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Sensing for feature identification in sewers

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Abstract

Multi-disciplinary research programmes have been established at Sheffield Hallam University to investigate specific areas of the Information Technology into the Construction Industry theme. Interest is currently centred upon the development of suitably robust knowledge-based and related engineering systems for application in non-man-entry (NME) sewer renovation. Initial efforts have been directed towards provision of an appropriate vision sensing facility. A task dedicated computer vision system combining edge detection and grouping algorithms with a controllable light source is proposed. The goal of this system is to extract descriptions of lateral connections from images captured during the survey pass of an Insituform process. Initial work has focused on the problem of lateral detection.

1. THE SEWER MAINTENANCE PROBLEM.

Much of the UK's sewerage system dates back to Victorian times. Although the provision of this system was a major engineering achievement, infrequent and inadequate maintenance has left a legacy of disrepair **[1, 2]**. Statistics relating to current sewer dereliction are elusive at best, though data gathered in 1985 **[3]** would not be considered outlandish today. These indicate that 2% of all UK sewers were in critical need of repair. Approximately 96% of the 260,000km of sewer surveyed were classified as Non-Man-Entry (NME), ie. of less than 1m diameter, accounting for over 5000km of NME pipe requiring immediate attention. It would not be unreasonable to assume, based on the general lack of funding for maintenance, that the current percentage exceeds this estimate

NME pipes are comparatively inaccessible. Moreover, the exact location of many NME sewers is unknown due to incomplete and/or out of date council records. Problems are generally recognised only when a collapse or flood occurs; hence maintenance is typically carried out on a crisis management basis. CCTV (closed circuit television) survey libraries are now being established by many local authorities: a sled-mounted camera and light source are winched through the sewer pipe, relaying a continuous sequence of images via umbilicals to a remote operator who records salient features.

Replacement is invariably costly, especially in urban areas. Trenchless renovation provides an effective alternative in many situations [4], generally requiring that a suitable liner be inserted into the damaged sewer section after an initial survey pass [5]. Industrial sources indicate that the most common lining material used for NME applications is the 'soft' Insituform type. Lateral connections are invariably blocked by such lining processes and lengthy relocation and reconnection techniques are required to reinstate these. Methods can be crude and mistakes occur. It is suggested that automation of such a surveying/cutting process offers benefits in terms of cost effectiveness, accuracy and safety, and the key aspects of visual sensing, task kinematics and autonomous control are being investigated.

2. A COMPUTER VISION APPROACH

Vision aims to describe the real world. Images provide the input from which the vision system produces a symbolic representation of the viewed scene. Implicit information is therefore made explicit. The information to be made explicit varies with circumstance and application. There is a huge psychological and physiological literature describing biological vision systems, though at present many visual processes are at best only partly understood.

Computer Vision is a relatively new science which aims to understand the processes and representations underlying vision in sufficient detail that they may be implemented on a computer [6]. Workers in computer vision seek to gain a better understanding of the principles underlying vision, and to make computers more useful.

The performance of present computer vision techniques does not match that of comparable biological systems. However, in some circumstances computer vision techniques may be better suited to the task at hand. One crucial difference is that biological vision systems do not provide their users with easily accessible, quantitative descriptions of world geometry. A human observer may know where viewed objects are to a high degree of precision and be able to use that information internally to pick up or navigate between objects. S/he is however unlikely to be able to state verbally *inter alia* the exact distance to a viewed surface. It would appear that sewer surveys require quantitative measurements; the more qualitative results now provided by human operators leave something to be desired.

To date machine vision systems have been successfully employed in industrial inspection tasks, bin picking exercises and for robotic guidance [7]. Most systems operate within structured environments where the data to be assessed is minimised; object(s) of interest typically occupy only a small proportion of the viewed world. The application of machine vision to unstructured environments like the NME sewer will require the ability to operate with reduced *a priori* knowledge whilst assimilating data from the full visual field.

Other established sensor technologies [8] are currently employed within sewer environments. Structured light methods have been investigated and a technique based on a light ring has been patented. Radar systems are under investigation. Although they provide accurate measurements, the uptake of these technologies is often problematic. Special purpose equipment is required and existing video records cannot normally be exploited. While structured light methods incorporate a CCTV camera, the lighting conditions imposed restrict the use of any images obtained.

