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Interactive 3D exploration of a virtual sculpture collection: an analysis of user behavior in museum settings

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Abstract

We present a usage analysis of an interactive system for the exploration of highly detailed 3D models of a collection of protostoric mediterranean sculptures. In this system, after selecting the object of interest inside the collection, its detailed 3D model and associated information are presented at high resolution on a large vertical display controlled by a touch-enabled horizontal surface placed at a suitable distance in front of it. The indirect user interface combines an object-aware interactive camera controller with an interactive point-of-interest selector and is implemented within a scalable implementation based on multiresolution structures shared between the rendering and user interaction subsystems. The system has been installed in several temporary and permanent exhibitions, and has been extensively used by tens of thousands of visitors. We provide here a data-driven analysis of usage experience based on logs gathered during a 24 months period in four exhibitions in Archeological museums, for a total of over 75K exploration sessions. The results highlight the main trends in visitor behavior during the interactive sessions, which can provide useful insights for the design of 3D exploration user interfaces in future digital installations.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction Techniques I.3.8 [Computer Graphics]: Applications—

1. Introduction

Digital acquisition technologies, as well as 3D modeling methods, have by now reached a level of maturity such that highly detailed and accurate 3D representations of cultural heritage artifacts can be created within acceptable times and costs. Applications of this digitization process include dissemination, archival, study, restoration, and fabrication of high quality digital replicas. Among the many possible application possibilities, visual communication remains by large the most common utilization. In recent years, cultural institutions have put enormous efforts on creating high quality accurate digital contents to be presented as online resources [si:13, PCD*15] or through interactive museum installations [ACB12, MBB*14].

While until recently most museum systems presented either precomputed material, or provide interaction with very simplified 3D objects, used only for illustration purposes, the current trends are towards flexible active presentation modalities, such as virtual navigation systems, which let users directly drive navigation and inspection of accurate 3D digital artifacts. These active presentation approaches centered around high-quality digital replicas are known to engage museum visitors and enhance the overall visit experience, which tends to be personal, self-motivated, self-paced, and exploratory [FD00]. However, despite the proliferation of interactive systems for presenting accurate representation of cultural objects, currently very few attempts have been made towards analyzing interacting user behaviors in order to get feedback for human-centred design of interfaces and for classifying and ordering the 3D information to be presented.

In this paper, we face the problem of analyzing the exploration behavior of thousands of casual visitors interacting with a digital collection of high detailed 3D representation of protostoric mediterranean sculptures through large-display visualization systems installed in various exhibitions. The visual presentation system under study is based on a scalable exploration software architecture which supports, in an integrated manner, distribution and rendering of massive annotated detailed models with high visual quality. In this system, after selecting the object of interest inside an object collection, its detailed 3D model and associated information are presented at high resolution on a large vertical display controlled by a touch-enabled horizontal surface placed at a suitable distance in front of it. The indirect user interface combines an object-aware interactive camera controller with an interactive point-of-interest selector and is implemented within a scalable implementation based on multiresolution structures shared between the rendering and user interaction subsystems. The system has been installed in permanent and temporary exhibitions around Europe (Cagliari, Cabras, Milan, Rome, and Zurich) for the exploration of the Mont'e Prama sculpture collection, a large set of extraordinary sandstone sculptures created by the Nuragic civilization in Western Sardinia [TVD05].

The system anonymously records user interactions, which allowed us to gather a very large body of information. We present here visual and quantitative analysis methods, as well as analysis results, starting from massive amounts of data acquired during explorations performed by tens of thousands of visitors during 24 months at the National Archaeological Museum of Cagliari, 10 months at the Civic Archaeological Museum of Cabras, 6 months at the National Prehistoric Ethnographic Museum Luigi Pigorini in Rome, and 6 months at the Civic Archaeological Museum in Milan. We have recently presented an early analysis of the usage time of the system in the museums of Cagliari and Cabras [BAB*16], comparing it with the presence of visitors at exhibition. This study is instead focused on analyzing the visitor behavior with respect to the exploration interface: specifically we aim to understand how the interface choices affect user performances, and how visitors use the various interface components. The user study is thus particularly focused on individuating the main visitor behaviors during 3D exploration by employing tools for deriving interest measures on surfaces [DCG12], and tools for clustering and knowledge discovery from high-dimensional data [LMW*15].

2. Related work

In this work, we analyze user 3D exploration behavior in the context of a museum installation based on a dual display setup that combines guided navigation through thumbnail selection with free viewpoint navigation. Fully covering the related work in the areas of interactive system designs, 3D navigation, and interest point analysis is beyond the scope of this paper. In the following, we briefly summarize only the most closely related work.

Interactive systems for 3D model exploration. Recently, a number of visualization systems have been presented that exploit two display surfaces. These systems employ an horizontal interactive touch table, and a large display wall visualizing the data, sometimes combining them in a continuous curved display [WVSB10, WHS*10]. Our system layout is similar to the one presented by Coffey et al. [CML*12], which however simultaneously displays a large-scale detailed data visualization and an interactive miniature. Instead, we use the horizontal surface exclusively for indirect interaction, so that users keep their focus on virtual exploration on the main display presenting the explored statue. Multitouch interaction on the horizontal surface controls camera motion on the large display. Constrained viewpoint navigation has often been proposed as an option to reduce the degrees of freedom in order to simplify the access to the user interface for novice users [MBB*14, Bou14, TR11]. Our work employs the approach recently presented by Balsa et al. [BAMG14] on an auto-centering virtual trackball controlled through the usual decomposition of motion into pan, zoom, and orbit. The virtual trackball is combined with a selection of precomputed viewpoints presented in a thumbnail bar. This dual interface setup allows us to compare in this paper the interactive behavior obtained by using a weakly constrained camera controller with a fully constrained one.

