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Three-Dimensional Description Of Sewer Laterals Via Reflective Photometric Stereo

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Abstract

Previous efforts [1] have been directed towards provision of a visual sensing facility capable of the detection of lateral pipe entries in non-man-entry (NME) sewers. Attention is now turned to lateral description. A novel variant of the established vision technique Photometric Stereo is presented. The current goal of the new technique, Reflective Photometric Stereo, is the 3D description of lateral connections from images captured during the survey pass of an Insituform process; this requires the integration of a single fixed camera and controllable light source.

Introduction

The maintenance and rehabilitation of urban sewers presents a significant problem [2]. For NME sewers, 'soft' Insituform relining technology is widely employed: closed circuit television (CCTV) equipment is used to initially survey the damage, followed by a sewer relining operation. Remotely controlled, CCTV monitored, sled mounted cutters then reconnect and make good the now blocked lateral connections which are to carry waste into the NME sewer. Final CCTV surveys assess the success of the overall renovation. Unfortunately remote reconnection proves an awkward task which is currently prone to human error.

It is believed that the automation of both the surveying [3, 4] and liner cutting processes [2] would improve the cost effectiveness of the overall renovation scheme, whilst reducing operator error. This is to be achieved through the implementation of a substantially autonomous robotic system.

Initial efforts have been directed towards the provision of an appropriate visual sensing facility. The early goal of this system [1] was to detect lateral connections in images captured during the survey pass of a conventional renovation process. Light source orientation was found to be of import and a distinction was drawn between orientations which cause the feature to be directly illuminated and others in which light is first reflected off the opposite wall of the sewer. It is now proposed that 3D descriptions of lateral intersections be determined via comparison of images captured from the same viewpoint under these different illumination conditions. This method is a novel adaptation of Photometric Stereo [5], which we term Reflective Photometric Stereo.

Photometric and Reflective Photometric Stereo

Photometric stereo is similar in some respects to the more widely known binocular stereo. Binocular stereo computes 3D object position by triangulation after comparing images obtained from two different viewpoints. If it can be determined that two image features, one per image, arise from the same object feature then the location of that object feature can be recovered. Photometric stereo also exploits differences between images captured under different circumstances. Here, however, multiple images are obtained by varying the illumination while keeping the viewing position constant.

For each lighting configuration, image intensity values and their relationship to surface properties, usually surface orientation, are stored in a Reflectance Map [5]. The reflectance map specifies the image intensity of a material for a given illumination source and viewer geometry. Reflectance maps for successive viewing conditions may be compared, assuming that the irradiance of a common point can be measured, to solve for surface orientation.

Photometric techniques are not used as widely as feature-based methods. A major reason is that in open environments (offices, factories, etc.) it is often not possible to control illumination conditions to the extent required. As a prime motivation for computer vision is to produce systems capable of operating in open environments, this tends to promote, inter alia, binocular over photometric stereo. While open environments are clearly important, there is considerable potential for the application of 3D vision systems in more enclosed environments; NME sewers, for example.

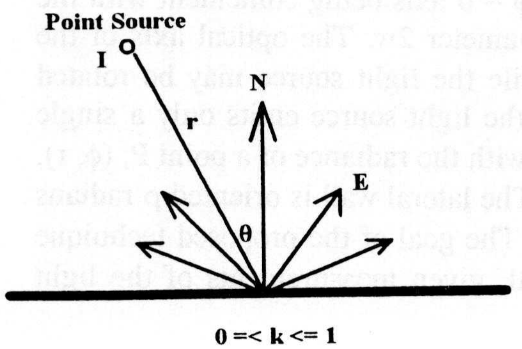
When designing vision systems for use in NME sewers, photometric methods are attractive. NME pipes are unlit; any vision-based device will be forced to incorporate some form of lighting. It seems only sensible to make this requirement to provide and, implicitly, control the illumination an advantage, rather than a chore. We are primarily concerned with clay pipes, which are synthetic elements readily adapted for laboratory testing. It should therefore be possible to acquire or approximate the necessary models of surface reflectance. Moreover, large areas of many pipe surfaces are effectively featureless - it may not be possible to employ a feature-based technique.

