THE DEVELOPMENT OF AN OPTICAL TRIANGULATION PIPE PROFILING INSTRUMENT

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Abstract.

The planned rehabilitation and maintenance of sewers is of great importance to water and waste utility companies. The usual method of inspection and analysis is by CCTV and manual annotation of observed defects. Video tapes are also recorded at the time for archive purposes. The method suffers from a lack of quantitative information. As part of a programme to improve the quality of survey information North West Water Plc (NWW), one of the major UK water utilities, commissioned City University to produce a system to measure sewer cross-sections. These sections provide a direct method of measuring deformation. The information derived from such surveys can assist not only in making repair decisions but also in the generation of the 3-D structure of the sewer by using inertial systems to measure the spatial location of the sensor. The optical triangulation method of distance measurement is used in this system which incorporates a CCD sensor and laser pointer.

1. Introduction.

Sewer maintenance decisions are currently made using the CCTV inspection information. An industry wide manual of sewer defect classifications [Manual, 1988] defines the state of any given sewer. There is often a wide variance in operator interpretation because, for instance, of the difficulty of judging the degree of deformation of a sewer. The cost of repairing sewers in considerable, hence the move towards more quantitative measurement methods.

2. Background to the project.

Optical triangulation sensors using position sensitive detectors have matured to a point where they are used routinely in many inspection tasks in industry. However, these devices have a limited range (typically a few tens of millimetres). For measurement over larger ranges (100 mm. - 5 m.) the CCD detector has usually been used to provide higher accuracy due to its higher geometric stability. Research at City University has looked into accurate measurement of distances of up to six metres from the sensor since 1987 (Figs. 1 & 2).

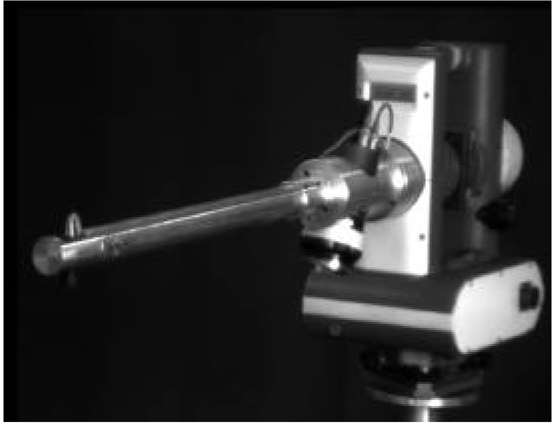

Fig. 1. Tunnel profiling device.

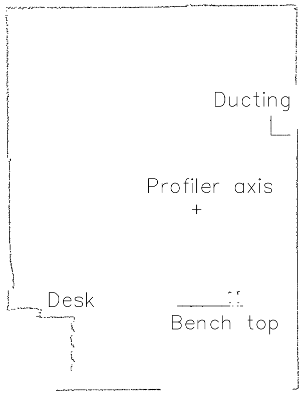

Fig. 2. An example profile.

These initial investigations were able to show that reasonable accuracy (approx. 1/3 mm rms.) could be achieved at three to four metres from the sensor (sufficient for deformation monitoring in railway tunnels, or for designing replacement sections for use in large bore sewers [Clarke, 1990a; 1990b; & 1990c]). The NWW project was concerned with a smaller range of measurement (0.3 - 1.0 m). This work was unusual - not so much in the use of optical triangulation or in the accuracy required - but in the environment to which it had to be applied. The specification was for an instrument which could: operate one hundred metres from the data storage device; measure cross-sections to a rms. precision of 0.5 mm. in a few seconds; withstand water sprayed onto the instrument; operate in a dirty environment; and store results for later analysis. A typical sewer is illustrated in Fig. 3.

Fig. 3. A typical sewer.

The manufacture of this instrument required a multi-disciplinary approach in the four areas of: mechanical; optical; electrical; and electronic design.

3. Instrument design.

3.1 Optical design.

A high intensity spot of light is required in optical triangulation systems which can be identified by a CCD sensor. A diode laser collimator is often used, however, the beam is relatively large (approx. 2 mm. x 5 mm.) so a small pinhole aperture was mounted in front of the collimator. A series of tests were conducted to find the most appropriate size (Fig. 4).