A computer vision approach is likely to be both economically viable and stable. Images captured under standard lighting remain the norm, so records of survey operations may be used in other contexts. No special hardware is needed, so little modification to current equipment is expected. However, should equipment standards change it is anticipated that CCTV cameras will continue to be employed; many clients insist on the production of a survey video. It may be suggested that the use of computer vision in sewer survey will both provide a robust basis for automation within this hostile environment and force new developments within the field.

3. IMAGING THE NME SEWER ENVIRONMENT

NME sewers may be constructed from brick, concrete or lengths of abutted clay pipe; where inlet pipes intersect the main sewer, lateral connections occur. We are concerned primarily with clay sewers. As sewer networks age, encrustation, arising from transported media and general abuse, builds along the walls. External ground forces are often compensated for by lateral movement between pipe sections. These generally result in what are termed 'displaced joints'. Such pressures may also produce longitudinal cracks along pipe walls.

A vital step in the design of a machine vision system is the determination of relations between the interesting features of the viewed world and measurable properties of the image. Figure 1 shows a typical image of a clay NME sewer. Wall encrustation gives rise to a dappling effect. Displaced joints appear as bright crescent shaped regions; the size of crescent is dependent upon viewing distance and amount of displacement. Longitudinal cracks are usually represented by series of random lines. Lateral intersections generate light image regions, usually smaller and less bright than those arising from similarly distant displaced joints. Lateral profiles are smooth, elliptical and generally complete. Key features are the large curvature changes occurring at the top and bottom of the profile.

The near edge of a lateral connection is marked by a sharp change in depth (distance from the viewer) while the far edge exhibits a similar change in surface orientation. These real-world changes are reflected by sharp changes in image intensity. The most common intensity change is the 'step edge', marking the boundary between two image regions with approximately constant but very different intensities. Step changes in image intensity are easily detectable features which may be used as cues to the image location of lateral intersections.

4. EDGE DETECTION FOR LATERAL IDENTIFICATION

Many edge detection algorithms exist **[6, 9, 10]**. All are based on image differentiation; the first derivative of the image intensity values are taken and the peaks marked. Edge detection relies on assumptions rather than on hard facts. As very little *a priori* knowledge of expected lateral profiles is available, it is considered an appropriate method for their detection.

A Canny **[10]** operator was chosen for this application as it has become a de facto standard for the computer vision community. The Canny algorithm involves removal of image noise by Gaussian smoothing followed by differentiation and a search for significant peaks. Variable parameters are 'sigma', which determines the degree of Gaussian smoothing, two peak height thresholds and one line length threshold. A low sigma value provides minimal smoothing, maintaining sharp boundary detail but generating a high volume of edge data, some of which may be the result of noise. A high sigma value gives greater noise reduction but will blur edge boundaries and may lose significant structures. The line length threshold enables short edge strings to be discarded, discounting unwanted edge detail. Illumination or other effects may however cause significant line structures to be fragmented. High length thresholds will subsequently lose these details. A sigma of 1.75 and a comparatively low length threshold of 4 were considered responsible values for this application.

The Canny algorithm was applied to the image of figure 1, the result is shown in figure 2. Edge strings produced are of varying length and occur across the entire image. Clear definition of the required lateral profile, evident in figure 1, is complicated by the sheer number of rogue edges detected in its vicinity. Much of the spurious edge data is attributable to wall encrustation. This is a little surprising, as the surface discontinuities introduced by encrustation are small relative to those involved in the lateral intersection. One would expect such minor surface distortions to elicit only a weak response from the Canny operator.

Examination of the lighting conditions under which the image was obtained gives some clue as to the reason for the rogue edges. Here the sled-mounted spotlamp is directed towards the lateral intersection. The 'direct' nature of the illumination provided tends to emphasise edges arising from noise elements, causing the algorithm to report many spurious features. Hence it may be suggested that other forms of illumination exist which would significantly reduce the number of rogue edges and thereby ease the lateral detection problem. Indeed, under current CCTV practice the notion of averting the illumination source away from the feature under consideration is already in use; primarily to avoid problems of glare.