Interest points detection. The methods dedicated to the detection of interest points on 3D mesh models are relatively recent. Most of them rely on local surface descriptors, such as curvature, extrema of which are assumed to correspond to candidate interest points. It is common practice to employ a multi-scale approach, where the algorithm analyzes the 3D surface at successive scales to search for interest points at various levels of detail. Various saliency measures have been recently proposed to individuate these interest points: integral volume descriptors [GMGP05], or differences of Gaussian-weighted mean curvatures at successive scales [LVJ05], or difference of gaussians applied to vertex positions [CCFM08]. Other saliency measures have been derived by extending to 3D popular 2D detection operators, like SUSAN [WAL08], or Harris [SB11], or by considering the Laplace-Beltrami spectral domain [HH09, SOG09]. Recently, Dutagaci et al. [DCG12] proposed an evaluation strategy based on human-generated ground truth to measure the performance of 3D interest point detection techniques. We propose here a novel metric for computing interest-based measures based on user exploration activity, aimed to find human-centred saliency points on 3D representation of work of arts.

Visual analytics of exploration activity. Using visual analytics techniques in cultural heritage applications is a relatively recent field of research [PBG*14], that has already provided interesting results in architectural documentation [DL14], investigative analysis across documents and drawings [DPT*12], analysis on wall painting degradations [ZKL*13], as well as risk assessment for cultural heritage sites [QSCZ15]. With respect to visual analysis of user 3D behaviors, mining methods have been mostly applied to trace tourist activity for discovering landmark preferences from photo mappings [JAAK10], recommending travel routes using geotags [KIIF10], and analyzing routing preferences in tourist areas [TSG*15]. Here, we analyze the virtual 3D exploration activity of museum visitors while inspecting a digital collection of sculptures, by considering histogram analysis of parametrization of view transforms and by employing classical cluster analysis methods [Jai10].

3. Overview

The methods and results presented in this paper are outcomes of a wide cultural heritage digital acquisition and presentation project, motivated by the valorization of the Mont'e Prama sculpture complex, a large set of extraordinary sandstone sculptures created by the Nuragic civilization in Western Sardinia [TVD05].

Digital sculpture collection. The collection is composed by 25 life-size human figures with height varying between 2 and 2.5 meters, depicting archers, boxers and warriors, and 13 approximately one-meter-sized building models representing typical nuragic towers. The sculptures were restored and reassembled by using modern non-invasive criteria starting from five thousands stone fragments, and contains various distinctive elements which make them peculiar and attractive examples of human creativity of mediterranean area protostoric civilizations. They are currently accessible to the public in the National Archaeological Museum of Cagliari (19 human sculptures and 9 nuraghe models), and the Civic Museum Giovanni Marongiu of Cabras (6 human sculptures and 4 nuraghe

Figure 1: ***Digital Mont'e Prama collection.*** *Digital 3D models of the sculpture collection.*

models). The digital valorization project consisted on the 3D high-resolution digitization of the complex, resulting in 37 quarter-millimeter resolution colored surface models [BJM*15] (see figure 1), and in the development of a visualization architecture for the distribution and real time interactive exploration of the models on commodity platforms, and for museal exhibitions.

System components. The interactive visualization system is built on top of multiresolution components for scalable rendering and distribution of high resolution surface models composed by billions of geometry primitives [CGG*04]. With respect to the user interface, we considered the increasing popularity and immediacy of touch screens, and we designed the various elements in a way that they could be easily usable with fast learning times by casual users. We integrated the following main components:

- a two-level selection widget for easily navigating through the entire sculpture collection (the statues are grouped and ordered according to the main classification in archers, warriors, boxers and nuraghe models);
- an object-based assisted system based on auto-centering virtual trackball [BAMG14], and tailored for both orbiting and proximal object inspection;
- a thumbnail-based selection component for navigating amongst a series of pre-defined viewpoints [BAB*15].

Exhibition setups. The architecture components were designed to be easily adapted to work with different kind of displays and devices. For high-end exhibition interaction stations, we decoupled interaction and rendering, in order to permit the use of large displays for rendering. The touch device in charge of the user interface is placed at a distance from the display enough to grant the user controlling the inspection with a whole view of the display (normally 1.5 meters from the main screen). At the same time, this setup enables multiple users to watch the display without occlusion problems, in a way to boost discussion and to permit group visits during the periods in which exhibitions are particularly crowded. This setup was customized to be installed in various temporary and permanent exhibitions. The two permanent installations, at the National Archaeological Museum in Cagliari and the Civic Museum G. Marongiu in Cabras, are placed in the same rooms that host the sculpture collection (28 statues in Cagliari and 10 in Cabras). Both exhibitions use a dual-screen setup, with statues presented on large back-projection screen in portrait mode (2.5m height). Temporary