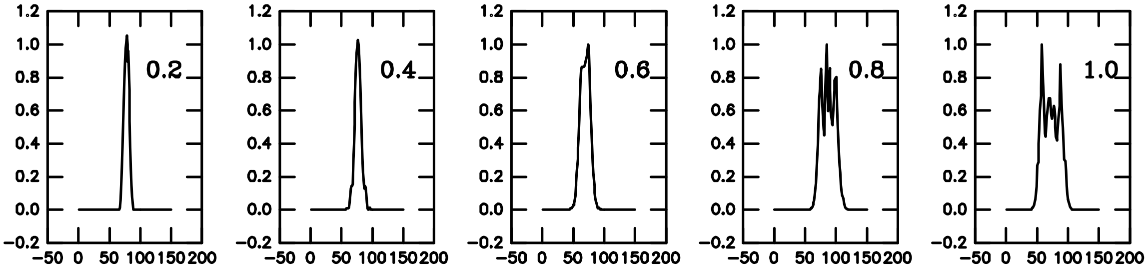

Fig. 4. Measurement of beam size at a fixed distance.

A compromise between beam spread, power loss, and divergence was required. The total transmitted power was measured for each pin hole. For the 0.2 mm. and 1.0 mm. pin holes

0.06 mW., and 0.920 mW. were transmitted respectively. The divergence of the beams was larger for the smaller pin holes due to diffraction, but the additional size of the larger beams meant that these were not so suitable. To determine the most appropriate pin-hole the CCD sensor was set up in the expected configuration and an object moved over the field of view of the sensor. This revealed that an aperture of 0.4 mm. would give an approximately constant image size with the change in magnification of the lens being offset by the increase in laser spot size. Hence, apart from the inevitable loss of light returned to the sensor with increased distance due to the inverse square law, this arrangement was considered satisfactory.

To ensure the optimum focus of the device the Scheimpflug condition was used to ensure that the image of the laser spot would be in sharp focus throughout the range of the device. The configuration of the laser, lens, and sensor were arranged to provide the required measurement range without excessive non-linearity or base length (Fig. 5.). To ensure that the system was waterproof, windows were used to protect the optics. All components were carefully aligned and fixed in firmly in place (Fig. 6.).

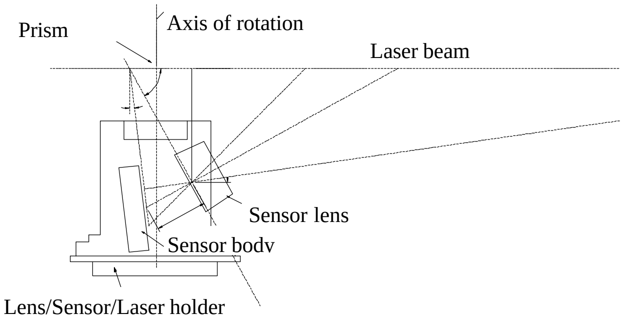

Fig. 5. The mechanical layout of the sensor head.

Fig. 6. An image of the sensor head.

3.2 Electrical design.

One of the main considerations with respect to electrical connections was the delivery of sufficient power to device at a distance of one hundred meters. As the instrument would be used underground, high voltages (> 24 Volts) could not be used. At low voltages the drop in voltage over this distance can be considerable. To achieve a flexible system (one that can use a variable input voltage) a number of wide-band DC to DC converters were used to ensure that a voltage range of between 9-18 Volts was acceptable. In practise, it was found that a 12 Volt battery was able to operate the system with both short and long distance cables. Suitable mixed wire cables are expensive, so a cable which had a large number of twisted pairs was selected where the redundant pairs were used for power.

The measuring head of the instrument had to rotate, so the question of transferring signals through slip rings was considered. Tests using back-to-back slip rings allowed input signals to be compared with output signals for a range of frequency inputs. It was discovered that at greater than 1 MHz signal cross-talk was encountered. Most linear CCD sensors do not use filters in the video path and hence, the signals have a much higher bandwidth than the 10 MHz clock that is often used. To circumvent this problem the majority of the circuitry was placed within the rotating part of the instrument so that only the low bandwidth communication and power signals were passed through the slip rings.

3.3 Electronic design.

The electronic design for this instrument entailed a number of differing elements: stepper motor drive, linear CCD sensor interface, A-D conversion, peak detection, exposure time setting, and communications. A modular design approach was adopted and several parts of the system were designed, prototyped, and finally produced in PCB form. The core of the system is the image processing and communication processes so these are described.

