1—2 Detection and Classification of Sewer Pipe Junctions using Reflective Photometric Stereo

(Late Arrival)

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Abstract

We focus on the detection and classification of sewer pipe junctions during the initial survey stage of a 'soft' Insituform lining process. Estimates are obtained of the diameter and orientation of interconnecting lateral pipes: smaller diameter pipes that join the main sewer from the side. These estimates are compared to a set of likely values of each and the member of this set closest to the estimated value is considered to represent ground truth. The proposed technique relies upon estimates of a) the distance from the camera to the lateral and b) the angle of intersection of the lateral and main pipes, both of which are obtained using a novel variant of Photometric Stereo termed Reflective Photometric Stereo.

1 Motivation

Surveys indicate that around 10% of Britain's 230,000km of sewers are likely to need renovation or replacement over the next ten years. Of these, approximately 96% are classed for safety reasons as non-man entry (NME, <1m diameter). For NME sewers, 'soft' Insituform lining technology is widely employed. During an initial survey a sled or tractor mounted camera and light source are propelled through the sewer, relaying a continuous sequence of images via umbilicals to a remote operator. A suitable liner is then inserted into the damaged sewer section. Remotely controlled, CCTV monitored, sled mounted cutters reconnect and make good any now blocked connections to adjoining pipes and a post-operative CCTV survey assesses the success of the overall renovation.

Remote reconnection proves an awkward task that is prone to human error. Methods can be crude and mistakes occur. The work reported here forms part of a project aimed at easing this problem by providing a semi-autonomous mobile robot capable of performing a number of sewer survey and renovation operations.

The current paper focuses on the detection and classification of sewer pipe junctions during the initial survey stage of the above process. The goal of the proposed system is to identify and classify junctions between main and interconnecting lateral pipes. Estimates of the lateral's diameter and orientation are compared to a set of likely values of each (45 or 90 deg., 150, 225 or 300mm respectively) and the member of this set closest to the estimated value considered to represent ground truth. The proposed technique relies upon estimates of both the distance from the camera to the lateral and the angle of intersection of the lateral and main pipes, both of which are obtained using a novel variant of Photometric Stereo termed Reflective Photometric Stereo.

Section 2 introduces the concept of Reflective Photometric Stereo, with details of the necessary mathematical models given in Section 3. The detection of lateral junctions and their classification via reflective photometric stereo are then described in Section 4. Some results are presented in Section 5 and conclusions drawn in Section 6.

2 Reflective Photometric Stereo

In traditional Photometric Stereo [1], multiple images are acquired by a fixed camera under varying illumination. Details vary, but it is common to assume distant, point-source illumination from widely separated directions. Image irradiance estimates then impose constraints on (usually) surface orientation. Photometric Stereo is not as widely used as comparable feature-based multi-image methods. One reason for this is the requirement that illumination conditions vary significantly and in a known manner between images. In open environments it is often not possible to control illumination to the extent necessary to support photometric stereo. Underlying the present work is the observation that there exists considerable potential for the application of 3D machine vision systems in enclosed environments such as air ducts, water and gas pipes and, of course, NME sewers.

When designing vision systems for use in enclosed environments, photometric methods are attractive. These spaces are often unlit; any vision-based device will therefore be forced to incorporate some form of