Figure 2: ***Exhibition setups.*** *Various temporary and permanent installations were set up considering two hardware solutions: projection-based with landscape orientation (on the left), and display-based with portrait orientation (on the right).*

exhibitions were presented at the National Prehistoric Ethnographic Museum Luigi Pigorini in Rome (November 29th 2014 to March 21st, 2015) and at the Civic Archaeological Museum in Milan (May 7th to November 29th, 2015), where the system is installed in a dark room with dual-screen setup, with statues presented on a large back-projection screen in landscape mode (3m x 2.5m). In addition, two temporary exhibitions based on a smaller system (85 inch 4k monitor in portrait mode) were presented at EXPO 2015, Milan (September 11th to 17th, 2015) and the Archaeological Museum of the University of Zurich (April 15th to September 25th, 2016).

4. User analysis overview

In this paper, we analyze the data recorded in the permanent exhibitions in Cagliari and Cabras, built around a portrait-mode projection system, as well as the two temporary exhibitions in Rome and Milan, built around a landscape-mode projection system. Many tens of thousands of people used the system, resulting in a very large number of exploration sessions (see Table 1).

Qualitative evaluation. In order to get a preliminary insight of main visitor behaviors and impressions, we carried out observa-

Museum	Exhibition	Period	# Explored sculptures	Usage time (hours)
National Archaeological Museum (Cagliari)	Permanent	Mar 2014 - Nov 2015	43943	816.6
Civic Museum Marongiu (Cabras)	Permanent	Mar 2015 - Oct 2015	23537	416.3
National Museum Pigorini (Rome)	Temporary	Nov 2014 - Apr 2015	2879	42.5
Civic Archaeological Museum (Milan)	Temporary	May 2015 - Feb 2016	4378	61.3

Table 1: ***Virtual exploration in museum setting:*** *main system usage statistics for the the permanent and temporary exhibitions.*

tion, recording and we performed informal interviews to acquire opinions and suggestions. In general, we could observe two main usage scenarios:

- **Individual or small group:** a single visitor, or small group composed by a family and group of friends interact with the system. In general one person, normally the most confident with touch based interface and 3D interaction takes the control of the console, and the rest of the group observes the screen and eventually give instructions on which sculpture display and which detail of the model put in evidence.
- **Medium/large groups:** according to the crowding level, heterogeneous groups can naturally form in front of the interactive station. In this case, one person controls the console, and the rest of the group observes the screen. In many cases, the person in charge of controlling the exploring interface is a museum guide who uses the system for describing the history and the main features and of the digital collection.

Usage data gathering. In order to interpret and understand the behavior of visitors during virtual sculpture explorations, we added a logger of interactive exploration system usage. Given the large duration of the exhibitions and the high-frequency usage of the system, we decided to limit the collection to representative exploration activities, recording the start and end time of the interactive exploration of sculpture X, the view position selected at time t from a list of preselected points of interests, and the view positions in which the user stayed for at least 5 seconds during free 3D inspection.

General statistics. From the log files containing the data collected during the observation periods, we were able to gather general statistics about the usage of the system. Table 1 contains the main statistics about the usage data gathering for each exhibition, including the collecting period, the number of sculptures virtually explored, and the total usage times in hours. Balsa et al. [BAB*16] present an analysis of the usage time of the system in the museums of Cagliari and Cabras, comparing it with the presence of visitors at exhibition. This study is instead focused on analyzing the visitor behavior with respect to the exploration interface: specifically we aim to understand how the interface choices affect user performances, and how visitors use the various interface components. Table 2 reports the main statistics for the most explored sculptures for each museum installation: specifically the number of times each sculpture is explored and the average exploration time are indicated. Interestingly, in the six top explored ranking, all categories of the sculpture collection are represented (boxers, archers, warriors, and nuraghe models). The average exploration time depends on the presence of features and attraction points, and varies from 30 seconds for the nuraghe models to 70 seconds and more for the most decorated boxer and archer sculptures.

5. Interest analysis

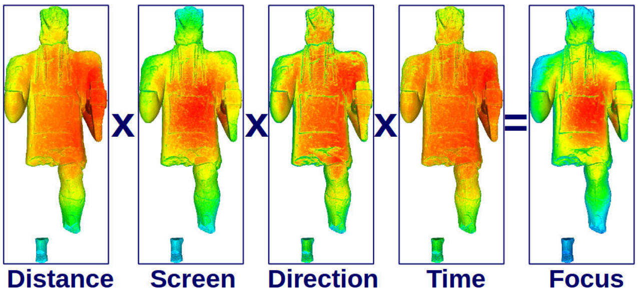

Figure 3: ***Interest map value composition.*** *A focus value is computed by multiplying various contributions depending on vertex position and the viewpoints from which it is observed. Specifically penalization factors depending on distance from vertex to viewpoint, screen projected distance, orientation and observation duration are considered. The colors are computed by employing the standard jet color map with respect to a log-normalized scale of contribution values.*

