Chapter 10[1]

A software system to work with 3D models in cultural heritage research[*]

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The availability of intuitive, user-friendly, and specialized software to work with 3D models of cultural heritage artefacts 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. The number of available high-quality digitized artefacts increases rapidly with the advent of low-cost 3D scanning technologies. 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 modelling packages motivated us to create a simple, freely available, and extensible measurement tools system, CH Toolbox, that was designed exclusively for cultural heritage research. Here we discuss our design decisions regarding the interaction scheme of the software system and introduce three virtual counterparts of real-world spatial measurement tools, specifically the tape measure, the caliper, and the rim-chart.

1. Introduction

With the emergence of accessible high-computing power and advanced interactive technologies it is now possible to develop digital tools for archaeology. There are a number of advantages of using digitised 3D models in cultural heritage research. Once an artefact has been digitised with the use of 3D scanner technology and modelling software, it is converted to a 3D model consisting of geometric and photometric

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information which can then be used in computer graphics, virtual reality or computational analysis. Computer graphics techniques make it possible to display cultural heritage assets in a cheaper, safer, and more secure way compared to traditional displays. Especially in the case of artefacts prone to decay and harm caused by environmental factors such as lighting, noise, temperature, humidity and pollution, a virtual display might be the only way to preserve and share these assets at the same time. Another factor in favour of digital replicas is their ease of storage, transportation, and duplication over the Internet and other computer networks. Combined with advances in network security, both cultural heritage researchers and the public can have different levels of access to these valuable assets without compromising the original artefacts. Such secure worldwide access, in turn, would allow greater options for collaboration between experts.

Computer aided cultural heritage research makes new techniques available that were not possible before. For example, irreversible processes such as reconstruction and restoration can be planned, simulated and evaluated on 3D models without harming the originals. Furthermore, the effects of ageing, oxidisation, and pollution can be simulated and visualised in order to gain insight as to how the artefacts looked in the past and how will they look in the future. Digitisation is also beneficial for research tasks that require computational analysis, such as the derivation and verification of statistical models, obtaining spatial measurements and estimations, as it makes it easier to compute and verify results by different experts.

Creation of 3D models

A detailed digital 3D model is obtained either through 3D optical scanning; or by means of 3D modelling software, such as Maya and 3Ds Max, with the help of photographs, drawings and measurements of an artefact. The quality of a manually created 3D model depends on the accuracy of the measurements taken with optical theodolites, tapes and calipers (Levy & Dawson 2006). A major drawback of manual modelling is the long amount of time it takes to collect the data and then model the artefact. The modelling skills of the researcher and her familiarity with the software are important factors determining both the cost and quality of the digital reproduction. By comparison, automated or semi-automated 3D modelling produces more accurate 3D models, and *is* faster. Automated modelling is achieved by first generating numerous partial range images of the artefact from all sides, then aligning these images, and finally merging them to create the 3D geometric mesh of the object (Kawasaki & Furukawa 2004). Range images, or maps, can be obtained with two different techniques, triangulation or time-of-flight (hereafter TOF)-based scanning. *See **Fig. 2** for two example system setups using triangulation and TOF-based scanning.*

A)

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 predetermined 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 *an* 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 (Guidi *et al*. 2002).

B) TOF-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 artefact and the site it belongs to, or when the error rate is found to be acceptable for the *intended* use of the 3D model.

2. Trends in 3D scanning technologies

The use of 3D scanning in cultural heritage research has been successfully demonstrated in a number of projects involving very detailed 3D models of sculptures, building, structures, and archaeological finds (Levoy *et al.* 2000; Miyazaki *et al.* 2001; Bernardini *et al.* 2002). 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. Kawasaki and Furukawa (2004) present their model acquisition system and handheld 3D digitiser 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. Another low-cost 3D scanning setup is presented by Pheatt *et al.* (2005) which consists of digital camera, a motor controlled turntable, laser diodes, and a simple micro-controller. They claim a cost of $250, excluding the camera and the PC, for the whole system. Callieri *et al.* (2004) 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. Motivation

