

A SOFTWARE SYSTEM TO WORK WITH 3D MODELS  
IN CULTURAL HERITAGE RESEARCH

by

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IN CULTURAL HERITAGE RESEARCH

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# Dedication

Dedicated to friends, family, and all my tutors.

# Acknowledgements

I would like to express my gratitude and appreciation to my thesis advisor Selim Balcisoý for his support and guidance through my masters education.

My sincere thanks goes to members of the Computer Graphics Laboratory whom I had the pleasure to work with. They include Selcuk Sumengen, Basak Alper, Ceren Kayalar, Ekrem Serin, Ismail Kasarci, Billur Engin, Merve Cayci, Mustafa Tolga Eren and Uraz Cengiz Turker.

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## Abstract

The availability of intuitive, user-friendly and specialized software to work with 3D models of cultural heritage artifacts is as important as the availability of low-cost and robust data acquisition techniques for the adoption of digitized 3D models in cultural heritage research. As recent developments in 3D scanning technologies have made the digitization of artifacts affordable; the amount of digitized models available for research increases rapidly. Consequently the need for specialized software for cultural heritage research and practice on 3D models becomes more apparent. The lack of spatial measurement tools familiar to cultural heritage experts in traditional 3D modeling packages motivated us to create a simple, freely available, and extensible measurement tools system, CH Toolbox, which was designed exclusively for cultural heritage research. The proposed system visualizes digitized models of artifacts in 3D and allows the user to analyze the pieces using a spaceball and mouse driven bi-manual interface. We describe here the component of the CH Toolbox system, specifically the virtual tape measure, caliper, rim chart and an surface area estimation tool. Additionally, we present justification for CH Toolbox's bi-manual interaction scheme according to Guiard's Kinematic Chain model for asymmetric human skilled bi-manual actions. We also discuss the design decisions that were taken for producing an extensible and free software system based on open standards and widely available open source technologies, such as the OpenGL graphics and the OpenSceneGraph scene hierarchy libraries.

# KÜLTÜREL MİRAS ARAŞTIRMALARINDA KULLANILMAK ÜZERE 3B MODELLER İÇİN GELİŞTİRİLEN BİR YAZILIM SİSTEMİ

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Anahtar Kelimeler: bilgisayar grafikleri, kültürel miras, çift-elli etkileşim,  
3B modeller

## Özet

Bilgisayar destekli arkeoloji ve sanat tarihi araştırmalarının yaygınlaşması için kültürel miras sayılabilecek arkeolojik buluntu ve sanat eserlerinin 3B modelleri üzerinde çalışmak amacıyla özel olarak geliştirilmiş ve kullanımı kolay yazılımların varlığı en az ucuz ve başarılı 3B sayısallaştırma yöntemlerinin varlığı ve yaygınlığı kadar önemlidir. 3B tarama tekniklerindeki gelişmeler sayesinde bahsedilen türde araştırmalara uygun 3B model miktarı da her geçen gün artmaktadır. Be ve benzeri modeller ile çalışan yazılımlardaki uzaysal ölçüm araçlarındaki eksiklik veya bu araçların kullanımındaki zorluklar bize uzmanların sıklıkla kullandığı bazı ölçüm araçlarının sanal hallerini geliştirmek için ilham kaynağı oldu. Geliştirilen sanal mezura, yarıçap tahmini, kompas, ve yüzey alanı tahmin araçları CH Toolbox adı altında toplanmışlardır. Araştırmamızda bu araçların geliştirme aşamaları ve detaylı anlatımlarına ek olarak, CH Toolbox'ın kullanıcı arayüzü olarak seçilen çift-elli etkileşim yönteminin Guiard'in yetenek gerektiren asimetric çift elli hareketler üzerine oluşturduğu Kinematik Zincir modeline göre tasarımda göz önüne alınan noktalar da anlatılmaktadır.

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# Chapter 1

## Introduction

This thesis deals with the design and development of a software system to work with 3D digitized models of cultural heritage artefacts and works of art. The work done can be summarized as investigating the workflow of cultural heritage researchers, analyzing their needs and requirements from such a software package, analyzing the usage of the tools chosen for implementation, devising an interaction scheme to maximize the ease of use and adoption of the software system, and finally the implementation of the tools according to the requirements collected by adopting appropriate techniques used in other computational geometry tasks.

Our contributions are :

- Introduction of an easy to use application for cultural heritage researchers to work with high detailed digitized 3D models of artefacts and works of art.
- Development of computer-aided versions of four spatial measurement tools that archaeologists, art historians, and other cultural heritage workers use in their workflow by adopting algorithms for other computational geometry tasks. The tools include an interactive tape measure, caliper, rim chart, and surface area estimation.

- Introduction of bi-manual asymmetric interaction to the computer assisted cultural heritage domain.

Two peer-reviewed publications have resulted from the work presented in this thesis. The tape measure and rim chart have been introduced in [29], followed by [30] where the caliper and a discussion of the interaction scheme was added.

The document starts with giving background information about the use of computer graphics in cultural heritage applications. Then, a review of the commonly used methods for digitization of artefacts and works of arts is presented. The next chapter defines the research problem and presents our motivation for choosing this topic. The asymmetric bi-manual interaction scheme design is presented next, followed by detailed descriptions of the tools themselves. Finally the document is finished with tests results, concluding remarks, and suggested topics for the future direction for this research.

# Chapter 2

## Background Information

### 2.1 Computer Graphics and Cultural Heritage

The increase in computing power and its availability, combined with the interest in preserving and displaying items deemed part of humanity's cultural heritage has made cultural heritage an important application domain for computing and information technology.

Berndt and Teixeira [3] state that these applications generally target two different groups of users;

First, a broad target group primarily consists of the general public, educational professionals, administrators, and investors. The main focus for this group is on presentation. A second target group consists of the experts themselves (such as art historians, historians, archaeologists, restorers, and so on), who are concerned with the collection, preservation, exploration, and mediation of our cultural heritage.

It can be said that the first group does and will directly benefit from the advances in the following areas of computer graphics research; photorealistic and non-photorealistic rendering (NPR), real time rendering which focuses on rendering for interactive applications, and specialized graphics hardware such as graphics processing units (GPUs). The increasing knowledge on rendering techniques will enable better presentation and the increasing processing power and consequently decreasing costs will enable more people to enjoy cultural heritage applications. Another important area with respect to presentation is display technologies. Bigger, sharper, and cheaper displays (both in traditional 2D and stereoscopic 3D) will spur greater adoption of computer graphics applications in cultural heritage.

The second group, on the other hand, demand better and more reliable ways of conducting research using computer assisted tools. Advances in computer vision help to create more accurate and more robust 3D scanners, which in turn enable the creation of better 3D digital replicas of cultural heritage sites and artifacts. Similarly, advances in computational analysis and human-computer interaction allow the creation of more advanced application software that eases research.

Similar to Berndt and Teixeira's categorization of end users, Sanders [34] further breaks down the two groups of users into the following five distinct target groups;

1. Archaeologists and historians,
2. Museums and on-site interpretation centers,
3. Schools and educational professionals,
4. Experimenters,
5. The entertainment industry

The reason for the first group's interest in computer assisted tools and virtual heritage applications, Sanders argues, is directly related to their professional interest



in learning more about the past. Thus archaeologists and historians have a pragmatic view about the use of computer graphics in the cultural heritage domain, i.e. they want to use these applications to do research, analyze sites or artifacts, and train new researchers. This group naturally prefers scientific accuracy and detail over a pretty rendering of the past produced with much speculation.

According to Sanders, the second group consists primarily of museums that have a collection of artifacts that have been thoroughly researched and catalogued. This group is interested in digitizing parts of their collection in order to produce content that can be used with digital media. They want to create digital exhibitions, show catalogues, and advertisement material to draw more interest to the original artifacts and to supplement their exhibits.

