GIGAPIXEL PHOTOGRAPHY FOR HIGH-ACCURACY FACADE DOCUMENTATION: MAPPING THE ORIGINAL LOCATION OF THE FORMA URBIS ROMAE

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KEY WORDS: Gigapan, Rome, Photogrammetry, Digitization, Forma Urbis, Cultural Heritage

ABSTRACT:

The Forma Urbis Romae was a monumental marble map of ancient Rome from the Severan Dynasty. It was originally attached to the interior wall of the Temple of Peace, but through the course of the Middle Ages the marble panels of the map fell off or were deliberately removed. They have been found mainly in the vicinity of the Forum, but only about 10% of the original surface have been discovered. The wall on which the map was mounted is currently an exterior wall of the Church of SS. Cosma e Damiano, and the original holes from the iron nails used to attach the marble panels of the map are still visible on unrestored areas. In order to attempt a full reconstruction of the map from the fragments, detailed measurements of the positions of the mounting holes are required. Access to the wall itself is difficult because of its height, and surrounding construction and excavation. A method was needed to map the surface of the wall without the expense and complication of erecting scaffolding for direct hand-measurement. To this end, digital photogrammetry and gigapixel photography with a telephoto lens were combined to produce stereo-models from the street level 50 m away. From these stereo-models of merged panoramic images in excess of 200 megapixels and a Ground Sample Distance of 1 mm it was possible to use stereo-plotting to create a map of archaeologically relevant features that will serve as the foundation for determining the positions of the surviving marble pieces.

1. INTRODUCTION

The *Forma Urbis Romae*, also known as the Great Marble Map of Rome or the Severan Marble Plan, was a 13 x 18 meter depiction of the city most likely made during the Severan Dynasty (193-235 CE) that showed the layout of every neighbourhood and building of the city (Carettoni et al. 1960). The Map was first rediscovered in 1562 and remains an important source for the architectural history of the city (Carrettoni et al. 1960). Originally mounted on the interior wall of the *Templum Pacis* (Temple of Peace) adjacent to the Roman Forum, this wall now serves as the north exterior wall of the 4th century Basilica dei Santi Cosma e Domiano, which faces the modern via del Fori Imperiali, a street radiating from the Colosseum. Gradually destroyed during the Middle Ages, the fragments of the map were reused as building material, with the 1200 surviving fragments recovered to date amounting to only an estimated 10% of the original area. Although the map is now gone and modern use has continued, the mounting holes from the metal clamps from an estimated 150 slabs of marble are still visible. Plotting the locations of these mounting holes on the wall is of utmost importance in the current efforts to reconstruct the map, which were initiated in 2018 as a partnership between the Ancient World Mapping Center at the UNC Chapel Hill, USA, and the Musei Capitolini in Rome, Italy, with additional collaboration with IUPUI, USA and Queen's University in Canada. The only previous documentation of these mounting holes was a hand drawing done in 1960 where each hole was measured and its dimensions provided in a list alongside the paper drawing (Carettoni et al. 1960). This previous drawing, however, did not include the lower socle below the main mounting area of the map.

Documenting the wall that once held the Map presents distinct document challenges. Extensive and deep excavations between the street and the wall, a distance of over 50m, mean that tripods for LiDAR scanning or similar techniques would be difficult or impossible to set-up. Short-range techniques at the foot of the wall, where instruments can be placed, would suffer from adverse look angles because of the wall's height. What is more, LiDAR techniques at a distance of 50 m would likely not provide the level of detailed texture required to map the holes, which are as large as 20 cm but can be as small as 3 cm, and can be very difficult to distinguish from the pitting caused by the decay of the wall over almost 2000 years. Consequently, a technique was needed that would produce an extremely detailed, but geometrically accurate, orthophoto of the wall, which for planning purposes we specified as having a Ground Sample Distance (GSD) of a half centimetre or less.

