GEOMATICS FOR THE 3D SURVEYING AND MAPPING OF CONFINED SPACES: A CASE STUDY IN BOLOGNA (ITALY)

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ABSTRACT:

This paper describes the experience of the 3D mapping of the Ravone torrent, which flows in the city of Bologna (Italy) for about 10 km, alternating above ground and underground segments. The work was commissioned by the Agency for the Territorial Safety and the Civil Protection of Emilia-Romagna Region, and the activities were performed by Forlì Ambiente Cooperative Company in collaboration with the DICAM Geomatics group of the University of Bologna and the UAS national training Centre of the Italian Red Cross in Bologna.
The aim of the work was the complete and reliable documentation and mapping of the torrent course, fundamental for the planning and execution of maintenance operations and basis for the project of the urban redevelopment in the areas surrounding the above ground segments.
The case study presents peculiar morphological characteristics that make its survey a challenging task: an elongated and repetitive geometry, a small transversal section and long underground portions. The geometric documentation required the use of different geomatic techniques performed in integration, with the aim to obtain the accurate 3D model of the whole torrent course: Terrestrial Laser Scanning, GNSS, photogrammetry by drones, classic topography by Total Station, high precision differential trigonometric levelling.
In the paper all the surveying and processing phases will be accurately described, underlying all the solutions developed to face the problems related to the peculiarities of this object, and presenting the obtained final products.

1. INTRODUCTION

Confined spaces and underground infrastructures are common in many urban and industrial scenarios.
Their peculiarities certainly make them difficult to explore, inspect and survey.
First of all, they could be hazardous for humans, given the possible presence of harmful gas, unhealthy oxygen levels and the risk of flooding or collapse.
Moreover, these places often present a difficult accessibility and a complex morphology, with narrow spaces, articulated plan and poor lighting conditions. Furthermore, these infrastructures are often characterized by a predominantly linear development (typical geometry of tunnels) which can induce a strong propagation of errors in the topographic survey (Stiros, 2009).
Due to all the mentioned factors, the survey and mapping of these places is nowadays still an arduous task.
The most adopted surveying techniques in these cases are Terrestrial Laser Scanning (TLS) and Simultaneous Localization and Mapping (SLAM) (Fekete et al., 2010; Ebadi et al., 2022).
The flexibility and versatility nowadays reached by the new generation of tools make feasible the surveying of difficult environments, thanks to the speed of capture and also to the possibility of the scanners to be mounted on backpacks or inverted tripod.
The use of autonomous mobile robots or drones, equipped with LiDAR sensor or RGB and thermal cameras, improve the safety by reducing the presence of human operators (Alsayed et al., 2021; Azpúrua et al, 2023, Di Stefano at al., 2021).
The morphological characteristics of these spaces, with an elongated and repetitive geometry, make them particularly “unlucky” cases to provide accurate and reliable 3D measurements, because of the error propagation that may occur in the alignment of the scans. For such reasons, high precision surveying with laser scanning in tunnels or similar spaces requires the establishment of a reliable control geodetic network, with two main purposes: to check the alignment of the scan data and to give a reference coordinate frame to all the acquired data (Pejić, 2013).

This paper describes the experience, carried out by Forlì Ambiente Cooperative Company in collaboration with the DICAM Geomatics group of the University of Bologna, of the 3D surveying and mapping of the Ravone torrent, which develops in the city of Bologna for about 10 km and a maximum cross section of 5 m, alternating above ground and underground segments, where it becomes a buried channel. The hydrographic basin is vast and subject to high hydrogeological instability.
The work was commissioned by the Emilia-Romagna region, in particular by the Agency for the Territorial Safety and the Civil Protection, with different aims.
Since there was no complete and reliable documentation of the torrent, the primary need was the knowledge of the geometric and morphological characteristics on a scale 1:200, with the