Continuing with Sanders' categorization, the third group is made up of educators that are searching for new teaching materials and cost-efficient systems to enrich the educational experience they provide. Although the level of education can vary greatly from institution to institution (i.e. from kindergarten to the university level), the needs of this group stays relatively similar between themselves as most teaching materials must be closely tied to a curriculum and follow a pre-defined lesson plan.

The experimenters group is different from the others in that they see the digitized cultural heritage content as a means to an end and not as the central piece of their work. As Sanders states;

This group ... often is focused on immediate results to suit a specific (and usually time-limited) purpose. Those purposes may be fulfillment of a course requirement, supplemental material for thesis work, testing specific capabilities of hardware system, such as new 3D scanners or projection systems, or testing the limits of new software (such as generating more realistic lighting or modelling better people). These experimenters are less interested in meticulous scholarly accuracy, richly detailed worlds,

or linked datasets and are more interested in proving a particular point or demonstrating specific functionality. [34]

The last target group is the entertainment industry which includes computer game development companies and the movie production studios. The needs of this group is different from the rest, as they are mostly interested in superior graphics at the expense of scientific accuracy.

# Chapter 3

## Review of the State of the Art

### 3.1 Creation of 3D Models

A detailed digital 3D model is obtained either through 3D optical scanning or it is created using a 3D modeling software, such as Maya and 3Ds Max, with the help of photographs, drawings and measurements of the cultural heritage artifact. The quality of a manually created 3D model depends on the accuracy of the measurements taken with optical theodolites, tapes and calipers [22]. A major drawback of manual modeling is the amount of time it takes to collect the data and then model the artifact. 3D modeling skills of the researcher and familiarity with the software is an important factor determining the cost and quality of the digital reproduction.

Comparatively, automated or semi-automated 3D modeling is usually a faster way to produce more accurate 3D models. Automated modeling is achieved by first generating numerous partial range images of the artifact from all sides, then aligning these images, and finally merging them to create the 3D geometric mesh of the object [18]. The geometric mesh is then combined with the intensity image, usually a photograph of the subject, to create the final textured model. Figure 3.1 shows the mentioned steps in the automated modeling process.

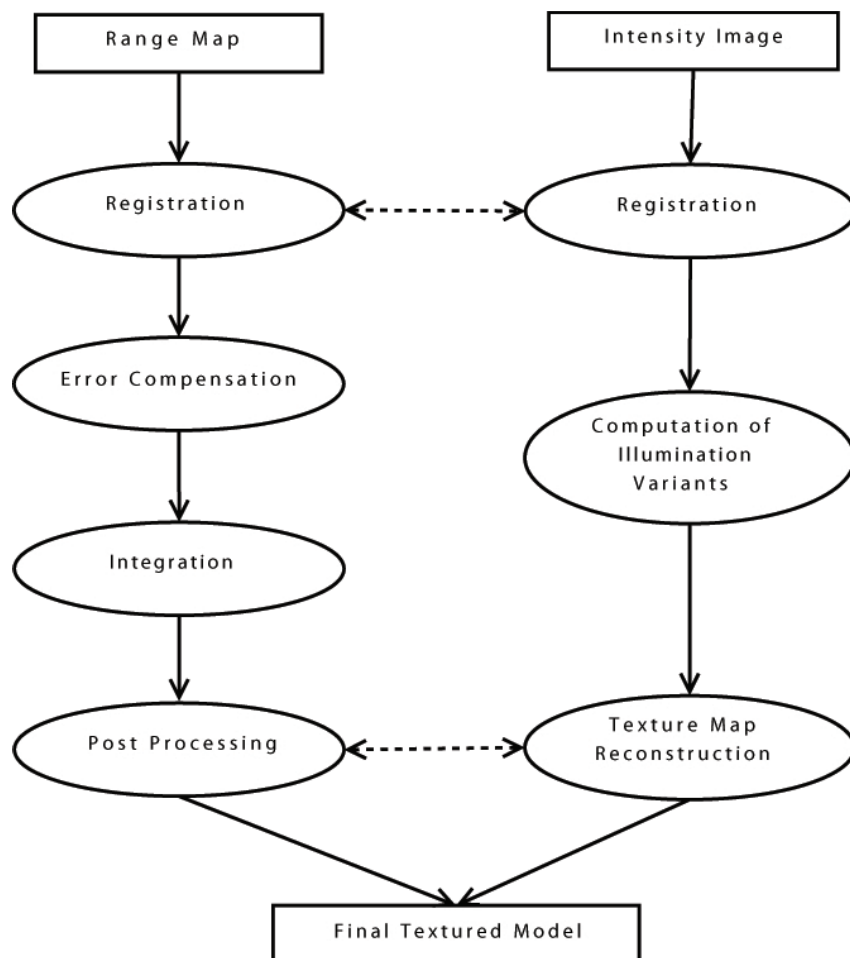


Figure 3.1: A diagram showing the steps in the 3D scanning process.

Range images, or maps, can be obtained with two different techniques, triangulation or time-of-flight (TOF) based scanning. See Figure 3.2 for a summary of these two common techniques.

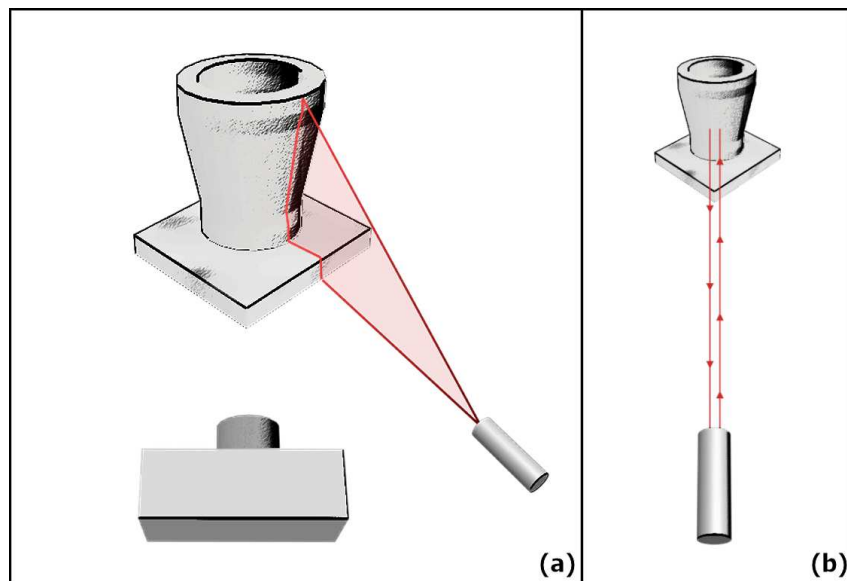


Figure 3.2: (a)Triangulation based scanning works by analyzing the captured projection of a defined pattern, here a straight line. (b)Time-of-flight based scanning works by measuring the time it takes for a reflected laser beam to travel back to the source.

### 3.1.1 Triangulation Based Scanning

Triangulation based techniques work by capturing a photograph or video frame of the object to be scanned that has been illuminated using a striped laser or light pattern. Afterwards, the projection of the pre-determined pattern on the surface of the object is used to generate a cloud of points with the help of image processing algorithms. This range image consists of the set of distances between the sampled points on the surface and the camera. As this range image is derived from a 2D photograph, a

single image is not sufficient to generate a point cloud that completely describes the object. A number of such partial images taken from different sides of the object, combined with the knowledge of the position and orientation of the camera, if the object is stationary and the camera is moved, or the knowledge of the axis and angle of rotation of the object, if the camera is kept stationary and the object revolved on a turntable, are aligned using complex algorithms to produce complete point clouds.