Photogrammetric techniques were the first choice in this sort of facade documentation (Grussenmeyer et al. 2002). In order to achieve this small GSD using an overlapping block of images we would need to move the camera at five metres or less from the facade and to a height of almost 20m. The erection of scaffolding or a temporary lift was deemed cost and time-prohibitive for the week allocated to this phase of the project. While a UAV could have been flown across the facade at this working distance, the risks and the permissions involved in the centre of Rome were similarly formidable. Gigapixel photogrammetry using fan-geometry and telephoto lenses (>200 mm), rather than overlapping strips of images at close range using a wide-angle lens (~24 mm) would fulfil the project goals. Fan geometry or panoramic photogrammetry, first widely used in open-pit mining to document distant pit walls, was adapted to use the robotic

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Gigapan panoramic heads to capture high-resolution panoramic images *and* to use the same high-resolution images to create similarly detailed stereo-models for mapping purposes (Sturzenegger et al. 2009; Luhmann, 2010).
This project will demonstrate how panoramic images, acquired with a telephoto lens at 50 m from the facade can create stereo-models suitable for stereo-plotting with a relative accuracy of less than 5 mm, and produce high resolution panoramic images ideal for qualitative inspection of the facade's condition without the need for scaffolding or UAVs.

2. HISTORY & PREVIOUS SCHOLARSHIP

The first collection of fragments found in 1562 were discovered behind the Church of St Cosmas and Damian which was the first clue to the plans' existence (Carattoni et al, 1960). In the centuries that followed, fragments continued to be discovered across the city during active archaeological excavations as well as by chance. Identifications of the pieces and their locations have been made by the visible incisions for locations in the city such as the Colosseum, imperial fora, and the Capitoline Hill (Figure 1). Of the discovered fragments, only approximately 200 have been identified, 500 are unidentified, and the remaining have no incisions (Almeida, 1980). Study of the fragments themselves is difficult due to their sometimes unidentifiable incisions and the sheer practical limitations of their size and weight.

This monument serves as one of the only recordings of urban planning of the city of Rome at the time, which is particularly important for residential and everyday areas that made up the majority of the city. The level of detail on the map itself is quite significant at a scale of 1:240 and includes everything from the size and shape of monumental buildings to individual sidewalks, doorways, and interior staircases (Carretoni et al. 1960). Some fragments have notation and labels for the more prominent structures, while others are simply their design. To date, the pieces include 55 identifiable structures, six streets, and seven areas.

Figure 1. Artist Rendition of the Map Mounted in the *Templum Pacis* (Meneghini, 2008)

The main source of modern scholarship for the *Forma Urbis Romae* comes from a two volume publication in 1960 edited by Carattoni et al. This publication is the primary reference for the history of the plan until this time and is the first complete presentation of the known fragments, the original location in the *Templum Pacis*, and their history, topology, function, and setting. While the plan is never directly mentioned in ancient sources, the fragments themselves and their remains have been dated to during the reign of the Emperor Septimius Severus, specifically after the fire in the *Templum Pacis* in 192 AD (Carattoni et al. 1960). A later publication by Rodriguez-Almeida in 1980 included new observations since the 1960 publication as well as a continuation of the catalogue for new fragments discovered since.

In 1999, Stanford University began a project to laser scan all of the fragments found to date and create an online database with the goal to digitally reconstruct areas of the plan and to find new matching pairs (Koller et al. 2006; Koller & Levoy, 2006). What was missing from this project was a corresponding 3D model of the wall that could potentially serve as a digital surface on which to match the clamp holes on the backs of the fragments with those remaining on the mounting wall.

The Great Marble Map of Rome Project launched in 2018 aimed to accomplish many goals related to the digitization and study of the marble fragments of the *Forma Urbis Romae* as well as the problem of documentation of the mounting wall which is the study of this paper. New 3D scans of the fragments were done using a handheld structured light scanner to update the previous database produced by Stanford. Research is undergoing in using these digital fragments to determine matching pieces using machine learning.