Although the use of digitised 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 artefacts. Both 3D scanning and 3D modelling requires familiarity with the hardware and software in order to produce digital models of required accuracy and detail for analysis and visualisation tasks. As recent developments in 3D scanning technologies have made the digitisation of artefacts affordable, the amount of digitised models available for research increases rapidly. Consequently, the need for specialised software for cultural heritage research and practice on 3D models becomes more apparent. The problem with using existing 3D modelling software for cultural heritage research on digitised artefacts is that using these programs effectively requires additional experience with the software and user interface which the researcher may lack. Such software are usually general purpose modelling tools or designed for digital content creation, architecture or manufacturing, and thus do not match the *modus operandi* of cultural heritage scholarship. Therefore, practitioners of the field cannot easily transfer their expertise in the domain to new software tools without further education or specific guidelines (Eiteljorg 1988). 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 (Melero *et al.* 2003; Sagiroglu & Ercil 2005). Similar problems arise in the medical field as well, where the disparency 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 (Preim *et al.* 2002).

4. Design decisions

CH Toolbox is a 3D application framework for analytical cultural heritage research. It visualises digitised models of artefacts in 3D and allows the user to analyse the pieces using a spaceball and mouse-driven interface **[Fig. 1]**. Several designs were considered for the user interaction scheme of CH Toolbox. One important consideration was the amount of functionality, meaning both the number of distinct tools and the way these are presented to the *user, which* 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.* (2002) consider the same issue in their digital tape drawing application, a computerised version of the technique commonly used by artists in car design, and say that although additional functionality similar to 3D modelling 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 modelling 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.

Interaction methodology

The three main operations in CH Toolbox are camera control, model selection and manipulation, and tool utilisation. 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 utilised next. Object selection and manipulation is useful in situations where more than one 3D model is visualised and the user finds it beneficial to move and orient the object instead of controlling the camera. Tool selection and utilisation commonly comes only after the user is satisfied with the position and orientation of the camera and the 3D model. According to Balakrishnan & Kurtenbach (1999), these actions can be categorised 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 utilisation, 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 parallelised actions. Guiard (1987) lay the theoretical foundations of skilled bi-manual action with his Kinematic Chain model. According to his model, humans accomplish many tasks with two hands complementing each other. He states three principles 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.
- Left-hand precedence in action.

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

A) 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 hand-writing and sewing for actions where the left hand orients and stabilises 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 by unrolling the tape with the right hand while the left hand stabilises 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 hand-writing, because the left hand stabilises the paper in both cases.

B) 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 utilisation 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.

C) 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. hand-writing, 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.

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 visualisation modes, select the artefacts to be manipulated, and precise utilisation of the measurement tool and the spaceball is used to translate and rotate the selected artefacts or the 3D widget that represents the tool, and to control the camera **[Fig. 3]**. 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 (Hinckley *et al.* 1998; Balakrishnan & Kurtenbach 1999). Considering the additional benefits gained by parallelisation 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.

5. Tools

Spatial measurements and estimations based on these play an important part in the analysis of cultural heritage artefacts. 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, and the rim chart. A discussion of the real tool along with its virtual counterpart is given.

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 digitised 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 optimisation. It is also an important step in many computer graphics algorithms such as mesh parametrisation, mesh segmentation and mesh editing (Krishnamurthy & Levoy 1996; Floater & Hormann 2002; Funkhouser *et al.* 2004). Current graphics hardware all use a triangular mesh format to process and visualise 3D geometries, thus most geodesics research is done for the discrete case (Mitchell *et al.* 1987). The Djikstra 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 Djikstra. Lanthier *et al.* (1997) 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 description of the algorithm using a fixed-point distribution scheme, which we used, will be presented in the next section. A survey of approximate algorithms can be found in Mitchell *2000*. Several algorithms giving an exact solution to the discrete geodesic problem have been proposed. The ‘single source —all destinations’ algorithm described by Mitchell *et al.* (1987)—henceforth MMP algorithm—uses the continuous Djikstra method and 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.* (2005), 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 & Han (1990).

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 visualise and measure geodesics originating from the start point as seen in **Fig. 4**. We solve the geodesic problem in the pre-processing stage before the artefact model is visualised inside the CH Toolbox environment. The approximate geodesic solution proposed by Lanthier *et al.* (1997) is used. The algorithm is as follows:

- The original mesh is loaded and converted to a triangle mesh.
- Original edges are sub-divided to create extra vertices, called Steiner points.
- 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.
- The single-source all-destinations Djikstra is run for each vertex.