For this particular application, the accuracy requirement was easy to meet using peak detection provided that a reasonably large sensor was used (hardware centroiding, and the transfer of the laser image information were also considered). A Fairchild CCD181 module was chosen because only TTL interfacing was required. The two video channels from this sensor were sampled using two eight bit flash A-D converters and the resulting byte representing the intensity at a given pixel compared with the value from the previous pixel. If the intensity at that pixel was greater than the previous intensity then both the current intensity and the location were stored. At the end of each line, the highest intensity value was stored together with its location with respect to the sensor. This location data (12 bits) was then sent to the surface and paired with the angular position to provide a measurement of the cross-section. In addition the most significant four bits of the intensity of the peak were also transmitted using the spare four bit locations in the two bytes of data containing the peak location. This information was then used to modify the exposure time of the line scan sensor. The exposure time was set by counters to allow a wide range of exposure times to be selected. In this way a useful means of feedback was gained which enabled the measuring system to cope with varying surface reflectivities with the minimum loss of signal compared to the background. Additionally, a peak intensity that was less than 32 could also be detected and that measurement discarded as either coming from a dark surface with an incorrect exposure time setting, or from an occluded laser image.

The communications between the surface and underground instrument were conducted via RS485 standard line drivers and receivers. This system gave the highest noise immunity commensurate with a reasonably high data rate (39k baud). An UART chip was used to interface to the circuits at the sensor end and a standard two channel RS485 serial interface card at the data collection end. In addition to two way communications between the master station and the sensor, two other lines (normally used for handshaking purposes) were used to control the stepper motor and sense the location of an angular reference point by use of an optical encoder.

3.4 Mechanical design.

The mechanical design of the instrument was partly based on the optical requirements for the CCD sensor and lens assembly, and the physical size of the selected components. The manufacture of this design was then contracted to an experienced firm of engineers who built the instrument. Special care was taken to ensure that the instrument was waterproof which entailed the use of close fitting joints and ‘O’ rings. The instrument is illustrated in Fig. 7.

Fig. 7. The pipe measuring instrument.

3.5 Software design.

The only unexpected problem encountered in the development of the system was in the reassembly of the two bytes sent from the profiling device. It was initially considered that sending two bytes together followed by a gap would enable reliable detection of which byte was which. Unfortunately this did not take into account how most UARTs work. In practise, the UART receives the first byte and stores it internally while it waits for it to be read and then it stores the second byte. This meant that it was practically impossible to determine whether the bytes had been transmitted together or apart. The solution to this problem was an interrupt routine which analysed the information, sorted out which was the first byte, and then proceeded to collect every pair from then on. The control program interrogated the appropriate memory location to find the latest distance and intensity information. A set of software programs were written to check the performance of the device; calibrate; and collect, save, and display cross-sections.

4. Calibration.

With all optical triangulation systems two approaches can be adopted for calibration - direct and indirect. In direct calibration a look-up table is used. The relationship between the location of the laser spot image and measured distance from some pre-defined location on the instrument is observed at a number of points. In this case all relevant parameters describing lens distortion, configuration, etc. are not required. An indirect method of calibration would involve constructing the correct functional model for the lens, laser, and sensor arrangement and fit the calibration data to the functional model to generate the relevant parameters. In the case of direct calibration an interpolation routine is used (e.g. linear or cubic depending on the number of calibration observations). A calibration curve for the profiling instrument is illustrated in Fig. 8.

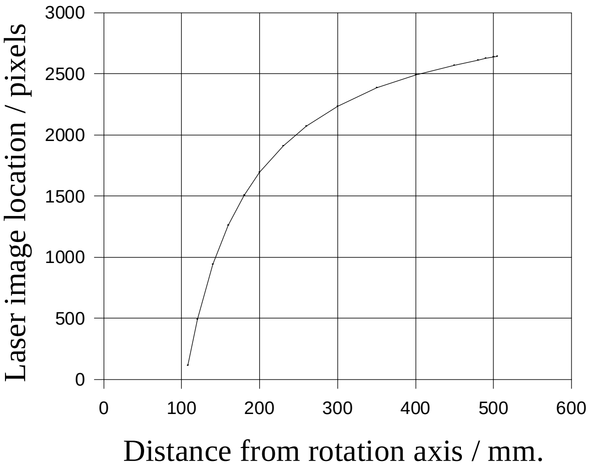

Fig. 8. A calibration curve from the instrument.