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production of the plan, the longitudinal profile and the cross sections.
Moreover, further demands were the elevation profile, the location of the manholes in the underground segments, the mapping of all the objects intersecting the torrent plot, as for example plumbing and cables, the establishment of some altimetric benchmarks along the course and the pertinent area. All the data collected are fundamental for the planning and execution of maintenance operations and will form the basis for the project of the urban redevelopment in the areas surrounding the above ground segments.
Many geomatic techniques were used in integration for the data acquisition.
TLS technique was adopted to obtain the 3D point cloud RGB coloured of the whole course, with in addition the spherical panorama.
High-precision differential trigonometric levelling was used to obtain the height of the benchmarks along the torrent course above geoid and a photogrammetric flight by drone, made thanks to a collaboration with the UAS national training Centre of the Italian Red Cross, permitted to complete the survey in a stretch above ground.
Traditional surveying techniques with a high-precision Total Station and GNSS observations were employed for the absolute georeferencing of all the data, taking advantage of the manholes to connect internal and external spaces.
The overlapping in GIS environment of the final products with some Geo Open Data, as cadastral and OpenStreetMap data, permits the connection between the position and cadastral parcels and properties located above or in the immediate vicinity of the torrent course.
In the paper all the surveying and processing phases will be accurately described, underlying all the solutions developed to face the problems related to the peculiarities of this object, in particular the very large amount of collected data, the logistic difficulties of the space, the need of intermediate constraints to limit the errors propagation.

2. THE CASE STUDY

The Ravone torrent forms in the hill of Bologna and it flows after about 10 kilometres into the right bank of the Italian Reno River. The torrent flows outdoors for the first four kilometres, then it becomes a buried channel, alternating above ground and underground segments until its mouth, with a maximum cross section of 5 m (Figure 1).

Figure 1. Two images of the course of Ravone torrent: a) a segment of the buried channel; b) an above ground portion.

Until the second half of the 20th century, the torrent flowed completely outdoors, and it was artificially covered after the 1960s to allow urban expansion towards the hills (Bracaloni, 2016).
The area pertaining to the torrent course is subject to high hydrogeological instability, being the 20% of the basin affected by numerous landslides, and in case of short but heavy rainfall, flooding problems may occur in the underground segments.
All maintenance and cleaning of the riverbed operations are therefore essential, in order to reduce the risk of damage to the ancient retaining structures and erosion to the banks. However, the planning and execution of interventions presuppose the accurate knowledge of the current state.
As said in the introduction, since there was no complete and reliable documentation of the torrent, the primary need was the knowledge of the geometric and morphological characteristics.
Of the total length, the survey concerned 5.5 kilometres, which is the section running through the urban area of Bologna.
In the next paragraph all the surveying and processing phases performed to this aim are described.

3. SURVEYING PHASE AND DATA PROCESSING

The three-dimensional survey was mainly conducted with a TLS. Given the characteristics of the object and the purposes of the commissioned survey, Leica GeoSystems RTC360 system was chosen. In fact, this instrument has numerous advantages in relation to the specific requirements: the compactness and low weight of the hardware component make it particularly suitable for operating quickly even in inaccessible locations. Using a tablet equipped with the app provided by Leica to conduct the scan acquisition, it is possible to carry out a rough registration of the scans using the VIS (Visual Inertial System) during the surveying activities, thus verifying the effectiveness and the progress of the operations in real time. The accuracy and range of distances are compatible with the dimensions and proportions of the object and the scale of the final drawings required. Finally, the possibility of acquiring High Dynamic Range (HDR) panoramic images on the one hand, and the possibility of attaching Geotags, i.e. supplementary images, documents, annotations, videos, audio recordings or 3D scans, georeferenced in real time on the acquired clouds, on the other, were of fundamental importance. This aspect, in the case of places inaccessible to the technical personnel in charge of their management, plays a fundamental role in order to be able to produce as faithful a replica of the work as possible, not only of the geometric aspects, but also of the exhaustive qualitative description of its real conditions (state of conservation, presence of drains, interferences, singularities, etc.).
The necessity to carry out a photographic survey and to exploit the sensors of the scanner's VIS system, imposed the use of artificial light in the underground sections completely lacking in natural lighting. To this end, three LED arrays for photographic use fixed directly to the legs of the scanner's tripod were used in order to obtain a good distribution of light around the instrumental station, and at the same time to simplify its transport and uniform the distribution of illumination along the interior development of the 3D model of the riverbed (Figure 2a).
Given the linear development of the object, the TLS survey was conducted with a succession of scans from the centre of the channel, with an overlap such that the clouds were aligned using ICP algorithms. The need for a correct level of illumination of the surrounding environment in order to obtain good quality photographs, made it necessary to maintain a maximum spacing of 15 meters between successive scans, thus making only minimal use of the width of the acquisition range offered by the instrument. Such a density of scans was also necessary because

