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To cite this version:

Brett Ridel, Patrick Reuter, Jérémy Laviole, Nicolas Mellado, Nadine Couture, et al.. The Revealing Flashlight: Interactive spatial augmented reality for detail exploration of cultural heritage artifacts. Journal on Computing and Cultural Heritage, 2014, 7 (2), pp.6:1-6:18. 10.1145/2611376 . hal-00986905v2

HAL Id: hal-00986905
https://inria.hal.science/hal-00986905v2

Submitted on 12 May 2014

The Revealing Flashlight: Interactive spatial augmented reality for detail exploration of cultural heritage artifacts

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Cultural heritage artifacts often contain details that are difficult to distinguish due to aging effects such as erosion. We propose the *revealing flashlight*, a new interaction and visualization technique in spatial augmented reality that helps to reveal the detail of such artifacts. We locally and interactively augment a physical artifact by projecting an expressive 3D visualization that highlights its features, based on an analysis of its previously acquired geometry at multiple scales. Our novel interaction technique simulates and improves the behavior of a flashlight: according to 6-degree-of-freedom input, we adjust the numerous parameters involved in the expressive visualization - in addition to specifying the location to be augmented. This makes advanced 3D analysis accessible to the greater public with an everyday gesture, by naturally combining the inspection of the real object and the virtual object in a co-located interaction and visualization space.

The *revealing flashlight* can be used by archeologists, for example, to help decipher inscriptions in eroded stones, or by museums to let visitors interactively discover the geometric details and meta-information of cultural artifacts. We confirm its effectiveness, ease-of-use and ease-of-learning in an initial preliminary user study and by the feedbacks of two public exhibitions.

Categories and Subject Descriptors: I.3.1. [**Computer Graphics**] Interaction Techniques; H.5.2. [**Interaction Techniques**] Input devices and strategies; H.5.m. [**Information Interfaces and Presentation (e.g. HCI)**] Miscellaneous

General Terms: Spatial interaction techniques

Additional Key Words and Phrases: Spatial interaction techniques, expressive visualization, spatial augmented reality, tangible interaction

ACM Reference Format:

Brett Ridel, Patrick Reuter, Jeremy Laviole, Nicolas Mellado, Nadine Couture, Xavier Granier. The Revealing Flashlight: Interactive spatial augmented reality for detail exploration of cultural heritage artifacts. *ACM JOCCH* 7, 2, Article 1 (May 2014), 17 pages.
DOI:http://dx.doi.org/10.1145/0000000.0000000

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1. INTRODUCTION

Cultural heritage artifacts provide tangible evidence to study and analyze the past, and to pass on our cultural values to future generations. They often contain geometric details that are difficult to distinguish due to aging effects such as erosion. Nowadays, with recent acquisition techniques such as 3D laser scanning and multi-view stereo from photographs, it is increasingly common to have precise 3D representations of these cultural objects for digital preservation.

These 3D representations may also help to improve our current understanding of the artifacts since their study can be computer-assisted. Indeed, beyond shadows that provide an effective cue to determine the shape, higher-order geometric features that are difficult to see with the naked eye can be extracted by advanced processing, analyzed and then used to change the object's appearance to exaggerate details during visualization. These so-called expressive rendering or non-photorealistic rendering techniques have proven

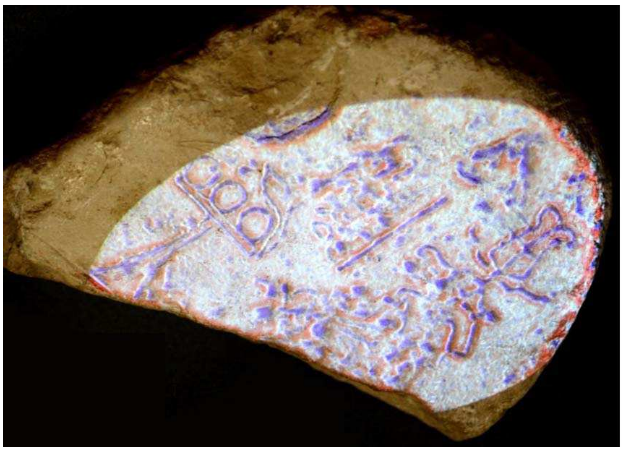


Fig. 1. Augmenting a cultural artifact by projecting an expressive visualization.

to be valuable for studying cultural artifacts since they emphasize detail while underlining the hypothetical aspect of the representation [Roussou and Drettakis 2003]. Usually, expressive rendering techniques involve 3D user interactions and complex parameter-tuning, and this leads to difficulties for archeologists to take ownership of and actually use the proposed approaches. Moreover, virtual exploration must always be combined with an observation of the real object itself since the real object gives us strong clues about the object's properties, such as size, material, and general appearance.