Photometric stereo methods, however, usually make two key, and problematic, assumptions. The first is that the illumination sources are distant from the target surface, the second that the illumination directions employed vary considerably. In an NME sewer there is simply not space for such widely different light source positions.

The notion underlying the proposed technique is that in enclosed environments radically different lighting conditions may be obtained by careful control of the orientation of a single light source. Reflective Photometric Stereo operates over two grey level images captured by a single fixed camera. The first is obtained by orienting the light source to directly illuminate a target surface - the inner wall of a laterally entering pipe. For the second, the source is rotated so that its light is reflected off another nearby surface - the opposite wall of the main pipe - before it reaches the target. Although the light source position remains constant the differences between direct and reflected illumination are sufficient to allow recovery of 3D shape.

Illumination Models

A key feature of any photometric technique is the model of surface reflectance it employs. It is assumed here, following **[5]**, that both the target and reflecting surfaces are lambertian. Lambertian reflectors have an ideal matte finish and reflectivity proportional only to the cosine of the angle at which an incident light ray strikes the surface. Light is reflected equally in all directions.



$$E = \frac{kI\cos\theta}{r^2} \qquad (1)$$

E = surface luminance
k = surface reflectivity
I = source intensity
θ = angle of incidence
r = distance travelled between light source and surface

Figure 1: Lambertian Reflectance

The lambertian reflectance function given in equation 1, and associated **Figure 1**, is the building block for the initial form of Reflective Photometric Stereo.

Figure 2 shows the illumination and surface geometry employed throughout the derivation of the proposed technique. A two-dimensional arrangement is considered, obtained by taking a horizontal slice through a 3D sewer and lateral pipe configuration (see **[2]** for pipe layout details).

