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Challenges of dimensional quantification in CCTV inspection in drain and sewer systems

L. L. Martins[1], A. S. Ribeiro[1], M. C. Almeida[1]

[1]LNEC – National Laboratory for Civil Engineering, Lisbon, Portugal, lfmartins@lnec.pt, +351 21 844 3000

Abstract **– This paper addresses the metrological quality of dimensional measurements based on images obtained from CCTV inspections in drain and sewer systems. In this type of indirect visual inspection, a significant number of absolute and relative dimensional quantities can be quantified, contributing to the characterization of the observations and, consequently, to the analysis of performance of drain and sewer systems outside buildings.**

Unfavourable environmental factors and conditions within the drain or sewer components affect estimation of the quantities of interest and the quality of the recorded images (lighting, lack of reference points, geometric irregularities and subjective assessments, among others). Quantification improvement of the dimensional quantities is a key objective to achieve a better value from these inspections. This study contributes to improve the quality of the dimensional measurements by defining experimental procedures, which can be applied to the optical systems used in CCTV inspection.

The paper describes the European normative framework for these inspection activities and proposes approaches aiming at increasing confidence in the dimensional measurements, based on the metrological characterization of the optical systems used, as well as their integration in a traceability chain. Results presented and discussed include the evaluation of measurement uncertainty.

Keywords – CCTV inspection, drain system, sewer system, dimensional measurement.

I. INTRODUCTION

Drain and sewer systems are integrated in urban areas, often large and complex. These networks are composed by multiple types of components, such as drains and sewers, manholes, gullies, combined sewer overflows, storage and retention tanks, pumping stations, among others. These systems operate essentially under gravity to convey wastewater and stormwater to a treatment works or receiving water.

In the last decades, extensive work has been carried out by European standardization committees [1-3], aiming at the harmonization and improvement of strategic, policy and operational activities concerning drain and sewer systems. The established framework ambition is to contribute to fulfilment of strategic objectives of these services (including protection of public and occupational health and safety, environmental protection and sustainability). Set principles and functional requirements detailed in the standards are related to three main lines of action: (i) investigation and assessment; (ii) design and construction; (iii) management and control.

The investigation and assessment of drain and sewer systems outside buildings [2] aims to establish an overview of their condition and performance and it can be defined as a sequential process, which includes: (i) purpose; (ii) scope; (iii) review of existing information; (iv) inventory update; (v) hydraulic, environmental, structural and operational investigations. The results of these investigations allow determining the hydraulic performance, environmental impact, structural condition and operational deficiencies, supporting the comparison with the established performance requirements from which non-conformities can be identified and management plans can be updated.

The investigations are carried out using several sources of information, including external or internal inspection activities for the detection and characterization of anomalies which can negatively affect the performance of the drain or sewer system. Close circuit television (CCTV) inspection is a largely used visual inspection technique for non-man entry components. The use of a remotely controlled CCTV camera is generally motivated by: (i) safety issues, avoiding direct visual inspection by persons inside the drain and sewer systems; (ii) faster and economic advantages, when compared with quantitative methods such as laser scanning, ground piercing radar, sonar, infrared thermography and other available techniques [4].

This technique allows recording videos and individual images of the anomalies in drains, sewers, manholes and inspection chambers. A standard European coding system has been developed [3], in line with existing national systems in member countries, facilitating common approaches and circulations of services within EU. Data on observations includes: (i) type (e.g. fissure, deformation, displaced joints, defective connections, roots, infiltration, settled deposits, attached deposits and other obstacles, subsidence, defects in manholes and inspection chambers, mechanical damage or chemical attack); (ii) characterisation; (iii) location (longitudinal and radial); (iv) quantification.

A significant number of absolute and relative dimensional quantities can be quantified, based on the recorded videos and images. Since these values are determining the results of the investigations and prioritization for correction actions [5], efforts towards reduction of systematic deviations and measurement uncertainties are extremely relevant. In parallel with technological developments, on-going research efforts include automated image processing techniques [6] aiming at the reduction of human intervention in image analysis (which is time-consuming, prone to human error and to subjectivity) and the increase of image quality e.g. by noise reduction [7]. However, discussion from a metrological perspective on the measurement accuracy was not found to be sufficiently developed.

In the following sections, this paper presents the problem of accurate dimensional measurements in CCTV inspections and proposes several approaches aiming to reduce subjectivity in the image dimensional analysis and increase measurement reproducibly, by the metrological characterization of the applied optical systems and their integration in a traceability chain.

