A digital measurement approach for structural condition assessment of sewers

Luís Lages Martins [1*], *Álvaro* Silva Ribeiro[1], *Maria do Céu* Almeida[2], and *Rita* Salgado Brito[2]

[1]LNEC – National Laboratory for Civil Engineering, Scientific Instrumentation and Information Technologies Centre, Avenida do Brasil 101 1700-066 Lisbon, Portugal
[2] LNEC – National Laboratory for Civil Engineering, Hydraulics and Environment Department, Avenida do Brasil 101 1700-066 Lisbon, Portugal

Abstract. This paper describes the application of photogrammetric digital reconstruction within the context of structural condition assessment of sewers. The acquisition of multiple images of the observation scenario and application of the bundle adjustment technique, supported by computational algorithms dedicated to image parallel computation and clustering, is the base for the approach adopted. An orthographic camera model with uniform scaling was adopted, supported by scale coefficients determined by the relation between digital and actual (SI traceable) dimensions of reference objects visible in the generated model. The paper details experimental and computational methodologies and presents several examples of digital sewer models. Finally, an evaluation of measurement data retrieved from the models is also shown, including identifying uncertainty components related to the input quantities and their propagation by the GUM method to the output quantity, considering the mathematical models related to the adopted camera model.

1 Introduction

The increasing digitalization of objects of interest in different scientific and industrial domains is a notable trend in recent years, motivated by technological progress and the proliferation of optical, electronic, and computational resources. In this context, a significant transition occurred in the digitalization processes, from contact measurement of points in objects using coordinate measuring machines to non-contact measurement approaches based on scanning systems. This transition originated the following advantages: (i) a higher number of measurement points per unit of observation time; (ii) an increased ability in the visualization of large-scale objects with complex geometry; (iii) the non-contact measurement of fragile objects of high heritage historical value.

Infrared or laser scanning systems are currently used for the digitalization of interest objects, obtaining a high number of measurement points in a reduced amount of time, which can support the graphical representation of the digitalized object in the dimensional (spatial coordinates), radiometric (intensity of the received signal) and photometric (colour system components) contexts.

Three-dimensional digital reconstruction, supported in multiple images of the interest object, is an alternative approach to scanning systems owing to their operational complexity, in particular observation scenarios and high economic cost.

The origins of this optical approach can be found in the second half of the XIX century. The photogrammetry field of activity was supported by analogue images that were used in the determination of spatial coordinates of points in natural or built heritage. In the meanwhile, in the last quarter of the XX century, the technological evolution of computational resources enabled the application of previously developed mathematical and statistical models to the field of Computer Vision, this time using digital images.

This paper describes the application of a photogrammetric digital reconstruction approach in the structural condition assessment of sewers in an aggressive and complex observation environment, with operational restrictions on the use of scanning systems. The primary objective of this application is the generation of digital models for SI traceable dimensional measurement of interest elements with known accuracy, namely anomalies found in the visual inspection of sewers.

Structural investigation activities of sewer systems in urban areas are crucial for safeguarding public and occupational health and safety, environmental protection, and promoting a more sustainable society. Visual inspection plays a relevant role in assessing the condition and performance of vast and complex components of underground drainage systems. According to the standard EN 13508-1:2017 [1], the structural investigation aims to determine the integrity of the sewer system components, commonly achieved via visual inspection, supplemented by specialized techniques if needed.

Inspections allow the detection and characterization of anomalies, which can negatively affect the system's

* Corresponding author: lfmartins@lnec.pt

hydraulic, structural, operational and environmental performance. Direct visual inspection of large confined spaces by personnel walking through the sewer is doable when ensuring human safety. Otherwise, robots equipped with CCTV are used. Typical CCTV robots do not make direct measurements, only digital videos and images. During inspections by personnel, dimensional quantities are measured for each identified anomaly if within reach. The harsh environment inside a sewer makes the *in situ* dimensional measurement challenging.

In the following sections, the paper describes the photogrammetric digital reconstruction approach, namely, the applied experimental and computational procedures. Several examples of digital models applied related to large sewers in Lisbon (Portugal) are shown. The evaluation of measurement data resulting from the proposed digitalization approach is discussed.