The accuracy of a range map produced with triangulation depends on the distance between the camera and the object, thus the striped area photographed must be kept small for accurate results. This in turn increases the number of range images that must be taken to cover the object and results in a increase in the time needed to scan the object and align the range images. Depending on the size of the object, hundreds of scans might be needed to keep the error in the range of 0.1 mm. [14]

### **3.1.2 Time-of-Flight Based Scanning**

The main difference between TOF and triangulation based scanning is the technique used to generate the point cloud describing the scanned object. The time of flight of laser pulses sent to the surface of the object is used to determine the distance between the light source and a point on the surface. This distance, combined with the vertical and horizontal angles between the point and the light source, is used to create the partial range image. Similar to triangulation based scanning, these partial maps then must be aligned to produce the cloud of points that completely describe the scanned object.

The error of TOF based scans is usually measured in centimeters, which is much worse than triangulation based scans. The strong point of this technique is that it allows long range scans and it is a faster process. Consequently, it is used in situations where close scanning and lengthy scan times would be harmful to the scanned artifact and the site it belongs to, or when the error rate is found to be acceptable for the

intended use of the 3D model.

## 3.2 Trends in 3D Scanning Technologies

One of the requirements for heritage applications that are made for analytical research is their need for high quality data. Godin et. al. [10], in their survey of scanning technologies for heritage applications, state that a high-resolution 3D model contains a wealth of information available for analysis, which in turn allows the study of fine details such as tool marks or surface texture.

The use of 3D scanning in cultural heritage research has been successfully demonstrated in a number of projects to produce very detailed 3D models of sculptures, building, structures, and archaeological finds [2, 21, 27]. In the next paragraphs I will list some of the important projects that aimed to construct highly detailed 3D geometric models of works of art or archaeological sites.

In 2000, Levoy et. al. [21] demonstrated the results of their Digital Michelangelo Project. The goal of the project was to make a detailed 3D archive of as many of Michelangelo's statues as could be scanned in a year. Levoy et. al. state that their particular aim was to capture the geometry of his chisel marks, which was found to require a resolution of 1/4 mm, and to scan the famous David statue that has a height of 5 meters not including the pedestal. During the 1998-1999 academic year the project team, which consisted of 30 faculty, staff, and students, were able to digitize 10 statues by Michelangelo, including the well-known figure of David, two building interiors, and all 1,163 extant fragments of the Forma Urbis Romae, a giant marble map of ancient Rome. Their work is considered to be one of the first demonstrations of scanning a large work of art in field conditions.

One statue of Michelangelo that was not scanned in the Digital Michelangelo Project, the Florentine Pieta, due to logistic problems was digitized by Bernardini et.



Figure 3.3: The scanner mounted on a moving platform to scan the head of the David statue as part of the Digital Michelangelo Project.



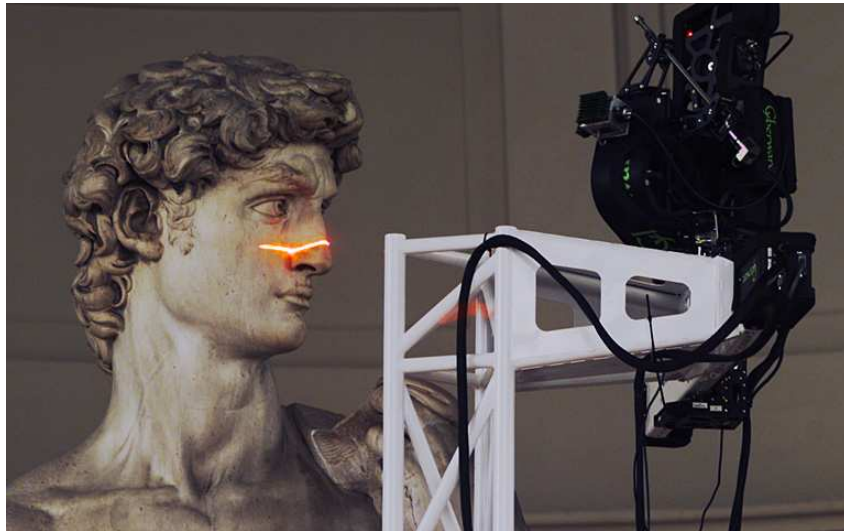


Figure 3.4: A close up showing the scanning of the head of the David statue.

al. [2] in the year 2002. Their aim, in addition to developing a more robust and cost effective 3D digitizing system, was ‘not simply to produce a model of the statue but also to provide the art historian with material and tools to enable him to answer his own research questions’. They also state that providing a precise measurement tool that works on the virtual model allowed the art historian to better understand the sculptor’s use of perspective and composition.

Again in 2000, Miyazaki et. al. [27] successfully scanned the Great Buddha of Kamakura. They state that although their project is quite similar to the Digital Michelangelo project, there were two points that made a different approach necessary. First, the size of the Great Buddha is almost thrice the David (15 meters compared to 5 meters), and second the Great Buddha is situated outdoors while the David figure is inside the Museo dell’Accademia. In order to compensate for the effects of sunlight on the scanning process, the members of the Great Buddha Project had to use a more powerful range sensor. The project is continued to this day and has

been extended ‘to create a digital library of the world great Buddhas, including three Japanese Buddhas, Sri Chum Buddha in Thailand, and Biyons in Cambodia’ [17].

As with any emerging technology, these initial systems are hard to operate, fragile, and are prohibitively expensive. Recent work in the area is in the direction of producing low-cost, robust, accurate, and automatic 3D scanning systems [18, 5, 31].

Kawasaki and Furukawa, present their model acquisition system and hand-held 3D digitizer with claims to improved user convenience. Their proposed system consists of a laser projector and a turntable, both tracked using computer vision techniques, and a video camera to track them [18]. Figure 3.5 shows the proposed 3D scanning system.



Figure 3.5: A computer vision based handheld 3D scanning prototype.

Another low-cost 3D scanning setup is presented by Pheatt et. al. which consists of digital camera, a motor controlled turntable, laser diodes, and a simple micro-controller [31]. They claim a cost of \$250, excluding the camera and the PC, for the whole system. Callieri et. al. [5] also state that 3D scanning remains an expensive process and underutilised technology and they tackle the problem by presenting a robot-controlled and unattended 3D scanning system called RoboScan. Their contribution is the development of a new software system to control a commercially available 3D scanner moved by a robotic arm and a turntable that rotates the scanned object.

The system is self-planning and can finish a complete scan unsupervised.

### 3.3 Applications That Work With Digitized Artifacts

After a high detailed scan of an cultural heritage artifact has been obtained and verified the resulting 3D model can be used by architects, archaeologists, restorers, and art historians for their research and professional work. These software applications should be able to visualize and let the researcher work on such huge models interactively to be considered succesfull. Applications that fit this criteria will be briefly introduced in this section.

Cavalieri [4], a computer-aided drafting system presented by Callieri et. al. in 2006, is a software application that semi-automatically produces large format prints of technical drawings called drafts of cultural heritage artifacts. Their system is designed to work on already available higly accurate 3D digital models and their target audience is restorers and archaeologists that have to rely on hand drawn technical drafts for part of their work. The proposed computer-aided approach is meant to augment and replace manual technical drawing, which the authors argue is ‘time-expensive and heavily dependent on human contribution and skill’. The resulting system is able to produce accurate technical drawings of the artifact according to the researcher’s wishes using standard 3D rendering techniques such as flat shading with per face normals or smooth shading with per vertex normals. The screenshot in Figure 3.6 shows the interface of the application that allows the user to set up the parameters for producing a draft from a detailed 3D model of the Minerva statue.