We used a fixed scheme to evenly add two Steiner points per edge, therefore six vertices and 27 edges are added to a triangle in the pre-processing stage **[Fig. 7]**. Lanthier *et al.* (1997) 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 visualised by traversing vertices on the shortest path between the two end points of the tape measure. We choose to visualise 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.

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 artefact 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 visualised as a semi-transparent plane that can be manipulated with the spaceball **[Fig. 5]**. 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. In our caliper implementation we used a very simple collision detection technique to determine if a tip touches the 3D model, and thus is unable to move into the object. The closest face of the cube is checked for intersections with the model, with only one point of intersection meaning that the tip has just touched the surface of the object.

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 function (relating to open versus closed shapes etc.). 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 then 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 (Gander *et al.* 1996). A best fit circle is computed and displayed interactively as the user moves the mouse over visualisation of the artefact model as seen in **Fig. 6**. The tool works as follows:

- The plane defined by moving the mouse is intersected with the model to obtain a set of points on the plane.
- The average of the points is taken as the initial estimate for the circle.
- The circle is fit iteratively using least squares fitting to these selected points **[Fig. 7]**.
- The center and the radius of the circle is computed.

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 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 visualised 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 artefact. 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 visualisation to prevent it from obscuring the artefact.

6. Results

CH Toolbox is developed in C++, using the open-source scenegraph library OpenSceneGraph[2] that helps visualisations in OpenGL by providing an organisational 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 AMD Opteron 2.6GHz PC with 8GB RAM. For a sherd mesh with 17K triangles, our algorithm takes 0.035 seconds for the pre-processing stage as seen in **Table 1**. The number of extra vertices and edges, and its impact on performance is also reported. Although the perfomance is not adequate for real-time interaction, our interviews with cultural heritage experts show that the *time needed for the pre-processing step* is acceptable for real world use cases.

Model	**Faces**	**Stn. points**	**time1 (s)**	**time2 (s)**
Sherd	17696	89859	0.03500	1.86438
Sphere	50986	255002	0.10150	6.77794
Sphere	204552	1023002	0.40625	28.22556
David	483498	2526815	1.02325	62.44571

Table 1. Performance of approximate geodesic algorithm

We also compared rim estimations and surface distances measured on a real pot with the approximate results we got using our virtual tools on a sherd mesh **[Table 2]**. The error rate of the *caliper and the bordimeter* is rather high, but is *still* consistent with the bound proven by Lanthier *et al.* (1997). *Since these measurements were taken on the rim of the sherd mesh and are almost as twice as great as the errors we encountered on generated meshes such our sphere model, we suspect that the difference is due to the accumulation of the error from the 3D scanning step.*

Tool	**Real (cm)**	**Virtual (cm)**	**Rel. error**
Tape	15.35	15.44	0.6%
Caliper	1.92	2.01	4.7%
Bordimeter	12.74	12.17	4.5%

Table 2. Error rate of virtual tools

7. Conclusion and future work

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[2] See http://openscenegraph.org.

Our main contribution is the development of a platform for interactive computer-aided cultural heritage tasks. We implemented measurement tools that archaeologists use daily 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 that 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 artefacts will provide us with the opportunity to test our tools more *thoroughly*. *Finally,* CH Toolbox is released as an open-source application to aid researchers in the cultural heritage domain and is available online.[3]

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[3] http://graphics.sabanciuniv.edu/chtoolbox.

