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A technology for sewer pipe inspection (part 1): Design, calibration, corrections and potential application of a laser profiler

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ABSTRACT

In order to ensure and extend the serviceability of sewage infrastructure, sewer managers need more accurate data to estimate its actual state. For that purpose, various inspection techniques can be implemented. A first prototype of an unbiased laser profiler was developed to improve the accuracy of collected data (Clemens, Stanić, Van der Schoot, Langeveld, Lepot, 2015). However, a higher accuracy needs to be achieved. This article presents the results of an improved prototype that delivers an increase in the measuring accuracy of 5–10 times, which was achieved by using more accurate equipment (lasers and cameras) and by improvements in the methodologies applied (e.g. removing the last bias image distortion by camera calibration). The new design presented hereafter provides accurate measurements ($\sigma < 2$ mm) of cross section and accurate 3D image of a pipe. The potential applications of the improved laser profiling technique are comprehensive: e.g. deposit measurements, roughness measurements.

1.1. Introduction

Urban drainage networks (as well as water supply networks) are capital-intensive underground infrastructures and vital components of a sustainable urban system which are intended to have a long service life. Consequently, it is necessary to maintain a certain level of serviceability of the infrastructure. Often operators are under pressure to minimise their maintenance costs while keeping the risk of failures at an acceptable level. Information on the current status of the assets can enhance proper decision-making. Wirahadikusumah et al. [1] present an overview of several techniques available for the assessment of sewer conditions: visual inspection by closed circuit television (CCTV), radar (e.g. in [2]), acoustic techniques (e.g. in [3]), sonar [4], laser profiling [5] or a combination of these technologies in order to benefit from the strengths of each technology [6,7]. CCTV, as the predominantly applied inspection technique, is effective only for detecting gross defects and like any other technique has its own advantages and disadvantages [1]; the main issue is that CCTV does not provide any quantifying information like dimensions of the pipe, deformation or information that enables the quantification of hydraulic capacity or structural strength and stability. Apart from that, CCTV suffers from the subjective interpretation of footage by inspectors as was shown in [4,8], making CCTV results subject to unknown systematic errors. As a consequence, there is a lack of suitable information on the actual status and performance level (in terms of hydraulic capacity and structural strengths and stability) of the sewer for adequate asset management (e.g. in sewers by [9]).

The laser profiling technique has been applied in practice since circa 2000 for pipe inspection [10–17] with the following main objectives: *i*) to detect and quantify the ovality or other significant deformations of the geometry and to detect structural damage like cracks or obstacles (see *e.g.* [4,5]), *ii*) to quantify the loss of wall thickness due to surface damage - corrosion [4]. Laser profiling offers challenging perspectives for measuring the interior geometry as well as some characteristics relating to functionality (e.g. quantifying the physical roughness enabling the quantification of hydraulic capacity) of a sewer pipe. Further, this technology can be used for the condition assessment of other pipe systems like water supply mains, oil pipelines and small diameter pipes (e.g. in the chemical industry) [14,15,18]. A commonly overlooked issue when using results obtained from laser profiling is that misalignments and/or improper orientation of the laser sensor can cause a significant systematic error when measuring the internal geometry of pipes [5,19]. The fact these factors pose limits on the accuracy of the laser profiler is noted in the ASTM International standards F3080-14 and F3095-14, though they are not addressed in any depth by these standards [20,21]. Clemens et al. [19] briefly introduce a first version

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of an unbiased (i.e. applying corrections for the current position and orientation of the device on the obtained measuring result) laser profiling technique. Both the mathematical calculations and laboratory experiments highlight the feasibility of a more robust technique by increasing the camera and laser distance meter accuracies.

This paper presents an improved version of the laser profiling technique in some detail - Prototype 2.0; more accurate and unbiased results are obtained due to the application of high-end components and some improvements in the methodologies are applied for compensating for systematic errors. Detailed information on hardware and data acquisition software are published under the common creative license CC BY-NC-SA [22]. A website [23] devoted to sewer inspection techniques was recently uploaded to share all the required information, tutorials and data acquisition software.

A detailed design and drawings of the set-up are given in Section 1.2 of this paper. Section 1.3 presents the mathematics and protocols applied for sensor calibration (i.e. cameras and lasers) and (laser) misalignment as well as the data processing method. Finally, some results are presented to demonstrate the accuracy of the proposed technology. Overall, this study strengthens the reliability of such a technique thus suggesting its wider application in inspection practice.

This paper is the first of two papers devoted to the new improved version (Prototype 2.0) of the laser profiling technique. It presents (*i*) the synchronization of the independent measuring platforms, (*ii*) the accuracy and calibration of the laser distance meters and cameras, and (*iii*) the performance of the Prototype 2.0 compared to the Prototype 1.0 (first design [19]). The second paper presents experimental results of an extended set of laboratory tests [24]. All the components linked to the prototype development at TU Delft are listed on the website previously mentioned.