Hence, both the real artifact and a detail-aware visualization of the 3D representation contribute to gaining knowledge about the past. However, their separate study hinders the global understanding since one has to permanently switch between inspecting the real object and its virtual counterpart in order to obtain all information. This induces a non-negligible cognitive overhead to establish the link between both, which could sometimes prevent the deciphering of highly eroded features, only visible when both the 3D representation and the real artifact are combined in the same place.

In this paper, we propose the *revealing flashlight*, a new interaction and visualization technique that combines the advantages of studying both the real object and its 3D model in an integrated system using spatial augmented reality (Figure 1). Our solution consists of three key ingredients. First, we analyze the previously acquired 3D model geometrically by computing curvatures for every surface sample and at multiple scales in order to capture finer or coarser convexities and concavities. Second, by using a videoprojector, we use spatial augmented reality to superimpose an expressive visualization directly onto the real artifact that highlights the detected features of its geometry. And third, we provide a novel interaction technique that simulates and improves an interaction metaphor everybody is familiar with - the use of a flashlight: according to the position and orientation of a 6-degree-of-freedom input, we adjust the numerous parameters involved in the expressive visualization - in addition to specifying the location to be augmented. We implemented two variants of the *revealing flashlight* for providing the position and orientation in the 6-degree-of-freedom input, one based on an electromagnetically tracked prop having the shape of a classical flashlight, and one based on optical tracking of direct finger pointing input.

Our work has a number of advantages for exploring cultural heritage objects, and makes the following contributions. Besides the idea of our solution itself that lets users simultaneously and effectively inspect real objects and their acquired precise 3D geometry seamlessly, our main contribution lies in the interaction technique, that is the way we map the position and direction of the flashlight to the parameters of the expressive visualization based on a multi-scale geometry analysis. This makes advanced 3D analysis accessible to the greater public with an everyday gesture, by naturally combining the inspection of the real object and virtual object in a co-located interaction and visualization space. We confirm the effectiveness, ease-of-use and ease-of-learning of our technique in a preliminary user study.

Since the 3D object is acquired and analyzed in a preprocess, our system operates in real-time irrespectively of the object's complexity, making our solution appropriate for concrete application scenarios. There are two principal application types. First, archeologists and museum curators have a powerful tool to inspect cultural artifacts and might improve their knowledge about them while staying focused on their actual task. For example, they can decipher hardly visible inscriptions in eroded stones. Second, since traditionally heritage institutions wish to inform visitors about lost physical properties, with the *revealing flashlight*, museums and exhibition visitors can explore real artifacts and gain additional geometric information on demand, resulting in a completely novel interactive experience, that is today crucial for attractive exhibitions. Our system can be easily extended to project meta-information such as text and images for annotating cultural artifacts as well, in addition or replacement of long and painful-to-read museum labels. We are convinced that our system is inspiring and stimulates the design of more applications.

The remainder of this paper is organized as follows. In the following section, we present some related work. In Section 3, we present the *revealing flashlight*, its setup, and the expressive visualization techniques used. In Section 4, we focus on our new interaction technique. In Section 5, we present a preliminary user study for deciphering inscriptions as well as feedbacks from two public exhibitions. We conclude with directions for future work in Section 6.

2. RELATED WORK

Detailed 3D representations of cultural heritage artifacts are getting more and more available, especially since the impact of the remarkable 3D scanning Digital Michelangelo project [Levoy et al. 2000]. Nowadays, 3D scanning is complemented by multi-view stereo techniques that also generate precise 3D models, from input as simple as multiple photographs [Seitz et al. 2006], also known as *photogrammetry*. Moreover, depth-cameras (such as the Kinect or KinectFusion [Izadi et al. 2011]) are becoming available to the greater public.

Taking as input a precise 3D representation, our interaction and visualization technique integrates three concepts that have recently been applied to the study of cultural heritage artifacts rather separately: expressive visualization, spatial augmented reality, and spatial interaction techniques. In the following, we will first review the most relevant previous work in these three areas, with a special focus on their application to cultural heritage, followed by some related systems that have been proposed recently.