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CAPTIONS

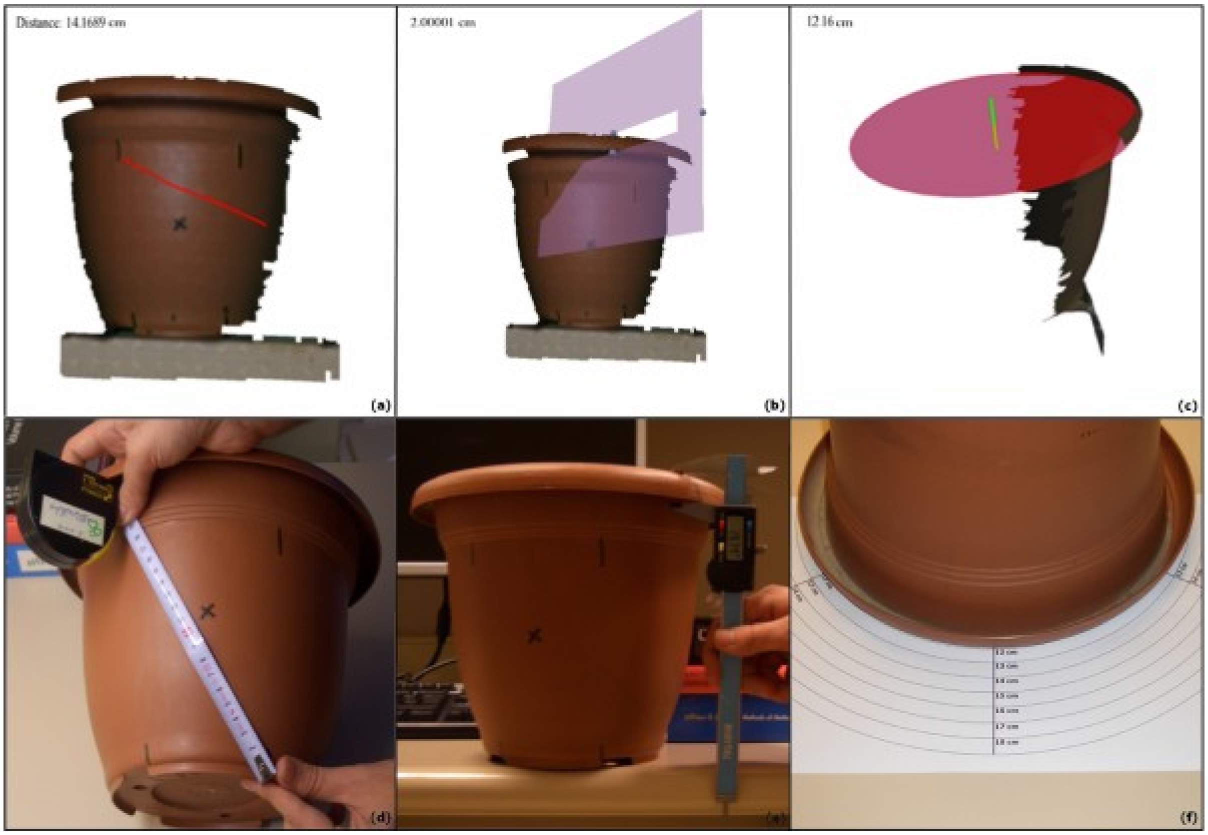

Fig. 1.

a) Screenshot of the virtual tape measure; b) the virtual caliper; c) the virtual radius estimator versus their real-life counterparts; d) a tape measure; e) a caliper; f) a rim chart.