3. METHODOLOGY

3.1 Project Planning

Prior to undertaking the work on site in Rome, the documentation workflow was planned through discussion with the partners and evaluation of the accessibility to the wall using satellite imagery and Google Earth Pro. The ground level directly in front of the exposed wall was under archaeological excavation and modern conservation construction of the adjacent buildings and as such, inaccessible. Measurements were taken from prospective locations on the street level to determine the number of stations required to reach the desired level of detail (Figure 2). From this plan, seven panoramic image station locations were selected at roughly 5 m apart at street-level 50 m away from the facade.

Figure 2. Project Planning in Google Earth Pro

The camera selected for the project was the Nikon D800e, a 36 megapixel full-frame DSLR with a pixel size of 4 microns. The Nikon AF Micro-Nikkor 200 mm f/4D IF-ED lens was selected for its superior image quality and extremely low radial distortion characteristics. This lens-camera combination yielded an average GSD of 1.5 mm for the project. Ground Sample Distance is given by the following formula:

$$GSD = \left(\frac{distance}{focal\ length}\right) \times pixel\ size\ on\ the\ sensor$$

The base of the wall could not be seen from the panoramic camera station at street level. In order to capture the lower 4 m of the wall obscured from the street, a strip of images using the same D800e camera and a Nikon AF-S Nikkor 24 mm f/1.8G ED were taken from the ground level in front of the wall. This lens-camera combination at 5 m from the base of the wall would match the 1.5 mm GSD of the panoramic stations and could, consequently, be easily and accurately matched to the merged panoramic images. This lower level, the *socle*, would not have had map components mounted on it, but did have mounting holes for what were likely decorative marble slabs.

An advantage of photogrammetry is the ability to calculate accuracy a priori. In this project we followed the guidelines of the CIPA 3x3 method and pre-calibrated the lens and camera to an accuracy of 0.25 pixels using the ADAMTech CalibCam software. This level of calibration accuracy set a baseline for project planning. Planar or horizontal accuracy in the project is given by the following formula:

$$Accuracy\ Horizontal = GSD \times pixel\ accuracy$$

Consequently, a maximum horizontal accuracy of 0.3 mm. Depth accuracy is given by the following formula:

$$Accuracy\ Depth = Accuracy\ Horizontal \times \left(\frac{distance}{base}\right)$$

The base-to-distance ratio between adjacent stations was 1:8, but we selected instead stereo-pairs at a base-to-distance ratio of 1:2 (stations 7 and 2, and 6 and 1), the standard for stereo-plotting (Wolf et al. 2014). Consequently, in this case, a maximum depth accuracy of 3 mm can be achieved.

3.2 Gigapixel Photography

The Gigapixel robotic camera head has been extensively used in the documentation of cultural heritage, as well as in applications like Geological Engineering, where detailed photos of slopes or facades are needed, sometimes at some distance away (Lato et al. 2012; Romeo et al. 2019). The camera head can be programmed to automatically acquire images over a defined rectangular area at a pre-determined overlap. The camera and lens are mounted on a nodal slide such that the point of rotation corresponds with the no-parallax point of the lens (Figure 3). The no-parallax point is a position where foreground and background features will remain aligned when rotating the camera between two images dependant on the geometry of the lens (McGlone & Lee, 2013; Littlefield, 2006). This point is normally found empirically in the field for each camera-lens combination and permits the images to be stitched together without the need to correct changes in image perspective Each camera station in this project was programmed to take 30 images with 60% overlap to create merged panoramic images of approximately 300 megapixels (Figure 4). These images can easily be shared online through the Gigapan online gallery, or downloaded and viewed locally with free tools like IrfanView.

Figure 3. Gigapan System Mounted on the Pedestrian Fence Across from the Wall

Figure 4. Composite Images from a Single Gigapan Station. Final Image: (https://www.gigapan.com/gigapans/208812)

The images acquired from each camera station were processed in the ADAM Technologies 3DM Analyst Research Suite, a photogrammetric suite commonly used in mine mapping and rock face analysis (Birch, 2006; Sturzenegger and Stead, 2009). The software has the capability to merge individual images taken at the no-parallax point in the CalibCam module, and to produce stereo-models that can be mapped in the Analyst module. For the present project, this capability will allow images of 300 megapixels to be stereo-plotted in the 3DM Analyst module.

