Vision System and Calibration for Pipe Inspection

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Abstract-The development of an image system for measuring erosion in waste water pipes is discussed focusing on the calibration of the system using non-linear optimization for tuning. The image system is based on a simple structured light approach which is complicated by the curvature of the pipe.

I. Introduction

The extent of erosion in small wastewater pipes is often difficult to measure due to the nature of these pipes. They are generally buried underground which makes them difficult to get to and long lengths of pipe make it impossible to inspect them by manually. It is important to have information on the extent of any damage so that decisions can be made on the need for repair or replacement of such pipes.

It is common to use a robotic platform with CCTV modules attached to gather information on the pipe. This generates a large amount of video data that must be manually examined and processed offline to gain any insight about the condition of a pipe. This raises the need for a system that can automatically process the data and provide real time information on the pipe such as the extent and volume of erosion.

Processing the data in real time usually requires transmitting all of the data to a PC where the processing is performed. An umbilical cable can be used for this but these introduce difficulties such as paying it out at the correct speed, retracting it, and ensuring it does not get snagged or break. In straight pipes it is possible to use a wireless transmission.

Transmitting all of the data will require a large bandwidth. The transmission medium (such as an umbilical cable or wireless transmission) will also impose limitations on the system, and these two factors will affect the speed at which the robotic system can perform its inspection. To counteract this, the data could be processed on board the robot and only the relevant information be transmitted. This would require a hardware implementation such as a field programmable gate array (FPGA) as there is far too much processing for a low power embedded microcontroller to handle in real-time.

Structured lighting is a common method for measuring the heights of objects on a planar surface and works on the basic principle of triangulation [1-3]. A sensor is used to measure any deviation of the light projected on the object from the reference plane, and this provides the profile information. This same approach can be used to measure the erosion in a pipe; however, the circular cross-section of the pipe introduces an extra level of complexity. Using this structured lighting, the FPGA would process the image and produce a profile of the erosion in the pipe.

This paper describes the development of such a system, outlining the imaging system and the processing involved. It then develops a model used to generate a reference curve of the uneroded pipe surface as seen by the laser and camera system. The parameters of this model are then calibrated to match the images obtained in the real world set up.

II. Image System

The imaging system consists of a red laser line that is shone on the pipe wall and this is imaged using a camera. This is seen in the image as an elliptical curve representing the pipe cross-section.

This approach is a simple application of triangulation where the camera and laser form two vertices of the triangle and the third is made by the intersection of the laser and image plane projections on the surface of the pipe. As such, there are two main configurations of the camera and laser. One configuration is to have the camera facing vertically downwards and the laser on an angle to the camera. The other is with the laser vertical and the camera pointing on an angle. Reference [4] compares these two setups and provides justification that the second configuration is best for this application by comparing their relative advantages and disadvantages. The main advantage of the camera being on an angle is that it can use a smaller angle of view to cover the same width across the bottom of the pipe with the disadvantage that the laser may not always be visible to the camera. With the laser on an angle this is far less likely to be the case but it has the disadvantage that the position of the laser along the pipe is dependent on both the angle and the level of any erosion present making it more difficult to obtain samples at uniform intervals.

The angle between the camera and the laser directly affects the depth resolution and the likelihood of occlusions due to the camera being too shallow to detect sudden changes. For this application, an angle of 40° was chosen. The camera was mounted on a bracket on top of the robotic platform with the laser cantilevered out in front of the camera.

The camera used for implementation was a Terasic D5M camera [5]. This is a 5 megapixel colour Bayer pattern sensor with a native resolution of 2592×1944. Only the red pixels are of interest, and column binning is used so the maximum effective resolution in this application reduces to 648×972.

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This camera was coupled with a Terasic DE0 FPGA to perform the onboard processing [6]. This is a low cost entry level board which is ideal for this application. It has an onboard VGA connection supporting up to 1280×1024 resolution with a refresh rate of 60 Hz, and an RS232 port which was used for the data transmission.