II. THE PROBLEM OF ACCURATE DIMENSIONAL MEASUREMENTS IN CCTV INSPECTIONS

According the EN 13508-2:2003+A1:2011 standard [3], a number of quantities should be recorded as to fully characterise the observation identified in the inspection.

In the case of absolute dimensions measurements (e.g. in millimetres or in degrees), record of the quantities that can be required include:

- width of fissures, cracks, connections, channels and sections;
- height of connections and channels;
- length of breaks, collapsed regions, intruding connections and sections;
- maximum dimension of obstacles;
- thickness of deposits;
- depth of sediments, anomalies in walls;
- longitudinal and radial displacement of joints;
- level difference between coverage and surface;
- curvature;
- angular displacement at joints.

In addition, relative quantities that can be required (expressed in percentage) include [3]:

- dimensional reduction;
- level relative to the diameter or vertical dimension;
- reduction in effective cross section area;
- intrusion length relative to the diameter or vertical dimension.

Examples of images obtained from a CCTV camera (e.g. Figure 1) in drain and sewer systems inspections are shown in Figures 2 and 3, illustrating some anomalies and the corresponding quantification parameters.

Fig. 1. Remotely controlled CCTV camera used in drain and sewer systems inspections [8].

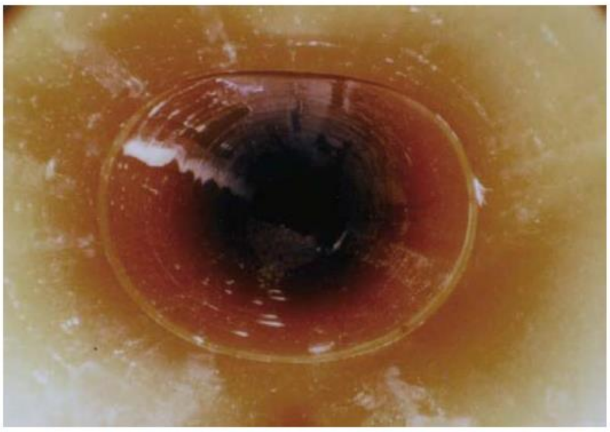

Fig. 2. Inspection image showing dimensional reduction by deformation effect [8].

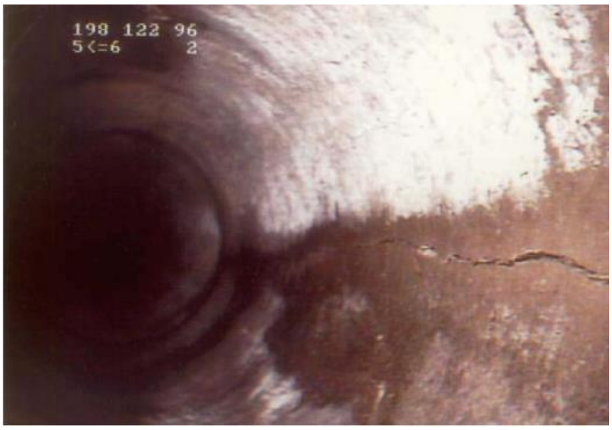

Fig. 3. Inspection image showing fissure [8].

As a rule, the longitudinal location of observations in this type of inspection, is measured by the CCTV system and recorded with a recommended resolution equal to 100 mm and the operational speed should be in the range of 0.1 m/s and 0.2 m/s to ensure adequate detection of observations.

In order to improve the accuracy of the measurements, special attention is given to the CCTV camera position inside the sewers or drains, thus reducing geometrical projection deviations. A tolerance up to 10% is defined for the CCTV camera vertical position (1/2 and 2/3 of the drain/sewer height, for a circular/regular or egg shape, respectively).

Lighting tests should be carried out before each inspection, using image quality testing charts such as the Marconi Resolution Chart no. 1, allowing in situ qualitative evaluation of the recorded images, namely, the radiometric and spatial resolution as well as the geometrical distortion.

Although benefits arise from these operational practices, limitations on non-existence of reference points inside the component under inspection makes any dimensional measurement vulnerable to subjective image analysis. In the following section, approaches aiming at improving measurement accuracy are proposed as well as the comparability between measurements undertaken by different operators or in different moments in time.

III. PROPOSED APPROACHES

A first approach, aiming at increasing the confidence in the dimensional measurements carried out, is to ensure the traceability of the metrological characterization of the optical system – the CCTV camera – used in drain or sewer inspection. This characterization includes both a geometrical component and a radiometric component, allowing a rigorous comparison between different CCTV cameras available in commercial solutions and their corresponding suitability to the measurement environment.