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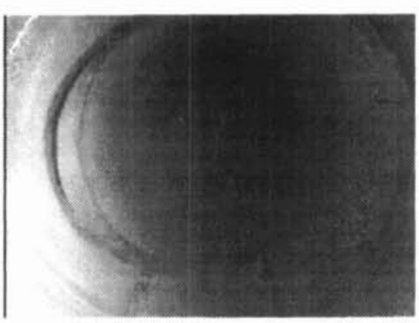
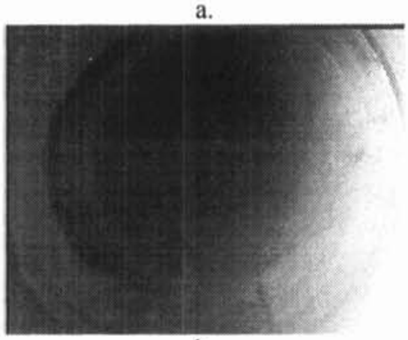
lighting. It seems only sensible to make this requirement to provide and, implicitly, control the illumination an advantage, rather than a chore. Many enclosed environments are man-made, it should therefore be possible to acquire or approximate the necessary models of surface reflectance. Moreover, many of the surfaces involved are effectively featureless: it may not be possible to employ a feature-based technique. Although the work reported here uses sewer survey as its forcing domain, it is anticipated that the techniques developed will find application in a variety of settings.

The notion underlying Reflective Photometric Stereo is that in enclosed environments radically different lighting conditions may be obtained by careful control of the orientation of a single light source. One image is obtained by orienting the light source to directly illuminate the target surface - the inner wall of a laterally entering pipe, for example. The source is then rotated so that its light is reflected off another nearby surface – the opposite wall of the main pipe – onto the target. The hypothesis to be addressed is that although the light source position remains constant, the differences between direct and reflected illumination are sufficient to allow the recovery of 3D parameters.



a.



b.

Figure 1. A lateral junction viewed under a) direct and b) reflected illumination. Images were acquired using a Watec CCD camera mounted on a sewer-going tractor [2] and a DT Fidelity 100 frame grabber.

Figure 1 shows a pair of images of a 450mm concrete sewer pipe captured with the light source (a) directly illuminating the lateral junction to the left of the image and (b) aimed at the opposite wall of the pipe. For present purposes, the goal of reflective photometric stereo is to recover from these images the distance to and orientation of the visible section of the inner wall of the lateral pipe. For this to be possible, the relationship between image irradiance and the desired parameters must be established.

3 Modelling Surface Luminance

A key feature of any photometric technique is the model of illumination and surface reflectance it employs. Here we follow Woodham [1] in assuming that both the reflecting and target surfaces are Lambertian. Figure 2 shows the illumination and surface geometry adopted. A two-dimensional arrangement is considered, obtained by taking a horizontal slice through the 3D environment. In doing this we implicitly assume the walls of the pipe to be locally planar and vertical. We further assume the camera and light source to be coincident, lying at the origin O of a polar co-ordinate system centred on the axis of a sewer of radius w. The line $\phi = 0$ coincides with the pipe axis and is parallel to the reflecting surface. A notionally infinite target surface (the lateral wall) with normal N_T lies at an angle ρ to $\phi = 0$. The light source at O emits a ray towards a point P, (ϕ, r), on the target surface, which arrives with angle of incidence θ.

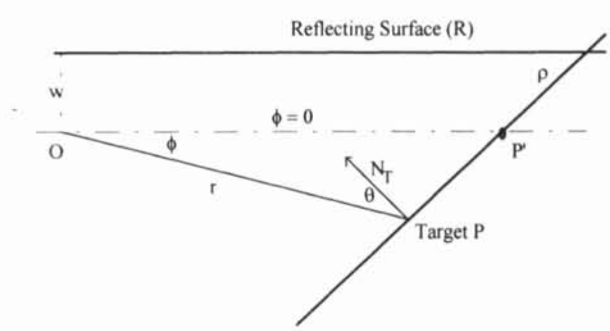


Figure 2: The geometry of direct illumination

If the surface luminance at P is to be modelled, expressions for ϕ and r are required. To achieve this we assume that P lies on the intersection of the main and lateral pipe walls, i.e. the perpendicular distance from P to the pipe axis is w. Some error is, of course, associated with this assumption. In the circumstances considered here, however, P can only vary from this ideal position by a few centimetres. At viewing distances of 2-3m this will have a negligible effect on estimates of ϕ and r. Surface luminance at P under direct illumination is then given by

$$E_d = \frac{kI\sin(\phi + \rho)}{\left(\frac{1}{\cos\phi}\left(d - \frac{w}{\tan\rho}\right)\right)^2}$$

where

$$\phi = \arctan\left(\frac{w}{\left(d - \frac{w}{\tan\rho}\right)}\right)$$

d is the distance OP'and k is the albedo of the pipe surface. We now have one constraint on the desired parameters ρ and d.

