

Interactive Domitilla Catacomb Exploration

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Abstract

In this paper we present an approach for interactive visualization and manipulation of huge point clouds. Archaeological monuments like the Domitilla Catacomb in Rome lead to data sets surpassing 1 Billion (10^9) points or 20GB of storage space, which makes standard techniques like mesh conversion or in-core point-based rendering infeasible. Our system uses an out-of-core octree structure and a number of interactive editing tools to enable many archaeological tasks to be carried out on the whole point cloud that would not be possible using traditional methods. We allow fast selection, insertion and deletion of points, and through out-of-core rendering, the frame rate always stays above 20 frames per second on a fast workstation. To the best of our knowledge, this is the first interactive visualization of the complete data set of a large subterranean catacomb, and we show that direct point cloud visualization on the complete data set of a scan campaign is an important tool in archaeological practice.

1. Introduction

The documentation of a large archaeological monument like a catacomb is not a trivial task due to the sheer physical dimensions of the monument. In the last 10 years, laser range scanning evolved as a viable means of recording the actual state of an archaeological monument. It is a fast and accurate method of measuring distances in a dense grid on an object, resulting in detailed representations that could not

be achieved by traditional means like drawing. Laser range scanning is usually combined with digital photography to capture color information.

In this paper, we explore the use of range scanning and the subsequent visualization and interaction possibilities on the example of a very large and complex monument, the *Domitilla Catacomb* in Rome. The Domitilla Catacomb is the largest of Rome's over 60 known catacombs, built by the early Christian communities between the late 2nd and the early 5th century. The soil around Rome consists mostly of tuff, which allows easy digging, and therefore catacombs were extended frequently and without plan. The result is a very irregular network of galleries, 15km in the case of the Domitilla Catacomb, which is challenging to document. Only recently the development of mobile laser range scanning equipment made it possible to comprehensively measure the extension of the catacomb galleries in all 3 dimensions.

However, the sheer amount of data that is produced by scanning and photographing a catacomb is huge (about 30GB 3D data for the Domitilla catacomb), surpassing the available memory on commodity computer hardware. Therefore, archaeologists currently only work with very small subsets of the data, which are usually converted into 3D meshes. Mesh conversion is tedious and error-prone, especially for models with a non-manifold structure, or for areas that suffer

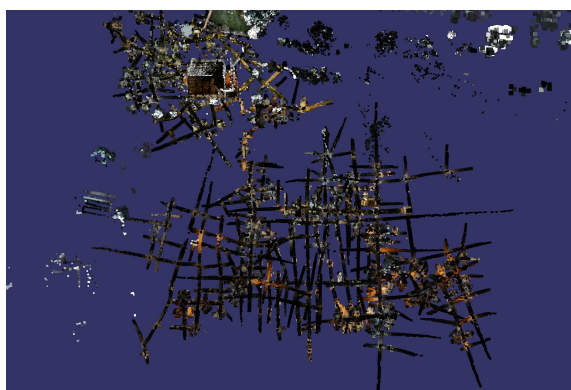


Figure 1: The model of the Domitilla Catacomb from bird's eye view. The model consists of 1.2 Billion points.



Figure 2: (Left) A close up of the bird's eye view of the model. (Center) The viewpoint is hovering between the 1st and 2nd floor of the catacomb, showing the detailed scanning of the galleries. (Right) A cubiculum from the inside. The registration markers are clearly visible.

from undersampling, both of which appear inevitably when scanning large monuments. Furthermore, a mesh is already an interpretation of the original data, which is often not desired by archaeologists.

For these reasons, mesh conversion may be suitable for small artifacts like statues, or for producing high-quality visualizations of small parts of a monument. But especially in a large monument like a catacomb, it is important to be able to interact with the whole monument at any one time. Therefore the only resort is to work with a severely subsampled version of the original data set, for example using an in-core point renderer, which is usually part of the software that comes with the laser scanner. However, subsampling makes it impossible to inspect details, and simple point renderers use constant splat sizes, causing surfaces to “dissolve” when approached. This makes it difficult to get a correct 3D impression of the model.

