with 4 triangulation modules. The higher the rotation speed of the sensor rotor $\text{rpm}_{\text{Sensor}}$ the steeper are the scanning lines. The spiral inclination $X_{\text{Spiral}}$ strongly depends on the velocity of the crawler $v_{\text{Crawler}}$. With a number of $n_{\text{Laser}}$ triangulation modules the measurement resolution in pipe direction $X_{\text{Spiral}}$ can be calculated applying the following equation:

\[ X_{\text{Spiral}} = v_{\text{Crawler}} \left( \frac{\text{rpm}_{\text{Sensor}}}{60} \right)^{-1} \frac{1}{n_{\text{Laser}}} \]

Furthermore, the rotation speed $\text{rpm}_{\text{Sensor}}$ of the sensor influences also the angular resolution $\Phi_{\text{Res}}$ of the measurement. The higher the rotation speed $\text{rpm}_{\text{Sensor}}$ the lower the angular resolution will be at a constant sampling rate $T_{\text{Sample}}$. The so called circumference resolution, which mainly influences the scanning grid size, depends on the angular resolution and pipe diameter $D_{\text{Pipe}}$. Assuming a centric positioning of the sensor the circumference resolution $c_{\text{Res}}$ can be calculated with respect to the sampling time $T_{\text{Sample}}$ of the sensor modules by the following equation:

\[ c_{\text{Res}} = T_{\text{Sample}} \frac{\text{rpm}_{\text{Sensor}}}{60} \pi D_{\text{Pipe}} \]
To ensure an optimal 3D reconstruction of the inner pipe surface, the spiral height $X_{\text{Spiral}}$ should ideally correspond to the circumference resolution $c_{\text{Res}}$: 

$$c_{\text{Res}} \approx X_{\text{Spiral}}$$

In practice this assumption would yield to a nearly equally spaced quadratic scanning grid of the inner pipe surface - as an example figure 4 illustrates the correlation between pipe diameter, crawler speed and rotation speed of a sensor rotor equipped with 4 equal laser triangulation modules. It should be noted, that a centric positioning of the sensor head is assumed.

As can be seen from figure 4 depending on the scanned pipe diameter $D_{\text{Pipe}}$ an adaptive rotation speed $rpm_{\text{Sensor}}$ of the sensor rotor and an adaptive crawler speed $v_{\text{Crawler}}$ is required, to ensure a circumference resolution $c_{\text{Res}}$ equal to the spiral height $X_{\text{Spiral}}$. A larger pipe diameter $D_{\text{Pipe}}$ requires a lower rotation speed $rpm_{\text{Sensor}}$ of the sensor rotor to ensure an acceptable circumference resolution $c_{\text{Res}}$. As an example a pipe with a nominal diameter of 400 mm would ideally require a rotation speed of approximately 470 rpm and an inspection speed of 320 mm/sec, at an acceptable circumference resolution of 10 mm.

Considering these nonlinear dependencies the developed ROGS system uses an adaptive strategy for setting the rotation speed $rpm_{\text{Sensor}}$ of the rotor with respect to the crawler speed $v_{\text{Crawler}}$ and the measured inner (nominal) diameter $D_{\text{Pipe}}$.

3. SENSOR CALIBRATION

To ensure precise and reliable measurements with the ROGS sensor system a calibration methodology has been developed, which allows the identification of the extrinsic and intrinsic parameters of the sensor. The extrinsic parameters are mechanical layout parameters, as there are the displacement of the triangulation modules from the rotation axis in $x$ and $y$ direction ($X_{\text{Offset}}$, $Y_{\text{Offset}}$). In principle these two parameters can be taken from the construction layout of the system, but to eliminate mechanical uncertainties the calibration procedure should be capable to determine these parameters for each triangulation module based on the calibration measurements.

Beside the mechanical parameters the calibration procedure has to identify the intrinsic parameters of the sensor system which model the A/D conversion step of each triangulation sensor. For the A/D conversion a linear model is assumed which can be described with the following equation:

$$R_{i,\text{Laser}} = u(r_i - w_{\text{Offset}}) + X_{\text{Offset}}$$

Figure 4. Correlation between pipe diameter $D_{\text{Pipe}}$, crawler speed $v_{\text{Crawler}}$ and rotation speed $rpm_{\text{Sensor}}$ of the sensor rotor.
The measured distance $R_{i,Laser}$ is determined by the raw measurement $r_i$, the parameter $w_{Offset}$ and the conversion factor $u$, which converts the raw radius measurement to the measured distance in $mm$. The intrinsic parameter $w_{Offset}$ reflects the minimum raw radius which can be measured by the triangulation modules. This parameter can be easily determined by placing the rotating sensor system near to a flat surface with defined distance. By reducing the distance between sensor center and surface $w_{Offset}$ can be identified.

