MOBILE MAPPING FOR DIGITAL DOCUMENTATION OF ANCIENT ROMAN ROADS WITHIN A MULTI-SENSOR FRAMEWORK: THE APPIAN WAY IN ROME

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ABSTRACT:

Digitization of complex Cultural Heritage sites requires the integration of several strategies to achieve a comprehensive description of the site. This is the case of the digitization project of the Appian Way in Rome involving a section of 12 km from Capo di Bove to Frattocchie under the superintendence of the Parco Archeologico dell’Appia Antica. This paper presents some first results of the project with a specific focus on the acquisition of the primary data needed for the further steps of the project. In particular, the paper discusses the integration of different sensors such as lidar-based Mobile Mapping Systems, spheric (360°) cameras and digital (frame) calibrated cameras, for the reconstruction of point clouds to be used as input data for the digitization process. A specific attention is paid both on acquisition speed and to accuracy of the obtained results. The paper presents also some results showing the transformation of the acquired data into a GIS system to be used as a support tool for decision making of the public administration.

1. INTRODUCTION

In the last few years, digitization projects addressing Cultural Heritage (CH) sites are becoming more and more challenging and fascinating: wider areas to survey, higher detail to catch, user-friendly utilization the acquired data, extended possibility of interaction for end-user with smart devices, development of Virtual and Extended Reality environments, etc. Those new requirements are revolutionizing the digitization projects. Indeed, not only new functionalities are required for the public administration and manager of CH sites but also new methods for rapid and reliable acquisition are needed. This paper discusses about the digitization of a section of the Appian Way in Rome. The Appian Way is the ancient roman road whose construction started in 312 BC. The road connected the city of Rome with southern Italy. During the roman period several sections were added and in its maximum extent it connected Rome with Brundisium. Nowadays some segments of the road are still existing. The main one is in Rome and its vicinity, till the hamlet of Frattocchie. This paper presents the survey of a branch of approximately 12 km (between Capo di Bove – Rome and Frattocchie - Marino) of the Appian way by using a strategy combining Mobile Mapping sensors and photogrammetric techniques to acquire mass data and create accurate 3D models supporting, conservation, communication, and fruition. For these purposes, a detailed documentation of the roads and of the moments in the nearby is of major importance.

Starting from this need a surveying strategy of the Appian way was designed based on the final goals of the documentation project, which were an overall documentation of the road, a set of detailed cross-sections of the main monuments, and a detailed orthophoto of the paving in the 4.0 km between Via di Fioranello (Rome) and Frattocchie. To achieve these goals, a combination of techniques was used, including a handheld mobile mapping system for the overall documentation, static laser scanning for the detailed cross-sections, and a ground-based photogrammetric approach for the orthophoto. The choice of surveying techniques was based on factors such as productivity, the need for detailed information, and environmental constraints. This paper will mainly focus on the mobile mapping strategy used for the overall documentation of the road and will discuss the products derived. The remaining of the paper is structured as follows: section 2 will discuss about related works, section 3 is presenting the case study and the peculiarities of the Appian Way, section 4 will present the survey strategy combining laser-based mobile mapping system and photogrammetry, section 5 introduces the development of a GIS data management environment for the Appian Way, conclusions are drawn in section 6.

2. RELATED WORKS

The topic of 3D recording and digitalization of tangible cultural heritage is covered in a number of literary works (Giulio et al., 2018; Nocerino et al., 2018; Chen et al., 2018, Hussein and Ismaeel, 2020; Marra et al., 2022; Bastem and Cekmis, 2022). Generally speaking, they are taking into consideration buildings (Brumana et al., 2018), monuments (Apollonio et al., 2017; Adamopoulos and Rinaudo, 2021), old city centers (Cecchini, 2019; Ramírez Eudave and Ferreira, 2021), and even rural places (Merchán et al., 2021, Boboc et al., 2022). The topic of historical roads is covered in fewer publications (Martnez et al., 2015; Intignano et al., 2021). In the case of historical roads, the digitization process is complicated by some of their particularities. The majority of historical ways are, in fact, linear structures with lengths of several kilometres, while the width of the roadway itself and its immediate surrounds is typically only a few tens of meters (as in the case of the Appian Way here presented). For a road it is important to evaluate historical routes' pavement and roadways as well as the various

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monuments that line the route, their connections to contemporary buildings, and their surroundings. There are numerous methods that can be used to implement the geometric documentation of cultural heritage components. A thorough analysis of them is outside of the scopes of this study, to emphasize the distinctive qualities of the survey strategy presented only the main elements of each technique will be here presented.