The image processing was implemented following the algorithm developed in [4]. This focuses on the red component of the image and extracts the laser profile by averaging each column and finding the row with the largest red value. This processing all occurs in real time on board the robot as it inspects the pipes.

III. MEASURING EROSION

Using structured light to measure the erosion in a pipe is not as simple as it would be on a planar surface due to the curvature of the surface. It is possible to determine the effects of this by deriving a mathematical model for the system as in [4]. Here the coordinate system was defined as in Fig. 1, where x is the direction along the pipe, y is across the width and z is the vertical height. The radius of the pipe is r, with the angles of the camera and laser stripe θ and φ respectively. It is assumed that the laser stripe along the bottom of the pipe is centered on the field of view of the camera.

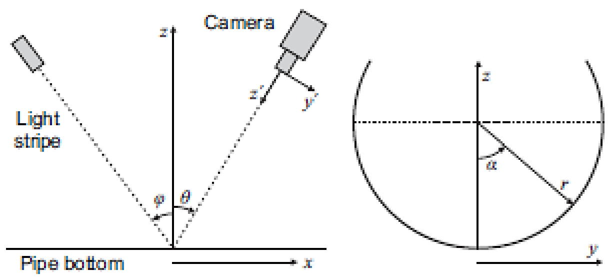

Figure 1. Coordinate system and definitions from [4]

By making the laser angle (φ) zero and assuming that all angles and measurements are exact the functions describing the images x and y positions were derived as

$$\hat{x} = f\frac{y\cos\theta}{\left(\sqrt{r^2-y^2}-r+d\right)\cos^2\theta+z_c} \quad (1)$$

$$\hat{y} = f\frac{\left(\sqrt{r^2-y^2}-r+d\right)\sin\theta\cos\theta}{\left(\sqrt{r^2-y^2}-r+d\right)\cos^2\theta+z_c} \quad (2)$$

where z_c is the camera origin position relative to the center of the pipe, and d is the depth of erosion. It is assumed that the erosion, d, is purely vertical.

This set of equations gives a basis for determining where the laser stripe will appear in an image in ideal conditions but will not be sufficient for anything more than an approximation.

As part of the image processing algorithm as described in [4] the laser line is detected within the image, with the position in each column of the image giving a profile of the pipe. This profile is subtracted from a reference profile to give the level of erosion across the pipe. In order to do this a reference profile is needed. By developing a more accurate model of the system this reference could be calculated by calibrating the parameters of the system based on a profile of a section of non-eroded pipe.

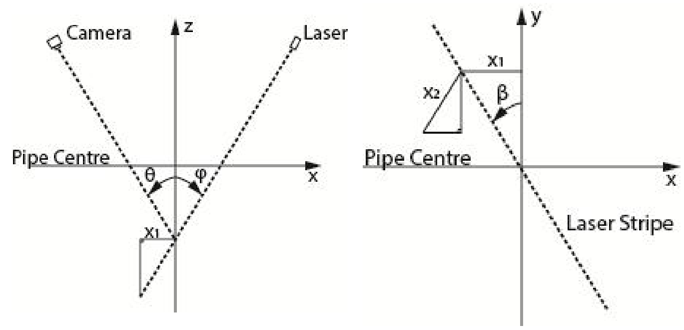

Figure 2. New coordinate system and definition

The model above makes many assumptions about the precise positioning of the camera and laser. To properly calibrate the system, it is necessary to take into account all of the degrees of freedom in the system. The previous model only included rotation of the camera about one axis whereas there is the potential that it could be rotated slightly about its other two axes. Similarly, the camera offset is only considered in the x and z directions whereas the potential for a small y offset should also be considered. Also, it is assumed that the angle of the laser in both the x-y, and x-z planes is zero whereas this may not be the case if the laser is not aligned exactly. It is very unlikely that any of these parameters will be exactly zero. Rather, it is more likely there will be a very small error, which will affect the image coordinates to a varying degree.