In this paper, we use the example of the Domitilla Catacomb (see Figure 1) to present a point rendering system that overcomes the drawbacks of mesh conversion and simple point rendering: the system uses the *original points* from the laser scans, but has no limits on the size of this point cloud for visualization and interaction. Furthermore, the system estimates a *closed surface* on the point-based model on the fly, which can then be used for easy selection of points. The selected points can then be deleted or segmented. The system builds on a hierarchical out-of-core representation of the point cloud that is fast to create.

While high-quality accurate reconstruction using meshes might be necessary for some tasks, one important contribution of this work is that we show that there are many tasks that can be carried out perfectly well using the raw point cloud, making direct point visualization and interaction an extremely relevant topic for archaeological work. These tasks include exploring the large-scale structure of the model, classification of findings, taking measurements, virtual anastylosis (i.e., creating hypotheses about the original structure of the monument), creating sliced views, visualizations limited to different building phases, and acquiring

an understanding of the 3D structure of the monument in general. The system we present makes all these tasks possible due to the interactivity afforded by the out-of-core data structure and rendering algorithm.

2. Previous Work

The documentation of the geometry of archaeological monuments, buildings, or findings by laser-scanning evolved rapidly over the last years, as scanning devices became more precise and are able to record more points in one pass [Rie09]. One of the first large scan projects was the Digital Michelangelo Project [Lev99], where 10 statues created by Michelangelo were digitized. The largest single data set, the statue of David, consists of 2 Billion triangles. For visualization the models were resampled, and point-based models were created. The largest point-based model consists of 127 million points, and is rendered with the QSplat system [RL00], which is an out-of-core point-based rendering system based on the software rendering pipeline, i.e., it uses no hardware acceleration as found on graphics cards today. The models were scanned using triangulation laser scanners.

The huge difficulties encountered when working with such huge point datasets were already reported by Beraldin et al. [BBC*06], who acquired about 630M points while scanning of a large subterranean area, the Grotta dei Cervi, a Neolithic cave located in South-eastern Italy.

Havemann et al. [HFDA03] discuss different LOD techniques and rendering acceleration techniques for large archaeological polygon-based models. Boubekeur et al. [BDS05] convert large “surface-like” point data sets into a coarse mesh, and recover the details of the point scans by calculating and rendering normal maps. The simplification allows for fast, appearance preserving rendering on today's graphics hardware.

For general point-based models, Duguet et al. [DDGM*04] presented a multi-resolution data structure that uses hardware acceleration to render point-based models which fit in memory. The data structure was used

for the visualization of a laser scanned model of the Ancient Greek “Dancers Column” monument in Delphi. Guidi et al. [GRR*08] present an approach for the integration of multi-sensor, multi-resolution data, where the archaeological site of the Roman Forum of Pompeii can be explored in resolutions from aerial photographs to very fine details. The high-resolution models are recorded with terrestrial laser scanners for geometric data, and digital cameras for the texture of the objects. The resulting data (the laser scanners gathered 1.2 Billion points), was then subsampled for visualization.

Several other point rendering data structures and point rendering algorithms were developed. Dachsbaue et al. [DVS03] developed a hardware accelerated LOD point rendering algorithm for models that can be stored in-core. At full resolution the rendering speed decreases significantly, because all points have to be rendered. Gobetti and Marton [GM04] showed a point rendering system for very large models that uses only the points of the original point cloud and is therefore memory efficient. The point-based models have to be preprocessed though, because they assume a homogeneous point density for rendering. Pajarola et al. [PSL05] extended the work of [DVS03] for an out-of-core setting. They had to introduce a global indexing scheme on the point data, which makes their data structure not well suited for manipulations on point clouds. Wand et al. [WBB*07] present a multi-resolution data structure that can be used for interactive visualization and for editing of point clouds, but it requires 3 times the size of the original point data on disk.