The scaling and orientation of the project required careful consideration. Absolute orientation of the models into a local coordinate system was not deemed necessary, but accurate vertical orientation and dimensional scaling was essential. Scale was obtained using custom scale bars of 50 cm printed on rigid Alupanel and placed vertically and horizontal in three locations across the wall. One pair of scale bars, on the right-hand side of the facade, were configured in an L parallel to the facade such that the targets would define the X and Y axes for the facade (Figure 5). Care was taken to mount this L-target with a spirit-level such that the vertical axis was plumb and the horizontal bar was parallel to the wall. Residuals on the four scale bars after a bundle adjustment in CalibCam were less than 0.5 mm. This approach to orientation also meant that the facade could be considered to have the same orientation as an aerial stereo-pair with the Z axis corresponding to a nadir view-angle. This meant that traditional stere-plotting could be employed (Figure 6).

Figure 5. Scale Bar Placement in L Configuration

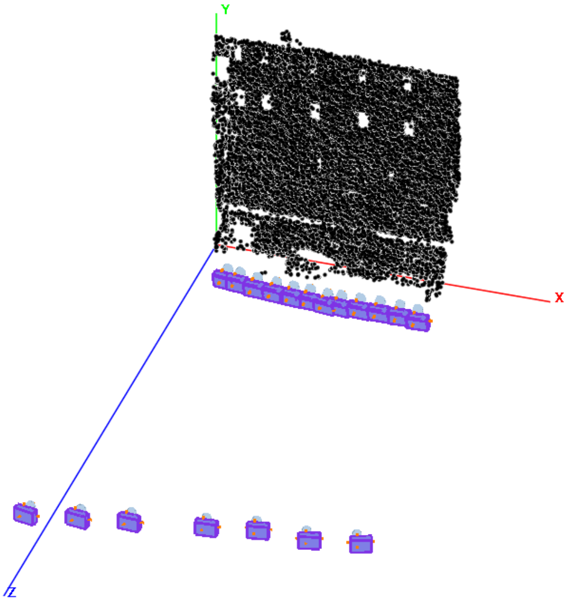

Figure 6. Station and Camera Locations in CalibCam

3.3 Digital Drawing and Stereo-Plotting

Contemporary approaches to photogrammetric documentation have employed Structure-from-Motion techniques since the early 2010s, a technique that use large numbers of images with high overlap, often in the hundreds or thousands, to create detailed, photo-realistic 3D models (Roncella et al. 2011, Barazetti et al. 2011). This present project did not have the goal of creating such a digital surrogate. Instead, differentiating the original holes from pitting due to decay and accurate vectorization of the holes and other salient features on the facade were the overriding goals. Stereo-plotting, though a technique that is a century old and typically one used for aerial mapping, remains an extremely accurate way to pick up features not on texture reprojected onto a 3D model, but on the original images (Dallas, 1996; Jones & Bevan, 2019). Only two stereo-pairs from the seven image stations were required in the end for the full stereo-plotting of the wall, meaning that only 55 images in total were needed to map a 13 x 18 m to accuracy of approximately 2 mm (Figure 7).

