Chapter 13
Virtual archaeology and computer-aided reconstruction of the Severan Marble Plan

The Severan Marble Plan was an immense marble map of Rome constructed in the early 3rd century during the reign of Septimius Severus, and is a primary source of topographical knowledge of the ancient city. We have digitized the 3D shape, surface appearance, and incisions of the extant fragments of the Plan, and use this data as input to geometric matching algorithms to perform computer-aided reconstruction of this monumental artifact, resulting in the discovery of new joins and topographical identifications among the fragments. Additionally, we have created an online information system to make the digital versions of the fragments accessible to scholars and the public.

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The Severan Marble Plan

The Severan Marble Plan of Rome, or Forma Urbis Romae, was an enormous map of the ancient city constructed during the reign of Emperor Septimius Severus between 203-211 CE. The Plan measured approximately 18 m wide and 13 m tall, and was carved onto 150 rectangular marble slabs affixed to an interior wall of the Templum Pacis in central Rome. The map depicted the ground plan of every architectural feature in the ancient city at the remarkable scale of 1:240, including monumental structures and major streets, as well as tiny rooms and stairways in individual residences [Fig. 1].

The Plan is thus an unparallel source of information concerning the urban topography of ancient Rome. Whereas many notable Roman monuments are well known from ancient literary descriptions or modern archaeological excavations, the detailed coverage of the entire central city provided by the Plan supplies much of our knowledge of the lesser known neighbourhoods that have been destroyed in the intervening centuries or are otherwise not amenable to direct archaeological study.

Unfortunately, the Plan was itself destroyed due to neglect and scavengers, beginning in the 5th century and extending into the Middle Ages. In 1562 the Plan was rediscovered, in the form of many surviving marble fragments. Over the past 500 years, archaeologists have recovered over 1,000 fragments of the Plan, representing approximately 10% of the surface area of the original map. Reassembling these pieces like a giant jigsaw puzzle and reconstructing the Plan of the city has been a continuing challenge for Roman topography scholars.

Two primary publications in the 20th century documented the recovered fragments of the Plan and

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Fig 1. Several surviving fragments of the Marble Plan that have been identified and reconstructed as depicting a portion of the Subura neighborhood and Porticus Liviae; straight lines indicate boundaries of the rectangular marble slabs (digital fragment photos composited after Carettoni et al. 1960).

the progress in their reconstruction: *La pianta marmorea di Roma antica* (Carettoni et al. 1960) and *Forma Urbis Marmorea* (Rodríguez-Almeida 1981). Our recently developed Digital Forma Urbis Romae Project website also documents the fragments using unique digital technologies and provides updated information about scholarly research on the Plan. Readers are referred to these sources for further background information on the Plan.


**Digitizing the Plan fragments**

While the Plan is an artefact of great importance in understanding the topography of ancient Rome, the previous generations of researchers working with its remnants have encountered difficulty. The surviving fragments of the Plan are numerous, and many are large and unwieldy, with the heaviest fragments weighing several hundred pounds each. Access to the fragments has been very limited; since 1998 the fragments have been stored away in crates in a basement storeroom of the Museo della Civiltà Romana. Even access to the fundamental publications about the Plan is limited, as
few copies were printed and they are difficult to find outside of specialist research settings.

In an effort to increase the accessibility of the fragments and to accelerate their reconstruction, the Stanford Digital Forma Urbis Romae Project, under the aegis of the Sovraintendenza ai Beni Culturali del Comune di Roma, has digitized the shape and surface appearance of all the extant fragments (Koller et al. 2006). The 3D shape of each fragment was captured using a Cyberware optical triangulation 3D laser range scanner, which measured the fragment surface shapes at a resolution of 0.25 mm. These digital measurements were then input to a 3D scan data software processing pipeline to create complete 3D geometric computer models for all the fragments. Additionally, the top and bottom surfaces of each fragment were photographed with a colour digital camera at a resolution of 100 dpi. An example 3D model and photograph are shown in Fig. 2.