1.2. Material and methods

The main goal of the laser profiling technique is to inspect linear infrastructures (like sewers) along the reach, which is limited by the maximum distance measurable by the laser distance meters or by a change in direction of the pipe. The prototype was designed and built to determine the position of the device (*x*, *y* and z), rotation (pitch θ_x, yaw θ_y and roll θ_z) and to ensure highly accurate results. A left-handed coordinate system is applied, while the rotation angles are defined in the Tait-Bryan formalism (Fig. 1). To avoid the limitation of cables in practical applications (i.e. an unexpected disconnection, cable length limitation, cleaning and damaging of the cables), the system was divided in two parts: a fixed one with laser probes and a moving one with the laser profiler and cameras (Fig. 2).

The set-up consists, as with the ordinary laser profiling technique, of a laser profiler (Ibak, ILP) combined with a camera (Allied Vision Technology, Prosilica GT3400C), referred to as a cam_{FRONT}. The laser profiler uses a reflecting cone to project a laser sheet on the inner pipe wall,

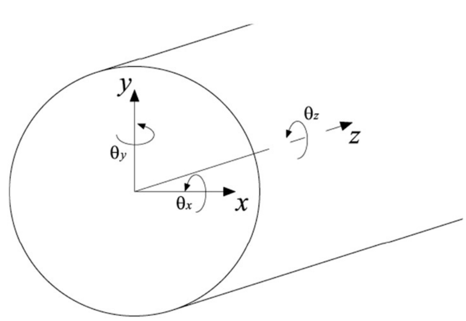

Fig. 1. Left-handed coordinate system and definition of the Tait-Bryan angles.

creating a line perpendicular to the profiler and thus the moving platform of the prototype which is captured by the cam_{FRONT}.

The fixed platform of the set-up consists of three laser distance meters (Dimetix, FLS-C10) each measuring the distance between the fixed platform and the moving part. The lasers point at the reflection board mounted on the moving platform of the prototype thus acquiring the information on the position of the moving part along the length of the pipe (z-axis) and two of the three rotation angles (θ_x and θ_y). A second camera (Allied Vision Technology, Manta G-282C), referred to as a $cam_{BACK,}$ which is fixed on the moving part, records the position of the three points projected by the parallel lasers on the reflection board. By applying image processing techniques and ellipse fitting, the *x* and *y* location of the centre of the points (in sensor coordinates) are derived, thus acquiring the remaining information on the position (along the *x* and *y axes*) and the third rotation angle (θ_z).

The three laser distance meters (on the fixed platform), two cameras and a projected laser (on the moving platform) are the main parts of the first design: additional details and photos have been given in [19]. This previous study highlights the reliability of the laser profiling technique and the need for more accurate sensors i.e. laser distance meters, higher camera resolutions. The new version tries to tackle these disadvantages by implementing the following improvements (Table 1): *i*) cameras with a higher image quality, *ii*) adjustable positions of cameras, *iii*) more accurate laser distance meters and *iv*) two data acquisition systems that are optically synchronized in order to avoid cables for data acquisition between the two parts of the prototype (Fig. 3).

In order to properly assess the geometry of the pipe (data were post-processed), both data acquisition systems have to be perfectly synchronized. What should be emphasized is that synchronization between the parts for the first version of the prototype was not needed due to the fact that the fixed and moving platforms were connected to the same computer and thus shared the same internal clock. In the new design it was decided to avoid synchronization by cables since these are not reliable because of mechanical stresses during the operation, and therefore another form of synchronization between the two data acquisition systems had to be implemented (Fig. 3). The synchronization was ensured with the 4th laser (Osela, Streamline laser (660 nm)), behaving like a pulse laser (through a bijective time series On-Off), on the fixed platform recorded by the back camera (Fig. 4); both system clocks could be lagged with an accuracy due to light travel duration (negligible). Overall, wireless synchronization was achieved. Table 1 highlights the main improvements between the two prototypes. The Prototype v2.0 is dedicated to demonstrating the feasibility of more accurate measuring. In order to increase the accuracy, it was necessary to invest in highly accurate equipment. Apart from this, the highly accurate components (e.g. high-resolution cameras) also make it possible to measure in bigger pipes up to 2000 mm diameter. Of course, the costs for the prototype development are much higher compared to the production in series, and consequently it can be expected that the price of the equipment will drop in the future. The position of the cameras and lasers will change depending on the pipe diameter. In addition, the size of the reflection board will have to be changed with an increased pipe diameter (board build-up available). For the bigger pipe diameters, the distances between lasers will be increased (allowing higher accuracy), as well as the distance between the laser profiler and cam_{FRONT}, and cam_{BACK} and the reflection board.

1.2.1. The fixed platform

This part is basically a platform on which four lasers are fixed: three laser distance meters to assess positions and rotation angles; and a pulsed laser to ensure an optical synchronization through a known sequential time series between data acquisition systems located on both platforms. The distances between the three lasers' distance meters on the fixed platform was determined using a program written in Matlab® to calculate the prototype's optimal settings for a given set of sewer