One drawback of using photorealistic rendering for producing drafts is that the resulting prints do not look like traditional drafts which use techniques like stippling

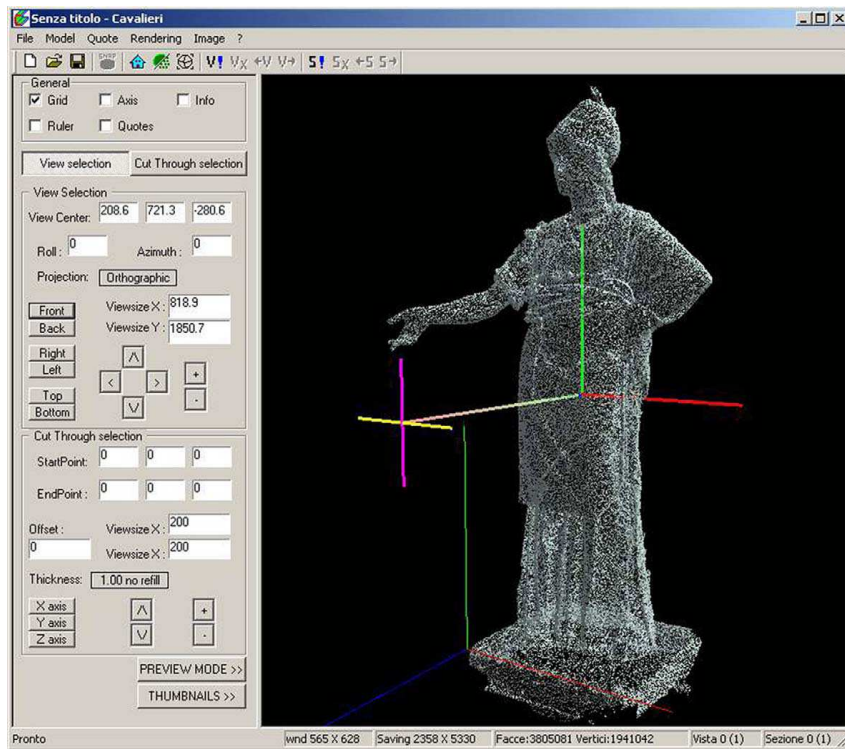


Figure 3.6: Screenshot from the Cavalieri computer-aided drafting application.

or hatching with vectorial elements in order to convey shadows, depth, shape, and curvature information. The advantage of non-photorealistic rendering techniques is that the resulting drawing is easier and faster to understand by humans, and also is more robust to low quality copying and printing [11]. See Figure 3.7 for a comparison between the software rendered draft and a traditional draft produced by a skilled artist.

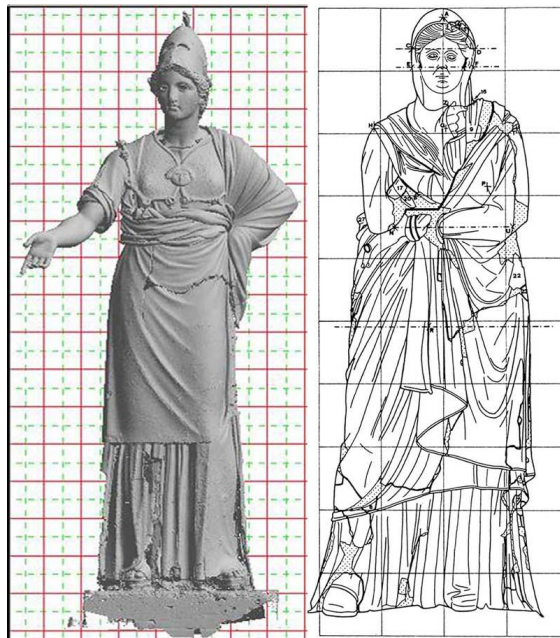


Figure 3.7: The traditional technical drawing of the statue conveys more meaning in simpler curves and shadows even though the rendered model is more realistic.

# Chapter 4

## Problem Statement

Although the use of digitized models in cultural heritage research is beneficial, the adoption of such techniques is problematic because nearly all experts are trained for using traditional tools on physical artifacts. Both 3D scanning and 3D modeling requires familiarity with the hardware and software in order to produce digital models of required accuracy and detail for analysis and visualization tasks. As recent developments in 3D scanning technologies have made the digitization of artifacts affordable; the amount of digitized models available for research increases rapidly. Consequently the need for specialized software for cultural heritage research and practice on 3D models becomes more apparent.

The problem with using existing 3D modeling software for cultural heritage research on digitized artifacts is that effectively using these programs needs additional expertise with the software and user interface which the researcher may lack. Such software are usually general purpose modeling tools or designed for digital content creation, architecture, or manufacturing and thus do not mimic the traditional way cultural heritage researchers work with artifacts. Therefore, practitioners of the field cannot easily transfer their expertise in the domain to new software tools without further education or specific guidelines [16]. Applications targeting specific tasks such

as archaeological pottery reconstruction exist, but they are limited by their tight focus and cannot be easily extended to other domains in analytical cultural heritage research [24, 33]. Similar problems arise in the medical field as well, where the discrepancy between computer tools and formal education methods is acknowledged. In the medical domain, the generally preferred solution to this problem is to present tools with a familiar interface based on their real world counterparts [32].

# Chapter 5

## Description of the System

### 5.1 Design Decisions

CH Toolbox is a 3D application framework for analytical cultural heritage research. It visualizes digitized models of artifacts in 3D and allows the user to analyze the pieces using a spaceball and mouse driven interface.

Several designs were considered for the user interaction scheme of CH Toolbox. One important consideration was the scope of functionality, meaning both the number of distinct tools and the way these are presented to the user, that was suitable for CH Toolbox in order to make it as accessible as possible for cultural heritage researchers with differing backgrounds and computer skills. Grossman et. al. [12] consider the same issue in their digital tape drawing application, a computerized version of the technique commonly used by artists in car design, and say that although additional functionality similar to 3D modeling programs would be beneficial, the amount of functionality that can be introduced before tape artists reject it because of the perceived similarity with complicated 3D modeling software is an important question. The question is of similar importance in the design of CH Toolbox, and in the end we chose to present only a small subset of the possible functionality in order to keep



our tools as simple and as close as possible to their real-life counterparts.

### 5.1.1 Interaction Methodology

The three main operations in CH Toolbox are camera control, model selection and manipulation, and tool utilization. Typically the user moves the camera to get an understanding about the object loaded into the environment and to find a suitable view for using the tool that is to be utilized next. Object selection and manipulation is useful in situations where more than one 3D model is visualized and the user finds it beneficial to move and orient the object instead of controlling the camera. Tool selection and utilization commonly comes only after the user is satisfied with the position and orientation of the camera and the 3D model. According to Balakrishnan and Kurtenbach [1], these actions can be categorized as either pragmatic or epistemic actions. All of camera control and some object manipulation are considered epistemic actions if they are done with the intention of increasing perception and cognition. All other actions, such as tool selection and utilization, done with the intent of getting closer to accomplishing certain goals of a task are considered pragmatic actions. Epistemic and pragmatic actions complement each other, thus they do not necessarily have to be in sequential order and can be conducted in parallel.

Asymmetric bi-manual interaction is a familiar human trait that lends itself well to such parallelized actions. Guiard [13] lay the theoretical foundations of skilled bi-manual action with his Kinematic Chain model in 1987. According to his model, humans accomplish many tasks with two hands complementing each other. He states three principals that govern the asymmetry of human bi-manual gestures:

1. Right-to-Left Spatial Reference in Manual Motion,
2. Left-Right Contrast in the Spatial-Temporal Scale of Motion,
3. Left-Hand Precedence in Action.

Guiard's terms refer to a right-handed person, thus the dominant hand is right hand and the non-dominant hand is the left hand. The following subsections explain these principals and their impact on our user interaction design.

### **Right-to-Left Spatial Reference**

Guiard's first principle is that in bi-manual motions of the right hand finds its frame of reference from the motions of the left hand. He gives the examples of handwriting and sewing for actions where the left hand orients and stabilizes the subject of the motion so that the right hand can perform its manipulating motion easier.

