David Koller

The Digital Forma Urbis Severiana

Abstract: The Forma Urbis Romae, or Severan Marble Plan, was a giant 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 map, and are using 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.

The Forma Urbis Romae

The Forma Urbis Romae, or Severan Marble Plan of Rome, was an enormous map of the ancient city constructed during the reign of Emperor Septimius Severus between 203–211 CE. The map measured approximately 18 by 13 meters, and was carved onto 150 marble slabs which hung on an interior wall of the Templum Pacis in 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.

The Marble Plan is thus an unparalled source of information concerning the topography of ancient Rome. Whereas many famous 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 neighborhoods that have been destroyed in the intervening centuries or are otherwise not amenable to direct archaeological study.

Unfortunately, the Marble 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 last 500 years, scholars and archaeologists have recovered over 1000 fragments of the Plan, representing approximately 10 percent 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 over the last few centuries of Roman archaeological work.

Two primary publications in the 20th century documented the recovered fragments of the Marble Plan and the progress in their reconstruction: "La pianta marmorea di Roma antica" by Carettoni et al. in 1960 and Rodríguez-Almeida's "Forma Urbis Marmorea" in 1980. Our recently developed Digital Forma Urbis Romae Project website (http://formaurbis.stanford.edu, described below) also documents the fragments using unique digital technologies as well as providing updated information about scholarly research on the Plan.

Digitizing the Forma Urbis Fragments

While the Marble Plan is an artifact of tremendous importance in understanding the topography of ancient Rome, working with its remnants has been difficult in the past. The surviving fragments of the plan are numerous, and many of them are large and unwieldy; the largest fragments weigh several hundred pounds each. Access to the fragments has been very limited; since 1998 the fragments have been stored away in crates in the basement storeroom of a Roman museum. Even access to the fundamental publications about the Plan is difficult, as they are normally found only in specialist research settings.

In an effort to increase the accessibility of the fragments and accelerate their reconstruction, our 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 of the map. The initial fragment digitization process was conducted in 1999 in the basement of the Museo della Civilità Romana in Rome, where 1,163 of the fragments have been stored in crates since being moved from the Braschi Palace in 1998. An additional digitizing session took place in May of 2001 at Stanford University, to digitize a new set of 23 fragments which were discovered during excavations of the Templum Pacis in 1999. We used two Cyberware optical triangulation 3D laser scanners to scan the fragments, capturing their shapes at 0.25 mm resolution, and then processed the scan data to create corresponding 3D models. Additionally, we photographed the top and bottom surfaces of each fragment with a color digital camera at a resolution of 100 dpi. An example 3D model and photograph are shown in *Fig. 1*.

An Archaeological Research Tool

As a means of organizing our digitized fragment representations, incorporating them with related scholarly materials, and supporting further analysis and scholarship of the Marble Plan, we have constructed an online database of the fragments. In addition to our 3D scanned models and color photographs, the database and its associated website includes up-to-date archaeological information about each fragment, as well as the Marble Plan in general. The fragment database was developed using the freely available MySQL database software to store the information about each fragment in a relational database. 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 us to easily update the archive with the current state of research about the plan, and to disseminate the updated information immediately through a familiar interface (a web browser) that reaches a wide audience.

Information about each of the Marble Plan fragments in the database is presented via 1,200 dynamically-created web pages, one for each fragment. An example screenshot of a fragment entry webpage is shown in *Fig. 2*. Through these pages, the 3D model of each fragment is accessible using a custom 3D viewer that allows users to rotate the model, zoom in and out, and change virtual lighting settings. Each database entry also includes our color digital photographs of the fragment surface, as well as the relevant digitized photographic plates from the 1960 "La pianta marmorea di Roma antica" publication. An information box provides essential information including the identification numbers assigned to a fragment, which other fragments it adjoins, and general characteristics 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

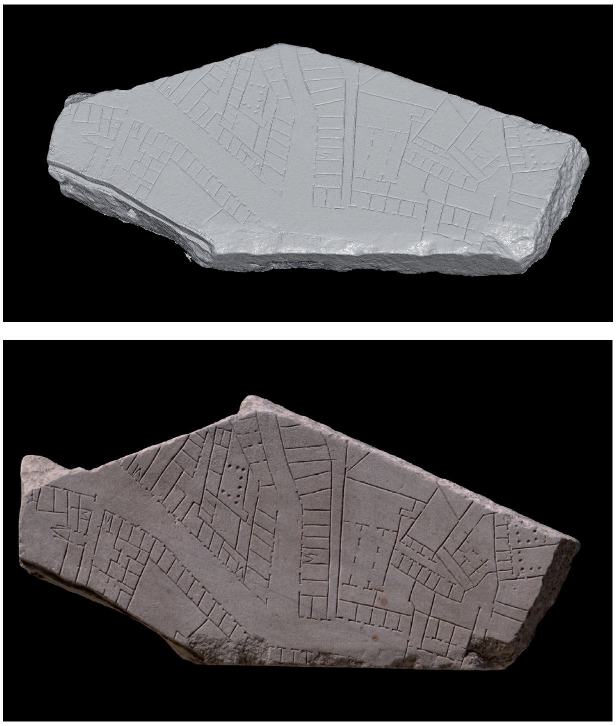

Fig. 1. 3D model (top) and photograph (bottom) of fragment 10g.