**An online archaeological research tool**

In order to organize and share our digitized fragment representations, and to incorporate them with related scholarly materials in order to support further study of the Plan, we have constructed an online database of the fragments. In addition to our 3D scanned models and colour photographs, the database includes up-to-date archaeological information about each fragment, as well as the Plan in general. The fragment database was developed using the MySQL database software to store the information about each fragment in a relational database, and the scripting language PHP is used to organize this information into a set of dynamic online web pages. The entire database resides on an Apache web server, and can be accessed by any user with an Internet connection. Organizing the database as a website allows for easy updating of the archive with the current state of research about the Plan, and disseminates the updated information through a familiar interface (a web browser) that can reach a wide audience.

**Fig. 2.** 3D model (top) and photograph (bottom) of fragment 10g. Fragment 10g measures 0.68 m in length and is 0.07 m thick.
The database presents information about each of the Plan fragments via 1,200 dynamically-created web pages, one for each fragment; an example screenshot of a fragment entry webpage is shown in Plate 3. The 3D model of each fragment is accessed and manipulated using a custom 3D viewer that allows users to rotate the model, zoom in and out, and change the virtual lighting. Each database entry also includes our colour digital photographs of the fragment, as well as the relevant digitized photographic plates from Carettoni et al. (1960). An information box provides essential data including the identification numbers assigned to the fragment, which other fragments it adjoins, and general observations about its condition and archaeological features. The textual analysis section of the fragment entry includes a detailed analytical description of the fragment, a synthesis of the most relevant scholarship, and the fragment’s history. Bibliographic citations specific to the fragment are linked to an annotated bibliography, and all the fragment data fields are searchable by means of a database search engine.

The online Digital Forma Urbis Romae database has been gradually deployed in phases over the last few years, as the processing of the voluminous fragment data has been slowly completed. Tens of thousands of users have accessed the database, ranging from Roman topography experts to curious laypeople. Scholarly users in particular have been empowered by the increased accessibility, searchability, and cross-referencing capabilities afforded by this new digital archaeological tool for studying the Plan. The online database eliminates many of the obstacles that had previously restrained research on the Plan, as the fragments themselves and their associated research literature were often unavailable for study. The multiple representations of each fragment presented in the database (3D model, colour photograph, scanned photographic plates, analytical drawings, textual description) have also proved valuable for users studying the Plan. These different digital representations can easily be juxtaposed and compared, allowing a more complete view and understanding of the fragments than has been possible previously, and users have a unique opportunity to conduct ‘virtual archaeology’ on the Plan. Measurements of fragment dimensions and observations of fractured edges can be performed simply by loading the digital 3D models into a 3D software program. We have found the 3D fragment models particularly useful for confirming several new reconstruction results proposed during our computer-aided fragment reconstruction research.

As valuable as the virtual fragment representations have proven, however, users must recognize their limits relative to working with the actual fragments themselves. The computer models and photographs of the fragments contain minor defects and distortions, and may not reflect very fine details accurately. For example, the ancient sawing marks (scalini) present on the backs of some fragments are too small to be adequately resolved by our 3D laser scanners, and other subtle characteristics of the marble such as texture, veining, and colour variations may be beyond the limitations of our capture devices. These details can only be accurately observed by examining the real physical fragments in person in Rome. Similarly, the valuable haptic feedback that one can feel when test fitting actual matching fragments together along their fractured edges is absent when simply manipulating virtual 3D models on a visual computer display.

**Computer-aided fragment reconstruction**

Beyond the archival value of digitizing the Plan, the digital representations of the map fragments enable new kinds of research and analytical study. In particular, we have investigated using computer searching and matching algorithms to aid in reconstruction of the Plan through virtual reassembly of the fragments. Traditional scholarship efforts have also focused on joining the surviving fragments and reconstructing the map, but progress has been painstaking and slow, in part due to the difficulty of accessing and working with many hundreds of unwieldy marble fragments. However, computer programs that operate on digital models of the fragments can very rapidly and systematically consider many thousands of possible fragment positions.
and combinations. Such computer-aided fragment reassembly procedures have been previously applied to archaeological problems (Smith & Kristof 1970; Kalvin et al. 1999), and are an active area of research in computer science.