This principle can also be observed with the spatial measurement tools that we adopted for use with digital models. A tape measure is used unrolling the tape with the right hand while the left hand stabilizes the starting end of the tape. A caliper is used by holding the object to be measured with the left hand while the right thumb carefully adjusts the jaws of the caliper to fit the object. The usage of a bordimeter is similar to handwriting, because the left hand stabilizes the paper in both cases.

### **Asymmetric Motion Scale**

The second principle states that the two hands operate in different scales during bi-manual action both temporally and spatially. The left hand moves less frequently and makes comparatively larger movements than the right hand.

We can again confirm this principle in the utilization of the spatial measurement tools selected for CH Toolbox. The right hand performs the fine adjustment of either the tool, by moving the measuring end of the tape, altering the jaw opening of the caliper, or the object, by positioning the rim sherd to fit the circle drawn on the bordimeter.

### **Left-Hand Precedence**

The last principle follows the first principle, and it states that in a human skilled bi-manual task, the left hand starts its action before the right hand. This principle is observed especially in tasks where the postural and manipulative roles of the hand are clearly separated, e.g. handwriting, sewing, driving a screw.

Such a distinction between roles is also apparent in the usage of tapes and calipers, and consequently the principle of left-hand precedence can be observed in these actions. In the case of the tape measure, the left hand must place and hold the end of the tape before the right hand can unroll it. Similarly, in the case of caliper use, the left hand must position and hold the object to be measured before the right hand can position the caliper and adjust its dial to obtain a precise measurement. In the final case of bordimeter use, the left hand must hold the paper steady while the right hand moves the sherd to be fitted, and thus its actions must precede the actions of the right hand.

### **5.1.2 Input Device and Interaction Scheme**

Based on the initial analysis of the real world counterparts of the spatial measurement tools and their usage, we chose a bimanual interaction scheme for CH Toolbox, where the mouse is used to switch between tools, toggle visualization modes, select the artifacts to be manipulated, and precise utilization of the measurement tool and the spaceball is used to translate and rotate the selected artifacts or the 3D widget that represents the tool, and to control the camera (see Figure 5.1).

As stated earlier, bi-manual interaction is a familiar human trait and increases productivity in 3D camera and object manipulation tasks by enhancing depth perception through motion [15, 1]. Considering the additional benefits gained by parallelization of pragmatic and epistemic actions, such an interaction scheme is a good candidate

for tasks that follow Guiard's theory of skilled bi-manual interaction.



Figure 5.1: System setup showing the spaceball on the left (non-dominant hand) and the mouse on the right (dominant hand)

# Chapter 6

## Tools

Spatial measurements and estimations based on these play an important part in the analysis of cultural heritage artifacts. In the next subsections, we consider the case of archaeological pottery reconstruction and three tools that are commonly used. These are the tape measure, caliper, rim chart, and area estimation. A discussion of the real tool along with its virtual counterpart is given.

### 6.1 Tape Measure

The tape measure is used for determining the dimensions of a sherd and the surface distance between any two points on the sherd. These measurements are used for classifying a piece, along with its weight and thickness. It is also used for measuring fracture lengths to aid in reconstruction. The main purpose of the tape measure is to find geodesic distances either on the surface, along the rim, if the sherd is part of the rim, or along the fractured edges.

The tool is used with two hands. The protrusion on the edge of the tape is fastened to one of the end-points of the distance to be measured, then it is held in place using one hand while the other hand pulls the measure and extends the tape to

the other end-point. The measurement can be more easily read by locking the tape at the desired length. The tape measure is, in essence, an easier to use metered rope.

We use the notion of a geodesic curve to implement a virtual tape measure that works on 3D digitized models. A geodesic curve is the shortest path between two points on a surface. Common areas of use include navigation, path-finding, motion planning and network optimization. It is also an important step in many computer graphics algorithms such as mesh parametrization, mesh segmentation and mesh editing [19, 8, 7]. Current graphics hardware all use a triangular mesh format to process and visualize 3D geometries, thus most geodesics research is done for the discrete case [26].

The Dijkstra shortest-path algorithm is not sufficient to solve the discrete geodesic problem because the shortest path on a surface does not always follow along the edges of the mesh. The simplest solution is to augment the original mesh with extra points before running Dijkstra. Lanthier et. al. [20] compare different ways of populating a mesh with additional vertices on existing edges, called Steiner points, and show that a bounded approximation to the geodesic can be obtained with this method. The error bound and complexity of the algorithm depends on the number and distribution of these Steiner points. A detailed survey of approximate algorithms can be found in [25].

Several algorithms giving an exact solution to the discrete geodesic problem have been proposed. The “single source - all destinations” algorithm described by Mitchell, Mount and Papadimitriou (MMP) uses the continuous Dijkstra method and it has a worst case running time of  $O(n^2 \log n)$ , where  $n$  is the number of vertices. The MMP algorithm was recently implemented by Surazhky et. al. [35], who conclude that it performs much better than the worst case analysis suggests. An exact algorithm with  $O(n^2)$  running time based on surface unfoldings was proposed by Chen and Han [6].

The virtual tape measure is used for measuring the surface distance between two

points on a model. The user fixes a point then moves the mouse to interactively visualize and measure geodesics originating from the start point as seen in Figure 6.1.

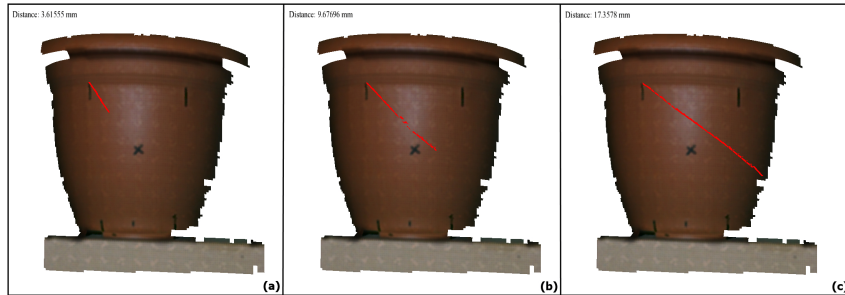


Figure 6.1: (a)The virtual tape measure is used by fixing the starting point and (b,c) moving the end point with the mouse.

We solve the geodesic problem in the pre-processing stage before the artifact model is visualized inside the CH Toolbox environment. The approximate geodesic solution proposed by Lanthier et. al. [20] is used. The algorithm is as follows:

1. The original mesh is loaded and converted to a triangle mesh.
2. Original edges are sub-divided to create extra vertices, called Steiner points.
3. New edges are created between two Steiner points if they are adjacent on the same triangle edge or they lie on different edges of the same triangle.
4. The single-source all-destinations Dijkstra is run for each vertex.

We used a fixed scheme to evenly add two Steiner points per edge, therefore 6 vertices and 27 edges are added to a triangle in the pre-processing stage (see Figure 6.4). Lanthier et. al. [20] proved that the algorithm runs in  $O(n^5)$  for the single-source all-destinations problem, where  $n$  is the number of triangles in the original mesh.

The geodesic is visualized by traversing vertices on the shortest path between the two end points of the tape measure. We choose to visualize the extra edges only if they lie on the shortest path solution, thus the tool has negligible impact on the interactivity of CH Toolbox. The bi-manual interaction scheme of the framework is also conserved while using the virtual tape measure.

## 6.2 Caliper

The caliper is used for measuring the linear distance between an object's two opposite sides. The thickness of a sherd is useful in pottery analysis as it might give insights about the material and techniques used in making the pot as well as the intended usage of the vessel. Furthermore precise drawings and reconstructions of any artifact depend on precise measurements taken with a caliper.

The tool is held with one hand, while the other hand manipulates the object to be measured. The tips of the caliper are then adjusted to get a firm touch on the surface of the object, after which a reading can be made. A too tight clamping action can deform both the caliper and the object depending on their material properties, which can yield an inaccurate measurement.