As already stated in section 2 the pipe geometry is reconstructed by the calculated polar coordinates $P_i(R, \Phi)$ of the different measurements $i$. With respect to the sensor parameters equation 1 expands to:

$$R_i = \sqrt{(u(r_i - w_{Offset}) + X_{Offset})^2 + Y_{Offset}}$$ (7)

With the known parameter $w_{Offset}$ there are three unknown sensor parameters left, which can be determined by three measurements. In practice this approach is difficult to apply due to the fact that it would require a very precise perpendicular positioning of the triangulation modules to the measurement object and a precise measurement of the distance between the sensor center and the reference object.

To overcome this problem, the developed calibration procedure is based on the idea to utilize a calibration geometry with known inner dimensions. Therefore a calibration geometry of rectangular shape, illustrated in figure 5, is chosen. The sensor system is mounted on an adjustable positioning unit, which allows a precise positioning of the sensor in the reference rectangle.

To center the sensor unit in the reference geometry, an online calibration tool has been developed to assist this procedure. The basic idea is to calibrate the system under working conditions in the reference geometry, where the inner dimensions $L_1$ and $L_2$ are known precisely. Therefore the rotor of the sensor system is driven by the servo motor with a slow rotational speed. The raw measurement data $r$ from each triangulation module is recorded. As an example figure 6 illustrates the measured raw radius from one laser triangulation module. As can be seen the scanned radius data has four characteristic minima which reflect the minimum distance between the laser module and the corresponding side of the reference rectangle. Due to the rectangular geometry chosen, the minima correspond to the position of the rotor, in which the triangulation module is oriented with the minimal distance to the corresponding rectangle side.

With the developed online calibration tool the recorded raw radius $r$ is analyzed and the four local minima ($r_1$, $r_2$, $r'_1$, $r'_2$) are determined. To center the sensor unit precisely the minima $r_1$ and $r'_1$ as well as $r_2$ and $r'_2$ are compared pairwise. With the positioning unit the position of the sensor is adjusted until the minima $r_1$ and $r'_1$, respectively $r_2$ and $r'_2$ are equal. If this status is reached the sensor is positioned in the center of the reference rectangle.
With the centered setup it is possible to acquire the necessary measurements to identify the unknown intrinsic sensor parameter $u$ and extrinsic sensor parameters $X_{Offset}$ and $Y_{Offset}$. Therefore the measurements of the two different minima ($r_1$, $r_2$) and the measured maxima ($r_3$) are taken into account. It should be noted that the four maxima are also equal to each other if the sensor is positioned precisely in the center of the calibration rectangle. With the known inner dimensions $L_1$ and $L_2$ and the equations 6 and 7 the intrinsic parameter $u$ can be calculated by:

$$ u = \pm \frac{1}{2} \sqrt{\frac{r_1(L_2^2 - L_3^2) + r_2(L_1^2 - L_3^2) + r_3(L_2^2 - L_1^2)}{-r_1^2r_2 + r_1r_2^2 + r_3^2(r_2 - r_1) + r_3^2(r_1 - r_2)}} $$  \hspace{1cm} (8) $$

Due to the quadratic form, the equation gives two solutions - clearly the negative solution can be neglected because the resulting measurement $R_{i,Laser}$ of equation 6 has to be positive. Based on this solution the external parameters $X_{Offset}$ and $Y_{Offset}$ can be calculated by the following equations:

$$ X_{Offset} = \frac{L_2^2 - L_1^2 + 4u^2(r_1^2 - r_2^2) + 8w_{Offset}u^2(r_2^2 - r_1^2)}{8u(r_2 - r_1)} $$  \hspace{1cm} (9) $$

$$ Y_{Offset} = \pm \frac{1}{2} \sqrt{L_1^2 - 4(X_{Offset} + (u(r_1 - w_{Offset}))^2)^2} $$  \hspace{1cm} (10) $$

As already stated, the developed calibration procedure has to be performed for every single laser triangulation module. The developed sensor calibration is capable to identify the sensor parameters very precisely - with respect to a series production of the ROGS sensor system it can be applied as an easy to handle end-of-line calibration tool.