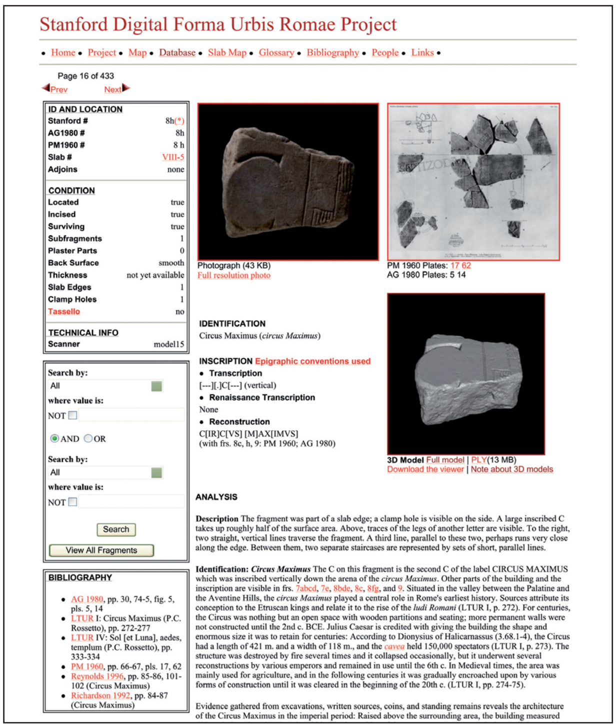

Fig. 2. Screenshot of the database page for a fragment.

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. Tens of thousands of users have accessed the database, ranging from Roman topography experts to curious laypeople. Scholarly users in particular have been pleased and empowered by the increased accessibility, searchability, and cross-referencing capabilities afforded by this new digital archaeological tool for studying the Marble 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 our database (3D model, color 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 Marble Plan. Measurements of fragment thicknesses, incision widths and depths, and observations of fractured edges can be performed simply by loading our digital 3D models into a 3D software program. We have found the 3D fragment models particularly useful for confirming several new proposed reconstruction results.

Computer-aided Reconstruction of the Fragments

Aside from the archival value of digitizing the Marble Plan, the digital representations of the map fragments enable new kinds of research and analytical study of the plan. In particular, we have used computer searching and matching algorithms to aid in the reconstruction of the plan by virtually reassembling the fragments. Traditional scholarship has 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 hundreds of unwieldy marble fragments. However, computer programs that operate on digital models of the fragments can 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 represent an active area of research in computer science.

The remains of the Marble 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 fit together like pieces of a jigsaw puzzle. Fragments that originated from the same marble slab typically share several common characteristics. The thicknesses of adjacent fragments from the same slab are usually similar, and the thickness gradient can be useful for determining placement and orientation of fragments within a slab. The marble veining direction of fragments within a slab is also normally consistent. Some slabs had rough back surfaces while others had smooth 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 providing 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 position 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 are useful in reconstruction that we have not exploited, such as geological characteristics of the marble (color, 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 Forma Urbis 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 that we have implemented outputs listings of proposed fragment matches with their specific relative positions, scoring each proposal according to its match quality and sorting the output lists in ranked order. Archaeological experts can then review the top scoring matches proposed by the computer, and apply further higher-level reasoning beyond the simple geometric constraints.

Using our computer-aided approaches, we have discovered a number of new Marble Plan fragment joins and placements that were overlooked in the prior centuries of reconstruction scholarship (Koller / Levoy 2006). A brief overview of the various reconstruction algorithms is given below; a more detailed discussion is available elsewhere (Koller 2007).

3D Fracture Matching

Our initial intention 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 / McKay 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 fragment match 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 we used as input exhibited distortions due to misregistration of the raw 3D scan data. We are optimistic that 3D fracture matching may prove fruitful eventually, and we are currently pursuing new registration techniques (Brown / Rusinkiewicz 2007) and matching algorithms (Huang et al. 2006) that have proved suitably robust for Forma Urbis fragment reconstruction in preliminary studies.

Boundary Incision Matching

The most successful fragment reassembly method that we have developed is based on boundary incision matching. We first annotated fragment images 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 feature type (such as rows of columns, aqueducts, etc.). The computer algorithm 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.

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 Marble 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. 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 of the valid positions and orientations of fragments on the wall and outputs a ranked list of the strong matches.

Multivariate Clustering

Whereas other matching algorithms require some directly corresponding geometric features among fragments, multivariate clustering simply 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, direction of slab edges, and the back surface condition of the fragments (i.e. whether the backs are rough or smooth).

Topographical Area Matching

Because a large number of Marble Plan fragments have already been identified and located on the wall map through prior scholarship, the positions of many distinctive topographical areas on the map, relative to the grid of slab boundary edges, have become well defined. 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 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.