The plane of the laser stripe will intersect the circular pipe and form an ellipse. If the position around the ellipse is paramertised as α (as previously done in [4]) then the points along the ellipse can be expressed as (x, y, z) where the center of the pipe is the origin.

From Fig. 2 we can get that

$$x_1 = -(z-r)\tan\Phi \quad (3)$$

$$x_2 = -y\tan\beta \quad (4)$$

where β is a counter-clockwise rotation of the laser on the x-y plane and Φ is a clockwise rotation of the laser on the x-z plane. From this we can get the x coordinate of the points as being

$$x = -y\tan\beta - (z-r)\tan\Phi\cos\beta. \quad (5)$$

This takes into account the potential error in the alignment of the laser. With the access to precision engineering methods it is possible to get the laser to be almost vertical relative to the robot, however, because most laser modules come in a cylindrical case it is very difficult to align the laser such that the laser is perpendicular to the x axis.

From Fig. 1 we can derive y, and z using the same method as [1], as follows

$$y = r\sin\alpha + d\sin A \quad (6)$$

$$z = -r\cos\alpha - d\cos A. \quad (7)$$

Where d is the depth of the erosion defined along the angle of view of the camera and A is the angle of the line of sight of the camera depending on α. This can be derived as

$$A = \alpha - \tan^{-1}\left(\frac{r\sin\alpha}{r\cos\alpha + z_c}\right) \quad (5)$$

To determine the effect of this on the image, it is necessary to transfer these points into camera centered coordinates. To do this we need to rotate the camera by the rotational matrix R.

$$R_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x \\ 0 & \sin\theta_x & \cos\theta_x \end{bmatrix} \quad (6)$$

$$R_2 = \begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y \\ 0 & 1 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y \end{bmatrix} \quad (7)$$

$$R_3 = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 \\ \sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (8)$$

$$\mathrm{R} = R_1 R_2 R_3 \quad (9)$$

where θ_x is the clockwise rotation of the camera on the *y-z* plane, θ_y is the counter-clockwise rotation of the camera on the *x-z* plane, and θ_z is the clockwise rotation of the camera on the *x-y* plane.

The offset of the camera in the x, y, and z directions must also be taken into account. These offsets are x_c, y_c, and z_c respectively. This gives us the camera centered ($\acute{x}$, $\acute{y}$, and $\acute{z}$) coordinates as

$$\begin{bmatrix} \acute{y} \\ \acute{x} \\ \acute{z} \end{bmatrix} = \mathrm{R} \begin{bmatrix} x - x_c \\ y - y_c \\ z - z_c \end{bmatrix} \quad (10)$$

Finally, to give the image coordinates we can use a camera pinhole model

$$\hat{x} = -f\frac{\acute{x}}{4\acute{z}} \quad (11)$$

$$\hat{y} = f\frac{\acute{y}}{2\acute{z}} \quad (12)$$

where f is the effective focal length in pixels, and the center of the image is defined as the origin. The scale factors are necessary to compensate for the column binning and skipping every second row and column (to eliminate all but red pixels). This introduces a scale factor of 0.5 (skipping) in the vertical direction, and 0.25 (skipping and binning) in the horizontal.

This gives us the final expressions which can be used to accurately map the points along the pipe to an image given accurate parameters.

In (6) and (7) the erosion, d, has been defined along the line of sight of the camera instead of vertically. This gives the advantage of making it easier to accurately calculate the erosion. Using the original definition there was a nonlinear distortion imposed on the image both horizontally and vertically that must be compensated for by scaling to obtain the erosion profile. Using the new definition the difference between the actual data and reference profile can be determined using (12) and rearranged to give

$$d = \frac{\Delta\hat{y}}{k_1\Delta\hat{y} + k_2} \quad (13)$$

where d is the erosion in millimeters, $\Delta\hat{y}$ is the difference between the actual data and that reference profile, and k_1 and k_2 are constant for each column. Assuming the same initial parameters as previously done in [4], k_1 and k_2 can be simplified to the following

$$k_1 = \frac{-\cos A}{r\cos\alpha + z_c + (z_c + r)\tan^2\theta} \quad (14)$$

$$k_2 = \frac{f\tan\theta\cos A\,(z_c + (z_c + r)\tan^2\theta + r)}{2(r\cos\alpha + z_c + (z_c + r)\tan^2\theta)^2} \quad (15)$$