5. DIRECT VS REFLECTED ILLUMINATION

Figure 3 shows an image obtained under radically different lighting conditions; the spotlamp is pointed at the wall opposite the lateral connection. The lateral intersection is thereby bathed in a more diffuse light of lower intensity, resulting a better defined profile.

The images shown in figures 1 and 3 were obtained from 'industrially sourced' VHS video tapes. Current CCTV surveys are conducted under effectively arbitrary illumination conditions. In general, a single light source is mounted on the sled in a fixed position relative to the camera. As the sled moves along the pipe it may be deflected by obstacles, while the action of the winch often introduces lateral sway. These motions have a significant and unpredictable effect on the direction of illumination. Figures 1 and 3 were therefore taken from disparate surveys. The sewers concerned are however of similar internal diameter, with similarly placed and sized lateral intersections. Viewing distances are also comparable.

Application of the Canny operator to figure 3 produced the edge data of figure 4. String length again varies considerably and edges occur across the image. In the direct illumination case (figure 2) 676 edge stings are identified, compared with 746 in the reflected case (figure 4). However in a 200*200 pixel region of interest centred on the lateral profile of figure 4, the density of edges is much reduced. Indeed only 93 edges are present compared to the 120 detected in a similarly sized and placed region of figure 2. Under reflected illumination the lateral profile is clearly defined with no edge string break up.

Intensity profiles taken horizontally across the lateral intersections of figures 1 and 3 are shown in figures 5 and 6 respectively. Under direct illumination (figure 5) it is quite difficult to distinguish edges resulting from the lateral profile from those arising from minor surface distortions; the contrasts of the edge features detected are similar. However under reflected illumination (figure 6), edges arising from the lateral profile have much higher contrasts than those generated by surface encrustation. These high relative contrasts ease the task of differentiation between the desired lateral feature and spurious edges.

Sewer encrustation or structural damage typically gives rise to surface distortions which may be modelled by small 'blips', like that shown in figure 7. Under direct illumination a shadowed area is produced behind the blip. The contrast between the blip and the shadowed area produces a step edge of a magnitude not too dissimilar to those associated with lateral profiles. For the reflected illumination case, light emanating from first sewer wall assumes an elongated Gaussian-like distribution. All points along this wall emit light in all directions, fully illuminating the blip so that no, or a vastly reduced, shadowed area is produced. This results in a smaller step edge. The contrast between this edge and those generated by the lateral is proportionally greater than under direct light.

Basically, reflected illumination eliminates the spurious shadow edges that are generated under direct lighting leaving only those arising from real surface discontinuities. As these discontinuities are more pronounced at the lateral intersection the edges produced here are bigger. Direct light superimposes viewpoint-dependant shadows onto viewpoint-independent edges, emphasising noise-generated edges.

It is therefore proposed that detection of lateral intersections within enclosed sewer environments may be achieved more satisfactorily under reflected than under direct illumination conditions. It is envisaged that any proposed robotic system will control the illumination direction and create diffuse illumination by bouncing light off the sewer wall opposite to that being inspected. Under such conditions edge detection can be used to identify image points likely to lie on lateral profiles. These features can then be linked together **[6]** to form point strings which may mark the boundaries of lateral profiles. Thought must now been given to the development of decision criteria capable of selecting true laterals from this possibly misleading point string data.

6. THE PROPOSED VISION SYSTEM.

After examination of a variety of sewer images the following methods and criteria for lateral detection are proposed.

(i) As the camera rig may sway laterally within the pipe, profiles may appear almost anywhere within the image (ie. over the full clock range). It is however expected that laterals will be detected from a distance of approximately 1m. The volume of edge data is therefore reduced by considering only a circular region of 150 pixel radius about the image centre. In general, this region should be elliptical and centred on the *vanishing point* of the pipe; the image projection of the infinitely distant point at which the walls of the sewer intersect. In figures 1 and 3, the camera is approximately aligned with the central axis of the pipe, the vanishing point is therefore near to the image centre and the region is approximately circular. Techniques for the automatic detection of the vanishing point and determination of the appropriate region of interest will be the subject of a future report.