2.1 Expressive visualization

Precise 3D models of the surfaces of artifacts are more and more used for a computer-assisted analysis, as for example for quantitative analysis such as distance measurements [Sun et al. 2009] or curvature estimations [Gal and Cohen-Or 2006]. And beyond, the analyzed quantitative information can be used to highlight surface features on the object during visualization. This is commonly known as expressive (or *non-photorealistic*) visualization.

One of the first methods to highlight surface features is known as *accessibility shading* [Miller 1994] that highlights cavities by darkening hardly-accessible surface points. The analysis of normals has been used for *normal enhancement* [Cignoni et al. 2005] and *Polynomial Texture Maps* [Malzbender et al. 2006], extended to multiple scales in the *exaggerated shading technique* [Rusinkiewicz et al. 2006]. The variation of incoming radiance is used in *Radiance Scaling* [Vergne et al. 2010].

Differential geometry can be used to detect ridges and valleys [Ohtake et al. 2004] or demarcating curves [Kolomenkin et al. 2008]. Pauly et al. [Pauly et al. 2003] combine the geometric analysis at multiple scales to detect and highlight features lines. Some approaches use a decomposition of the surface geometry into base and relief layers (e.g. [Zatzarinni et al. 2009]), and study the details of the relief layer, such as *surface* *relief analysis* [Ammann et al. 2012] or *prominent fields* [Kolomenkin et al. 2011]. The latter technique was recently applied to the study of cultural heritage artifacts.

All these techniques require the adjustment of several parameters. Most of the time, for a local estimate of differential quantities, a neighborhood at every surface point has to be taken into account, and the appropriate size of this neighborhood, also called *scale*, is yet to determine. Mellado et al. [Mellado et al. 2012] studies the impact of this neighborhood size directly on acquired point clouds by determining a discrete number of pertinent scales, known as *Growing Least Squares*. This analysis can be used to highlight features at different scales.

An exhaustive study of expressive rendering techniques is clearly out of the scope of this paper. Nevertheless, note that some of the expressive rendering techniques do not require a 3D representation of the artifact, but get by with images with normals for fixed viewpoints [Toler-Franklin et al. 2007] that could by acquired by varying light directions, as for example in *Polynomial Texture Maps* [Malzbender et al. 2006], also known as *Reflectance Transformation Imaging (RTI) Imaging*. However, the lack of guaranteed error bounds on the estimated geometry (e.g. with shape from shading techniques [Nayar et al. 2006]) makes those techniques impractical for studying precise geometric detail: higher-order geometry analysis and detail exploration at various scales for varying viewpoints require a 3D representation of the artifact, being crucial for instance for distinguishing features from erosion. Since we do not rely on a specific acquisition technique, our approach can be applied to study any kind of acquirable artifacts, ranging from small engraved rocks to tall sculptures with deep concave structures. On the other hand, shape from shading approaches such as RTI are more adapted to planar-like geometries with an estimation of the local relief. Moreover, for spatial augmented reality, due to the involved perspective projection, a precise alignment of the superimposition over the real artifact requires its 3D geometry. Consequently, in our approach, we rely on a precise 3D representation of the object and use *Radiance Scaling* [Vergne et al. 2010] and *Growing Least Squares* [Mellado et al. 2012] for the expressive visualization.

2.2 Spatial augmented reality

In augmented reality, the user's view of the real-world is augmented by computer-generated information. There are two principal techniques to achieve this. On the one hand, *see-through augmented reality* augments the display of a real scene on a screen (mobile phones, tablets, head-mounted displays, or glasses) by additional information. This was successfully applied to archeology, for example by the ArcheoGuide project [Vlahakis et al. 2002] to augment the Delphi archeological site in Greece.

On the other hand, spatial augmented reality [Raskar et al. 1998b; Raskar et al. 2001; Bimber and Raskar 2005], augments the user's physical environment with images that are integrated directly in the real-world, and not simply on a display. Most of the time, this is done by using a videoprojector. Note that spatial augmented reality for entertainment is sometimes called "Projection Mapping", "video mapping", or even "Projection-Based Augmented Reality" [Mine et al. 2012].

One of the major advantages is that since a display is not associated with each user, spatial augmented reality scales naturally up for numerous users, thus enabling community experiences and collocated collaboration. According to the Reality-Virtuality continuum of Milgram [Milgram and Kishino 1994], augmented reality is closer to the real environment than to the virtual environment. And by refining the Reality-Virtuality continuum (Figure 2), spatial augmented reality is also closer to the real environment than see-through augmented reality.

This is particularly interesting for cultural heritage applications: the virtual information layer integrates almost seamlessly, and non-3D experts may continue to reason in the real-world.