We considered recent and classic 3D visualization and knowledge discovery tools to analyze and interpret the visitors behavior while exploring and interacting with the single sculptures. For the most explored sculptures of each category we carried out an analysis of the visitor behaviors, trying to understand which parts of the sculptures were considered the most appealing. In our case, in order to have an immediate visual representation of visitors interest to be mapped to the sculpture models, we extended the interest function defined in [BAB*16]. Specifically, we define a **focus map**, in which, for each vertex v_k of a surface model, a value ϕ_k is computed with respect to the visitor view points represented by projection and view matrices P_i and V_i, from which it was visible, through ray casting operation. Specifically, given a ray d_{ik} connecting the current viewpoint $e_i = V_i^{-1}O$ and the vertex v_k, the following contributions were considered:

- **Distance-based penalization**: a factor δ_{ik} based on the distance $\|d_{ik}\|$ in world coordinates, representing the fact that closest viewpoints indicate a bigger visitor interest in specific features of the sculptures (d_{max} is chosen in function of bounding box size, in our case we put 3 meters)

$$\delta_{ik} = (1 - \frac{\|d_{ik}\|^2}{d_{max}^2})^2 \quad (1)$$

						
Cagliari	$V: 9479$ $T(s): 98.4$	$V: 4254$ $T(s): 79.53$	$V: 2912$ $T(s): 71.56$	$V: 2892$ $T(s): 61.52$	$V: 2851$ $T(s): 73.41$	$V: 1694$ $T(s): 42.47$
Cabras	$V: 5037$ $T(s): 97.61$	$V: 2827$ $T(s): 74.71$	$V: 2315$ $T(s): 67.01$	$V: 1478$ $T(s): 56.12$	$V: 2142$ $T(s): 65.73$	$V: 1536$ $T(s): 45.5$
Rome	$V: 543$ $T(s): 70.48$	$V: 272$ $T(s): 64.94$	$V: 239$ $T(s): 60.52$	$V: 284$ $T(s): 52.73$	$V: 218$ $T(s): 64.59$	$V: 142$ $T(s): 30.65$
Milan	$V: 986$ $T(s): 69.06$	$V: 399$ $T(s): 52.93$	$V: 367$ $T(s): 57.9$	$V: 386$ $T(s): 52.39$	$V: 310$ $T(s): 51.61$	$V: 223$ $T(s): 29.27$

Table 2: ***Sculpture explorations:*** *main statistics for the most visited sculptures. For each museum installation, it is indicated the number of times the specific statue has been explored with the system as well as the average exploration time in seconds.*

- **Screen-based penalization**: a screen-space factor σ_{ik} based on the distance between the projected vertex and the center of screen, representing the fact that more central is the vertex v_k according to the current view, more interesting is the surface element for the view position represented by transform P_iV_i

$$\sigma_{ik} = (1 - \|P_iV_iv_k\|^2)^2 \tag{2}$$

- **Orientation penalization:** a factor ν_{ik} depending on the angle between the direction $\hat{d_{ik}} = \frac{d_{ik}}{\|d_{ik}\|}$ from the viewpoint to the vertex and the normal at the vertex $\hat{n_k}$, representing the fact that surface portions directly facing the view point are more interesting for the current viewpoint

$$\nu_{ik} = max(0, \hat{n_k} \cdot \hat{d_{ik}}) \tag{3}$$

- **Time penalization:** a factor depending from the duration t_i of the current observation (t_{max} is the maximum duration, and set to 20 seconds), representing the fact that more time a view position is kept, more interesting is that view

$$\tau_i = (1 - \frac{t_i^2}{t_{max}^2})^2 \tag{4}$$

The interest value for all sculpture mesh vertices is computed by accumulating the contribution coming from all view points through ray casting and by simulating depth buffering in order to avoid to add contributions to invisible vertices. Hence, for each vertex v_k, the focus interest value is

$$\phi_k = \sum_i \delta_{ik} \cdot \sigma_{ik} \cdot \nu_{ik} \cdot \tau_i. \tag{5}$$

Figure 3 shows how the various contributions compose the interest map: the colors are computed by employing the standard jet color map with respect to a log-normalized scale of contribution values (with $s = \frac{log(\phi_k+1)}{log(\phi_{max}+1)}$). The same jet log-normalized colormap ranging from blue to red has been employed in all analysis and it has been chosen to highlight the local maxima of the interest map. The interest map provides a fast and visually significant tool to recognize the main attractive points in the sculptures and it can be employed for visual analysis of interest and to find differences in behaviors between the various museum installations and between the two user interfaces employed in the interactive stations (free 3D exploration interface, image-based points of interest selection interface). By computing the focus map for the most appreciated sculptures, and by subdividing the viewpoints reached through free exploration and through image selection, and the data gathered during different exhibitions, we were able to visually identify eventual differences due to the exhibitions and to the interface. For space reasons, we restricted our analysis to the four sculptures mostly explored: a boxer, an archer, a warrior and a nuraghe model. We experienced that for the most explored sculptures, the most appealing features resulted in focus interest global maxima independently from the user interface employed and exhibition. Table 3 shows the different focus maps computed for the different sculptures: from top to bottom, the boxer, the archer, the warrior and the nuraghe; from left to right, the the museum exhibitions of Cagliari, Cabras, Milan and Rome, separated for positions reached through free exploration and through image selection. Only slight differences can be noticed between the maxima highlighted in the various focus maps, indicating that the most significant features of the sculptures attracted users in all exhibitions, and they were reached easily and in similar way through both user interfaces. Main color differences between the interest maps computed for permanent exhibitions (Cagliari and Cabras on the left side) and temporary exhibitions (Milan and Rome on the right side) are due to the significantly different number of views employed for the computation. As expected, the most decorated and distinctive elements were the ones who attracted visitors: the boxer and warrior schematic faces, defined by the heavily rendered eyebrows and straight nose forming up a prominent T-shape as well as the magnetic eyes represented