The remains of the Plan include a number of properties that are potentially useful as clues for automated fragment reconstruction. The most obvious is the inscribed map topography on the marble surface, which has been the primary source of information for prior reconstruction scholarship. Another strong clue is the fracture shape along the fragment edges; adjacent fragments with edge geometry that is not substantially eroded should match together like pieces of a jigsaw puzzle. Fragments that originated from the same marble slab also typically share several common characteristics. The thickness measurements of adjacent fragments from the same slab are usually very similar, and the gradient of the thickness across a fragment can be useful for determining its placement and orientation within a slab. The marble veining direction of fragments originating from the same slab is also normally consistent. Some slabs had rough back surfaces while others had smooth sawn back surfaces, providing another property useful for the grouping and matching of fragments. The presence of straight slab edges, clamp holes, and wedge holes (tasselli) on the fragments can help join fragments together, as well as provide information about the orientation and position of fragments on the original map wall. All of these fragment attributes are appropriate for use in our computer algorithms due to their geometric nature. We are easily able to model the location and nature of these features in our digital representations of the fragments, and our algorithms utilize these geometric constraints to search for and find potential fragment matches. There are many other properties of the fragments that may be useful for matching that we have not yet exploited, such as geological characteristics of the marble (colour, texture, etc.), the style of incisions (ductus), and correlation of Latin inscriptions and the depicted topography to known excavated architecture.

We have developed and experimented with several different computer algorithms for automating reconstruction of the Plan fragments. Though the various methods employ different combinations of particular reconstruction clues as their primary inputs, all of the techniques operate by searching a large space of possible fragment correspondences and positions, and seeking the configurations which best satisfy the specified set of geometric constraints. Each automated technique outputs listings of proposed fragment matches with their specific relative positions, and assigns a score to each proposal according to its match quality. When these output lists are sorted in ranked order, archaeological experts can then review the top scoring matches proposed by the computer, and apply further human reasoning beyond the simple geometric constraints evaluated by the algorithms.

Using our computer-aided approaches, we have discovered a number of new Plan fragment joins and placements that were overlooked in the prior centuries of reconstruction scholarship. A brief overview of the various reconstruction algorithms is given below; a more detailed discussion and further new results are available in Koller (2007).

3D fracture matching

Our initial intent was to use computer algorithms to search for new matches among the fractured edge boundaries of the fragments. We experimented with adapting 3D Iterative Closest Point algorithms (Besl 1992) used for scan data registration to the fracture matching problem, and also tried converting the fragment edges to 2D contours (by extracting slices parallel to the flat fragment top surfaces) and then to 1D signals in order to apply approximate string matching algorithms. However, these initial attempts did not result in any significant new discoveries. We have attributed this failure in part to the high degree of erosion on many of the fragment edges, which can leave little salient information for matching. Additionally, some of the digital 3D models that we used as input exhibited distortions due to misregistration of the raw 3D scan data.
Boundary incision matching

The most successful fragment reassembly method that we have developed is based on boundary incision matching. We first annotated 2D images of the fragments by hand, extending all of the incised lines representing topographic features that leave the boundaries of each fragment, and indicating their relative position, direction, and architectural feature type (such as rows of columns, aqueducts, etc.). The automated computer algorithm then searches this collection of fragment boundary annotations, and returns a list of suggested pairwise fragment matches, based on a geometric scoring metric that measures the quality of the alignment of the annotated boundary features.

As an example of boundary incision matching, consider the two fragments identified as fn23 and 28a in the fragment numbering scheme. Their boundary feature annotations are depicted with varying colours in Plate 4. The boundary incision matching algorithm suggested a very high scoring match between these two fragments, with the five incisions at the top of fragment fn23 aligning with five similar features along the bottom edge of fragment 28a. When we checked this new suggested match between the two fragments, we were able to verify the correctness of its placement by further observing a matching correspondence between fragments fn23 and 34b. Fragment fn23 fits nicely in the corner between fragments 28a and 34b [Fig. 5], both of which had been identified and positioned together in earlier scholarship. The new positioning for fragment fn23 appears to depict the interior of a multi-storey warehouse that was partially visible on fragments 28a and 34b.