2 Photogrammetric digital reconstruction

Photogrammetry is a dimensional measurement method of three-dimensional coordinates of points in an object of interest using bi-dimensional images of that object. It starts to be used in the second half of the XIX century in built heritage architectural records and mountain and glacier cartography. The development of computational algorithms, resources, and digital image acquisition devices at the end of the XX century extended its range of application to science and industry. For example, in the Civil Engineering context, it became an alternative solution for geodesic measurement, a time-consuming technique limited in the number of points and with restrictions regarding access and space required for instrumentation.

One of the most common techniques used in photogrammetry is the bundle adjustment, where stereoscopic images of the same object are not required, compared with other available techniques. It considers the perspective propagation of a beam of light from a certain point in the object, passing through a projection centre and up to the corresponding point in each image where the object point is visible.

Mathematically, the bundle adjustment aims to determine the three-dimensional coordinates of points in the object, intrinsic (focal distance, projection centre coordinates, and distortion coefficients) and extrinsic (position and orientation) parameters of the cameras used for image acquisition. This is achieved by the correspondence between points in the object and in the images, minimizing the re-projection error. The least squares method is used to solve the high number of non-linear collinearity equations, supported in optimization herein using the Levenberg-Marquardt algorithm. Therefore, the photogrammetric digital reconstruction based on the bundle adjustment is a high-dimension computational calculation process.

The recent evolution of parallel computing, supported by the dissemination of central and graphic processing units with multiple cores, allowed for overcoming memory and bandwidth restrictions of photogrammetric digital reconstruction calculation procedures, which were known to be extremely time-consuming and numerically unstable. In this context, it is important to point out the algorithms and applications developed by [2], characterized by a high-efficiency level and reduced processing time.

3 Experimental procedure

The experimental procedure includes the acquisition of multiple images in the observed sewer scenario, considering (i) the photographic scanning of the sewer interest region, assuring a high overlap rate in consecutive images and the visualization of reference objects (targets, for example), which can support the calculation of the scale coefficient of the digital model; (ii) the absence of movement in the interest object; (iii) the interest region must include heterogeneous elements and areas.

The proposed approach assumes a parallel geometrical relation between the image plane and the plane related to the recorded sewer anomaly or interest region, considering a uniform-scale orthographic model [3]. This defines a relation between an observed dimension L (expressed in millimetres, for instance) and the corresponding dimension in the digital model, p (expressed in a digital value), i.e.

$$L = K \cdot p, \tag{1}$$

where K is designated by scale coefficient (usually expressed in millimetres by digital value)

Dimensional measurements can be performed in the sewer digital model using a suitable computational application capable of providing digital values of points of interest and the parameterization of the scale coefficient, which is determined by

$$K = L_{\text{ref}} / p_{\text{ref}}, \tag{2}$$

where L_{ref} and p_{ref} the real (metric) and the digital (virtual) dimensions, respectively, of a visible reference object in the digital model in the same plane of the recorded sewer anomaly or interest region. In this context, reference objects in a sewer can be added targets and measurement instruments (crack width or graduated scales, metric tapes), the dimensions of the sewer's cross-section or construction elements (such as bricks, stones, aggregates, among others). The corresponding dimensional reference values must be determined using SI traceable calibrated measurement instruments.

In this work, reference targets (see Fig.1) were added to the observed scenarios for digital model generation. These were previously calibrated in a metrology laboratory, in a controlled environment, using an SI traceable optical measurement machine with known measurement accuracy, close to 10 μm. Since the targets were included in the sewer digital model, the scale coefficient was calculated based on the Euclidian distance between the same points, with known actual (metric) and digital spatial coordinates.

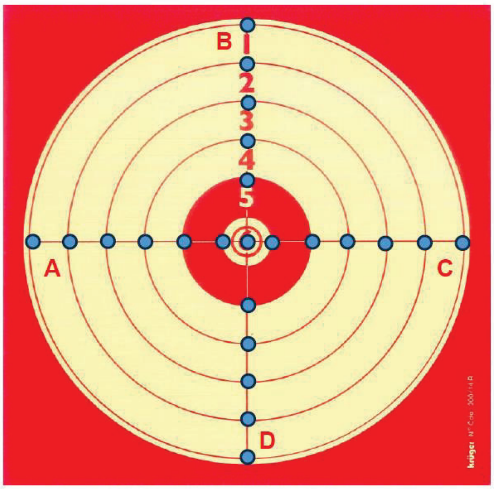

Fig. 1. Measured reference points in the applied target.