Current and Future Work

Our current work on the Digital Forma Urbis Severiana involves transferring the online database to assure a long-term, sustainable home for the project archive. As a result of my recent graduation and move from Stanford to Virginia, the database will now be at least partially hosted by the University of Virginia Institute for Advanced Technology in the Humanities (IATH). In addition to establishing a new instance of the online database, we are expanding the infrastructure to make our data archive more of a collaborative research tool for the Plan and its fragments, inspired by the Wiki model and its use in scholarship.

We are continuing with further reconstruction scholarship, both by investigating matches previously proposed by our computer algorithms and by exploring new techniques. We are revisiting the potential of fractured edge matching on the digital 3D models, and also investigating new technologies (such as transmissive scanning and geological techniques) for measuring properties of the physical fragments that may yield new matching clues. Additionally, we are developing an updated map of the reconstructed Marble Plan, and experimenting with new visual representations of the varying levels of uncertainty in the proposed reconstructions and fragment identifications.

Another new research direction is studying the Marble Plan in its relation to other topographical sources and depictions of ancient Rome. In *Fig. 3*, for example, we can compare the architecture incised on Marble Plan fragment #24c to the corresponding riverfront architecture modeled by Gismondi on his 1:250 scale model of the city (Il Plastico). Many of the buildings in Gismondi's model are clearly based directly on the floorplans from the Forma Urbis

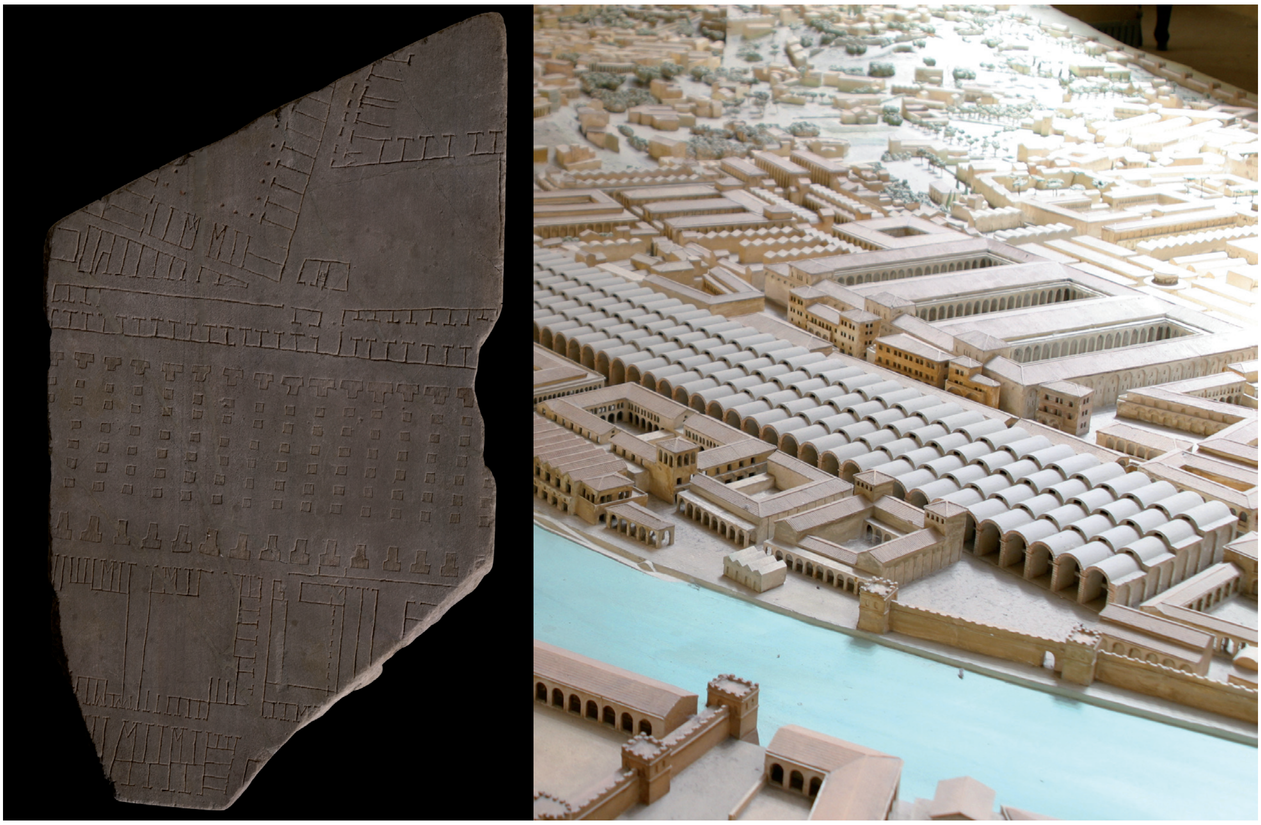

Fig. 3. Marble Plan fragment 24c (left) and the corresponding area of Gismondi's model (right).

fragments. Similarly, our study of the Severan Plan will inspire our own efforts to build an accurate digital 3D model of ancient Rome, which we are undertaking at the University of Virginia IATH.

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David Koller

University of Virginia
Institute for Advanced Technology in the Humanities
Alderman Library
P.O. Box 400115
Charlottesville, VA 22904-4115, United States of America
koller@virginia.edu