The survey methods that are most frequently employed for Cultural Heritage documentation, with a specific focus on roads, are:

- Topographic techniques and Global Navigation Satellite Systems (GNSS). They can be used to identify some specific points (vertices). Some of the identified vertices can define the boundaries of the object to be surveyed, which can be used to describe it with simple shapes (Lienhart, 2017). However, the complexity of objects in the Appian Way and the amount of archaeological remains make this solution not feasible. On the other hand, GNSS and topographic techniques can be used to identify benchmarks or Ground Control Points (GCPs) used in other survey activities (laser scanning and/or photogrammetry).
- Scanning techniques. Using active sensors and a laser beam, scanning techniques directly record the object's 3D geometric data. By utilizing various measurement techniques, such as time-of-flight or phase shift measurement, these devices are able to collect 3D data, which results in the definition of a 3D point cloud with a high density. The two primary categories of scanning methods are static and mobile. Static scanning necessitates that the acquisition system remains motionless throughout the acquisition, which typically lasts a few minutes. Such a technique has proven to be effective for recording uneven surfaces, monuments, and buildings. Nevertheless, the time needed for each acquisition and the need of overlap between different scans restricts its effective utilization for large site documentation like the one here presented. In Mobile Mapping Systems, or MMS, the system does not have to be stationary throughout the acquisition (El-Sheimy, 2000; Ellum, and El-Sheimy, 2000). The instrument's path can be determined either by employing Simultaneous Localization and Mapping (SLAM) algorithms or by combining inertial platforms and GNSS systems. For city modelling and road network monitoring, large MMS are put on a car. Lightweight systems are made to be carried around or worn like a backpack. MMS typically display a point cloud with a lower density and less precision than static laser scanners. Effects from MMS drifts may become considerable, necessitating the consideration of specialized solutions.
- Image-based and photogrammetric techniques. These surveying techniques are easily portable and have reasonably priced sensors. With those techniques, dense 3D point clouds are derived based on automatic image correlation (Remondino, 2011; Bianco et al., 2018). Digital cameras can be used on various platforms, such as Unmanned Aerial Vehicles (UAV), to reconstruct vast areas. Furthermore, the field survey benefits from the integration of different photogrammetric techniques, i.e. spherical cameras (Masiero et al. 2018; Lichti et al. 2020). However, extensive image post-processing is required to produce the 3D data that will constitute the model, particularly if the survey region is large and numerous hundreds or thousands of photographs must be taken. In order to provide georeferencing and prevent deformation during bundle adjustment, GCPs are also necessary. The ability to apply textures and produce a photorealistic representation of the 3D model is a benefit of those techniques.

This study presents a combination of the methodologies previously mentioned to address the various requirements for the development of the Appian Way digitalization project.

3. THE APPIAN WAY

The Appian Way (Figure 1) is an ancient roman road that was constructed in 312 BC to connect Rome and the South of Italy, it was named after Appius Claudius Caecus who started its construction (Sartorio and Ventre, 2004). Although it was built for military reasons, it became a funerary road as many noble families built their funerary monuments on the roadsides. Over time, the road declined due to wars and invasions and the Church started to acquire properties on the side of the road during the 6th century. Many garrison towers and fortified villages were built close to or over the road during the Middle Ages. The Appian Way lost its funerary function and became a suburban road during this period. The road was used as a quarry for construction materials, but interest in Roman monuments increased during the Renaissance. In the 19th century, the road was studied and protected, and was turned into an open-air museum with scenographic architectural walls to showcase the findings from excavations. Canova and Canina were two artists and architects who played a significant role in the preservation and restoration of the Appian Way's monuments. Nowadays, the Appian Way is a significant historical site that requires a multidisciplinary approach to interpret the nearby landscape, archaeology remains, and its value as infrastructures. The road is a unique archaeological infrastructure that crosses different landscapes, recalling images of the past depicted by great artists. The Appian Way holds tangible and intangible meanings, making it a cultural route and a memorial place. To restore the Appian Way, both the roman monuments and the restoration works carried out in 19th century need preservation. Its valorisation is also passing through the utilization of new technologies for its digitization and the development of new immersive and user-friendly experiences (Liestøl, 2014; Chrysanthi et al., 2021; Banfi et al., 2023).

Figure 1. Typical lanscape of the Appian Way in Rome of high historical and landscape value: basolato and cypress (top left);

monuments (top right); margines (bottom left); basolato and pines (bottom right).