as the channel is very narrow (a few meters wide), at short distances from the instrument, the laser beams were grazing the wall surfaces.
Despite the short distance between successive scans, the uniformity of the shape and texture of the channel walls often made the pre-alignment of the clouds in progress ineffective: to ensure the possibility of reliable alignment with the more effective and refined tools offered by cloud registration software at a later date, operators had to use tie-points, made from 30 cm square panels resting on the bottom at the sides of the channel (Figure 2b).

Figure 2. The TLS survey: a) configuration of the instrumentation used with the LED arrays mounted on the tripod; b) targets placed on the sides of the riverbed to facilitate alignment between successive scans.

A total of 767 medium-density clouds with a total of about 23 billion points and about 950 geotags were acquired with the Leica system.
For the georeferencing of the cloud in a cartographic reference system, a support survey was carried out with the integration of GNSS-NRTK and total station. The UTM 32N mapping projection was adopted referred to the ETRS89 geodetic reference system. The surveyed points were distributed over approximately 20 sites located along the entire course of the canal with an average distance of a few hundred metres, particularly in the underground sections at the manholes. At each site, two three-dimensional points were materialised and surveyed with the GNSS. Using the Total Station from these reference points, the coordinates of white and black targets used as ground control points (GCPs) of the laser scans were measured. At each site, clouds were then acquired within the channel bed, on the road surface to reveal GCPs and in intermediate positions for the connection between underground and outer levels (Figure 3).
The use of targets of known coordinates at intermediate positions along the course made it possible to constrain the alignment of the scans so as to limit error propagation, which is particularly insidious given the geometric characteristics of the survey object. The optimisation of the alignments between the scans forced by the 56 GCPs used in total to georeference and constrain the entire course of the torrent led to mean square deviations on the target coordinates of a few centimetres on average. Given the instrumental accuracies and the operating procedures used, both for the operations in the field and for the subsequent processing, it can be considered that the georeferenced point cloud obtained has an overall accuracy compatible with the production of 1:200 scale drawings, as established in the design phase of the surveying.

Due to the large amount of data collected, in order to simplify both processing and subsequent data management by the end user, the surveyed kilometres were subdivided during processing into nine sections at some of the sites used for georeferencing, in order to ensure that GCPs were bound at both the beginning and end of each section.

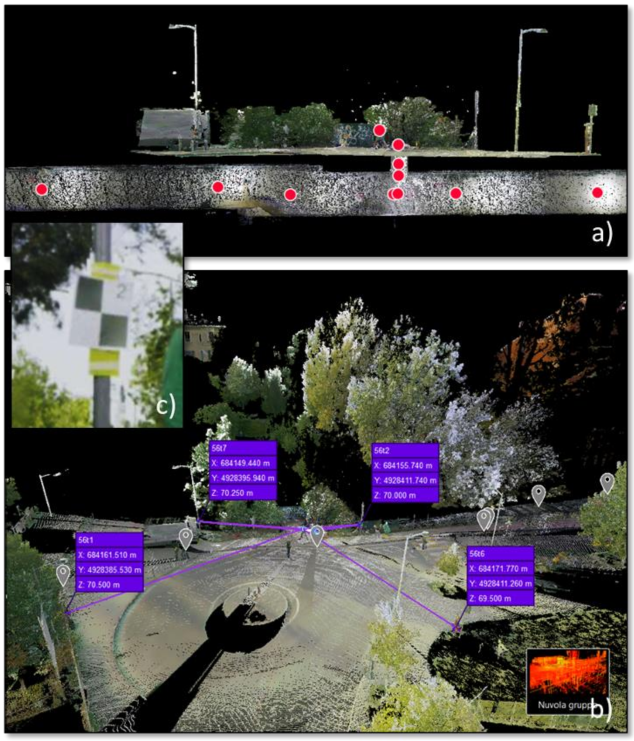

Figure 3. Connection between the torrent course and the overlying urban fabric at a manhole for georeferencing scans: a) resulting cloud for one of the georeferencing sites, each red circle represents a scanning station; b) distribution of GCPs around the manhole, purple squares show the cartographic coordinates of the targets; c) example of a black and white target used for georeferencing.