3. Domitilla Catacomb

3.1. History

The Domitilla Catacomb in Rome is the largest of more than 60 catacombs in Rome. It was built not only as a large subterranean graveyard, but also as a place of pilgrimage. It holds artifacts of the early Christian communities like wall paintings and inscriptions, but also a subterranean basilica. The catacomb grew within a period of some 300 years, beginning from the late 2nd century, from isolated tombs to a network of 15km of galleries on 4 different levels. Some galleries have a height of 5 meters, which seems to be the result of several building phases. There are also separated tombs which can be accessed from the galleries. About 80 of these tombs, called cubicles, feature artistic wall paintings. Until the 8th century, the catacomb was used as a place of pilgrimage to the graves of the two saints Nereus and Achilleus. When their relics were moved to another place, the catacomb fell into oblivion until the 17th century. At that time it was rediscovered and has since been studied by archaeologists. Even after 400 years of research, a complete documentation of the findings and the structure of the catacomb is not available [ZE07].



Figure 3: This cubicle in the region “Flavi Aureli” cannot be reached at-grade. The red lines denote the different height levels of the floor (a difference of more than 2 meters) and were later added to the image for visualization.

3.2. Model of the Domitilla Catacomb

In 2006, the Austrian Science Fund project “The Domitilla-Catacomb in Rome. Archaeology, Architecture and Art History of a Late Roman Cemetery” started to document the current state of the catacomb, including galleries, paintings, and finds. The 3D structure of the catacomb is recorded with a RIEGL LMS-Z420i laser scanner, capable of scanning 12,000 points/s in a range between 1-800m and with a depth accuracy of $\pm 10\text{mm}$ (standard deviation). Each scan is colored by photographs taken while scanning by a Nikon D100 digital camera mounted on top of the scanner. For lighting the photographs a flash has been used. The individual scans were registered in a global coordinate system using markers. In some particularly interesting areas, paintings were also photographed separately with a Canon 1Ds. Photogrammetric methods [ADA09] were used to get fully textured mesh models [May08]. From reduced versions of the point clouds, archaeologists also created 2D plans using standard software [Geo09, ZE07].

Scanning a confined space like a catacomb proved difficult because each scan position only captured a small part of the structure. Furthermore, some rooms that were abandoned can only be entered using ladders (see Figure 3). At present time, after accomplishing 8 out of 9 projected scanning campaigns, most of the gallery system and the basilica has been scanned, resulting in a point cloud of about 1.2 Billion points from 1,121 individual scan positions. When only position (3 single precision floats) and color (4 bytes for RGBA) information is stored for each point, this results in a massive 19.5GB of storage space. Figure 2 shows some views of the model. The last campaign will add another 600 Million points for a total model size of about 29GB.

4. Direct Point Visualization and Interaction

For handling huge point-based models like the Domitilla Catacomb on commodity hardware, we use an out-of-core point rendering system that is based on the work of Wimmer and Scheiblauer [WS06]. We highlight here the main features and also describe some enhancements to the system, like selection, insertion and deletion of points, on-the-fly surface estimation, and an improved build-up algorithm.

4.1. Data Structure

The points are stored in an octree, where not only the leaf nodes but also the interior nodes can hold points. At each node the points are sorted into a grid. The points of one octree node are stored in one file on disk, which is encoded in a way that it can be loaded directly to the GPU when rendering the model. When points are inserted or deleted, the file of one node is easy to manipulate. The data structure uses only the original scanned points, so the memory requirements on disk are the same as for the original point cloud. The idea of the hierarchical structure is that each node is a *refinement* of its parent node, making the model more dense.

4.2. Rendering

The level-of-detail algorithm for rendering the point cloud collects all points from the upper levels of the octree to render the current LOD. Rendering continues down the hierarchy to a front of nodes that are within the view frustum and are at the correct LOD, i.e., one cell of the contained grid projects to approximately one pixel. Interactivity is guaranteed by rendering only nodes that fit within a prescribed rendering budget, where nodes are prioritized according to some properties like eccentricity, detail level etc. Nodes that are not currently present in memory are requested from disk in a separate thread.

We do not do any splat size or normal vector estimation in preprocessing. However, it is important to render surfaces in the model without holes. In order to allow this, we estimate surfaces on the fly. Starting with the sizes of the grid cells of the rendered nodes, point sizes are adapted so that areas that are sparsely sampled are rendered with larger points, while densely sampled areas are rendered with smaller points.