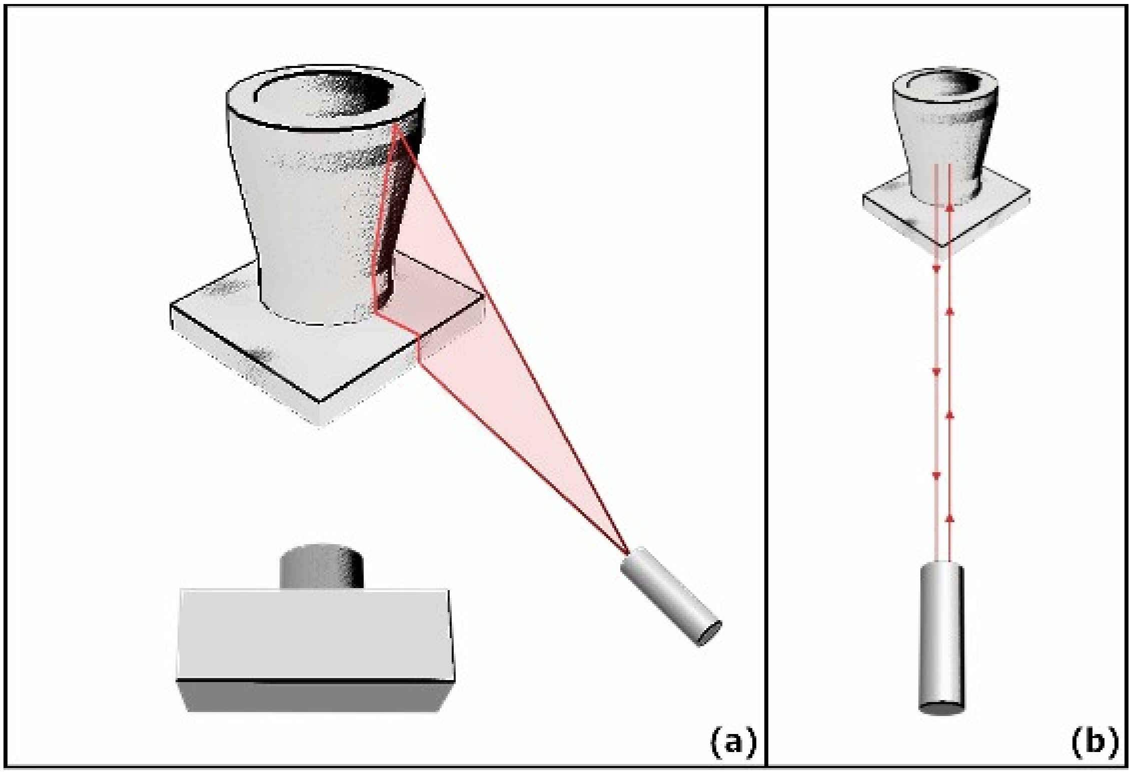

Fig. 2.

a) Triangulation-based scanning works by analysing the captured projection of a defined pattern, here a straight line; b) TOF-based scanning works by measuring the time it takes for a reflected laser beam to travel back to the source.

Fig. 3.

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

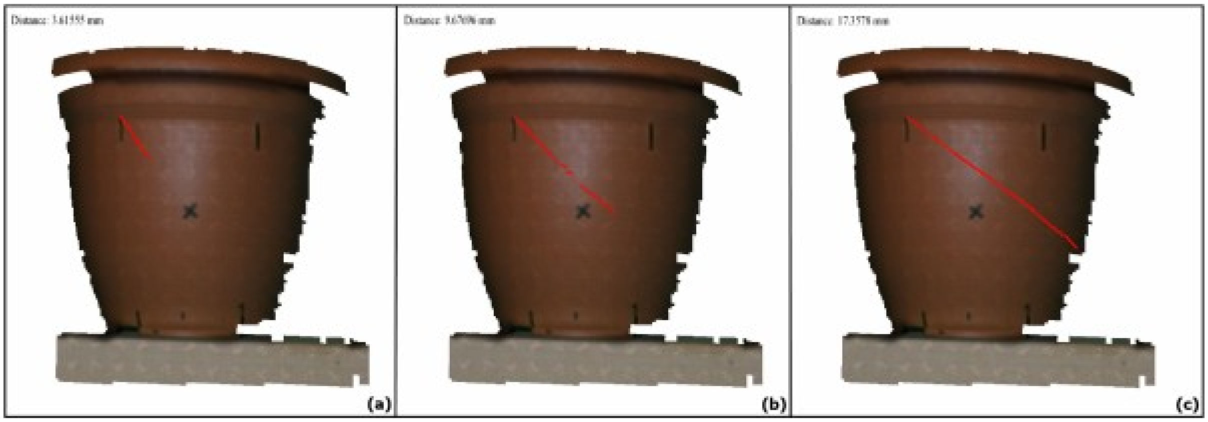

Fig. 4.

a) The virtual tape measure is used by fixing the starting point; b), c) moving the end point with the mouse.