We developed a virtual caliper based on the same idea of clamping the tips to the point of touching the measured object. The caliper is visualized as a semi-transparent plane that can be manipulated with the spaceball (see Figure 6.2). The plane has four cubes on the midpoints of each side, the top and bottom ones being fixed. The left and the right cubes are movable using the mouse wheel or the keyboard left and right arrows. These moveable cubes represent the tips of the caliper, which upon clicking get stuck in their relative positions. In a regular caliper only one tip is moveable, but in our virtual caliper implementation either the left, right or both tips can be adjusted.



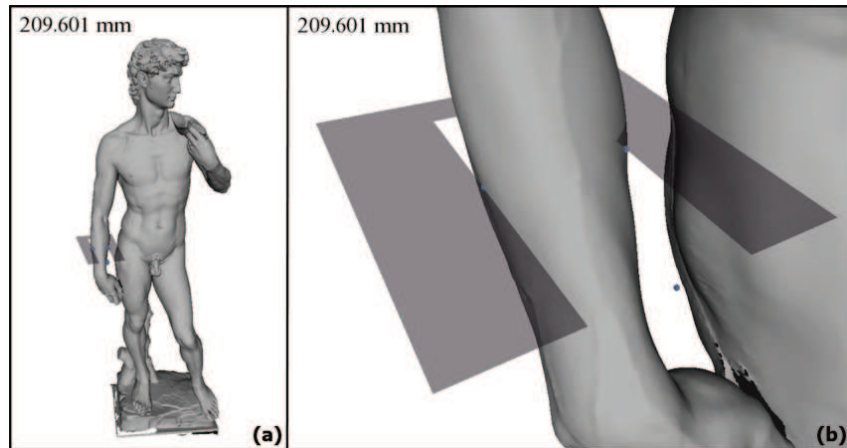


Figure 6.2: Screenshot of the caliper in action

In our caliper implementation we used a simple collision detection technique to determine if a tip touches the 3D model, and thus is unable to move into to the object. The closest face of the cube is checked for intersections with the model, with only one point of intersection meaning the tip has just touched the surface of the object.

### 6.3 Radius Estimation

A bordimeter, also called a rim chart, is a set of concentric circles drawn on a piece of paper or cardboard. It is used for estimating the rim radius of a vessel given a sherd belonging to the vessel's rim. The rim radius is used in calculating the rim size, which in turn helps archaeologists to assess a pot's usage. Radius estimation is also used in volume, and consequently capacity estimation. Both assessments help in the classification of the vessel.

The tool is placed on a flat surface, then a rim sherd is put rim-side down to find the best fitting circle, which is then used to estimate the radius. Because the

bordimeter is a solid piece of paper, radius estimation cannot be done with pieces other than rim sherds.

The problem of fitting a circle to a given set of co-planar points is called 2D circle fitting. It is a nonlinear least squares problem, which can be solved iteratively by reducing it to a set of linear least squares problems [9]. A best fit circle is computed and displayed interactively as the user moves the mouse over visualization of the artifact model as seen in Figure 6.3.

The tool works as follows:

1. The plane defined by moving the mouse is intersected with the model to obtain a set of points on the plane.
2. The average of the points is taken as the initial estimate for the circle.
3. The circle is fit iteratively using least squares fitting to these selected points (see Figure 6.4).
4. The center and the radius of the circle is computed.

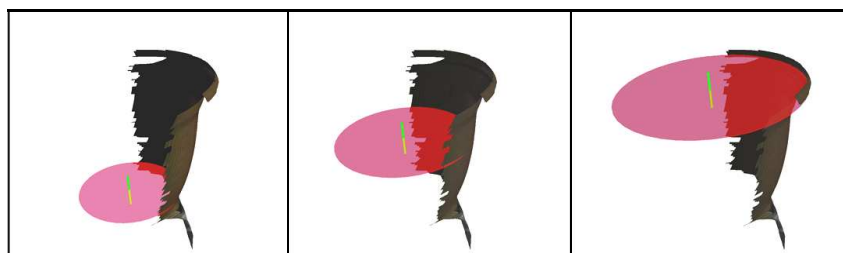


Figure 6.3: Screenshot of the virtual bordimeter in action

Even if the least squares solution does not converge, the iteration for fitting the circle is stopped after a certain number of steps to maintain interactivity. We found

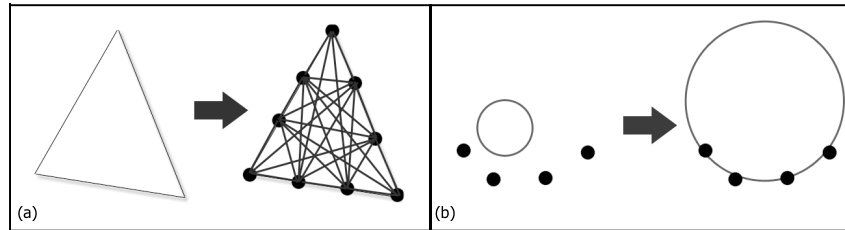


Figure 6.4: (a) Additional vertices, called Steiner points, and edges are added to the original triangle for better accuracy. (b) A circle is iteratively fit to a set of points.

that the solution converges in sufficient time if the points are not nearly linear. Otherwise, a warning message is displayed. This is not a problem with our test case since archaeological pottery has a curved surface.

The circle and its center is visualized in addition to the text display of the location of the center and its radius because it helps the expert to visually verify the suitability of the numeric solution as the rotational axis of the artifact. During the measurement process the expert can use the spaceball to move and orient the model. She can also change the transparency of the circle visualization to prevent it from obscuring the artifact.

## 6.4 Area Estimation

The purpose of the area tool is to estimate the surface area of a particular part of the digitized artifact specified by the user. However, unlike the other tools the area estimation tool has no real-life counterpart. Therefore the interaction scheme for the tool was designed to be similar to other computer based selection schemes that would be familiar to the target user group.

One interface element that almost all operating systems and software applications use to select multiple elements is called the selection rectangle. The usage of this

elements employs rubberbanding, the effect that occurs when a shape is drawn on the screen and the shape resizes as the interface pointer is moved. As the name implies, the element acts like a rubber band that is stretched and hold in place with the use of a utensil. The same technique is also used commonly in graphics applications to draw a shape or select any part of an image or 3D model interactively.

Consequently the rubberbanding technique was chosen for the area estimation tool based on the familiarity the user group would have with the scheme. After the selection rectangle is finalized by the user with the release of the mouse button, a set of rays originating from the eye point and passing through points on the rectangle present at a fixed interval is created. Each element of this set is then tested for a possible intersection with the triangles that make up the 3D model. The first intersected triangle for each ray, if it exists, is added to the surface to be summed to find the desired area. Finally the sum is calculated and displayed in the application. See Figure 6.5 for a close up of showing the intersected triangles and the intersection points.

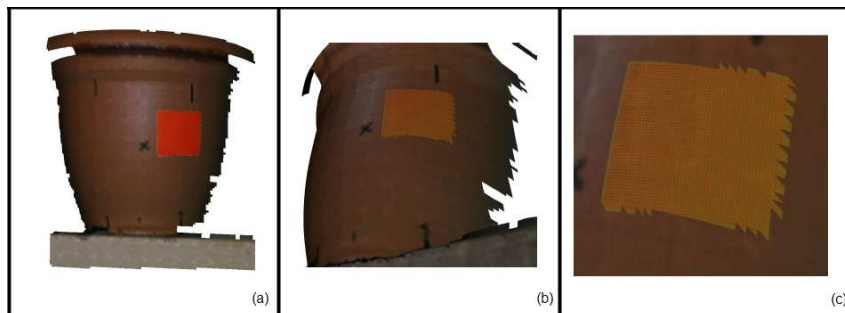


Figure 6.5: (a)A selection rectangle is used to fire of rays into the scene (b)The intersected triangles are colored yellow and the intersection points are colored red for clarification (c)Close-up of the selected area

The computational complexity of this technique is  $O(n m)$ , where  $n$  is the number

of rays and  $m$  is the number of faces to be tested for intersection. In first iteration the tool worked interactively, that is intersections were computed on each update of the selection rectangle, but this proved to perform unsatisfactory on huge meshes where the number of faces are near 500000. The second version of the tool works by computing the intersection after the selection rectangle is finalized.