For each section, the first processing step conducted with the Leica GeoSystems Cyclone Register 360 software involved aligning the acquired clouds. This operation was particularly critical in the underground sections: where possible, only ICP algorithms were used, but in most cases manual intervention was necessary to guide at least a first approximation of the alignment with the recognition of homologous points. Even in the open-cut part of the course, some difficulties were encountered, linked above all to the presence of vegetation within the riverbed (in the sections where mowing was not planned prior to the laser scanner survey) and to the limited visibility of the surrounding urban context due to the fact that even in the open-cut sections the scanner was always kept within the riverbed of the torrent. In this case, the removal of the vegetation was therefore performed manually, both to facilitate the use of the ICP algorithms and the subsequent production operations of the final CAD drawings. Automatic cleaning algorithms were also exploited to eliminate artefacts due to the presence of the operators where necessary.

On the clouds acquired on the georeferencing sites, the detected GCPs were collimated and the known coordinates from the support survey were associated: the global optimisation of the alignment achieved the application of the constraints and the framing in the cartographic system. Finally, for each of the 9 sections into which the torrent was divided, a coloured cloud was produced in real colours with a density of 5 mm in e57 format (Figure 4). With the same cloud density, a file in LGS (Leica GeoSystems) format was also exported, which allows the additional information obtained from the survey to be stored with a high degree of data compression: panoramic images in HDR and Geotags of various types (texts, images, documents) attached to the clouds and georeferenced.

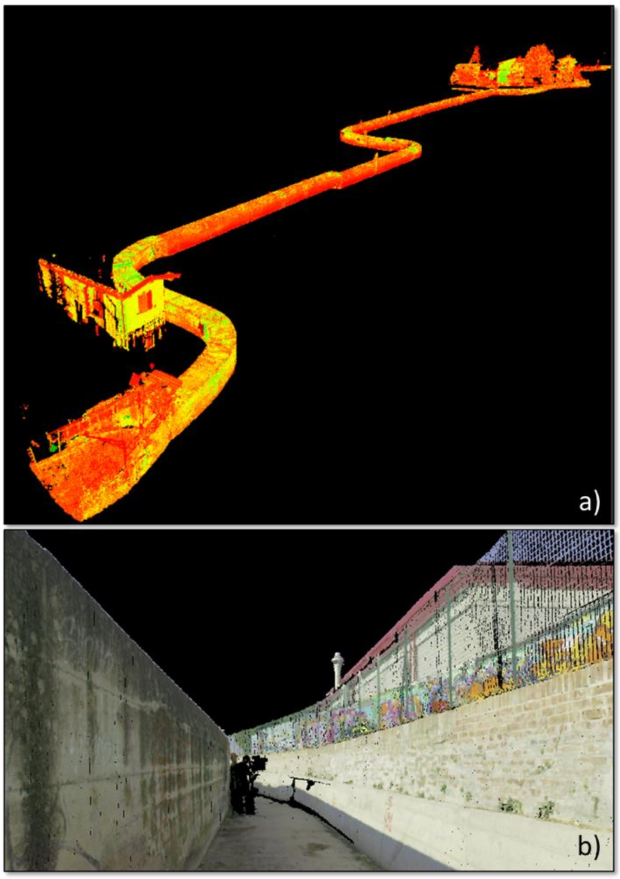

Figure 4. 3D point cloud obtained by TLS survey: a) the overall point cloud of the first section of the torrent where it flows underground (colour by intensity value); b) a detail of the cloud in an uncovered section (RGB coloured).

For a stretch of approximately 2 kilometres between Via Malvasia and Via Borgatti, the Ravone torrent flows openly between the cycle path on Via del Chiù and the Ghisiliera canal on the other. Since the general plan of the route and the cross-sections of both canals were also required as part of the final drawings, it was necessary to supplement the laser scanner survey by extending the survey to the area surrounding this section of the torrent. With the support of the pilots of the UAS national training Centre of the Italian Red Cross in Bologna, a UAV aero-photogrammetric survey was therefore conducted. Since this is an area subject to constraints due to its proximity to the Bologna airport, it was necessary to request the appropriate authorisations from ENAC, defining specific procedures for the execution of the flight.