4 Computational procedure

The Visual SFM – A Visual Structure from Motion System application (version 0.5.26) was used in this study. It contains validated parallel processing algorithms proposed by [2]. In addition, the optional CMVS – Clustering Views for Multi-view Stereo algorithm [4] was also applied for the image decomposition in a set of clusters with a dimension suitable for parallel processing and independent for each cluster. This led to a reduced computation time without a significant loss of information when merging the resulting reconstructions.

In the Visual SFM application, the input data corresponds to the photos taken during the sewer observation from multiple views (camera positions and orientations). After loading the photos, pair-wise matching is carried out to calculate the missing match. The output data is a sparse cloud of points (with a low detail level) related only to the bundle adjustment parallel processing, and a dense cloud of points (with a high detail level) that results from the execution of the CMVS algorithm.

The obtained point clouds were loaded in the MeshLab application (version 2022.02) [5], aiming at the generation of a mesh of three-dimensional points and its edition, namely, removal of non-interest points and faces, mesh simplification, and surface and texture generation in the digital model. This application contains a tool dedicated to dimensional measurement, supported in the previously described orthographic model with uniform scaling, allowing the definition of the scale coefficient related to the observation scenario. The obtained digital model can be visualized with different magnifications and views suitable for the required measurement.

5 Examples

This section shows some examples of sewer digital models obtained using the previously described digital measurement approach.

The first example – shown in Figures 2 to 4 – is in a stone masonry sewer, built in the XVIII century, in Lisbon's historical downtown district (underground to Rua da Prata), with an inverted U-type cross-section with nominal dimensions of 2,15 m by 2,85 m.

Fig. 2. Stone masonry sewer underground Rua da Prata.

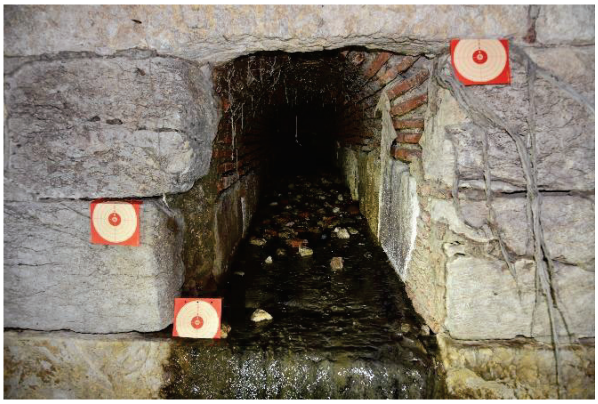

Fig. 3. Image of the digitalized region in the sewer.

Fig. 4. Sewer's digital model, showing the measurement of its cross-section dimensions.

In this case, the region digitalized through photogrammetric digital reconstruction corresponds to a connection to the main sewer. Due to the geometrical irregularity of the masonry stone elements, SI traceable reference targets were used, aiming at enhancing the scale coefficient measurement accuracy. In total, 32 overlapped photos were acquired (with a Nikon / D750 camera), with variable observation distances and camera orientations.

The second example is in a segment of the Alcântara large sewer (concrete arch type, with cross-section dimensions of 6,22 mm × 4 m) in Campolide, Lisbon (see Figure 5).

Fig. 5. Alcântara large sewer collector in the underground region of Campolide.

In this case, the selected observation for digitalization was a joint between sewer segments with visible signs of erosion. A reference target (shown in Figure 6) was added to the observed region, and a total of 35 overlapped photos were acquired and used as input data for the previously mentioned computational procedure.