The main objective of the geometrical characterization is the quantification of CCTV camera intrinsic parameters such as the focal distance, the principal point coordinates and the lens distortion coefficients, which are input quantities for the determination of accurate dimensions in the field-of-view. This task can be achieved in a laboratorial setup, using traceable reference dimensional patterns and applying known algorithms such as the DLT – Direct Linear Transform [9], the Tsai [10] and the Zhang method [11].

The radiometric characterization can be carried out following the EMVA standard guidelines [12], allowing to determine the CCTV camera sensitivity, linearity, noise, dark current, spatial non-uniformity and defect pixels.

In addition to the CCTV camera metrological characterization, the measurement model itself must be defined and used in the dimensional measurement uncertainty evaluation, following the GUM framework [13-14].

If both the intrinsic (focal distance, principal point coordinates and lens distortion coefficients) and extrinsic (camera position and orientation in the world coordinate system) parameters of the camera are known, the perspective camera model [15] can be used to determine the coordinates related to points of interest inside the sewer or drain. Assuming, in a first approach to this problem, that the lens distortion does not have a significant impact on the dimensional accuracy when compared with other uncertainty components, the perspective camera model assumes a straight line between the interest point in world (X, Y, Z) and in the image (x, y) coordinate systems, defining the so-called collinearity equations

$$X = X_0 + (Z - Z_0) \cdot \frac{r_{11}\cdot(x-x_0)+r_{12}\cdot(y-y_0)-r_{13}\cdot f}{r_{31}\cdot(x-x_0)+r_{32}\cdot(y-y_0)-r_{33}\cdot f}, \quad (1)$$

$$Y = Y_0 + (Z - Z_0) \cdot \frac{r_{21}\cdot(x-x_0)+r_{22}\cdot(y-y_0)-r_{23}\cdot f}{r_{31}\cdot(x-x_0)+r_{32}\cdot(y-y_0)-r_{33}\cdot f}, \quad (2)$$

where: (i) intrinsic parameters – f is the focal distance and (x_0, y_0) are the principal point image coordinates; (ii) extrinsic parameters – (X_0, Y_0, Z_0) are the camera's coordinates in the world and r_{ij} are the rotation matrix elements defined by the camera's orientation angles Ω, Φ, K, given by

$$r_{11} = \cos\Phi \cdot \cos K, \quad (3)$$

$$r_{12} = -\cos\Phi \cdot \sin K, \quad (4)$$

$$r_{13} = \sin\Phi, \quad (5)$$

$$r_{21} = \cos\Omega \cdot \sin K + \sin\Omega \cdot \sin\Phi \cdot \cos K, \quad (6)$$

$$r_{22} = \cos\Omega \cdot \cos K - \sin\Omega \cdot \sin\Phi \cdot \sin K, \quad (7)$$

$$r_{23} = -\sin\Omega \cdot \cos\Phi, \quad (8)$$

$$r_{31} = \sin\Omega \cdot \sin K - \cos\Omega \cdot \sin\Phi \cdot \cos K, \quad (9)$$

$$r_{32} = \sin\Omega \cdot \cos K + \cos\Omega \cdot \sin\Phi \cdot \sin K, \quad (10)$$

$$r_{33} = \cos\Omega \cdot \cos\Phi. \quad (11)$$

If the camera's intrinsic and extrinsic parameters are not available, a less rigorous approach can be followed, assuming a parallel geometrical relation between the image plane and cross-section plane in the drain or sewer and using an orthographic projection camera model [15] to define a scale coefficient, *SC*, between real dimension (in millimetres) and image dimension (in pixels). In the observed field-of-view, the only available dimensional reference is related to the height of the drain or sewer, *H*. Therefore, the dimensional quantification of a certain observation must be supported by the determination of the scale coefficient relative an average cross-section plane in the drain or sewer which includes the quantity to be measured and where its height is also visible, as shown in Figure 4.

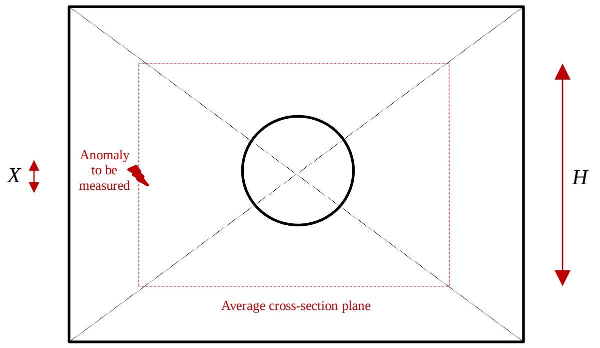

Fig. 4. Schematic representation of the measurement procedure in CCTV camera images.