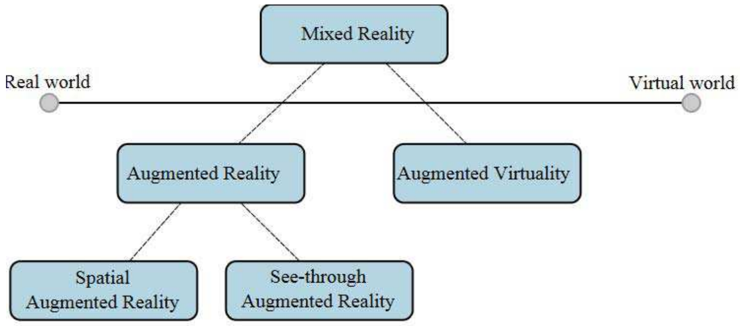


Fig. 2. The extension of Milgram's Reality-Virtuality continuum to account for see-through and spatial augmented reality.

2.3 Spatial user interaction

In spatial augmented reality, the co-location of the visualization and interaction space enables efficient and natural interaction when spatial user interaction is used. Spatial user interaction is a growing field as the sensing and display technologies are reaching a larger audience [Stuerzlinger and Steinicke 2013]. However, the design issues on spatial user interaction were already explored almost two decades ago [Hinckley et al. 1994].

Input modalities in spatial user interaction are either hands-free or use dedicated devices. Such devices can be specific such as the wand [Bandyopadhyay et al. 2001], pen [Jones et al. 2010] or finger caps [Mistry et al. 2009]. A device makes it easier for the user to understand how to use the system since it provides task-specific affordances. In contrast, hands-free input enables instantaneous interaction with the system. This kind of input generally relies on optical tracking using an RGB [Lee and Hollerer 2007] or depth camera [Harrison et al. 2011]. Another possibility is the instrumentation of the environment [Sato et al. 2012], however this technology relies on conductive surfaces. Consequently, it is not well suited for cultural heritage artifacts, since direct touch manipulation is not adapted for fragile objects.

In addition to the choice of the input modality, one of the most important factors in spatial user interaction is the interaction technique itself, that is how the provided user input is actually mapped to the accomplishment of a task, and hence to the parameters of the system. In this paper, we present such an interaction technique that is suited to two input modalities, one using a prop device, and one using finger gesture input.

2.4 Related systems

Spatial augmented reality was used to enhance pictorial artwork by projecting 2D imagery [Bimber et al. 2006]. It can also reveal information contained in an image [Schöning et al. 2009], or on the human body [Hess 2010]. The use of a flashlight for public exhibitions has also been explored [Green et al. 2013]. Note that see-through augmented reality has also been used to reveal information that is totally hidden to the user [Spindler and Dachselt 2009]. However, this method requires the use of a tablet.

Maybe the most related system to ours is the *context-aware light source* [Wang et al. 2010]. By means of a camera, a projector, and a proxy light, it enables to interactively superimpose information on a scene that is acquired and processed in real-time. This approach is limited by the resolution of the camera and to 2D image processing. As explained in the remainder of the paper, our approach uses a previously acquired 3D geometry information of the object, which enables us to display a larger range of augmentations and to be far more precise in the analysis. Concerning the interaction technique, since we do not depend on a proxy light source, we have less constraints to map the 6 degrees-of-freedom input to the parameters of the visualization that augments an artifact.

3. THE REVEALING FLASHLIGHT

In this section, we present the *revealing flashlight* and the involved hardware and software. Note that a 3D representation of the artifact to inspect is required. This decoupling of the acquisition from the use of the *revealing flashlight* makes it possible to work on a highly detailed 3D model, in contrast to techniques that do the acquisition on-the-fly. In the following examples, in a preprocess, we generated 3D point clouds ranging from 300K to 860K samples using either laser range scanning or photogrammetry, from series around 70 photographs per artifact (see Table I).

Table I. The artifacts used in this paper.