The photographic survey was carried out with separate flights in three successive stretches in order to optimise the use of batteries and limit the time of the block to the circulation of pedestrians and bicycles in the area affected by the overflight. At the same time, the coordinates of photographic GCPs were acquired with GNSS-NRTK. The images were processed using Structure from Motion methodology. From the photogrammetric block, a three-dimensional point cloud was extracted, which was used to integrate the clouds of the Ravone torrent from the TLS survey, and an orthomosaic with a ground resolution of 3 cm was used to trace its path (Figure 5).

Figure 5. Detail of the orthomosaic obtained by the aero-photogrammetric survey by UAV: on the left the Ghisiliera canal bed, in the centre the Ravone torrent and on the right the pedestrian and bicycle path of Via del Chiù.

The final stage of 3D data processing was carried out with the Leica GeoSystems Cyclone 3DR software: the 9 clouds obtained from the laser scanner and the dense cloud extracted via photogrammetry were imported into the software for the subsequent stage of extraction of the various vector products. Particularly useful for this purpose was the high level of interoperability between Cyclone 3DR and the Autodesk platform, where the graphical dressing and final editing of the various products, which will be presented in the following paragraph, were prepared.

To complete the description of the topographical survey activities carried out, it is necessary to mention that, as requested, levelling benchmarks were materialised with an inter-distance of 250 metres, in the open sections, for the establishment of an altimetric reference system along the Ravone torrent. The heights above geoid of the strongholds were measured by means of high-precision differential trigonometric levelling.

4. FINAL PRODUCTS AND GIS APPLICATION

The main products extracted by the surveying activities concerned the preparation of traditional CAD products: general planimetry, cross sections and longitudinal profile of the torrent. As already mentioned, the vector elements were extracted from the clouds with the automatic or semi-automatic tools of Cyclone 3DR and then edited in the Autodesk environment.

The planimetry shows the maximum size of the inner section of the Ravone torrent in both the underground and open sections.

Variations in the shape of cross section and elevation discontinuities, the cover in the underground sections and the torrent bottom in the open-cut sections have also been plotted. Finally, the positions of the manholes with the correct code ID and the position of the cross-sections with their identifiers have been reported for ease of reference.
The longitudinal elevation profile of the torrent was produced from a polyline extracted by tracing the centre of the channel bottom in the point clouds. The polyline was constructed by sampling points with a distance of no more than 6 metres in the most regular sections and inserting intermediate points in the presence of singularities.
The cross-sections of the torrent were extracted from the overall point cloud obtained from the survey, in order to characterise the different types of cross-sections assumed by the channel in order to extract the essential data regarding shape and dimensions (Figure 6). The cross sections were extracted with a maximum distance of 50 metres along the entire route, but additional sections were included in the presence of singularities linked to the geometric characteristics of the torrent riverbed or to any gaps in the point cloud (for example, in the case of the presence of water at the bottom of the torrent or due to the excessive presence of vegetation).

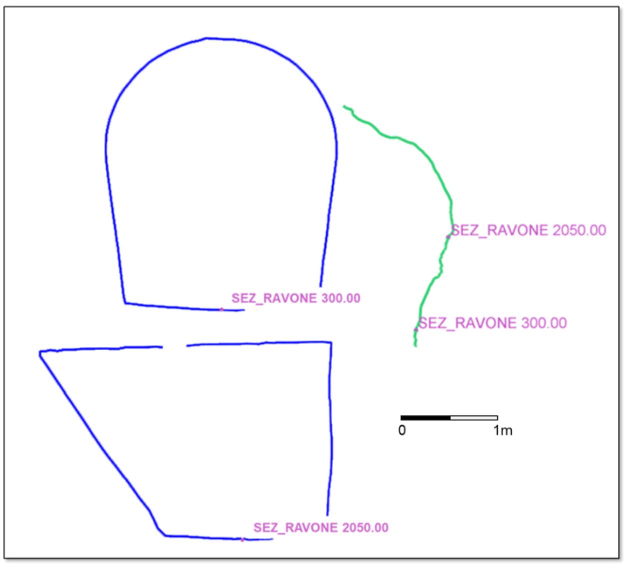

Figure 6. Example of two cross sections and their locations along the torrent course.