4. SURVEY STRATEGY: MOBILE MAPPING AND PHOTOGRAMMETRIC DATA ACQUISITION

The Appian Way survey, in between Capo di Bove (Rome) and Frattocchie (Marino) was conducted using a multisensor approach combining both laser-based mobile mapping systems and photogrammetric approaches. Laser-based MMS was used to provide an overall documentation at 1:100 scale of the whole branch on the Appian Way (approximately 12km) to derive, in a second stage of the project, a GIS system to be used by the Public Administration to manage the archaeological site and to support further interventions of valorisation of the site. On the other side, the photogrammetric survey was aimed at a detailed documentation of the original roman paving from Via di Fioranello to Frattocchie (approximately 4 km). The final product was a detailed orthophoto (pixel size 5.0 mm).
An overview of the surveyed area is presented in Figure 2.

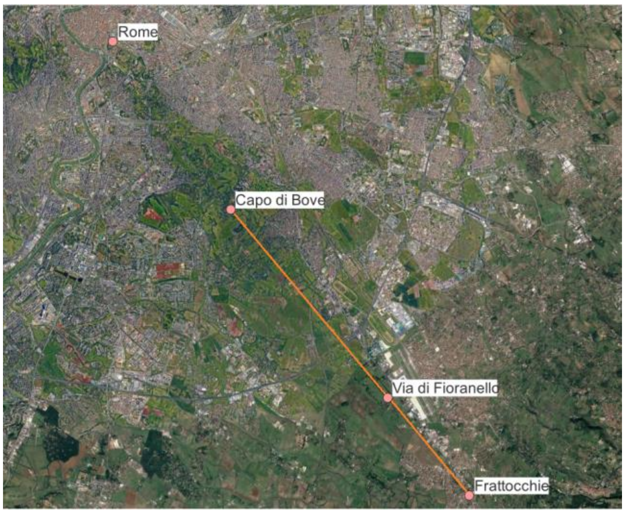

Figure 2. Overview of the surveyed area of the Appian Way in Rome.

4.1 Laser-based Mobile Mapping survey

The handheld GeoSLAM ZEB Horizon system was used for the overall documentation of the Appian Way (12 Km) in between Capo di Bove and Frattocchie. This system has a range of 100 m, allowing for the survey of the road and its surrounding area. It has a resolution of 300,000 points/sec and a rangefinder accuracy of 1.0-3.0 cm, which can be further improved with post-processing. The choice of a handled system with respect to different solution based on other platforms (e.g., car-based), is

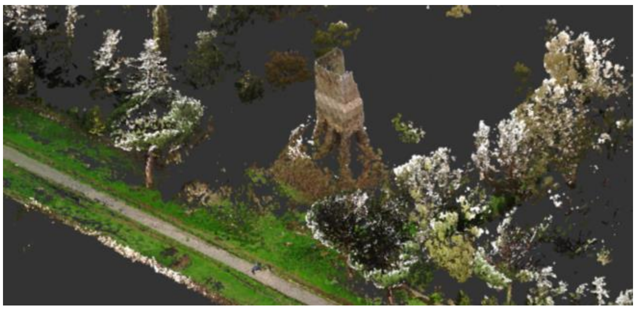

Figure 3. Detail of a point cloud acquired along the Appian Way.

due to the fact that several monuments are present in the nearby of the road. To completely survey those monuments, and not only the side facing towards the road, it is necessary to use paths around them that can be accessed only on foot. A handed solution revealed more flexible to manage those situations. To prevent drift effects in MMS data, the road was divided into sections of approximately 200 m, with each section surveyed and closed loop created. In particular, the starting and the end point of each acquisition were the same. A section of 200 m was surveyed in approximately 20 minutes that is the maximum time suggested by the producer to avoid data overload during the post-processing of the data.
Control points were measured using GNSS with an RTK acquisition scheme and residuals after registration were in the order of ±5.0 cm. Each section has in between 8 to 15 GCPs distributed at an approximate distance of 30 m on both sides of the road. The closest GNSS permanent station was located in Rome (ROUN) with an approximate baseline of 10 km. The same control points were measured with the MMS too.
To record position of GCPs with the MMS it is necessary to stop on them during the acquisition for 10 seconds. In total, 55 mobile scans (Figure 3) were acquired in the area between Capo di Bove and Frattocchie. Each 200 m branch the same operations were carried out: placing the GCPs performing the survey with MMS and measure the GCPs with a GNSS topographic receiver. The survey of the 12 km was completed in 10 working days.