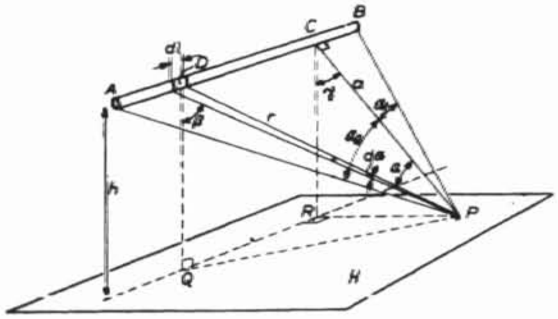


Figure 3. Illumination by a linear light source Keitz[3].

Our model of reflected illumination relies upon the formation of a notional, extended light source on the reflecting wall. Keitz [3] models the illumination of a point P lying on a plane H by a linear source AB suspended parallel to H (figure 3). If AB is uniformly diffuse, the total illumination E at P is given by

$$E = I_1 \frac{h}{a^2}\frac{1}{4}\left[2(\alpha_2 - \alpha_1) + \sin 2\alpha_2 - \sin 2\alpha_1\right]$$

where I is the maximum luminous intensity of a part of AB one unit in length, h is the height of the source above H, a is the perpendicular distance from P to AB and $\alpha 1$ and $\alpha 2$ are the angles subtended by the parts of AB on each side of the perpendicular from P to AB

In the current application, P is coplanar with AB and so a = h = 2w. Derivation of expressions for α_1 and α_2 requires knowledge of the position and extent of the linear source. To achieve this we assume that the true light source lying at O is directional, with its principle axis oriented α degrees from the pipe axis. We further assume that this lamp emits light only in directions lying within +/-β degrees of its principle axis. Both the position and length of the linear source are then functions of α, β and w. If points A and B mark the endpoints of the linear source and d_A and d_B are the distances, measured in the direction of the pipe axis, from O to A and B respectively, then we have

$$d_A = w.\tan(90 - (\alpha + \beta))$$
$$d_B = w.\tan(90 - (\alpha - \beta))$$

and

$$\alpha_1 = \tan^{-1}(w.\tan(90 - (\alpha - \beta)) - d)/2w$$
$$\alpha_2 = \tan^{-1}(d - d_A = w.\tan(90 - (\alpha + \beta)))/2w$$

which, after substitution, provides an expression for the total illumination at P.

It remains to produce an expression for surface radiance at P. To achieve this, the standard lambertian reflectance assumption is made and the principle direction of illumination is taken to be along a line to P from the midpoint of our notional linear source. Then surface luminance under reflected illumination is given by

$$Er = E.k.\cos\theta$$

where

$$\theta = \rho - \theta_1$$

and

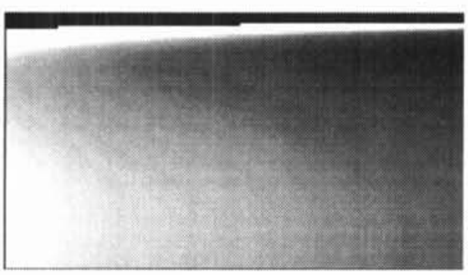
$$\theta_1 = \tan^{-1}((d - (d_A + (d_B - d_A)/2))/2w)$$

We now have two constraints on ρ and d, and can solve for them in the usual way.