The calibration curve indicates the measurement range of the instrument as well as the high degree of non-linearity typical of such triangulation systems. In this case the resolution of the device is approximately 0.06 mm./pixel @ 150 mm., 0.3 mm./pixel @ 300 mm., and 0.64 mm./pixel @ 450 mm. The linearity problem does not occur for many of the PSD based sensors that are used in industry because they are designed to be linear over a small range. A partial solution to the problem that was considered was the use of non-linear correction element in the optical path (Clarke, 1991a; & 1991b). A prism provides such an element as the exit angle is a non-linear function of the angle of incidence. If the prism is arranged so that one side of the measurement range coincides with the angle of minimum deviation of the prism then the non-linearity of the prism can be made to oppose the non-linearity of the triangulation system. A simulation of this method is illustrated in Fig. 9, where a corrected and uncorrected optical triangulation system are plotted together on the same graph.

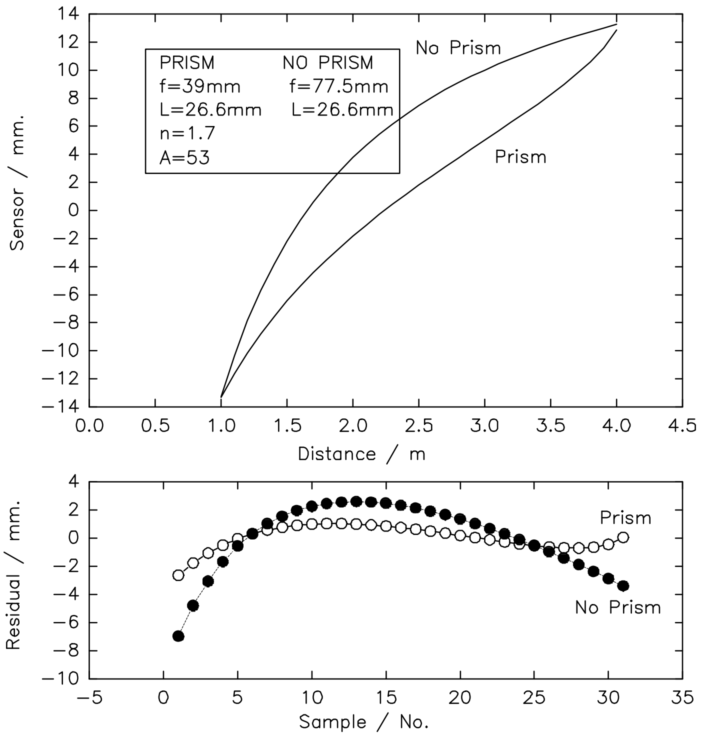

Fig. 9. Comparison between a corrected and uncorrected triangulation system.

However, while providing a useful correction such an element would have some undesirable characteristics such as light fall off at large angles of incidence to the prism. Hence, as accuracy was not a problem and a high resolution sensor (2500 pixels) was used, then this solution was not considered for this application.

5. Field testing.

The instrument was taken to a site of the clients choosing and lowered into a manhole. Two concrete pipes of 600 mm. and 525 mm. in diameter were then surveyed. This involved pulling the instrument through the sewer pipes to assess its operation and performance. A total of seventy profiles were collected. Various tests were conducted to assess the performance of the device. Fig. 10. is a profile of the brick manhole where the bricks and the skids of the instrument can be clearly observed. Fig. 11. illustrates a typical profile from within the sewer. The points within the cross-section at the bottom of the profile are places where the running water made measurement impossible. These plots were made in a different colour and at a closer range than the instrument is capable of measuring to illustrate that no measurement was possible at these points.

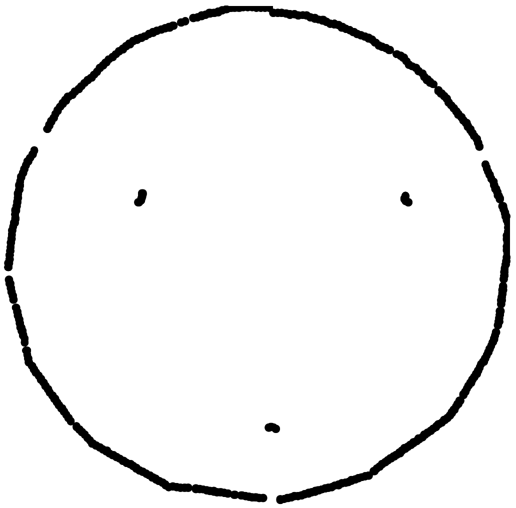

Fig. 10. Brick manhole cross-section.