4.3. Build Up

The data structure is built using an out-of-core algorithm. The input is a set of registered point clouds. In the first pass the bounding box of the model is created, and the points are stored in a binary stream on disk. In the second pass the points are sorted into the octree in such a way that each grid cell stores at most one point. In comparison to the original algorithm, points are inserted in batches of several thousand points. Furthermore, each octree node stores a regular grid instead of a secondary octree, which facilitates calculating

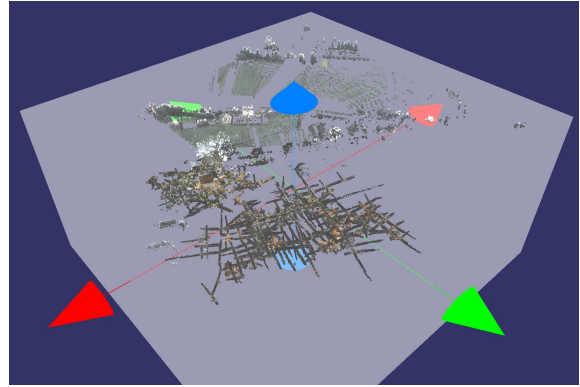


Figure 4: The box-tool can be used to cut outliers.

the position where the inserted point should end up. These improvements result in a speedup of about 3, so that processing the Domitilla model takes only slightly more than 2 hours.

4.4. Editing

Editing functionality is crucial for end-users like archaeologists. The most important features are selection, deletion and insertion of points.

For selection, we use a brush that always follows the surface of the model. Currently the brush has the shape of a sphere. If the user is in selection mode, all points within the brush are selected and rendered in a particular color. The selection of points persists even if the user moves within the point model, which is achieved by representing the selection as a separate data structure that “filters” points when they are loaded from disk. We can change the display format of the selected points and render them invisible to simulate deleting the points. Selecting and deselecting points and rendering a preview of the model are interactive operations and therefore do not block the workflow of the user.

Points can also be deleted completely from a model. Points from new scan positions can be added to an existing model, avoiding a complete new build up of the model. Deleting and inserting points cannot be done in real time, since the points are edited directly on disk, resulting in many disk accesses.

We also allow other tools for quick selection, like a box-tool (see Figure 4) that can be moved, scaled and rotated in order to quickly generate arbitrary cuts through the model.

4.5. Hybrid Rendering

The point-based model of the catacomb and the mesh-based models of the paintings can be rendered at the same time, resulting in a combined display of the point-based raw data

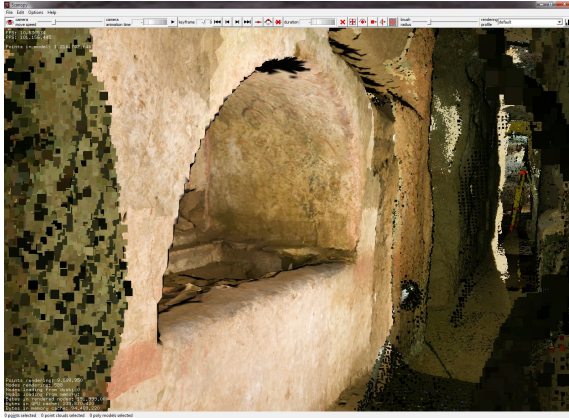


Figure 5: A mesh model of an arcosolium placed within the point cloud.

and the high-quality mesh models. An example can be seen in Figure 5.

5. Exploration

With the system described in this paper the user can explore huge point-based models like the Domitilla Catacomb interactively. One main point we wish to make in this paper is that using a raw point model and our system, a number of different archaeological tasks, as detailed in the following, can be completed without having to resort to mesh generation or other costly preprocessing operations.