In this approach, the image dimensions (in pixels) related to the drain or sewer height in the average cross-section plane, p_H, and to the observed anomaly, p_X, are obtained by image processing. Therefore, the scale coefficient, expressed in millimeters per pixel, is obtained by

$$SC = \frac{H}{p_H}, \tag{12}$$

while the dimensional measurement of the observation, *X*, (in millimeters) is given by

$$X = SC \cdot p_X. \tag{13}$$

Since these are linear mathematical models, the application of the Uncertainty Propagation Law [13], results in the standard measurement uncertainty expressions for the scale coefficient, $u(SC)$, and for the dimensional measurement of the anomaly $u(X)$, respectively,

$$u(SC) = \sqrt{\frac{1}{p_H^2} \cdot u^2(H) + \frac{H^2}{p_H^4} \cdot u^2(p_H)}, \tag{14}$$

$$u(X) = \sqrt{p_X^2 \cdot u^2(SC) + SC^2 \cdot u^2(p_X)}, \tag{15}$$

where $u(H)$ is the standard uncertainty of the height of the drain or sewer and $u(p_H)$ and $u(p_X)$ are the standard uncertainties of the image dimensions of p_H and p_X.

IV. RESULTS AND DISCUSSION

This section shows the evaluation of the dimensional measurement uncertainty related to the adoption of the perspective camera model or the orthographic projection camera model. The quantified uncertainty components and estimates are merely illustrative, reflecting values which are expected to have in a sewer or drain CCTV inspection scenario. Therefore, in a real case scenario, the presented probabilistic formulation and quantification must be confirmed and updated if required.

Due to the non-linear and complex mathematical models related to perspective camera model (expressions 1 to 11), the Monte Carlo method [14] was applied in the calculation of the dimensional measurement uncertainty. The computational simulation algorithm was developed in Matlab®, using the Mersenne-Twister pseudo-random number generator [16] and validated computational routines. 10^6 trials were used to obtain convergent solutions.

In the simulated observation scenario, the following estimates of the input quantities were considered: (i) camera location – the camera is placed near the centre of the drain or sewer cross-section (X_0=Y_0=0.10 m) and in a longitudinal position Z_0=1,00 m from the origin (the initial inspection position, for example); (ii) camera orientation – modern remotely controlled CCTV inspection systems often allow the camera rotation in three axis; in this case, the camera is considered to be orientated towards the centre of the drain or sewer cross-section, with reduced rotation angles (Ω=0.02 rad; Φ= 0.03 rad; K=0.01 rad); (iii) location of the observation plane – the point of interest is considered to be 50 mm in front of the camera location (Z=1.05 m); (iv) camera's intrinsic parameters, obtained from previous laboratorial characterization – focal distance, f=0.0010 m; the principal point is considered to be in the image centre (x_0=y_0=0); (v) image coordinates – the interest point is located in the following image coordinates: x=0.000 15 m and y=0.000 225 m.

Table 1 presents the adopted probabilistic formulation for the mentioned input quantities.

Table 1. Probabilistic formulation of the input quantities.

Uncertainty component	Probability distribution	Standard uncertainty
Camera location $u(X_0)$, $u(Y_0)$, $u(Z_0)$	Uniform	0.005 m / √3
Camera orientation $u(\Omega)$, $u(\Phi)$, $u(K)$	Uniform	0.01 rad / √3
Focal distance $u(f)$	Uniform	0.000 05 m / √3
Principal point coordinates $u(x_0)$, $u(y_0)$	Gaussian	$7.5{\cdot}10^{-7}$ m *
Location of the observation plane, $u(Z)$	Uniform	0.005 m / √3
Image coordinates $u(x)$, $u(y)$	Gaussian	$1.5{\cdot}10^{-4}$ m, $2.1{\cdot}10^{-4}$ m *

* Considering a ¼ squared pixel with 3 µm linear dimension.

Table 2 shows the obtained simulation results in terms of estimates, 95% expanded uncertainties and computational accuracy.

Table 2. Simulation results for X and Y.

Quantity	Estimate	95% expanded uncertainty	Computational accuracy
X	94.1 mm	5.0 mm	0.014 mm
Y	87.7 mm	5.5 mm	0.019 mm

Figures 5 and 6 correspond to the output normalized probability density functions related to *X* and *Y*, respectively, showing a trapezoidal shape as the result of the adopted input probabilistic formulation (uniform and Gaussian distributions).