The error introduced by making these assumptions is minimal and in general is less than a tenth of a millimeter. These constants can be calculated for each row using (14) and (15) and preprogrammed onto the FPGA. These could then be used to calculate the actual erosion for each column in real time using (13).

IV. Calibration

As it is impossible to accurately measure both angles and distances it is necessary to determine the parameters of the equation using a calibration process. This will take in initial approximations and optimize them in order to get the best fit to the known data. The output parameters are considered as the calibrated measurements and are used to determine the reference curve. It is only necessary to perform this optimization once for each set up or when parameters are likely to have been changed. This means that the optimization process need not be performed in real-time; rather it can utilize the processing power of a PC and then be transferred to the FPGA.

A. Non-Linear Optimization

Initial conditions were measured and input into an optimization routine developed in Matlab. The aim of this routine was to minimize the sum of the squared error between the points derived from the parameterized equation and the real data from the FPGA. The image based data is the position of the laser line in each of the 640 columns in the image. This means that $\hat{y}$ is known, and consists of consecutive integers. In contrast, the equations derived $\hat{x}$ and $\hat{y}$ values are parameterized by the angle α around the pipe. Therefore to determine the corresponding $\hat{x}$ value from the model, it is necessary to find α as a function of $\hat{y}$. This non-linear equation is not easy to invert, so is solved numerically. This creates an extra level of complexity for the optimization as the alpha values may change every iteration depending on the set of optimization parameters. Fig. 3, shows the image data plotted with a profile generated from the initial conditions. This is contrasted to the optimized profile plotted in Fig. 4, where it is almost impossible to tell the calculated profile and actual profile apart. Table I shows both the initial parameter values

TABLE I
INITIAL AND OPTIMIZED PARAMETER VALUES

	Initial	Optimized
f	3326	3325.9998
φ	0	4.8574
β	0	0.4956
x_c	-244	-244.0021
y_c	0	0.0004
z_c	125	125.0003
θ_x	0	-0.3498
θ_y	40	43.0297
θ_z	0	-0.1959
Total Error Squared	14319.9743	747.0813