# Chapter 7

## Results

### 7.1 Results

CH Toolbox is developed in C++, using the open-source scenegraph library OpenSceneGraph [28] that helps visualizations in OpenGL by providing an organizational hierarchy. The CH Toolkit and the interactive spatial measurement tools developed for it are available for all the operating systems that OpenSceneGraph supports. Our application runs in real-time on desktop PCs.

We tested the surface distance algorithm on an Intel Pentium D 2.8GHz PC with 1GB RAM. Separate stages of the preprocessing software was connected to scripts in the Lua language [23], which allowed batch processing and benchmarking capabilities. Please see Appendix A for a code sample that prepares and times some models used in testing.

#### 7.1.1 Performance

For a sherd mesh with 17K triangles, our algorithm takes an average of 1.320 seconds for the preprocessing stage as seen in Table 7.1. The preprocessing was timed 100

times with each mesh. The number of extra vertices and edges, and its impact on performance is also reported. Although the performance is not adequate for real-time interaction, our interviews with cultural heritage experts show that the cost of the preprocessing is acceptable for real world use cases.

Table 7.1: Mesh characteristics and preprocessing time

Model	Faces	Stn. points	Avg. time (s)	Std. dev. (s)
Sherd	17696	89859	1.320	0.009
Sphere1	50986	255002	3.805	0.011
Sphere2	204552	1023002	15.265	0.020
David	483498	2526815	1796.046	213.153

The performance of the approximate geodesic algorithm is reported in Table 7.2. The results were obtained by timing the solution for 500 randomly selected start points with the sherd mesh and 100 points for the other three meshes. For the sherd model with 17k original triangles and augmented with 2 Steiner points per edge, the average time to solve the single-source all-destinations shortest path problem is less than 2 seconds. This set of results for the sherd mesh have negligible variance which, combined with the 2 second delay between each selection of a new start point, allows interactive usage. The second mesh used Sphere1, a regular sphere with an original of 50k triangles, results in an average time of 4.4 seconds, which might be still considered suitable for interactive use of the tape measure tool. However, the average running times on more detailed meshes such as the second sphere with 200k faces and the David model simplified to 500k faces hamper the interactivity of the tool.

One approach to consider would be to let the user select the start and end points to calculate the geodesic distance between. This way, parts of the mesh not visible to the camera (either back-facing or out of the viewing frustrum) could be discarded before starting to solve the shortest path problem. Such a reduction in the number

of vertices and edges would in turn reduce the computation time. However, this change would make the interaction scheme that mimics the real world usage of a tape measure not possible. In our case, even if the time between a user attaches the end of the virtual tape and the time the tape is operational again is long, the tool still behaves like a real tape measure after the shortest path problem is solved.

Table 7.2: Performance of approximate geodesic algorithm

Model	Average time (s)	Median (s)	Std. dev. (s)	Std. error (s)
Sherd	1.84889	1.84788	0.23346	0.01054
Sphere1	4.36585	4.36408	0.11304	0.00682
Sphere2	18.14698	18.01450	0.69525	0.07370
David	971.84767	1005.77050	140.31828	14.32117

### 7.1.2 Error

We also compared rim estimations, surface distances, and caliper measurements taken on the real pot with the approximate results we got using our virtual tools on the digitized sherd mesh (Table 7.3). 5 points and 2 lines on the pot were marked before digitization in order to obtain enough reference points for measurement to find the error. Overall 17 spatial measurement were made 10 times each and then the differences between a real world measurement and its virtual counterpart were used to find the average relative error of the tools. The error rate of all the tools are near each other, 4.6%, 4.7%, and 4.5%. These similar percentages makes us suspect the underlying error of the scanning process dominates the error, thus making it impossible to reach a conclusion about the error of the approximation techniques without further tests using meshes digitized on systems with guaranteed precisions.



Table 7.3: Error rate of virtual tools

Tool	Avg. relative err.	Std. dev.
Tape	4.6%	7.6%
Caliper	4.7%	6.5%
Bordimeter	4.5%	7.3%

### 7.1.3 Interaction

The asymmetric bi-manual interaction scheme corresponds well with both the real world and the virtual versions of the tools implemented as part of the CH Toolbox software. The three principals stated by Guiard [13] that govern the asymmetry of human bi-manual gestures, right-to-left spatial reference in manual motion, left-right contrast in the spatial-temporal scale of motion, and left-hand precedence in action, is apparent in all the tools that make up the CH Toolbox.

These principals are not exclusive and they can be observed together in the usage of a tool, albeit some of them could be more apparent within a certain task than others. Let us start by considering the example of utilizing a tape measure to find the spatial distance between two points on the surface of a pot. The sequence of actions in this scenario can be seen in Figure 7.1.



Figure 7.1: A sequence of actions observed during tape measure utilization

The first action is the movement of the left hand to hold the end of the tape and

then the movement of the hand to connect it with the the point on the pot that the user wants to start the measurement from. This action confirms the third principle stating that the left hand precedes the right hand in starting the action. The next action is the movement of the right hand holding the tape itself to the desired point on the pot. The placement of the left hand on the pot and its fixation in space during this action confirms the first principle, right-to-left spatial reference, as the left hand (end of the tape) clearly provides the right hand (the rolled tape itself) a reference in space that allows the unrolling of the tape. The final action in the sequence is the fine adjustment of the position of the right hand to accurately locate the desired end point on the pot. This action confirms the second principle that states a contrast in the spatial and temporal scales of motion between the hands. Comparing the distance covered by the left hand in one movement to locate the first point versus the distance covered by the right hand to locate the end point, we can observe the difference in the spatial scale of motion. The temporal difference in scale is also apparent, as the left hand has to stay motionless while the right hand makes several movements to unroll the tape and match the end point with a reading on the tape to obtain the desired measurement.

The second tool implemented, a caliper, is used by holding the object to be measured with the left hand while the right thumb carefully adjusts the jaws of the caliper to fit the object. The first action is to pick up the object to be measured with the left hand while the right hand holds the caliper. This confirms the first third principle, left-hand precedence. The following action is the movement of the right hand to position the open jaw of the caliper to the desired area on the pot. Then the thumb on the right hand is utilized to move the wheel and thus adjust the opening between the ends of the tool (see Figure 7.2). This action is both slow and done in little increments in order to obtain a precise measurement. The said characteristics of motion of the right hand is a confirmation of the second principle, contrast in the

spatial-temporal scale of motion between the hands. Finally, the left hand must hold the pot steady during measurement, which confirms the first principle that states the right-to-left spatial reference in manual motion.