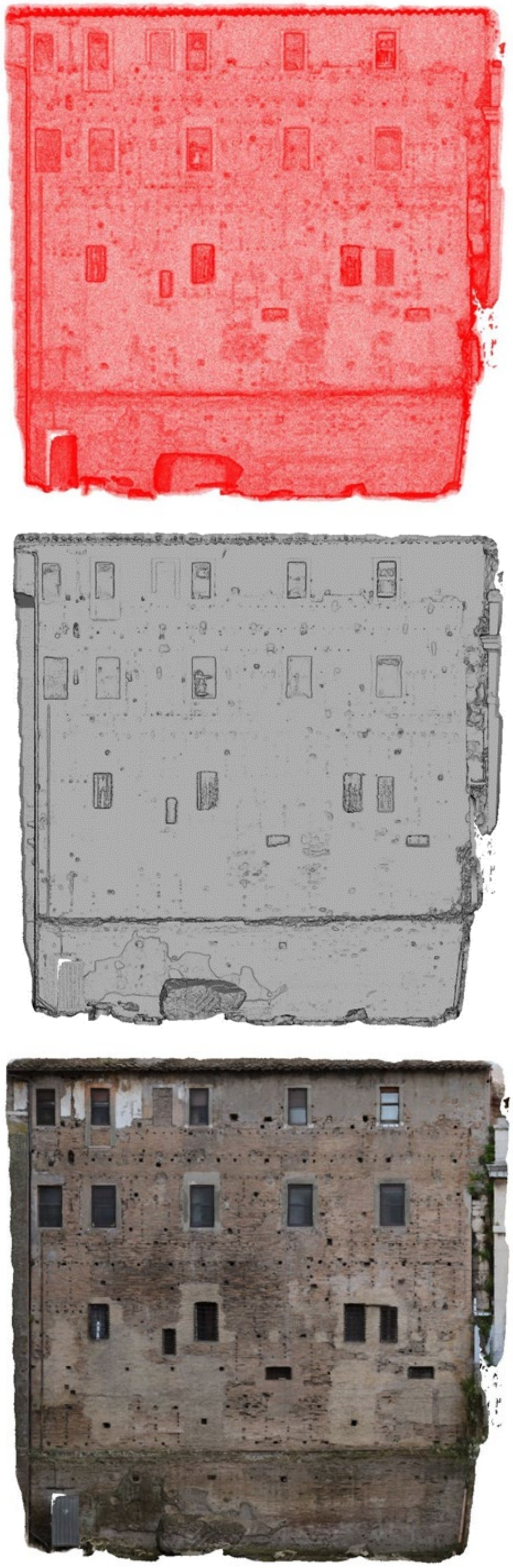

Figure 7. Resulting 3D Model of the Wall
(Top: Wireframe; Middle: Shaded Surface; Bottom: Textured)

Modern stereo display hardware using a commercial desktop computer, 3D monitors, and active-shutter 3D glasses allowed the wall to be examined in great detail and mapping of the holes to be done with considerable certainty. Several feature types were picked up and would be differentiated on the final drawings: Large Mounting Holes, Small Mounting Holes, Later Construction, and Windows (Figure 8). The stereo-plotted features were exported to AutoCAD Map3D where the line-work was cleaned and labelled for final presentation (Figure 9).