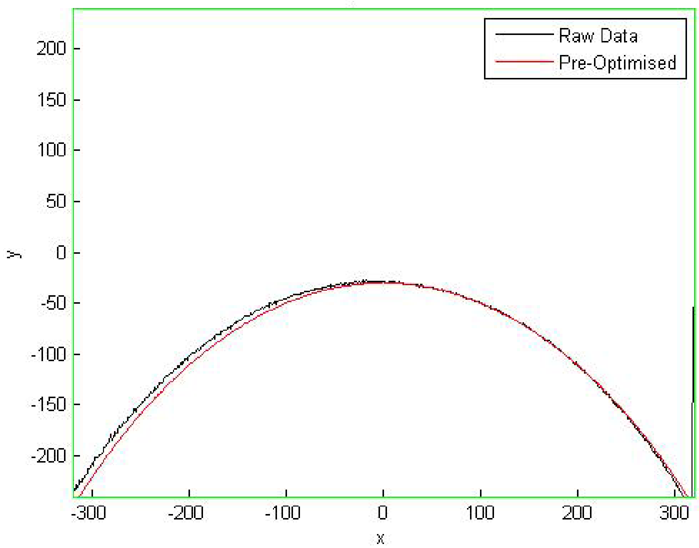

Figure 3. Actual and calculated profile before optimization

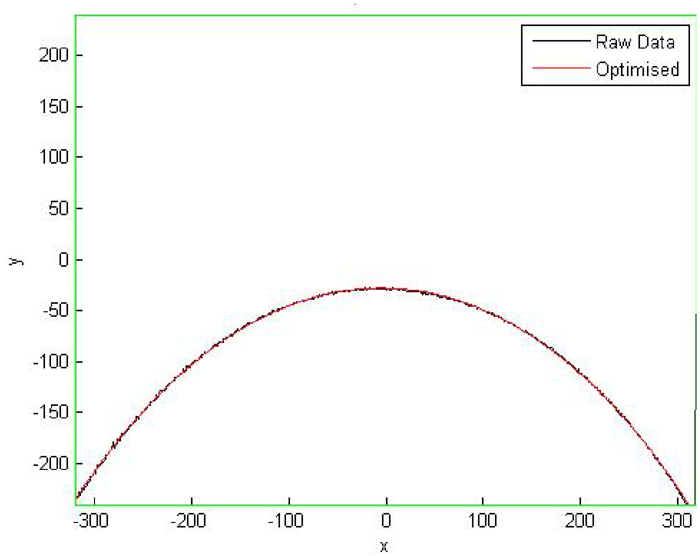

Figure 4. Actual and calculated profile after optimization

and the optimized values along with the sum of squared error residuals for each case. From this we can see that the optimization has significantly reduced the average error of the system.

B. Test for Dependencies and Relationships

It is possible, when preforming an optimization, to find a local minimum instead of the global minimum which is not the desired outcome. To test for this, a small change can be made to the individual parameters and if the outcome is the same set of parameters as before it is likely that it is not a local minimum. Different sets of changes can be combined to further explore this. As this can change depending on the initial parameters it is essential to do this for each individual set up.

It is also possible that there is more than one optimal solution. This may be caused due to relationships between parameters within the optimization equation. If this is the case it is necessary to determine these relationships and eliminate unnecessary parameters if possible. An example of this might be if either φ or θ_y could be altered to achieve the same optimum. In this case these two variables should be combined to create one parameter representing the angle between the laser and the camera.

To test for this scenario, a small error can be induced on each parameter in turn and this parameter excluded from the optimization. If the optimization converges on the minimum it is likely that the excluded parameter has a relationship to one of the other parameters.

One method for eliminating this is by performing an optimization on the parameters that are likely to influence (such as ignoring the parameters close to zero as originally done). These optimized parameters would then be set and an optimization preformed to tune the remaining parameters.

V. DISCUSSION AND CONCLUSIONS

In order to provide the level of erosion across the cross section of pipe, a reference curve representing that cross section without any erosion must be predetermined. It could simply be determined by finding the profile on a section of uneroded pipe or the average of several of these profiles but this may still be inaccurate owing to the noise integrated with the data.

This paper presents a more accurate method for determining this reference profile by developing a comprehensive mathematical model of the image system and calibrating this to the real world state using non-linear optimization to tune the parameters. The original model was not sufficient for achieving this as it did not incorporate all of the degrees of freedom of the system. In contrast, the model developed in this paper has proven to be more than sufficient for determining a reference profile for the system.

Once the calibration has been performed, an equation representing the profile height as a function of the position within the image can be loaded onto the FPGA and be used to calculate the reference profile for different setups (e.g. different diameter pipes).

One limitation of this approach is that it may be difficult to implement the calibration process on an embedded system on the robot because of the complexity of the mathematics involved. The calibration process can also be very time consuming even on a PC with high processing power. This is acceptable if the calibration does not need to be performed on a regular basis, but if the calibration parameters are likely to vary often this may not be an adequate solution. If this is the case other options must be explored. This may include altering the calibration process such as by using regression instead of an optimization routine or by exploring completely different options such as an adaptation of the calibration process used in [7] or [8].

This paper has also discussed implications of false minimums being detected and possible methods for identifying these as well as methods for identifying relationships between variables. These methods could be used to reduce the complexity of the model and potentially increase the calibration speed.

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