The georeferencing of the survey in a cartographic reference system allows the products derived from it to be used in a GIS environment. In particular, a project has been realised inside the open-source application QGIS in which a simplified version of the planimetry of the Ravone torrent constitutes a layer superimposed on the official open cartography available on the Bologna territory (Figure 7a), in particular the 1:5000 scale regional technical map and the AGEA 2020 orthophotos, offered by the geographic internet portal of the Emilia Romagna Region through the Web Map Service (WMS).
Other open cartographic data were also included:
- Google satellite images because, although less rigorous than the official cartography, they are updated very frequently
- OpenStreetMap data, because they show the house numbers of the buildings and can therefore be useful in identifying the addresses of the individual buildings depicted (Figure 7b)
- cadastral maps of buildings and land parcels, via the Agenzia delle Entrate website in order to be able to trace the owners of the buildings (Figure 7c).
Finally, the layer of the buildings of the CTC of the Municipality of Bologna was also added at a scale of 1:1000, extracting only the buildings within a buffer of 500 metres width around the torrent.
The superimposition of these layers makes it possible, on a graphic and analytical level, to highlight the relationships between the torrent and what lies within the area of the land and to trace the data of the cadastral parcels involved. The availability of all this data in a single environment is a powerful tool for the management of this hydraulic work, both as a whole and in its individual details.

Figure 7. A detail of the planimetry of Ravone torrent (in red) superimposed inside QGIS environment to the open data available for the city of Bologna: a) AGEA 2020 orthophoto; b) OpenStreetMap data; c) cadastral maps.

Monographs of the materialised and measured elevation references were also delivered in accordance with the client's explicit requests. Similarly, the monographs of the three-dimensional reference points surveyed with GNSS-NRTK were produced: since they are distributed along the entire route, they can constitute a useful three-dimensional reference for any further topographic surveys.

5. CONCLUSIONS

The case study presented in this paper originated from the need of the Agency for the Territorial Safety and the Civil Protection of Emilia-Romagna Region to arrive at a detailed knowledge of the geometry of the places involved in the section crossing the city of Bologna by the Ravone torrent. The work was carried out through a collaboration among the above-mentioned Civil Protection Agency, the Forlì Ambiente Cooperative Company, the DICAM Geomatics group of the University of Bologna and the UAS national training Center of the Italian Red Cross in Bologna.
Thanks to the specific skills of the various bodies involved, it was possible to integrate terrestrial, satellite, drone photogrammetric survey techniques and GIS applications for the description of a torrent located in a confined environment within the city of Bologna, both in the long sections buried within an underground tunnel, both for those sections where the bed of the torrent is flowing outside, due to the presence of the side banks within which a large part of the topographical survey had to be carried out.
For the survey of about 5.5 km in length of the torrent, 767 medium density acquisitions were carried out using a TLS with a total of about 23 billion points and about 950 geotags. The latter acquired to describe through images, texts and other types of documents, a vast series of details, such as state of conservation, presence of drains, interferences, singularities, etc.
For the georeferencing of the entire point cloud within the ETRS89-UTM 32N map projection a support survey was carried out with the integration of GNSS-NRTK and total station. 56 GCPs were used to constrain the entire survey of the course of the torrent.
The overall precision obtained from the residuals with respect to the coordinates of the target’s coordinates surveyed by Total Station and GNSS-NRTK, with respect to the aligned point cloud was a few cm levels, in line with the 1:200 representation scale.
The products extracted by the surveying activities concerned the preparation of traditional CAD products: general planimetry, cross sections and longitudinal profile of the torrent.
Furthermore, a GIS project was carried out, in which a simplified version of the planimetry of the Ravone torrent stratum was superimposed on the official open cartography available for the area. OpenStreetMap data and a layer with the cadastral map were also used to identify the street numbers of the buildings located on the Ravone torrent and their owners.

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