(ii) It is likely image noise will lead to some otherwise long point strings being broken into a number of shorter sections. Adjacent strings are therefore linked together; provided that the join between them is sufficiently smooth.

(iii) Once linking is complete, insignificant edges are eliminated by applying a line length threshold of 140 pixels.

(iv) The ideal curvature plot (curvature as a function of arc length) for a lateral profile string exhibits a line of constant curvature punctuated by 2 peaks corresponding to the top and bottom of the intersection. However, as sections of the profile may be missing, a string is accepted on the basis of just one peak, but rejected if more than two are located.

When the above criteria are applied to the data of figure 4, three strings are selected (figure 8). The lateral profile is correctly identified, along with two false positives. The string on the left hand wall may be discarded immediately. The light source is directed at that wall in order to provide reflected illumination of the opposing surface. Laterals would not therefore be sought in this region of the image. A displaced joint has also been selected, though this may be eliminated by considering an intensity profile taken across it **[11]**.

Application of the same criteria to the data of figure 2 produces the results in figure 9. The lateral profile has avoided detection, and instead two false selections have been made. The broken edge detail of the actual profile was connected to spurious edges detected within the lateral mouth; final application of the curvature criteria resulted in their dismissal.

CONCLUSIONS

It is suggested, then, that edge detection, point string formation and appropriate selection criteria provide the basis of a system for the detection of lateral intersections in images of NME sewer pipes. The illumination conditions under which these techniques are applied is however crucial. The task is greatly eased if light is reflected off the opposite wall so as to provide reflected, rather than direct illumination of the region under consideration. This observation has clear implications for the design of a robotic system. Detailed mathematical analysis of the properties of direct and reflected illumination is currently underway. The combined use of reflected and direct illumination for 3D description of lateral connections will be the subject of a future report **[11]**.

ACKNOWLEDGEMENTS

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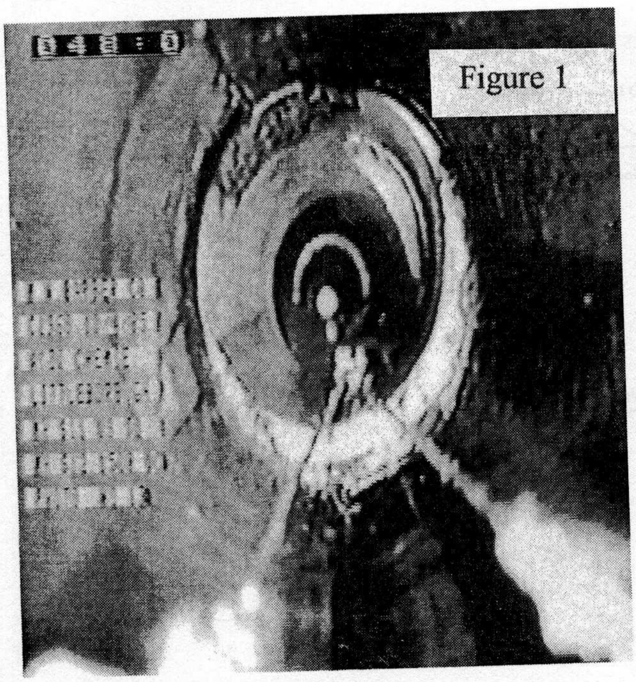