Cagliari		**Cabras**		**Rome**		**Milan**	
Free	POIs select	Free	POIs select	Free	POIs select	Free	POIs select

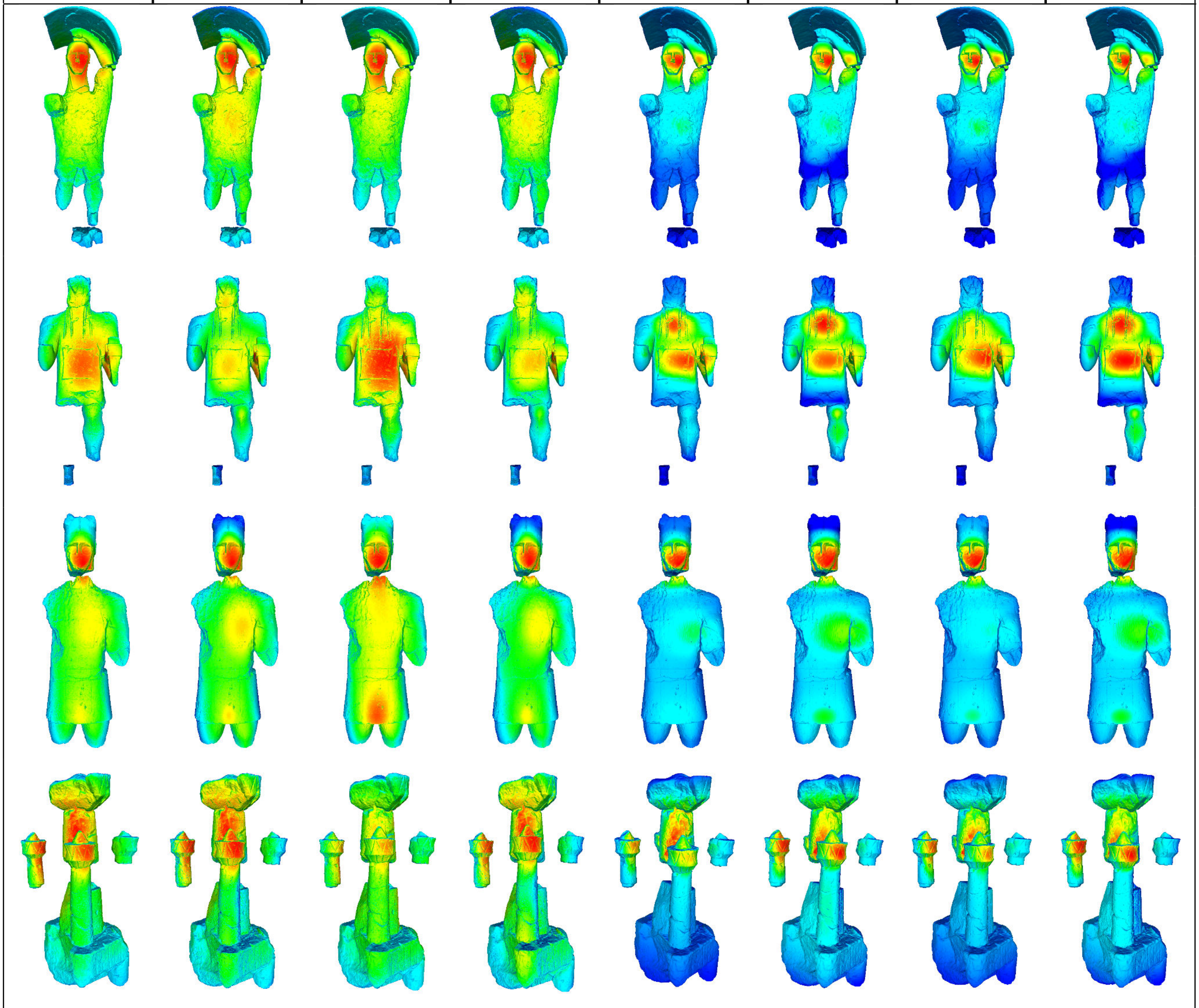

Table 3: ***Interest maps comparison for most explored sculptures.*** *From top to bottom, the boxer, the archer, the warrior and the nuraghe model. From left to right, the maps computed for the exhibitions of Cagliari, Cabras, Milan and Rome, separated in free 3D exploration and points of interest image-based selection.*

by two nested circles, the archer plate protection and bow and arm decoration, the warrior vest, and the nuraghe model tower decorations.