### 4. SENSOR INTEGRATION CONCEPT

The sensor concept allows a very compact mechanical layout - it can be attached to wheel based pipe inspection vehicles, or to commonly used cable rod based camera systems for pipes with a small inner diameter. Figure 7 illustrates schematically the mechanical layout of the sensor system.

The laser triangulation modules of the sensor are mounted on the sensor rotor. The rotor is fixed on a hollow shaft by two needle axis ball bearings which ensure a precise mechanical guidance when rotating. The rotor itself is driven by an electrical servo motor with gearbox. The mechanical layout with a hollow shaft axis allows...
the appliance of the ROGS sensor as an intermediate sensor module, e.g. between the crawler vehicle and the pan-tilt inspection camera. In contrast to other pipe scanners based on a rotating mirror, the ROGS system guarantees a full 360° scanning area.\(^7\)

For data transmission between the rotating laser triangulation modules and the stator of the sensor a non-contact inductive coupling module has been designed. The transducer module mainly consists of a stator and a rotor transducer part, which allows the power supply of the triangulation modules on the rotor side and the transmission of the analog-digital converted laser measurements from the rotor to the stator part of the sensor via a serial communication protocol. In contrast to a slip ring realization for data communication and power supply of the rotor part, the developed system is very robust with respect to abrasion and very compact in its mechanical dimensions.

![Figure 7. Sectional view of the ROGS mechanical layout.](image)

(a) Cable rod based inspection system. (b) Standard inspection vehicle based system.

![Figure 8. Two different mechanical realizations of ROGS.](image)

The mechanical realization of the ROGS system is illustrated for the appliance in fresh water pipes in figure 8(a) respectively for sewer pipes in figure 8(b). The two implementations only differ in their measurement
range of 120 \text{mm} up to 220 \text{mm} for small fresh water pipes and 200 \text{mm} up to 1000 \text{mm} in sewer pipes, assuming a centric positioning of the sensor system in the pipe.

5. INSPECTION OF A FRESH WATER PIPE

The ROGS sensor concept as shown in figure 8(a) is mainly used for the condition monitoring of fresh water pipes before applying a redevelopment procedure. Due to the typical pipe diameter range between 140 \text{mm} and 200 \text{mm} for fresh water pipe systems the ROGS sensor is attached to a marketable cable rod based inspection system instead of a wheel based inspection vehicle.

The appliance of the system is almost the same as with conventional camera based inspection equipment. After the cleaning procedure of the pipe the sensor system is inserted and pushed manually through the pipe by the flexible cable rod (forward run). Due to the flexibility of the cable rod the actual measurement is carried out when the sensor is pulled backwards to its starting position (backward run). This approach minimizes the "spiral effect" of the flexible cable rod and guarantees a more precise assignment of the sensor measurement to the pipe position.

Figure 10. Two different visualizations of a scanned pipe-surface.
As an example figure 9 shows a typical fresh water pipe section after the first cleaning step (high pressure jet cleaning). As can be seen, there are still strong sedimentations remaining on the inner pipe surface.

The result of an inspection run with ROGS sensor is shown in figure 10(a). The inner pipe geometry calculated out of the sensor measurements is displayed as a 3D plot. The green colored areas indicate pipe sections in which the estimated nominal radius corresponds to the measured radius - yellow respectively red colored sections indicate deviations to the inside of the pipe of more than 1.0 mm or 2.0 mm (sedimentation). The colored representation of the geometrical data is an ideal visualization for the fast localization of common defects by the users, especially when displayed in so called map representation as shown in figure 10(b).

6. SUMMARY

At Fraunhofer Institute of Optronics, System Technologies and Image Exploitation (IOSB) in Karlsruhe, Germany, a new Rotating Optical Geometry Sensor (ROGS) for pipe inspection has been developed which is capable of measuring the inner pipe geometry very precisely over the whole pipe length.

Due to the very compact mechanical layout of the system it can be attached to wheel based pipe inspection vehicles, or to commonly used cable rod based camera systems for pipes with a small inner diameter. In contrast to pipe scanning products already available on the market, the ROGS system allows a full 360° scanning angle. With the hollow shaft the sensor can be placed between inspection robot and video camera. This sensor arrangement allows the user to record all necessary data for a pipe reconstruction in a single inspection run.

The developed sensor concept has been applied successfully to fresh water and sewer pipes. Based on the measurement of the inner pipe geometry the pipe condition can be accessed very precisely compared with traditional CCTV based systems. The further development of the system focuses on the fusion of the geometric information with camera data for a complete virtual pipe reconstruction.

REFERENCES