Name	Origin	Vertices	Acquisition method	Context	Figures
Isis	Lighthouse of Alexandria	860.000	Photogrammetry	Exhibition	4,5,6,10
Stele	Private collection	300.000	Laser scan (Faro ScanArm)	Preliminary user study	1,3,7,8
Buddha	Private collection	300.000	Structured light laser scan	Proof-of-concept	3
Relief	Wall of Mastaba	400.000	Structured light laser scan	6-month museum exhibition	11

3.1 The setup

In the current version of our prototype, the *revealing flashlight* is configured to augment a real artifact at a fixed location, by using one single videoprojector. Note that this configuration scales well to several projectors, of course by correctly managing the overlapping regions [Raskar et al. 1998a]. Consider the five main components of the two variants of our setup illustrated in Figure 3. For the inspection of a real artifact *(item 1)*, the user provides 6 degree-of-freedom input by a controller (*prop*) or direct finger pointing input (item 2). The position and orientation are detected by an electromagnetic device, or an optical tracking device, respectively (item 3). In order to improve the visual analysis, the additional information about the object's geometry is superimposed directly on the artifact by using a videoprojector (item 4). A simple camera (item 5) is used in a preprocess for the calibration [Audet et al. 2010] and to locate the object and the camera with respect to the projector. This is done by calculating the projection matrices for the videoprojector and the camera from their respective intrinsic parameters. Note that for a fixed projector position, the ARToolKit markers in Figure 3(right) are only needed for this preprocess - they can be removed for the use of the *revealing flashlight.*

We instantiated two concrete variants of our setup, one using the electromagnetic tracking system *Razer Hydra* (items 2 and 3 in Figure 3 (left)), and the other one using optical finger input with the *LeapMotion* (items 2 and 3 in Figure 3(right)). In order to suppress tracking noise and to account for hand trembling, we low-pass filter the signal with the *one Euro filter* [Casiez et al. 2012]. For both setups, we use a Qumi Q5 projector with 500 lumens (item 4) that is located at a distance of about 70cm away from the object. For the tracking that is done in a preprocess, we use a Playstation Eye camera (item 5). This particular setting is suitable for real objects with a diameter of up to 40cm. Of course, this setup can be scaled to account for larger objects, as shown in one of the exhibition setups in Section 5.

3.2 Expressive visualization modes

Detail of cultural artifacts is often difficult to explore due to suffered aging effects like erosion, and 3D analysis and expressive visualization can reveal hidden features. We implemented two different techniques that emphasize surface features, the first one showing explicitly the curvature, and the second one improving

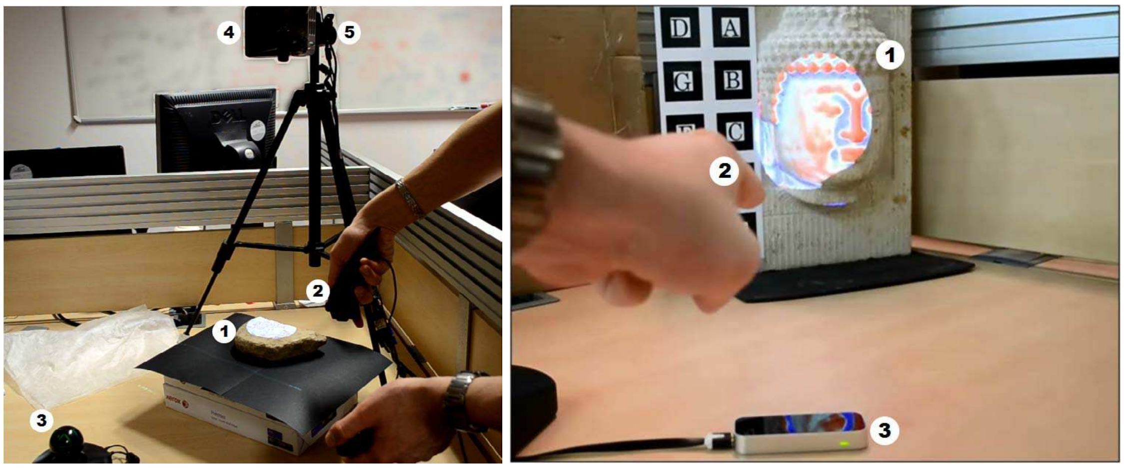


Fig. 3. Two variants of our setup. (Left) The position and orientation of a prop is tracked electromagnetically. (Right) The position and orientation of finger input is tracked optically.

shape depiction with *Radiance Scaling* [Vergne et al. 2010]. Both techniques use a multi-scale curvature estimation by *Growing Least Squares* [Mellado et al. 2012].

3.2.1 *Mode 1: Curvature visualization.* The first visualization mode is the *curvature mode* based on *Growing Least Squares* [Mellado et al. 2012]. After a multi-scale analysis of the acquired artifact that is done in a preprocess, the convexities and convexities are highlighted in red and blue, respectively. For the distinction of the magnitude of the curvature values, we use a transfer function to convert all the curvature values c to the unit $[-1, 1]$ interval: $c' = \tanh(c \cdot dist), c' \in [-1, 1], c \in \mathbb{R}, dist \in \mathbb{N}^*$ with $dist$ to be adjusted. The higher the intensity, the higher is the required curvature to show the effect, as can be seen in Figure 5.