6. 3D exploration analysis

The analysis of interest map provides an immediate visual tool to understand the main visitor preferences with respect to the various parts of the sculptures, but it is not enough to understand the visitor behavior and the main exploration paths. Hence, the visitor view positions need to be analyzed as high-dimensional data, in order to find main position clusters and classify the fundamental motions. To this end, we performed a visual analysis of the clouds of visitor positions by applying classic visual analytics techniques employed for knowledge discovery and data mining in various application domains [LMW*15]. Our goal was to find differences and connections between the two user interfaces employed in the interactive stations, and eventual behavior differences with respect to the exhibitions. We carried out this analysis on the two mostly explored sculptures in the collection, the boxer and the archer.

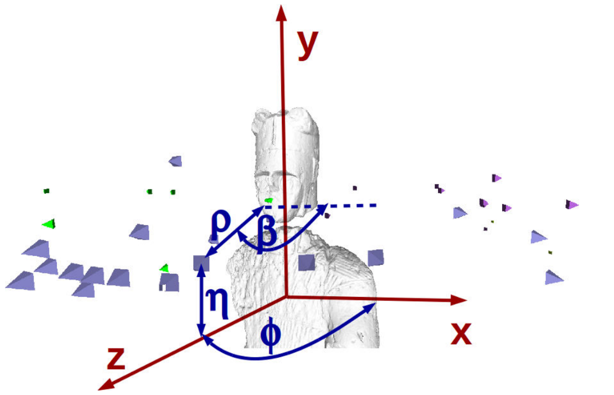

Figure 4: ***View parametrization.*** *Recorded view transformations obtained with auto-centering virtual trackball can be parametrized by considering a normalized distance* ρ*, a normalized height* η*, an orientation angle* ϕ *and a view direction angle* β *on the horizontal plane.*

View transform parametrization. Since the 3D user interface employed for free exploration in all interactive stations is composed by a servo-assisted virtual trackball with automatic pivot computation [BAMG14], and with fixed up direction, in order to simplify classification and clustering, we parametrized the recorded view transformations V_i by reducing the number of degree of freedom to four components:

- a distance value ρ_i from the view position e_i to the pivot on the surface, computed by employing the same stochastic sampling considered in the Automatic-Center Virtual Trackball (ACeViT) interface (the normalization is carried out with respect to the double diagonal R of the bounding box of the sculpture model) [BAMG14];
- a normalized height η_i with respect to the height H of the bounding box of the sculpture model;
- an orientation ϕ_i on the horizontal plane, computed according to the cylindrical coordinates of the view position e_i;
- an orientation β_i on the horizontal plane, representing the view direction.

A schematic representation of the view parametrization is shown in figure 4.

Histogram analysis. In order to individuate the main trends of visitors during interactive exploration we computed and analyzed frequency histograms of the view transform parameters. Figures 5 and 6 show the comparison with respect to the various installations of parameters histograms for the boxer and archer sculpture. From left, the first columns in red show the distance ρ frequency histograms and permit to individuate three main peaks corresponding to the three main exploration scales: from macro-structure to meso-structure to micro-structure. Differences in distance histograms between the permanent exhibitions (Cagliari and Cabras in the two top rows) and the temporary exhibitions (Milan and Rome in the two bottom rows) can be noticed and they are due to the different display setups (portrait display orientation versus landscape display

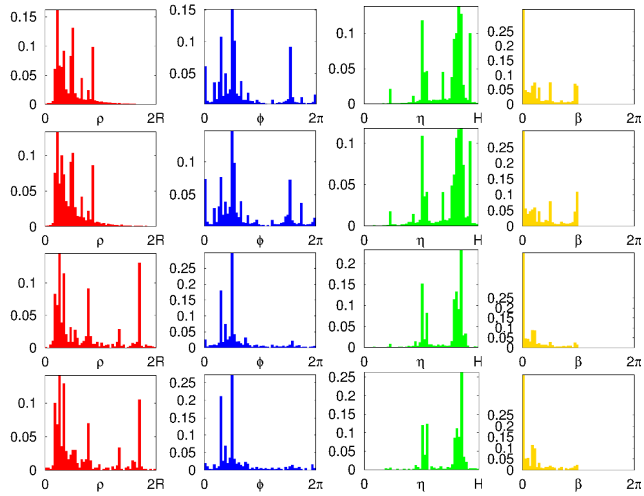

Figure 5: ***Frequency histograms of parametrized views for the boxer sculpture model.*** *From top to bottom histograms of view parameters for exhibitions in Cagliari, Cabras, Milan, and Rome. From left to right, the represented parameters are the distance* ρ*, the orientation* ϕ*, the height* η*, and the view direction orientation* β.

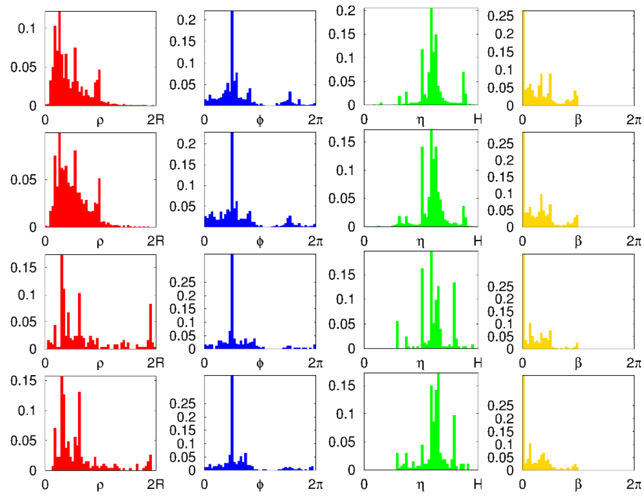

Figure 6: ***Frequency histograms of parametrized views for the archer sculpture model.*** *From top to bottom histograms of view parameters for exhibitions in Cagliari, Cabras, Milan, and Rome. From left to Right, the represented parameters are the distance* ρ*, the orientation* ϕ*, the height* η*, and the view direction orientation* β.