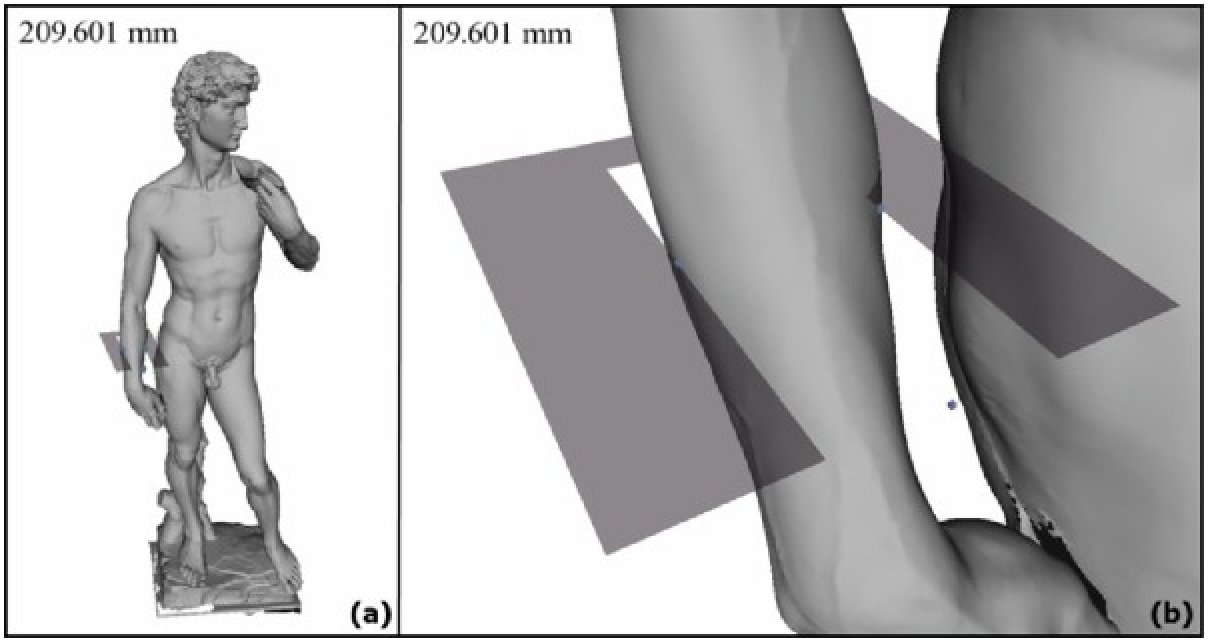

Fig. 5.
Screenshot of the caliper in action.

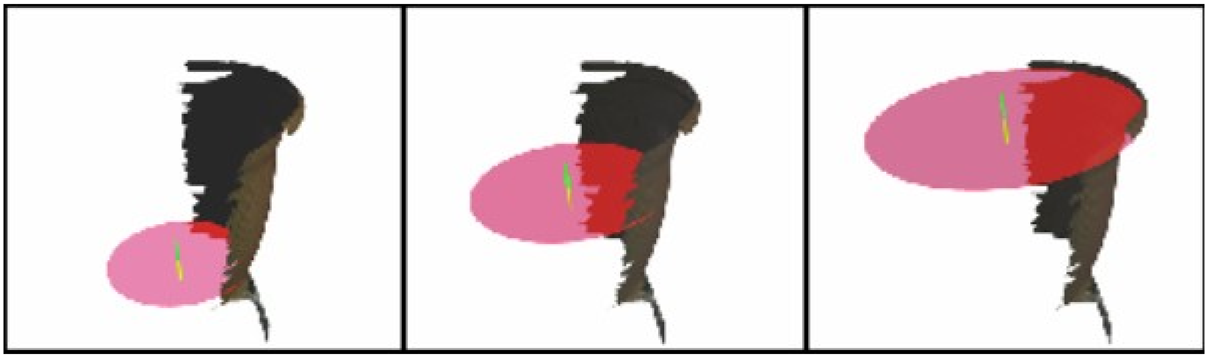

Fig. 6.

Screenshot of the virtual bordimeter in action.

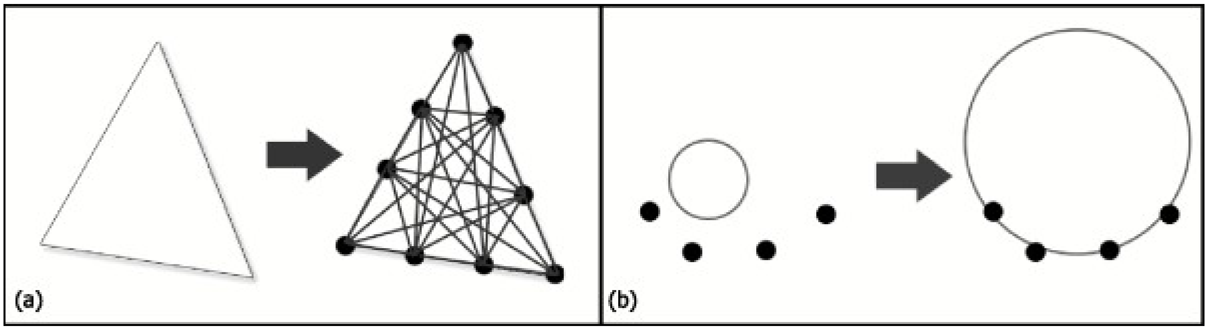

Fig. 7. a) Additional vertices, called Steiner points, and edges are added to the original triangle for better accuracy; b) a circle is iteratively fit to a set of points.