![Fig. 5. Fragment fn23 positioned in the corner between fragments 28a and 34b (after Carettoni et al. 1960).](image-url)
Another example of a new fragment match involves fragments 330 and 354 [Fig. 6]. In this case, only two parallel boundary incisions delineating a road matched well between the two fragments, but the presence of distinct marble veining provided an additional geometric matching constraint, as the veining directions for fragments in the same slab must align, thus restricting the possible relative orientations of the fragments. As a result, the two fragments were scored high enough by the matching algorithm to warrant further review and examination of the 3D models. In this case, the 3D models for the two fragments both exhibited very unusual smooth, flat regions along their fractured edges [Fig. 7]. This suggested a fragment match directly along their boundaries, and this was confirmed by later examining the fragments in person in Rome. Fig. 8 shows fragment 354 in its newly suggested position matching fragment 330; together the fragments seem to represent the groundplan of dense residential and commercial architecture spanning two city blocks.

Wall feature matching

Another computer algorithm that we have used successfully to reconstruct portions of the Plan is wall feature matching. This technique employs measurements of the still extant wall on which the Plan was hung, collected by L. Cozza for the 1960 publication of the map (Carettoni et al. 1960: 175-195). The clamp holes and masonry patches observed on the wall by Cozza are expected to correspond directly to the clamp holes and wedge holes (tasselli) visible on some of the fragments (Rodríguez-Almeida 1977). The relative spacings and directions between the clamp holes, in addition to the orientation of the fragment slab edges, provide a number of geometric constraints. We have digitized Cozza’s wall feature measurements, as well as the corresponding features on the fragments, and use this data as input to a computer matching process that searches all valid positions and orientations of fragments on the wall and outputs a ranked list of the strong matches [Plate 9].
Multivariate clustering

Whereas other matching algorithms require directly corresponding geometric features among fragments, multivariate clustering merely attempts to group fragments together based on common characteristics. We have experimented with hierarchical and partitional data clustering schemes such as the K-means algorithm to group potentially nearby fragments together, based on attributes including fragment thickness, marble veining direction, the primary axial direction of the architecture depicted on the fragment, the directions of slab edges, and the back surface condition of the fragments (i.e. whether the backs are rough or smooth).

Areal topographic matching

Because a number of Plan fragments have already been identified and located on the wall map through prior scholarship, the positions of many areal topographic features on the map (e.g. roadways and rivers) have become well-defined relative to the grid of slab boundary edges. Thus, we have attempted to develop some shape matching techniques that exploit this topographic knowledge to position unidentified fragments. The course of the Tiber River across the map, for example, can be interpolated with reasonable accuracy. We are able to identify candidate unlocated fragments that appear to depict a portion of the river, and then algorithmically search the configuration space for those fragment positions on the wall that maximize the overlap of the river region on the fragment with the hypothesized river region shape on the wall.

Conclusion

The digital capture and measurement of cultural heritage artefacts with high-resolution photography and high-precision 3D laser scanners has become increasingly realistic in the last decade, as the cost, availability, and usability of the technology continually improves. The Digital Forma Urbis Romae Project has been a pioneering effort to exploit these technologies and fully digitize, in three dimensions, a physically large and immensely valuable archaeological artefact. By creating digital representations of the Plan fragments and making them widely and freely available through an online database, we have dramatically increased the accessibility of this monument and hope to encourage a new surge in interest and scholarship concerning the Plan. Beyond simply enabling passive visualizations, we believe that the digital fragment models can enable new analyses that lead to unique archaeological discoveries. Indeed, our computer-aided fragment reconstruction algorithms are an example of one such type of digital analysis that has yielded a number of exciting new findings about the inter-relationships among the surviving fragments, with immediate applicability to better understanding the urban topography of ancient Rome.

Bibliography