orientation) leading to different exploration workspace sizes. The second columns in blue show the view orientation ϕ histograms and highlight that visitors mostly prefer to explore the sculptures frontally ($\phi = -\frac{\pi}{2}$), even if a smaller peak can be individuated in the back ($\phi = \frac{\pi}{2}$). The third columns in green show the height η histograms and highlight how visitors tend to explore the top parts of the sculptures since they contains the most distinctive features: face decorations and shield in the case of the boxer, plate decoration, breeds and bow in the case of the archer. Finally, for histograms in yellow representing the view direction orientation β, apart of the favorite straight direction, various small peaks provide indication about the clusters around the positions of interest.

Clustering view transformations. From histogram analysis, it appears evident that visitors view transformations tend to form clusters around the area of interest. In order to highlight the main visitor behaviors we carried out a supervised cluster analysis, by employing the K-means algorithm [Jai10] over the view transforms according to the same parametrization employed for the histogram analysis. Since we noticed similar behaviors in different installations, we report here as examples the results for the archer sculpture in the installation in Cagliari (in figure 7), and the boxer sculpture in the installation in Cabras (in figure 8). Since our goal is to find relations and differences between the two interfaces employed in the interactive stations, we compare the exploration cluster centroids with the view transforms of the point of interests employed for the image-based select interface. Specifically, figures 7 and 8 show the top, front, and side view of the clustered view transforms rendered as small pyramids, together with the cluster centroids rendered as dark blue bigger pyramids and the precomputed points of interest rendered as dark red bigger pyramids. In both figures, it is evident that most of cluster centroids are very close to the precomputed point of interests, confirming the visual impression derived from focus maps in table 3. Furthermore, it can be observed that the densest clusters match with the maxima in the interest maps (protective plate and bow in the case of archer, and face in the case of boxer). Finally, circular patterns are perceivable at macro and meso scale, confirming that visitors have also the tendency to explore the sculpture by rotating around it in order to get an overall idea of the shape.

Discussion. From the interest map analysis, and the 3D exploration analysis, we were able to derive the following considerations with respect to the visitor behaviors during the interactive virtual exploration of the collection of digital sculptures:

- **Uniform exploration workspace:** especially for the most explored statues, there is the tendency of users to freely inspect the models by using different scales and by performing circular movements around the distinctive features, for example the shield in the case of the boxer sculpture (see figure 7). We also noticed the tendency of exploring especially the front side of the sculptures, and use the back side mostly for macro-scale and meso-scale inspection. Similar behaviors were observed for all sculptures analyzed.
- **Influence of display orientation:** the analysis of distance histograms revealed significant differences with respect to the exhibition due to the display orientation (portrait orientation in permanent exhibitions versus landscape orientation in temporary exhibitions). We can infer that portrait displays appear more adequate for sculpture exploration since the zoom range is reduced either for macro-scale inspection (a lower zoom level is sufficient for viewing the entire sculpture) and micro-scale inspection (a lower zoom level is sufficient for observing the finest details).
- **Attractiveness of distinctive features:** independently from the user interface employed and the exhibition considered, both interest map analysis and cluster analysis revealed that the most decorated landmarks are considered the most attractive for visitors, and both the control metaphors (free 3D interface and image-based selection widget) are effective enough to permit the visitors to inspect very close details of the objects that would be otherwise hard to observe on the real ones (i.e., small carvings).
- **Interconnection between the user interfaces:** the similarities perceived in both interest map analysis and cluster analysis let us deduce that there is a tight connection between the two control metaphors. Moreover, from direct observation of visitor behaviors, we realized that users tend to use the image-based selection widget for reaching the most attractive points-of-interest and successively they move around locally with the free exploration interface to further find appealing surrounding views or to discover other details. Anyway, we think that the interconnection between the two interfaces greatly reduce the visitor efforts, enabling to perceive the aura of the work-of-art in less time and with greater satisfaction.

7. Conclusions

We presented visual and quantitative methods, as well as analysis results, for the user activity during virtual explorations performed on interactive stations for the visualization of highly detailed acquired models of a collection of protostoric mediterranean sculptures. The interactive stations have been used by tens of thousands of visitors during 24 months at the National Archaeological Museum of Cagliari, 10 months at the Civic Archaeological Museum of Cabras, 6 months at the National Prehistoric Ethnographic Museum Luigi Pigorini in Rome, and 6 months at the Civic Archaeological Museum in Milan. The user study has been focused on individuating the main visitor behaviors during 3D explorations by employing tools for deriving interest measure on surfaces, and tools for clustering and knowledge discovery from high-dimensional data. Results confirmed that the system permits casual users to inspect and appreciate the artworks at different scales: from general views to very close details that would be otherwise hard to observe on the real sculptures. Moreover we think that this usage analysis can provide useful insights for the development of constrained 3D interfaces for virtual explorations of scenes and models, and for creating precomputed paths with additional informative contents. We believe that the derivation of interest maps (as well as of tools for spatial visualization and analysis of recorded view positions) can open new scenarios for technology assessment and sociological analysis purposes. We plan to further explore this field in the context of systems for presenting annotated information spatially connected to the surface models [BAMG15].