5.1. Understanding the Complexity

Maybe the most immediate benefit of always having access to the whole model is that it allows users to quickly gain a thorough understanding of the object. When moving around the model fluidly, the parallax effect between close and distant areas gives important hints on the 3D structure of the object. In the Domitilla Catacomb, for example, the interconnections of the subterranean galleries changed over time. Some entrances were created while others were abandoned or became inaccessible. This development can be understood better by being able to roam the model freely and fluidly, allowing quick changes of viewpoint.

A subsampled model cannot give the same information: when the user wants to investigate an area more closely, the surface structure disintegrates, and important 3D information gets lost.

5.2. Area-of-Interest Extraction

Sometimes it is necessary to extract an area from the whole point cloud, for example in order to examine an object without occlusion by surrounding geometry (like galleries). This

can be done by marking the area of interest with the brush, inverting the selection, and then making the selection invisible. In practical use, archaeologists also found it convenient to directly mark the surrounding geometry using the brush (see Section 4.4). The area of interest can also be exported for further processing (e.g., for creating a detailed mesh for a show case).

Using the scanner software would be much less convenient: there the user has to know which scans influence the area of interest, merge these scans manually and extract the area of interest in the merge result. If there are more than a couple of scans involved in the area of interest, merging is not feasible anymore because it takes too long, and the extraction has to be done separately in each of the involved scans.

5.3. Videos for Presentations

Our system also allows generating videos for presentation. This is important because especially in large monuments like the Domitilla Catacomb, a presentation of the whole model is desired, and not only of the small parts that have been meshed in high quality. Our system can generate high-quality videos by disabling the rendering budget so that rendering proceeds to the optimal level of detail for the whole scene, and estimating surfaces for close-up views. Using the scanner software, the point cloud would have to be carefully downsampled in order to allow video generation, and close-up views would have to be avoided.

5.4. Cuts, Slices, Floorplans

Many archaeological tasks involve slices through the model. Our box tool allows quickly generating arbitrarily oriented slices through parts of the model. The area selected by the box can be visualized in an orthographic view to generate for example floor plans (horizontal cut at wall height), or orthophotos of walls (for aligned vertical cuts). Again, it is very convenient to have the whole model available for these tasks and not to have to sort through individual scans.

5.5. Virtual Anastylis

Archaeologists often make hypothesis about the original structure of a monument, which can be made more tangible by actually reconstructing a part of a monument using available parts. However, actual reconstruction is expensive and cannot be undone in case of errors, or is sometimes impossible because the involved parts are simply too large. Therefore it is convenient to be able to move parts virtually. For example, columns of a temple that have been found on the ground can be selected (using the brush) and then moved around freely (by deleting them from the point cloud and reinserting them at a new position). In the Domitilla Catacomb, there are questions about the original height of the complete basilica that could be tested using our tool.

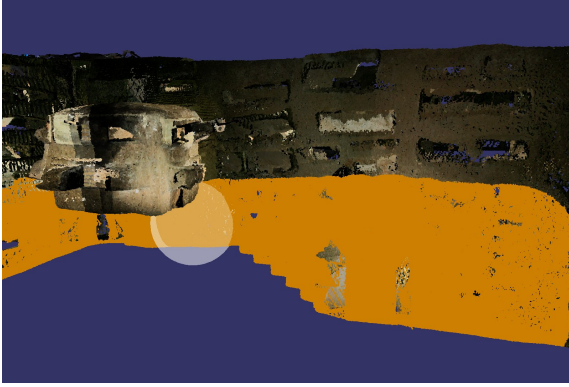


Figure 6: A close up view of a gallery in the region “Flavi Aureli”. Some areas are marked for deletion to gain a model of the initial building phase.

5.6. Measuring

Distances are easy to measure by selecting two points in the model. In the same way, it would be easy to include area and volume measurements for selections.

5.7. Reconstruction and Visualization of Building Phases

An archaeological monument is typically constructed in several distinct building phases, often spread over decades or centuries. Reconstructing the monument at a particular building phase gives valuable insights into the building history of the monument. This can be accomplished with our system by deleting the areas belonging to other building phases. An example can be seen in Figure 6. Here the building phases of the vertical high galleries are reconstructed. Initially, a gallery of the height of one man was dug out, and the cubiculum in the image was accessible at ground level. Over time the floor of the gallery was dug deeper, and the cubiculum in the image became inaccessible, at least without auxiliary means (see also Figure 3).