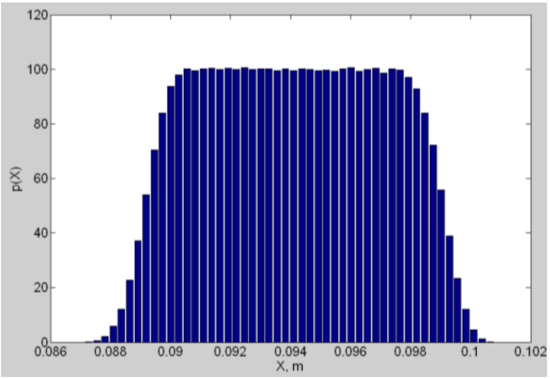

Fig. 5. Normalized probability density function for X

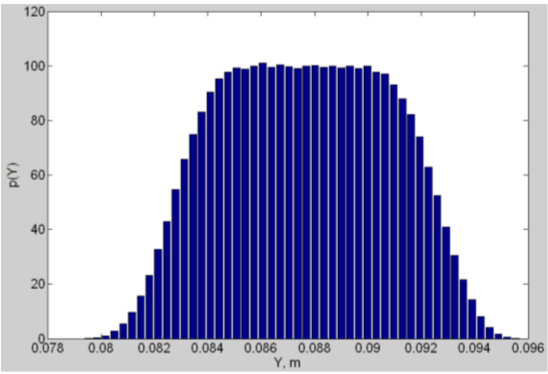

Fig. 6. Normalized probability density function for Y

A sensitivity analysis was performed with the develop simulation algorithm, revealing that the major uncertainty contributions correspond to the camera's location coordinates in the world coordinate system (X_0, Y_0, Z_0), as well as the *Z* longitudinal location of the observation plane (cross-section of the drain or sewer).

In order to evaluate their impact on the dimensional measurement accuracy, additional simulations were performed, considering extreme accuracy levels of 1 mm and 100 mm related to the above mentioned input quantities. The results are shown in Table 3.

Table 3. Impact of the camera and observation plane locations in the dimensional measurement accuracy

X_0, Y_0, Z_0 and *Z* accuracy levels	$U_{95\%}(X)$	$U_{95\%}(Y)$
1 mm	0.9 mm	1.1 mm
10 mm	5.0 mm	5.5 mm
100 mm	49 mm	54 mm

For the case of the orthographic projection camera model, Table 4 shows the input estimates used in the performed measurement uncertainty evaluation, while Table 5 refers to the probabilistic formulation of the corresponding standard measurement uncertainties.

Table 4. Measurement estimates of the input, intermediate and output quantities.

H	p_H	*SC*	p_X	*X*
/ mm	/ pixel	/ mm·pixel^{-1}	/ pixel	/ mm
300	350	0.857	30	25.7

Table 5. Probabilistic formulation of the measurement uncertainties of the input, intermediate and output quantities.

Uncertainty component	Probability distribution	Standard uncertainty	Relative standard uncertainty
u(*X*)	Gaussian	From 0.33 mm up to 4.3 mm	1% - 17%
u(p_X)	Gaussian	From 0.25 pixel up to 5 pixels	1% -17%
u(*SC*)	Gaussian	From 0.008 mm·pixel^{-1} up to 0.015 mm·pixel^{-1}	1% - 1.7%
u(*H*)	Uniform	5 mm / √3 = 2.9 mm	1%
u(p_H)	Gaussian	From 0.25 pixel up to 5 pixels	0.07% -1.4%

In the adopted formulation, the standard measurement uncertainty related to image dimensions was varied between 0.25 pixel and 5 pixels in order to show the impact of the image quality (related to lighting) and of measurement reproducibility (related to the manual selection of image points by different operators). The results show that, for a dimensional estimate of 25.7 mm, the relative standard uncertainty can vary between 1% and 17%.

V. CONCLUSIONS

This paper illustrated the main contributions of a metrological perspective to the problem of the accuracy of dimensional measurements in CCTV inspections. The proposed approaches constitute a first step towards the improvement of measurement accuracy in this field of inspection.

Measurement uncertainty analysis tools were developed and are now available to be used for the proposed approaches and experimental input information regarding estimates and measurement uncertainties. However, the results obtained so far in this study, already indicate a high impact of the accuracy related to the camera and plane locations in the perspective camera model. In the orthographic projection camera model, the results show the strong influence of the image quality in the accuracy of the dimensional measurements.

These calculation tools can also be used to quantify accuracy operational improvements, namely, due to changes in field lighting, image analysis, CCTV camera selection and metrological characterization.

Future work will be focused on determining the uncertainty component related to the adoption of the orthographic projection camera model, which is considered an approximation of the perspective camera model. In this last camera model, the impact of the lens distortion should also be investigated.

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