Figure 1

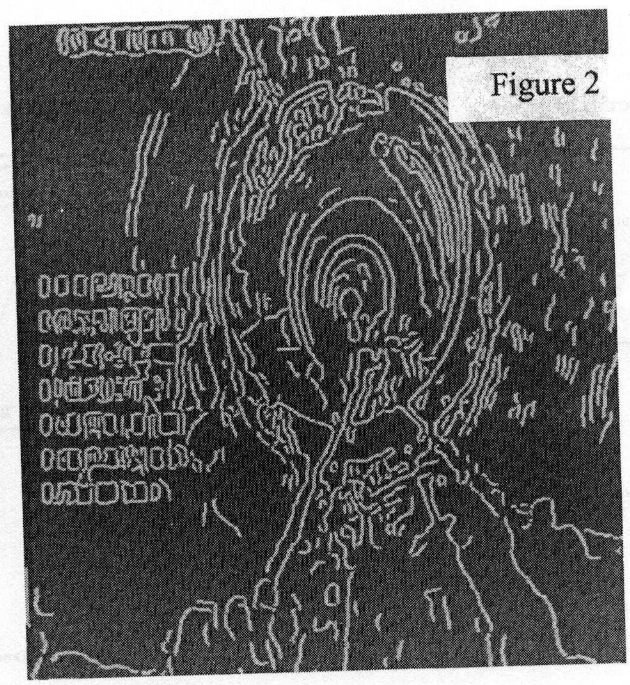

Figure 2

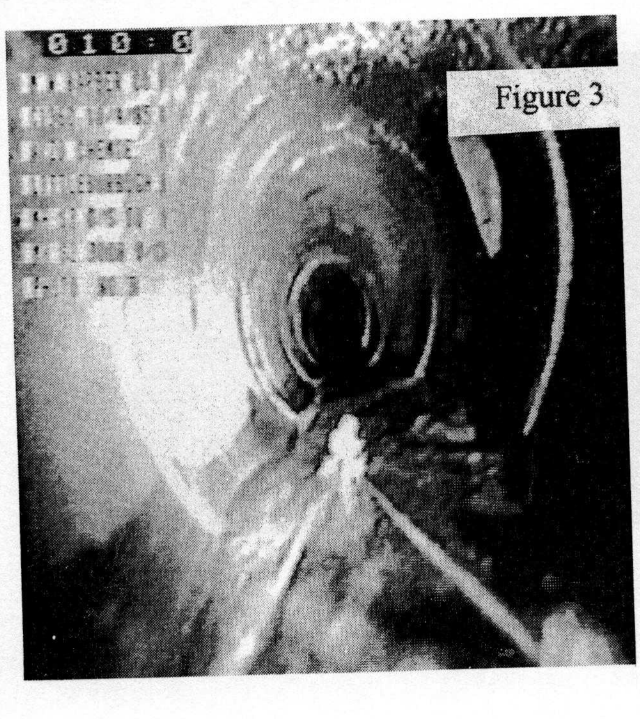

Figure 3

Figure 4

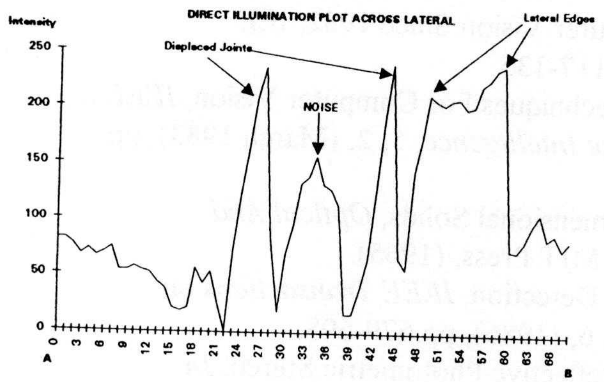

Figure 5