At a larger scale, it becomes even more important to have the whole model available for this task, for example when reconstructing different phases of growth of the whole catacomb, which started from different independent centers and grew together over time.

5.8. Impossible Views

An interactive exploration system allows views onto parts of the model that are not possible in reality, like from inside solid ground. For example, the basilica was built in honor of two saints, Nereus and Achilleus, and they were probably buried in the tombs in the center of the basilica, surrounded by the apsis. When looking from *below* the floor of the basilica towards the tombs, they are clearly visible, as can be seen

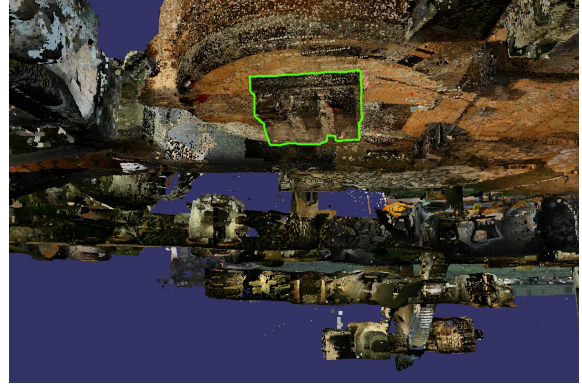


Figure 7: The tombs of the three saints buried below the basilica. The green border was added to the image to emphasize the tombs.

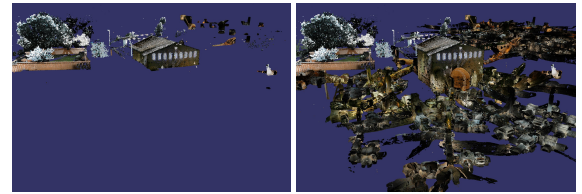


Figure 8: The basilica is partly above and partly below ground level. (Left) The point cloud is cut at the ground level, so that only objects above ground remain visible. (Right) Showing the whole catacomb, including the subterranean areas, the enormous expansion of the catacomb underground becomes visible.

in Figure 7. Views from below, or any other position normally not available, can provide a valuable tool for research. The shape of the graves and their exact position in relation to the grid of galleries could give hints on their origin.

5.9. Combining Viewing Regions

Only a virtual exploration tool allows combining model parts that are normally only visible from distinct viewing regions into one view. For example, the inside of the catacomb can be visualized together with structures that can only be seen from above ground. This allows showing which parts of the catacomb lie below which landmarks of the actual city today.

Another example is the basilica of the Domitilla Catacomb, where only the upper section of the building is visible from ground, the rest of the building is below ground level. The left image of Figure 8 shows the basilica cut off at ground level. The right image gives an impression of the landscape above the subterranean structure. The garden surrounding the main entrance of the catacomb is just above several cubicula of the Northern area of the catacomb.

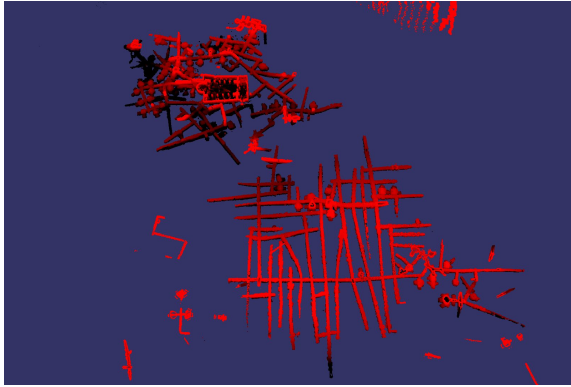


Figure 9: The second floor of the catacomb with elevation encoding. The height difference between pure red and black encoding is 3 meters.

5.10. Scan Campaign Support

Already during a scan campaign, it is very useful to have quick access to the whole model. In this way, areas that are not sampled densely enough or that are not captured at all can be identified and new scan positions can be planned.