4 Classification of Lateral Junctions

Lateral intersections are detected, in the image acquired under reflected illumination, via the process detailed in [2]. Edge detection is applied and a structural pattern recognition approach taken to locate the edge string arising from the lateral intersection. The upper and lower extremes of this string are recorded. As the principal axis of the camera is usually roughly aligned with the central axis of the pipe during sewer survey, the vanishing point of the pipe is generally visible, lying in a dark region towards the centre of the image. A crude estimate is obtained of the position of the vanishing point in each image by thresholding the grey level data and locating the centroid of the largest sub-threshold region [2]. The mean of these two positions provides a more robust estimate of the vanishing point, which is then used to extract intensity data from the images for use in reflective photometric stereo. A line is constructed which both passes through the vanishing point and bisects the lateral mouth. This line is truncated to fit inside the lateral mouth by noting its intersection with the relevant edge string. Two pixel tracks are then extracted, from the direct and reflected illumination images respectively. These pixel tracks are marked on the images of figure 1. In the current implementation, the mean intensity of the three pixels at the "far" end of each of the pixel tracks is recorded for use in the reflective photometric stereo system.

As is common in photometric stereo systems, the present implementation of the proposed system relies upon reflectance maps, parameterised now by ρ and d, to recover the depth and orientation of lateral pipes. These maps are generated using the mathematical models outlined in Section 3. As our models describe surface radiance, not image intensity, some calibration is required. Chainage measures, estimates of distance travelled down the sewer obtained from the umbilicals attached to the tractor, are therefore used to generate a piecewise linear scaling function which brings the predicted radiance and measured intensity values into agreement. It is envisaged that in normal service, this calibration would be applied when the first lateral is met; thereafter the tractor would determine distance to laterals using calibrated reflectance maps. Figures 4a and b show calibrated reflectance maps obtained for the direct and reflected illumination cases respectively.



a.

b.

Figure 4. Reflectance maps describing a) direct and b) reflected illumination of the target surface.

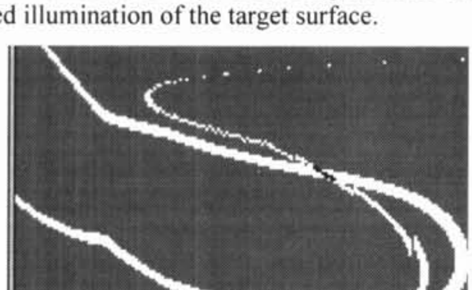


Figure 5. Intersecting isoluminance contours

Given a calibrated reflectance map and an estimate I_{mouth} of the image intensity at the main pipe/lateral junction, a binary image is created by setting all the pixels of the reflectance map whose intensity is within a tolerance of I_{mouth} to 1. All other pixels are zeroed. This is done for both direct and reflected illumination conditions, producing a registered pair of binary images representing the two isoluminance contours. A simple pointwise AND operation then produces a further binary image in which regions of intersection appear as clusters of 1's. The co-ordinates of the centroid of each cluster provide an estimate of ρ and d. Figure 5 shows an example.

5 Results

The techniques described above have been applied to 20 image pairs captured within a laboratory rig [2] comprising a 450mm concrete sewer pipe fitted with one 45 deg. and one 90 deg. 300mm lateral connection. A geodimeter was used to provide accurate estimates of d for comparison purposes.

Depth estimates were typically accurate to within 10cm at viewing distances of 2.5 to 3.5m., though in a small number of cases errors rose to 20cm. Measurements of lateral diameter obtained by back projecting the image of the lateral mouth to the estimated depth, however, allowed correct classification of lateral diameter in all cases. Similarly, although errors in lateral orientation were typically less than 5 degrees, correct classification was possible even when larger errors arose.

6 Conclusion

A variation on the theme of photometric stereo has been proposed and used to recover estimates of the distance to and orientation of lateral intersections in small bore sewers. These values may then be used to classify the lateral pipe on orientation and diameter. Experimental results have demonstrated the basic feasibility of the technique

References

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