4.2 Photogrammetric survey

The photogrammetric survey is aimed at the mapping of the paving of the Appian Way in between Via di Fioranello and Frattocchie. This area is the one that will be firstly addressed to valorisation projects and a detailed mapping of the paving was requested to identify the different areas preserving the original roman paving. To complete a detailed mapping of the existing paving (5.0 mm of Ground Sampling Distance), a ground acquisition rather than a UAV acquisition was planned because of the airport's proximity (Ciampino city airport is less than 500 m away) and the required resolution of the final orthophoto. Two different cameras were used for the acquisition a DSLR camera (Nikon D610) equipped with a full frame fisheye lens system and a 360° camera (Insta360 One X2).

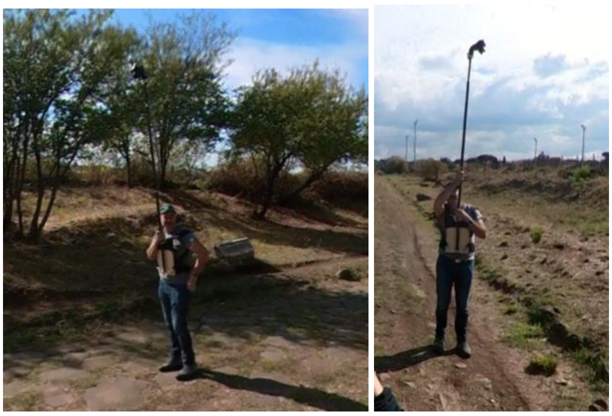

Figure 4. The mast system used for the acquisition of the images for the orthophoto of the paving.

The DSLR camera was mounted of the top of a system of musts (Figure 4). The camera on the top of the system (height 3.0 m) has an inclination of 60° with respect to the horizon and acquires an area of approximately 5 x 10 meters in front of the operator. Even if the fisheye lens allows to acquire a larger area, above the previously mentioned distances the GSD significantly increase not meeting the project requirements. However, the larger field of view of the fisheye system allows to have more overlap among the different images having this way a stronger geometry for the bundle adjustment. Generally, in between two to fours strips with the mast system were acquired to survey the entire road width and its vicinity.


a.


b.


c.

Figure 5. Example of the Orthophoto of the paving: orthophoto (red boundaries) overlaid to current cartography (a) and two details (b-c).

To strengthen the geometry of acquisition the survey was complemented with the acquisition of 360° videos (resolution 5.7k) from which a set of consecutive frames (1 Hz sampling) were extracted. Compared to traditional sensor a 360° image has the advantage of acquiring the entire area around the user. By using this feature, it is possible to create an image block configuration that is more robust than the one produced by using only photos that have been collected in a series of consecutive strips on top of the masts system.
The photogrammetric survey was carried out in parallel with the mobile laser one. For this reason, the survey was carried out considering the same portions of 200 m length used for the MMS survey as well as the same GCPs. The survey of the 4.0 km between Via di Fioranello and Frattocchie was completed in 4 working days. As a final step the images acquired with the mast system (approximately 6200 images) and 360° frames extracted from the recorded video (approximately 15000 images) were processed in a combined adjustment using a standard photogrammetric workflow. Orthophotos were obtained using only images acquired with Nikon D610 to guarantee a uniform GSD (Figure 5).

Figure 6. Mesh models regarding the same sectors of the Appian Way of Figure 5.

The photogrammetric survey allowed the generation of textured mesh models (Figure 6) that were used to integrate the 2D drawings (plan, sections, etc.) derived from point clouds (laser scanner). Furthermore, mesh models can be used for creating the environment for novel storytelling approach, such as the Virtual Reality platforms.


a.

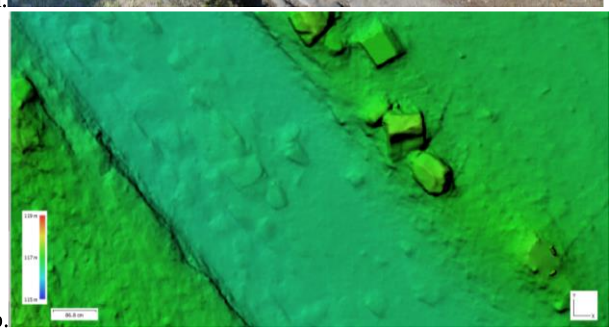
b.

Figure 7. Exampe of orthophoto (a) and DTM (b) of the Appian Way.

As a further element a detailed Digital Terrain Model (DTM) was obtained for the road branch. DTM grid size is 2.0 cm and can be used a fundamental element to be integrated into a GIS system of Appian Way Park both for the management of green areas and identification of areas with water discharge issues causing stagnation of water in the road section (Figure 7).
Both orthophotos and DTM are produced in the Italian cartographic refence system RDN2008/UTM zone 32 N.