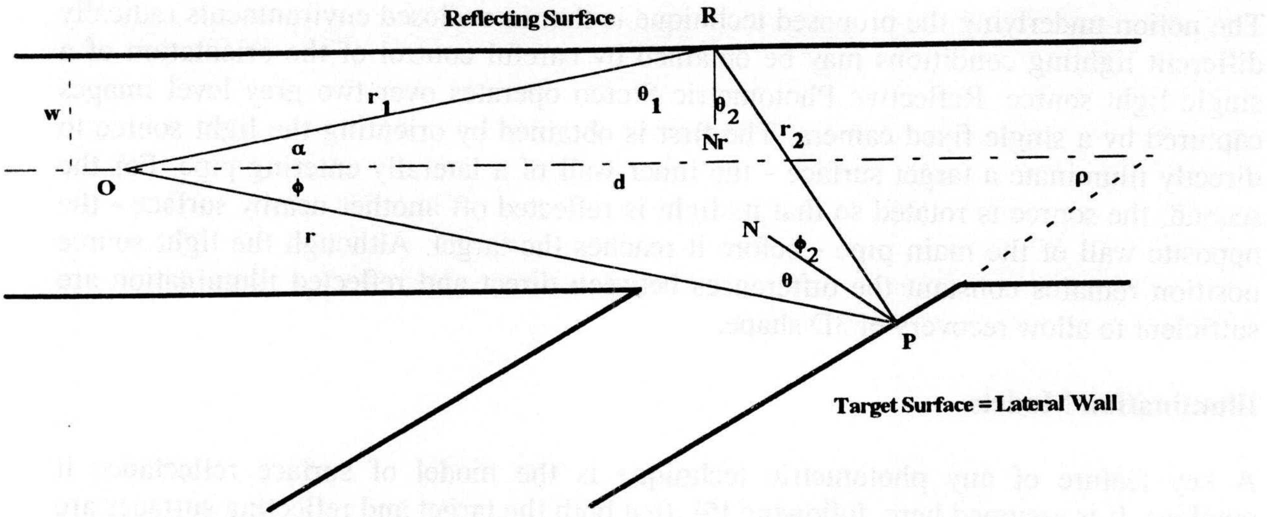


Figure 2. Plan view of a sewer and lateral pipe configuration

A light source and camera are both situated at the origin O of a polar coordinate system lying on the central axis of the main sewer pipe, its $\phi = 0$ axis being coincident with the sewer's centreline. The main sewer is of (known) diameter 2w. The optical axis of the camera is also assumed to coincide with $\phi = 0$, while the light source may be rotated about O. For the present it is further assumed that the light source emits only a single ray; we shall return to this below. We are concerned with the radiance of a point P, (ϕ, r), lying on the far wall of the intersecting lateral pipe. The lateral wall is oriented ρ radians from $\phi = 0$, which it intersects a distance d from O. The goal of the proposed technique is to recover the parameters (ρ, d) of the lateral wall, given measurements of the light emitted by P under direct and reflected illumination.

Under direct illumination, the light source is oriented ϕ radians from the centreline and so emits a ray towards P. This arrives with angle of incidence θ and is reflected according to the lambertian reflectance function, equation (1). After some manipulation it can be shown that the radiance E_d of a directly illuminated point P is given by

$$E_d = \frac{kI \sin(\phi + \rho)}{r^2} \qquad (2)$$

for a full derivation see [6].

Under reflected illumination a light ray is emitted from O towards a point R, (α, r_1), on the opposite wall. This ray makes an angle of incidence θ_1 with the reflecting surface normal N_r. As this surface is lambertian, light from R is reflected equally in all directions. One reflected ray, making an angle θ_2 with N_r, exits R and travels a distance r_2 to P, where it has an angle of incidence ϕ_2 and is again reflected, according to the lambertian reflectance function, from the target surface. By repeated application of equation (1) we derive (3) below, giving the radiance E_r of P under reflected light. Once again, a full derivation is given in [6].

$$E_r = \frac{k^2 I \sin^3\alpha}{w^2\left[r^2 - 2rw\left(\frac{\cos\phi}{\tan\alpha} - \sin\phi\right) + w^2\left(1 + \frac{1}{\tan^2\alpha}\right)\right]} *$$

$$\cos\left(\rho - \cos^{-1}\left[\frac{r\sin\phi + w}{\sqrt{r^2 - 2rw\left(\frac{\cos\phi}{\tan\alpha} - \sin\phi\right) + w^2\left(1 + \frac{1}{\tan^2\alpha}\right)}}\right]\right) \quad (3)$$

We assume that the relative position and orientation of the light source and reflecting surface are controllable, i.e. that we know w, ϕ and α. The intensity I of the light source and reflectivity constant k of the pipe surface are also assumed known or measurable a priori. Given (2) and (3) and recognising that

$$d = r(\cos\phi + (\sin\phi / \tan\rho)) \quad (4)$$

expressions may therefore be obtained for E_d and E_r in which the only unknowns are the two parameters ρ,d of the lateral wall. We can now attempt to solve for ρ and d.

Solution Procedure

Unfortunately, and as is usually the case with photometric stereo, the expressions obtained for E_d and E_r cannot be solved analytically. The reflectance map approach instituted by Woodham [5] is therefore employed. We first determine the range of ρ,d values which are of interest and then create a pair of two-dimensional lookup tables, one each for E_d and E_r, parameterised by ρ and d. Application of equations (2), (3) and (4) allows values of E_d and E_r to be computed for each ρ,d pair and inserted at the appropriate place in the relevant lookup table. These lookup tables are reflectance maps as illustrated in **Figure 3**; the procedure is analogous to the use of graphical methods familiar elsewhere in engineering mechanics.