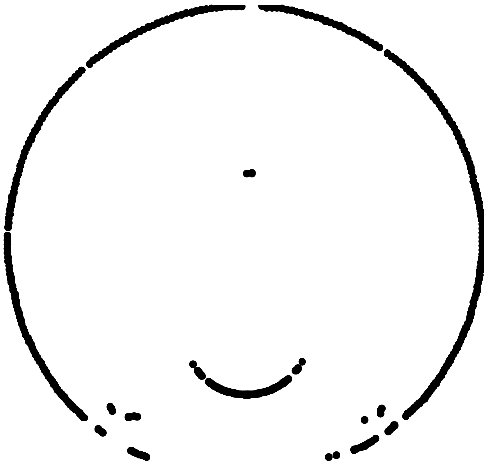

Fig. 11. Typical cross-section. **Fig. 12. An image of the profiler in the sewer.**

Fig. 12. Illustrates the position of the instrument when the cross-section shown in Fig. 11. was measured. By assuming that the profiling instrument was moved linearly down the length of the sewer a collection of profiles can be displayed in 3-D to illustrate the sewer shape along its length (Fig. 13 & 14).

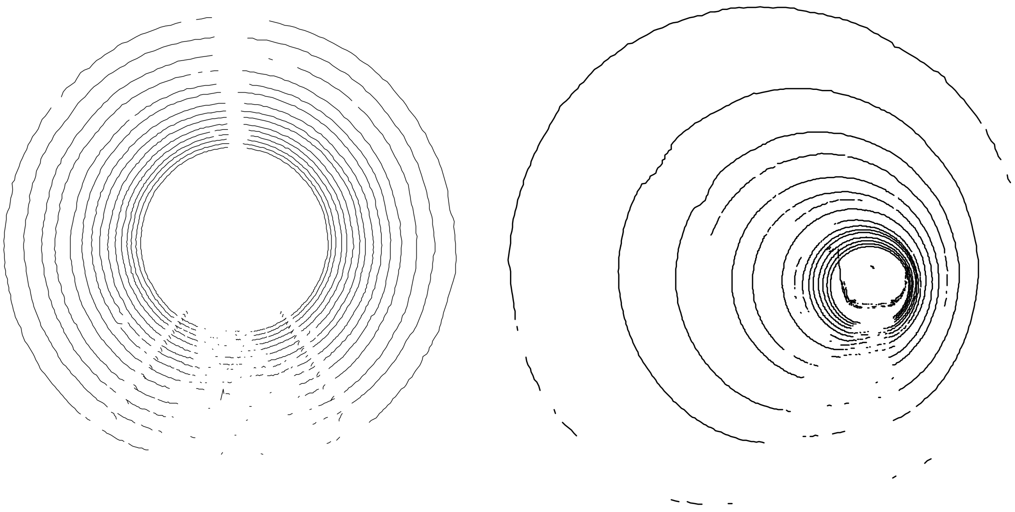

Fig. 13. & Fig 14. Two 3-D representations of a series of cross-sections.

The usefulness of these profiles to the engineer is illustrated in Fig. 15, where a small section of one of the profiles has been extracted and analysed. By fitting an ellipse to the cross-section it is possible to measure the size and shape of debris on the sewer wall. Similarly the shape of sewers can be recorded and assessment of any deformation used for future comparisons or engineering decisions.

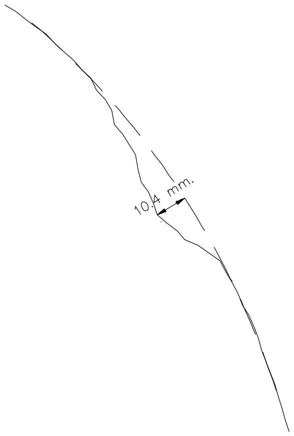

Fig. 15. Example use of the cross-section.

6. Conclusions.

An optical triangulation system has be built and tested to the clients satisfaction. The operating environment meant that a number of unusual requirements were addressed to comply with the clients specification. The system has a variable resolution, a variable measurement rate which is generally in excess of 100 measurements per second, it is capable of measuring to surfaces which range between matte black and white by using feedback in the measurement process, and measurement can be performed remotely to a distance of 100 metres. In the field tests a number of cross-sections were measured and subsequently analysed. At the present time a new instrument is in the design and planning stage for regular use and testing in the field. This instrument will be built to a higher standard. If successful this instrument would then be manufactured and to provide an enhanced surveying device for the water industries.

7. Acknowledgements.

This project was conducted for North West Water Plc between 1992 & 1993 who have given permission for the results to be published.

8. References.

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