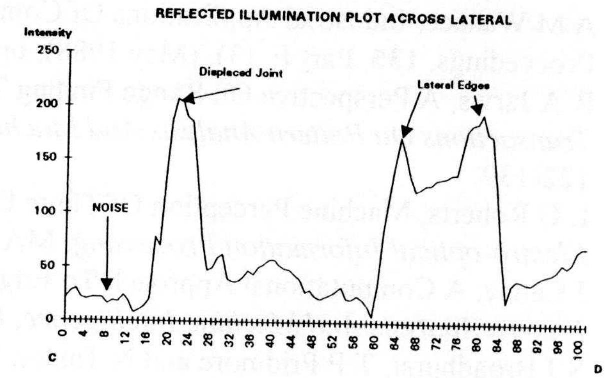

Figure 6

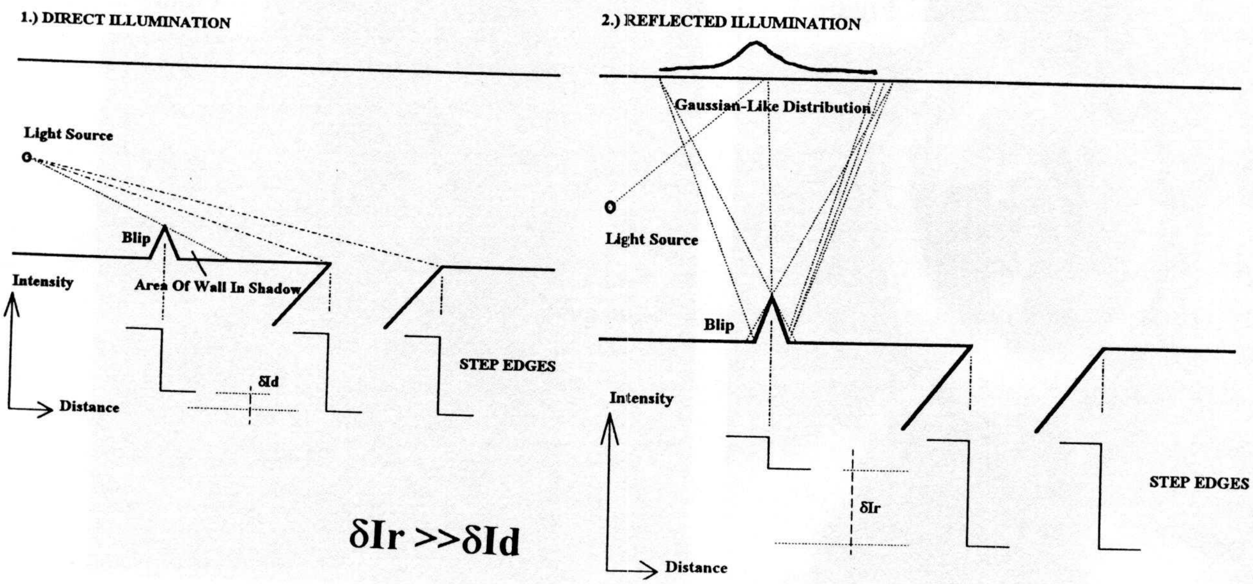

Figure 7

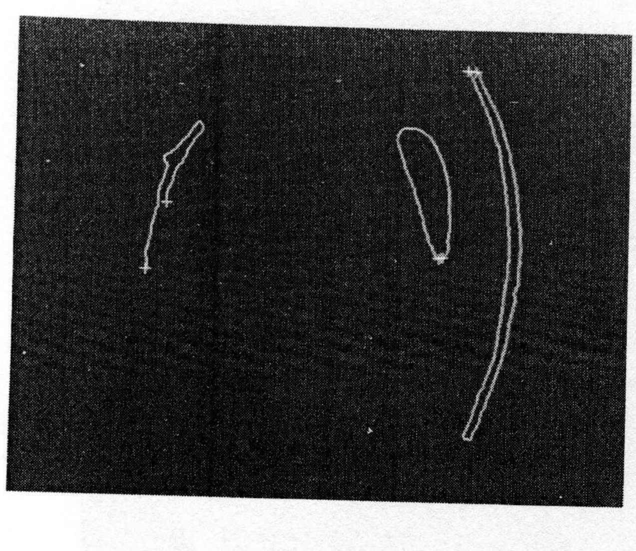

Figure 8

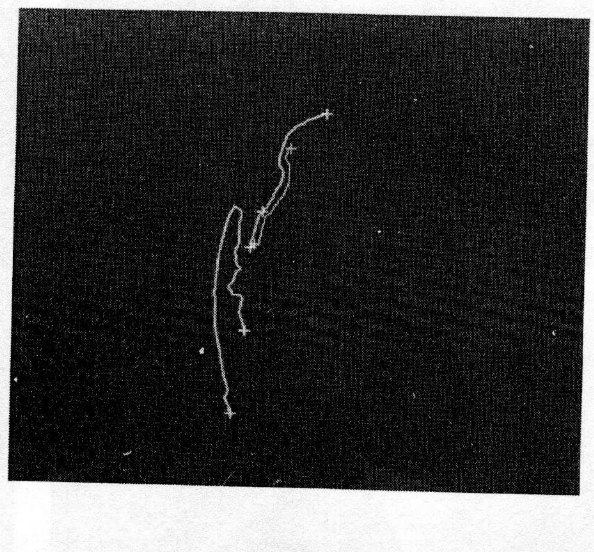

Figure 9