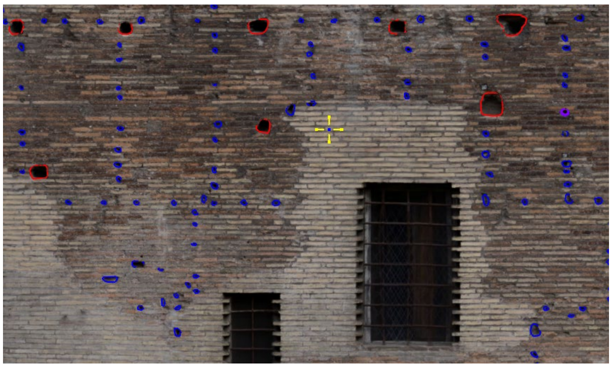

Figure 8. Stereoplotting in 3DM Analyst

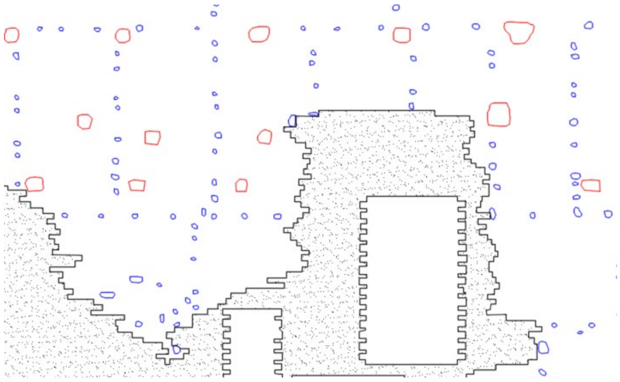

Figure 9. Imported Drawing in AutoCAD

AutoCAD was selected for the advantages of being able to ingest both DXF vector outputs as well as georeferenced and scaled orthophotos at a scale of 1:1 which allowed for viewing in real world size, as well as scaling for printing and presentation purposed. It also could be divided into layers that could be designed to represent different types of features as well as construction phases. In the future, this would allow for possible integration with historical data or vectorization of individual map fragments.

3. RESULTS

The imagery collected with the telephoto lens and Gigapan robotic head were processed along with the image strips of the bottom section of the wall in CalibCam. The processing of this data took less than one hour, while the stereo-plotting took approximately three working days. Comparison with the earlier hand drawing from 1960 shows that the new digital drawing has the same or greater detail. What is more, this new documentation includes the mounting holes on the socle for the decorative marble revetment (Figure 10). Finally, the new photogrammetric documentation also created a very high resolution orthophoto (Figure 11), something missing from earlier efforts. The total number of images used in the project was 235, although many of these were redundant.

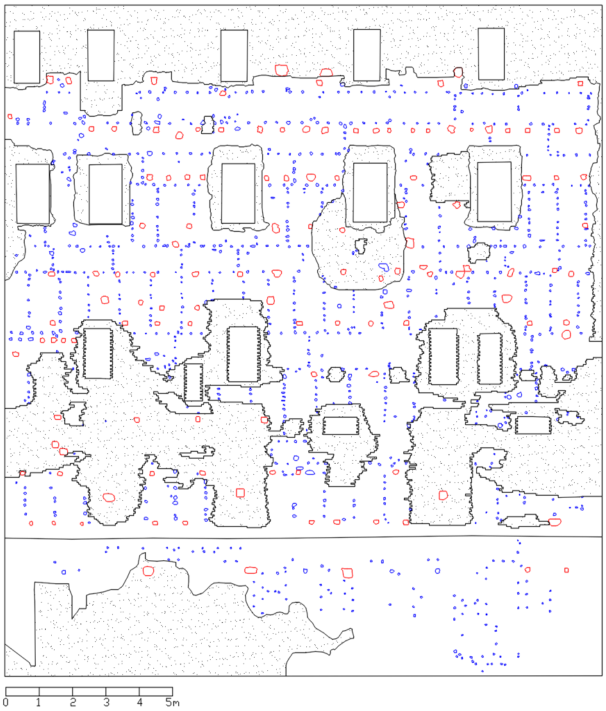

Figure 10. Final Line Drawing

Figure 11. Scaled Orthophoto

4. CONCLUSION

Planning was extremely important for the implementation of this project as we only had one week on site in Rome to complete the photography. Photogrammetry, specifically fan imagery using the Gigapan allowed for relatively efficient and low-cost recording and at the same time, projecting the wall in the X-Y plane allowed for the use of aerial mapping techniques for the digitization of the wall that can be imported directly into other software. Having a complete digital record of both the individual fragments and the original location of the map will serve as the basis for the reconstruction of this important cultural heritage monument. What is more, it shows that stereo-plotting, though an old technique, remains a very useful tool for facade documentation.

The project on the *Forma Urbis Romae* discussed in this paper addressed a need for an updated map of the current state of the mounting wall and the locations of the mounting holes of the slabs of marble. It is hoped that this data can be combined with previous and future laser scanning data in order to match the mounting holes on the wall with the holes on the backs of the fragments themselves to form new matches in the placement of the fragments on the surface of the map.

ACKNOWLEDGEMENTS

The authors would like to thank the Ancient World Mapping Center at the University of North Carolina (Chapel Hill), the IUPUI Library for Digital Scholarship, Francesca de Caprariis from the Musei Capitolini, and the Soprintendenza Capitolina ai Beni Culturali in Rome.

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