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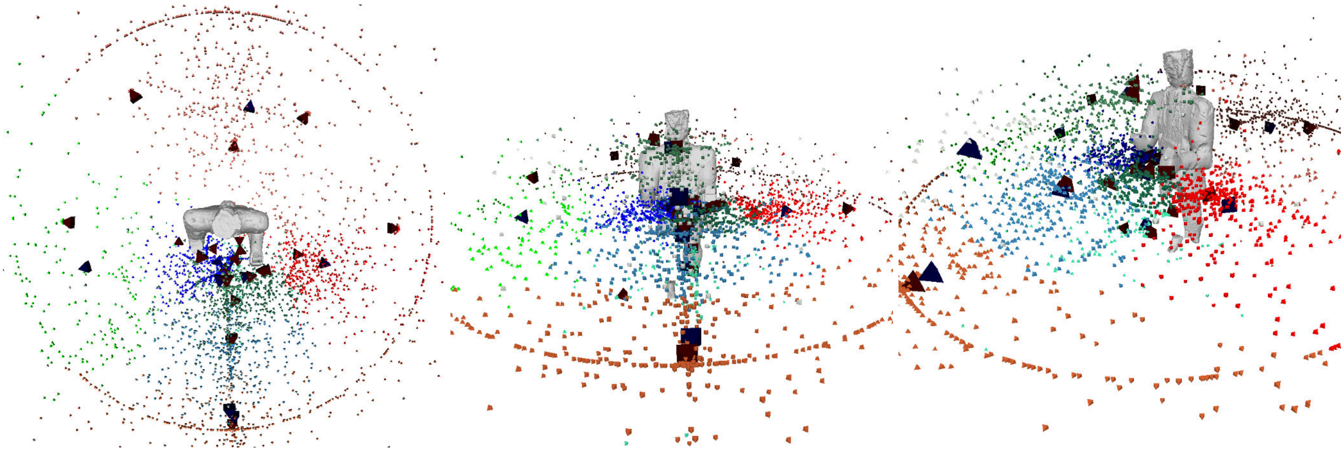

Figure 7: ***View positions clusters for archer at permanent installation in Cagliari.*** *From left to right, top, front and side view. Clusters are computed with K-means algorithm [Jai10] by considering by considering 10 clusters with the help of the main peaks of histograms in figure 6. Cluster centroids are indicated in dark blue, and compared to the precomputed point-of-interest view positions employed in the thumbnail-based selection interface indicated in dark red.*

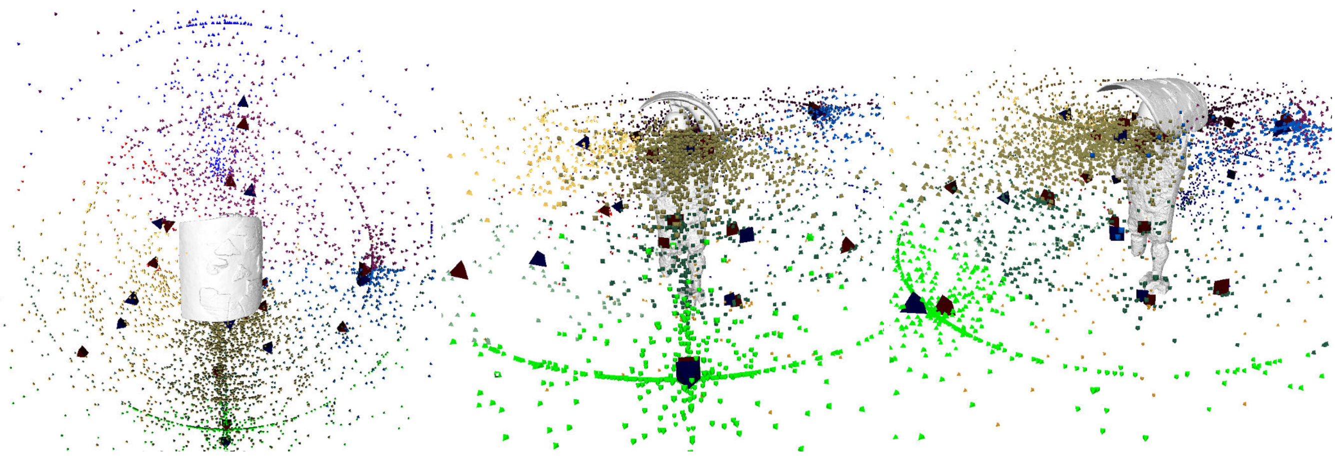

Figure 8: ***View positions clusters for boxer at permanent installation in Cabras.*** *From left to right, top, front and side view. Clusters were computed with K-means algorithm [Jai10] by considering 10 clusters with the help of the main peaks of histograms in figure 5. Cluster centroids are indicated in dark blue, and compared to the precomputed point-of-interest view positions employed in the thumbnail-based selection interface indicated in dark red.*

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