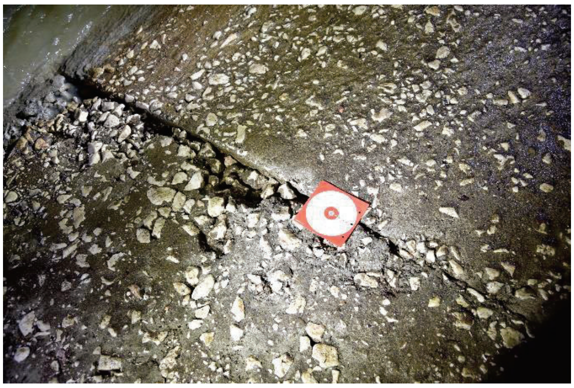

Fig. 6. Image of the digitalized region in the sewer.

Figure 7 presents the obtained digital model, which can be used in the dimensional characterization of the sewer joint erosion. In this case, the approach can be applied for the consecutive generation of digital models in long-term monitoring of the observed anomaly based on SI traceable dimensional measurements.

An additional model – shown in Figure 8 – was also generated, aiming at the digitalization and measurement of the sewer's cross-section, based on the acquisition of 55 images with different observation distances and camera orientations.

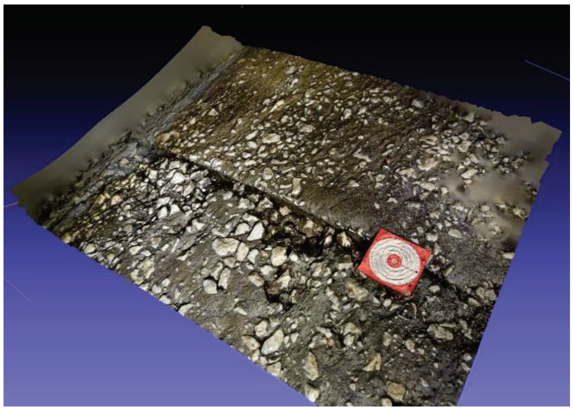

Fig. 7. Digital model of a joint between sewer segments.

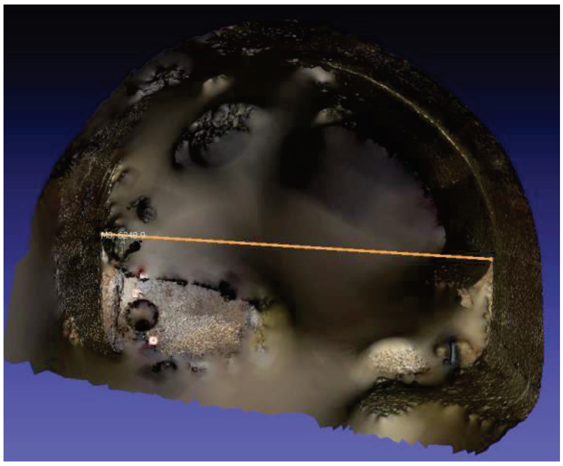

Fig. 8. Digital model of the sewer's cross-section.

The digital model presented in Figure 8 allowed the quantification of the section's width, although some regions were not digitally reconstructed due to the reduced illumination in the upstream region, and sewer flow (dynamic region of the observation scenario, that changes between multiple acquired images).

6 Evaluation of measurement data

In the proposed measurement approach, three input quantities are identified: the digital value and the reference dimension related to the calculation of the scale coefficient (intermediate quantity), and the digital value associated with the required dimensional measurement (output quantity).

The standard measurement uncertainty of the digital value gathers the contributions of two uncertainty components: the digital resolution and the operator's repeatability and reproducibility. The measurement tool embedded in MeshLab [5] provides a 0.1 digital resolution. Therefore, one can use a uniform probability distribution [6] with a semi-amplitude of 0.05 to calculate this uncertainty component, therefore equal to $0.05 / \sqrt{3} = 0{,}029$.

The operator's repeatability can be quantified by a dedicated experimental study where a repeatability condition is assured (same procedure, operator, measurement approach, operating conditions and location in the model) when performing replicate digital measurements on the same object. In the case of reproducibility, the measurement condition includes the effect of different locations in the model and operators (responsible for the spatial point selection in the model) in the obtained dispersion of digital values related to an object.