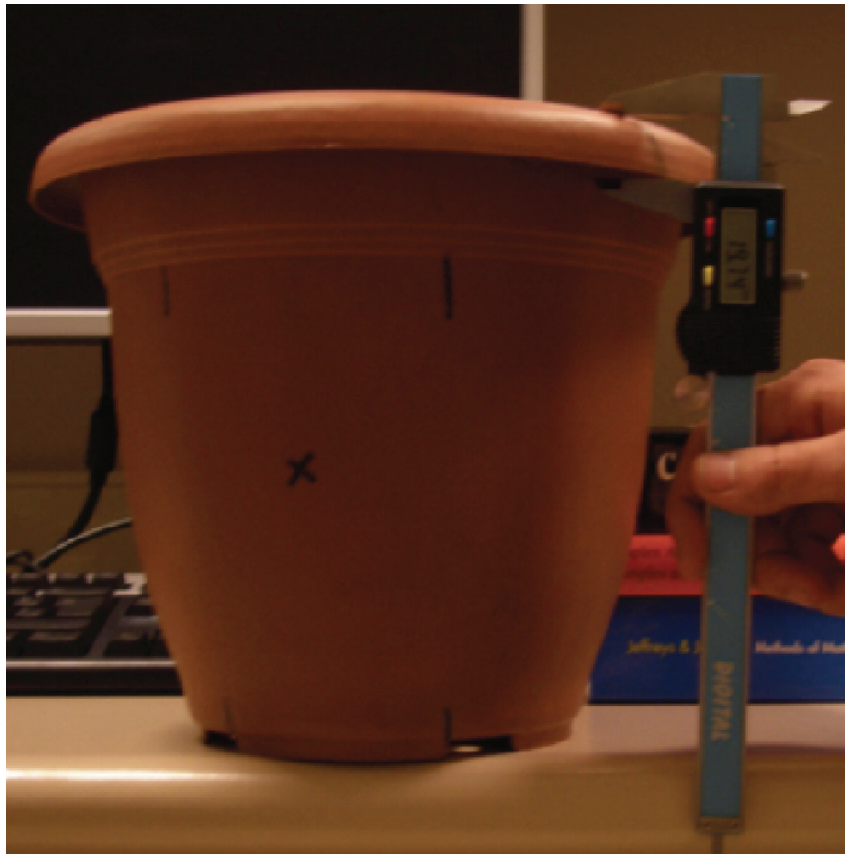


Figure 7.2: Caliper utilization in real life

The last tools, the rim-chart used to estimate the rim radius of a vessel and millimetric paper used to estimate an area on the surface of a pot, are both pieces of paper and thus the motions observed in their utilization show certain similarities. The starting action in their usage sequence is the positioning of the paper with the left hand. The rim-chart is placed on a flat surface and the millimetric paper is wrapped

over the area to be measured. Despite this difference, the first action still confirms the third principle of left-hand precedence in both tools.

The second action in rim-chart usage is the right-hand's placement of the pot or rim sherd on the paper and careful orientation of the piece in order to find a fitting circle segment. During the action of fitting the left hand can be used to orient the paper itself sometimes and to hold it steady other times (see Figure 7.3). This is done in order to help with the fitting task, and consequently confirms the first principle of right-to-left spatial reference. Furthermore, the differences in spatial and temporal scales between the hands in this task is a conformation of the second principle.

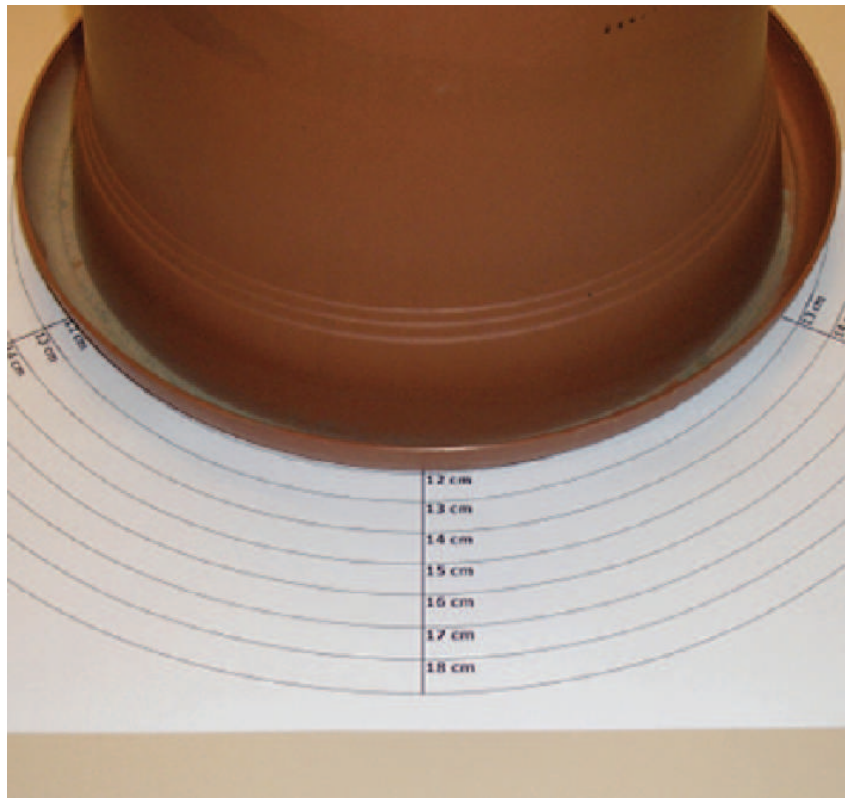


Figure 7.3: Rim-chart utilization in real life

Now the second action in the task of area estimation is the movement of the right hand holding a pen or pencil to mark the boundaries that correspond to the area to be measured under the millimetric paper. This action is similar to handwriting, but the paper must be securely held in place by the left hand in order to obtain a correct boundary. Here the left hand provides a spatial frame of reference to the marking hand, as predicted by the first principle. The underlying idea of the second principle is apparent if the actions of the right hand are observed. The pen must trace the boundary slowly and in little steps for correctness.

# Chapter 8

## Conclusions

### 8.1 Conclusion and Future Work

Our main contribution is the development of a platform for interactive computer-aided cultural heritage tasks. We implemented measurement tools that archaeologists daily use in real life by adapting algorithms developed for other computational geometry tasks. The algorithms we chose are suitable for use in a real-time interactive environment. Another contribution is the introduction of bi-manual interaction to the cultural heritage domain, though possible benefits need to be further investigated with usability studies conducted with cultural heritage experts.

The next step would be improving the accuracy of our tools, especially the radius estimation tool. We suspect the relatively high error rate is due to errors in the 3D scanning technology we used. Our tools should be tested with models obtained from other scanning technologies. We feel that the establishment of databases of peer-reviewed 3D models of cultural heritage artifacts will provide us with the opportunity to test our tools more thoroughly.

CH Toolbox is released as an open-source application to aid researchers in the cultural heritage domain and can be found at [36].

# Appendix A

## Example Script in Lua

```
-- File: timer.lua
--*****
-- This is an example input file for model2steiner.exe
-- You can easily write a benchmarking suite in Lua.
-- Enjoy!
--*****
-- Functions exposed from the c++ side are
-- load: loads a model file
-- parse: parses and augments a model file
-- makeadjacency: creates an adjacency list
-- writeadjacency: writes the adjacency list to a file
-- writemodel: writes a model to disk
--*****

function model2steiner(modelName, m)
    local now,object,edges,adjacencylist
```

```
now = os.clock()
object = load(modelName)
print("# Time to load model: " .. os.clock()-now)

now = os.clock()
edges, object = parse(object, m)
print("# Time to parse object: " .. os.clock()-now)

sum = 0
for i=1,1 do
    now = os.clock()
    adjacencylist = makeadjacency(edges)
    if i>1 then
        sum = sum + (os.clock()-now)
    end
end
end
print("# Time to make adjacency list (avg. of 1): " .. (sum/1.0))

now = os.clock()
writeadjacency(adjacencylist)
print("# Time to write adjacency list: " .. os.clock()-now)

now = os.clock()
writemodel(object)
print("# Time to write augmented model: " .. os.clock()-now)
end
```



```
print("\n## BOX.OBJ - 2 Stenier points per edge ##")
model2steiner("box.obj",2)
```

```
print("\n## IMG_9401.OBJ - 2 Stenier points per edge ##")
model2steiner("IMG_9401.obj",2)
```

```
print("\n## sphere_1442q.obj - 2 Stenier points per edge ##")
model2steiner("sphere_1442q.obj",2)
```

```
print("\n## sphere_B.obj - 2 Stenier points per edge ##")
model2steiner("sphere_B.obj",2)
```

```
print("\n## vcg_david_500k.obj - 2 Stenier points per edge ##")
model2steiner("vcg_david_500k.obj",2)
```

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