5.11. Elevation Encoding

The model can be rendered with elevation encoding, so the user can estimate the run of the height of a gallery or an entire floor. The top and bottom height for the encoding can be chosen by the user. Figure 9 shows the second floor of the Domitilla Catacomb. The change of shading of the galleries in the lower part of the image means that the galleries are not at the same elevation over their entire extent. The height difference between pure red and black encoding in this image is 3 meters.

6. Results

We tested the system on a workstation with an Intel Q6600 Quad-Core CPU, an NVIDIA GeForce 8800 GTX graphics card, and a RAID 0+1 disk array consisting of four 10,000rpm SATA hard disks.

For building the Domitilla model, the first pass of the algorithm (creating binary stream from original scan data files, bounding box calculation) took 51 minutes. The second pass, which creates the actual octree datastructure, took 80 minutes, so points were inserted at a rate of more than 250,000 points/s in the second pass. For comparison, copying the model using the file system takes 25 minutes.

For the visualization of the model, a rendering budget of 12M points was used (taking 192MB of GPU memory, which works for all modern GPUs, including laptops), which

resulted in a minimum frame rate of 20 frames per second while navigating the model. In most areas, however, the whole rendering budget was not needed to achieve the optimum LOD, so the frame rate can be higher.

The selection of points works in two phases: in the first phase, the user drags the sphere holding down the mouse button, and points are simply marked in the color channel, which does not lead to a noticeable slowdown. In the second phase, when the mouse button is released, a data structure storing the selection permanently is created. For small selections like a chair or a human, typically consisting of several thousand points, the user will not notice any delay for this operation. For larger areas with about 10 Million points (e.g., when using a large brush), this can last up to three seconds.

The time for deleting points completely from the model also depends on the number of points to be deleted, and on the shape of the selection. Deleting an area consisting of 360M points in the center of the model, which is more than 25% of the model and thus a worst-case scenario, lasts about 7 minutes.

We tested insertion of points on a half-built model of the catacomb, consisting of 669 scans, simulating the situation during a scanning campaign. We merged the point clouds of 3 new scan positions one after the other into the model, which lasted less than 4 seconds for each point cloud.

The actual evaluation how well the system works can only be done with end users. A formal study is difficult, though, since only the small team of archaeologists and architects involved in the documentation of this particular monument can interact with the system in a sensible way. Our informal discussions with this team, consisting of one archaeologist and two architects, resulted in the feedback that the interactivity of the system and access to the whole point data set was a huge help in their work. For example, they were all able to extract a region of the model and reconstruct different building phases by removing parts from later phases, which is maybe one of the most demanding tasks described. Apart from experimenting with capabilities of the system, they also came up with several ideas for features that would support further archaeological tasks. These ideas include for example an interface for classification and categorization. In the future, we aim to carry out a more formal study to quantify the benefit of our system versus traditional methods.

7. Conclusion

We have presented a system to interactively explore and interact with huge point data sets. The system's primary application is the exploration of large archaeological monuments that have been acquired using laser range scanning technology. We demonstrate the system on the example of the point data set of the Domitilla Catacomb, the largest catacomb in Rome. The model currently has about 1.2 Billion points, taking 19GB of storage space. Our system combines an out-of-

core octree data structure with fast interactive manipulation tools like a selection brush and the deletion or insertion of points. One important contribution of this paper is to show that many common archaeological tasks do not require conversion of the model into a high-quality mesh, which is a costly process. Instead, it is sufficient to work with the raw point data set, which our system makes accessible in an interactive way, providing intuitive manipulation tools aiding these tasks.

In the future we would like to include a classification mechanism, so that objects can be ordered and named. This could include information like the construction date, a time span for the usage of an object, the name of the material, or the theme or dating of a painting. For classification the user could take a laptop into the catacomb, with the model of the catacomb stored on the laptop, and classify the points on-site directly within the point cloud. Using these classifications it will be possible to select and visualize points based on their class.

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For more information on the Domitilla Catacomb documenting project, please visit the website http://www.oeaw.ac.at/antike/institut/arbeitsgruppen/christen/domitilla_engl1.html.

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