The standard measurement uncertainty of the reference dimension can have wide variability, depending on the use of calibrated targets and instruments or, as an alternative, cross-section and construction elements' dimensions. In the first option mentioned, a higher accuracy is expected since measurements are performed in a controlled environment (laboratory) and with transfer measurement standards. The second option, based on *in situ* measurements, is characterized by a lower accuracy due to the environmental factors inside the sewer and the spatial variability of the cross-section or construction element dimensions.

The application of the Law of Propagation of Uncertainty (LPU) [6] to expression (1) allows calculating the standard measurement uncertainty of the dimensional measurement performed in the digital models, $u(L)$, by

$$u(L) = \sqrt{[p^2 \cdot u^2(K) + K^2 \cdot u^2(p)]}, \quad (3)$$

where the measurement uncertainty of the scale coefficient, $u(K)$, is also obtained from the LPU, considering the expression (2), i.e.,

$$u(K) = \sqrt{[(1/p_{\mathrm{ref}})^2 \cdot u^2(L_{\mathrm{ref}}) + (-L_{\mathrm{ref}}/p^2_{\mathrm{ref}})^2 \cdot u^2(p_{\mathrm{ref}})]}. \quad (4)$$

Expression (3) shows that not only the magnitude of the standard uncertainties of the input quantities (scale coefficient and of the digital value) is contributing to the dimensional uncertainty, as expected, but also their measurement estimates. Therefore, it is important to have a low magnitude scale coefficient, i.e., a high spatial resolution digital model, to achieve a lower dimensional uncertainty. According to expression (4), this can be reached with low standard uncertainties of the actual (metric) and digital reference values of a target (for example) and a high spatial resolution digital model (reduced estimates of actual and digital reference values).

From an experimental point of view, the spatial resolution of the digital model is related to the acquired photos. High spatial resolution digital images can be achieved by reducing the observation distance between the camera and the object, and by using an image sensor composed of pixels with lower size.

7 Conclusions

This paper described a digital measurement approach in the context of sewer visual inspection for structural condition assessment. This approach was applied and tested in large sewers in Lisbon, showing its suitability for the generation of digital models, from which measurements can be performed with SI traceability in the dimensional domain.

It was possible to confirm that the proposed approach has lower operational complexity when compared with the use of scanning systems. In addition, from an economic perspective, its application is also advantageous since it is based on the use of a single digital camera and open-source software (Visual SFM and MeshLab).

The experimental and computational procedures described in this paper are, therefore, available for use in the context of sewer visual inspections, being particularly useful for long-term structural monitoring of dimensional features and anomalies. Confidence in the performed dimensional measurements is assured by SI traceability, namely, when using reference targets calibrated before being added to the observation scenario.

The performed evaluation of measurement data, based on the GUM method, identified the main uncertainty components of the input quantities. It revealed the importance of studying the operator's repeatability and reproducibility since the approach is supported by the manual selection of points in the digital model, both in the scale coefficient intermediated stage and in the final dimensional measurement stage. The application of the LPU also showed the importance of the spatial resolution of the digital model for measurement accuracy. Acquisition of images with shorter observation distances and using image sensors with lower size pixels is recommended, whenever possible.

The authors acknowledge the Lisbon municipality (Sanitation department / Maintenance and Conservation division) for funding and supporting the research project Structured Evaluation of Large Sewers in the city of Lisbon – R8 Contributions for measurement quality enhancement.

References

1. EN 13508-1 – Investigation and assessment of drain and sewer systems outside building. Part 1: General requirement (European Committee for Standardization, 2012)
2. C. Wu, S. Agarwal, B. Curless, S. Seitz, Multicore bundle adjustment, in Proceedings of the Computer Vision and Pattern Recognition Conference, Colorado Springs, Colorado, USA, June 20-25 (2011)
3. R. Szeliski, Computer Vision. Algorithms and Applications (Springer, New York, 2011)
4. Y. Furukawa, B. Curless, S. Seitz, R. Szeliski, Towards Internet-scale multi-view stereo, in Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition, San Francisco, California, USA, June 13-18 (2010)
5. P. Cignoni, M. Corsini, G. Ranzuglia, MeshLab: an Open-Source 3D Mesh Processing System, in ERCIM News (2008)
6. Evaluation of measurement data – Guide to the expression of uncertainty in measurement (GUM), (Joint Committee for Guides in Metrology, 2008)