5. DEVELOPMENT OF A GIS DATA MANAGEMENT ENVIRONMENT

The results obtained from the survey (point clouds, DTM and orthophotos) were processed to create s GIS data management for the Appia Park authority. Indeed, several professionals are involved in the management of Appian way (e.g., institutional operators, designers, expert of maintenance, etc.) the availability of a single data management environment is fundamental for all of them to interact, share information and execute specific analysis. To cerate a single platform aimed at this a GIS tool was developed.
The main element included in the GIS system were identified as:

- *Pavimentum*: the paved roman surface (*'Basolato'*);
- *Cobblestone paving*: area paved with cobblestone non linked with the original roman paving;
- *Margines*: the two side walls identifying the property of the Appia Way Park;
- *Archaeological artefact*: scattered stones or archaeological remains in the vicinity of the road;
- *Monument*: archaeological monuments in the surrounding of the road as remaining of funerary monuments;
- *Path*: pedestrian and cycle paths;
- *Green area*: areas to be mowed during ordinary maintenance works. Those areas are than further classified according to priority of intervention;
- *Trees*: large trees (as pines and cypress).

Figure 8. Exampe of the developed GIS data management system.

Starting from the products derived from the survey the previously listed elements were identified and redrawn in a CAD environment and then imported as polygon layer into a GIS environment. The final GIS data are stored as a geopackage layer that can be easily imported and used both in commercial and open-source GIS systems. As an example, in Figure 8 the developed GIS package is imported and visualized in QGIS (https://www.qgis.org).
The GIS package can be used in the area of Frattocchie (municipality of Marino) for the restoration and valorisation of the portion of the Appian Way (‘*miglia*’) excluded from previous interventions and improve the confluence with the route Appia Nuova (S.S. 7). This project can finalize the creation of an “open-air” museum in those areas currently not fully valorised.

6. CONCLUSIONS AND FUTURE WORKS

The development of large digitization projects in the field of Cultural Heritage is posing new requirements in terms of speed in data acquisition, processing and generation of outcomes for diversified users. The physical dimensions and the extensions of those projects is one of the main issues to be taken into consideration. Indeed, on the one side the vastness of the area to be surveyed impose the development of survey techniques allowing rapid acquisition of data. On the other hand accuracy of instruments designed for rapid survey may not be adequate when facing large areas due to drift effects, loss of accuracy between successive acquisition etc. Not to mention that when dealing with large areas significant cartographic effects can take place. While those effects can be considered as negligible at building scale, at the infrastructure level (like the 12 km branch of the Appian way here presented) those effects can prevent a successful survey when they are not taken into account. A second major problem in those massive projects is the data overload. Surveys are generally producing large dimension dataset of unstructured objects (like point clouds) that may be difficult to open, manage and process for any further analysis. In addition, those data are generally not characterised by any semantics, structure or organization posing problems in their utilization. The organization of the data, and their structuring is of outermost importance for users that are not expert of surveys and 3D data management. Operators of PAs and professionals (e.g., architects and engineer) require the availability of products that can be used in their everyday workflows. For this reason, results of survey need to be turned into other products to fully exploit their potential.
The presented work tries to partially cope with the previously listed issues. Indeed, on the one hand it presented a methodology combining laser-based MMS and a photogrammetric method using fisheye and 360° cameras that allowed a rapid mapping of 12 km of the Appian way. The complete survey was carried out in 10 working days. The two datasets are characterised by different characteristics both in terms of input data and in terms of metric accuracy. A detailed study and comparison between the two datasets is out of the scopes of this paper and will be investigated in future works. However, a preliminary check between the two data showed some differences in planimetry (up to some centimetres) that can be associated with two different elements: i) accuracy of RTK measurements (approximately ± 2.0 cm); ii) the lack of good geometry in some areas of the Appian way that may determine some minor drifts effects. However, those discrepancies are fully in line with the requirements of the project that is aimed at working at a scale 1:100-200. As a second aspect this paper introduced a management system based on a GIS package that can be used as a framework for the collaboration among different users involved in the maintenance and the valorisation of the area (e.g., operator of the PA, professionals, archaeologists, etc.). The GIS environment is generally well known and accepted by those operators in their daily workflows.

However, the present work represents only the first stage of the entire project. Indeed, further steps of the project foresee the development of a digital twin of the Appian Way. The aim of this digital twin is to be a repository of information and models to be continuously updated. The digital twin will also provide specific views of the model to the different end-users in order to provide each one of them the most relevant information and in the desired format. In addition, the potential of Virtual and Extended reality environment for the creation of immersive experiences both for designers and end-users will be tested.

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