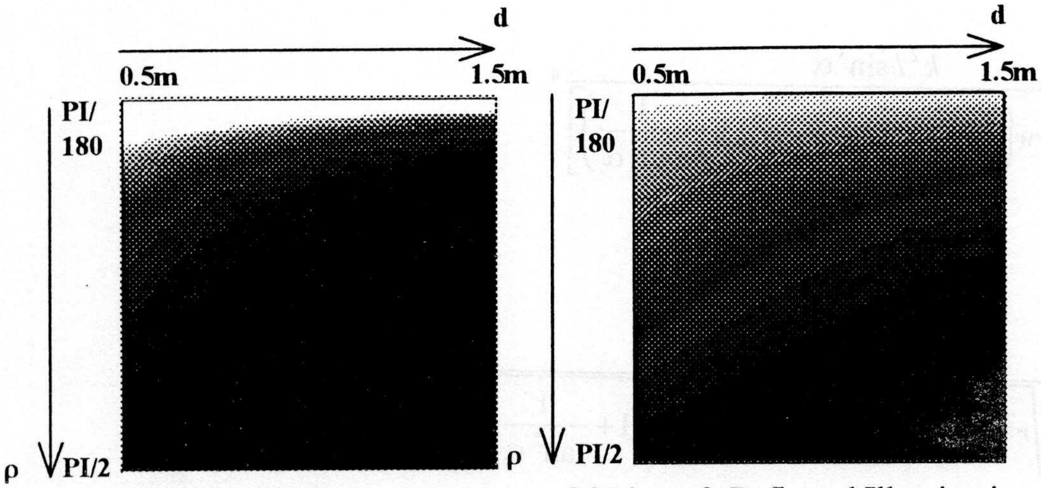


Figure 3: Reflectance Maps Of Direct & Reflected Illumination
for k = I = 1.0, ϕ = 0.7 radians, α = 0.7 radians and w = 0.225m

Suppose we now obtain, via our camera, estimates of E_d and E_r for some point P. Consider the E_d value first. In general, many ρ,d pairs could generate a given E_d. One would therefore expect to see E_d at many locations. These locations form an "isoluminance contour" [5] on the E_d reflectance map. Similarly, the E_r value will also be generated by many ρ,d pairs. If the isoluminance contours for both E_d and E_r are overlaid, the intersection of the contours affords solution of ρ and d at point P.

As an example, **Figure 4** shows isoluminance contours obtained from the reflectance maps of figure 3 by marking pixels in which $E_d = 1.978 \pm 0.05$ and $E_r = 0.980 \pm 0.10$ respectively. These contours intersect at approximately ρ = PI/4 and d = 1m as predicted by equations (2) and (3). The reflectance maps employed are 256 by 256 pixels; each pixel represents 0.006 radians on the ρ axis and 0.004m on the d axis.

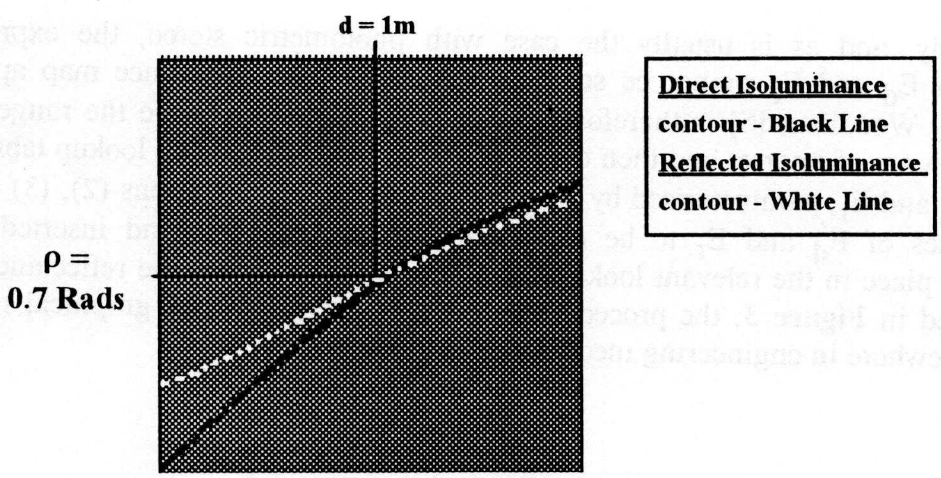


Figure 4: Intersection Of Isoluminance Contours; d = 1m and ρ =0.7 radians

Obtaining a 3D Description

Once a lateral intersection has been detected [1], the vanishing point of the sewer is estimated and straight lines (corresponding to horizontal slices) are projected onto the image, through the lateral, as illustrated in **Figure** 5. By applying the procedure described above to many such slices a 3D description of the lateral profile is obtained; each slice should provide constant ρ values, but varying d.

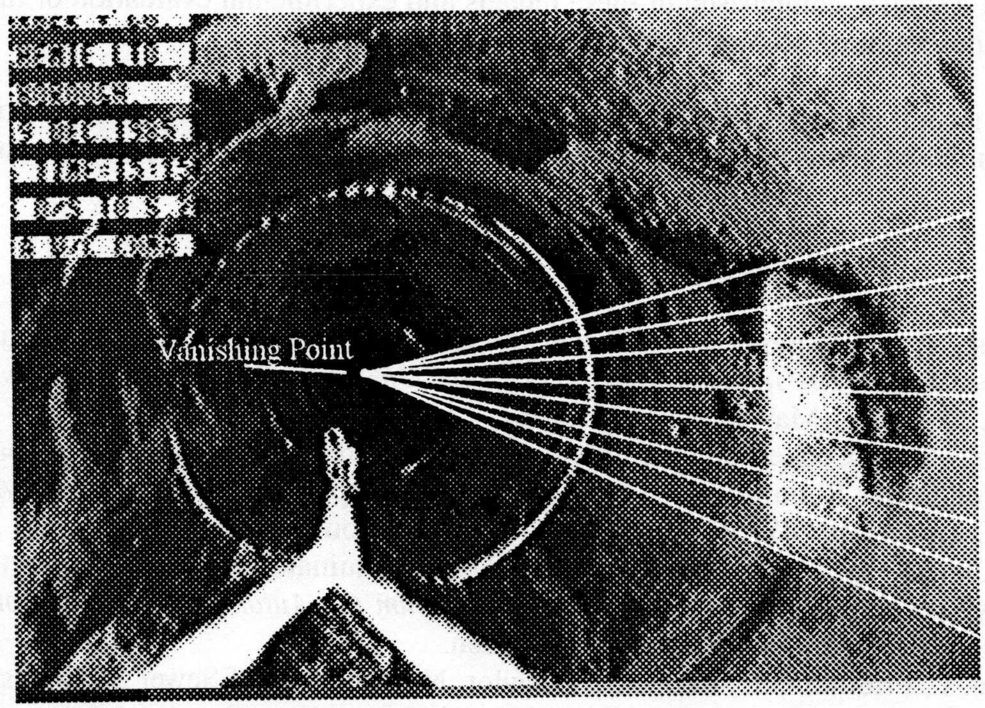


Figure 5: Multiple Horizontal Slices

Exact pixel accuracy from the above proposed method is not expected. Instead, only an estimate of actual distance to the lateral is required, as the robustness of the envisaged robotic system [4] will allow compensations to be made for exact positioning, closer to target. Currently little estimate of lateral intersection angle is afforded. As only certain angles of intersection are common, i.e. 30, 45, 60 and 90^{o}, the accuracy of the point of intersection in relation to the ρ axis is not critical; intersection occurring within a tolerance of PI/36 are not expected to be problematic.

Discussion and Conclusion

A novel form Photometric Stereo, termed Reflective Photometric Stereo, has been presented. The illumination, viewing and surface geometries employed reflect the small-bore sewers with which we are primarily concerned. The proposed technique is expected to allow the 3D description of lateral pipe intersections. Some extensions are, however, likely to be necessary.

The illumination model employed here considers only a single light ray. It is quite inappropriate to assume that the lamps actually used within the construction industry emit such illumination. In fact lamps tend to produce a spray of light which may be approximated by a Gaussian distribution; maximum illumination intensity is achieved along the axis along which the lamp is principally directed, on either side of this principal axis light intensity is assumed to tail off exponentially. This, and other intermediate forms of, lighting model have been used as the basis of further equations for E_d and E_r [6]. Detailed comparison of these models and experimental evaluation of their use in lateral description will be the subject of future reports.

In the longer term it is envisaged that Reflective Photometric Stereo will find application in similarly enclosed environments elsewhere within the construction, and perhaps other, industries.

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