The estimation of the curvature at each location depends on the scale, i.e. the size of neighborhood taken into consideration. We estimate curvatures at various scales. To this end, we use an approximation of algebraic spheres [Guennebaud and Gross 2007], re-parameterized according to [Mellado et al. 2012]. The smaller the scale, the more visible are the finer local details. The bigger the scale, the more visible are the global features of the artifact (see Figure 4). Concerning timings, the preprocess takes several minutes for moderately sized objects as used in this paper, and we store the results for further use. Of course, the inspection itself runs in real-time and highlights convexities and concavities of the object. According to the *scale*, more or less fine details are emphasized.

3.2.2 *Mode 2: Radiance Scaling visualization.* The second visualization mode is the *Radiance Scaling* mode according to [Vergne et al. 2010]. The main idea is to adjust the light intensity emitted by the object depending on its material, its curvature, and the direction of incident light. An external parameter modifies the intensity of the visualization. This technique highlights hardly visible details of the artifact. In our implementation, we use *Radiance Scaling* by simulating a *Phong* light model [Phong 1975] (Figure 6).

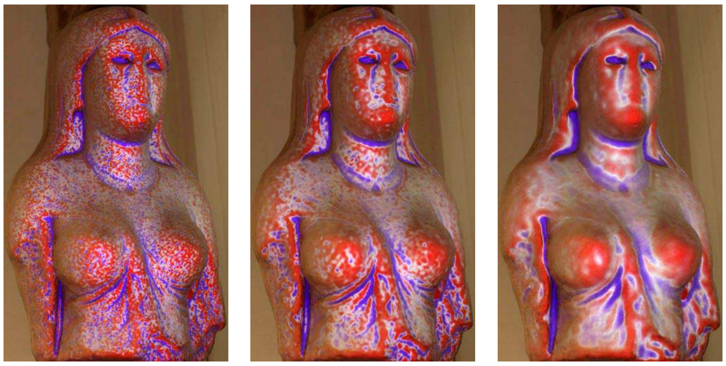


Fig. 4. Mode 1: Visualization with the *curvature mode* at growing scales.

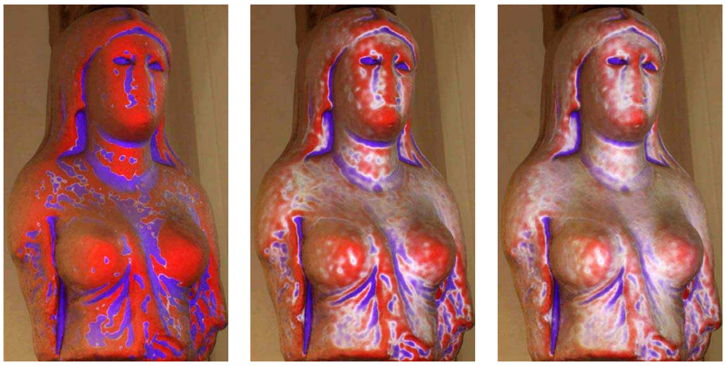


Fig. 5. Mode 1: Visualization with the *curvature mode* at growing intensities according to the *dist* parameter.

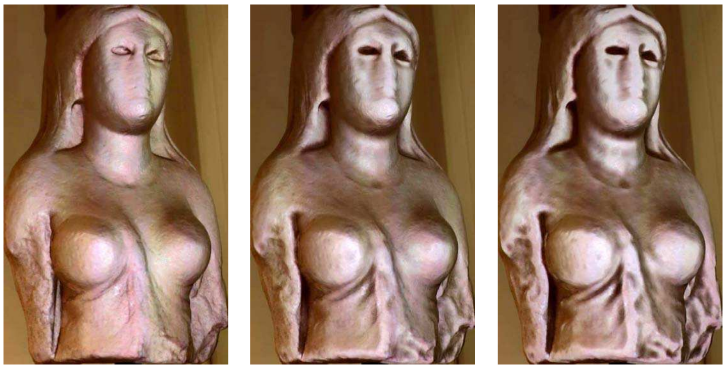


Fig. 6. Mode 2: Visualization with the *Radiance Scaling mode* at growing intensities.

4. THE INTERACTION TECHNIQUE OF THE REVEALING FLASHLIGHT

In order to understand the interaction technique that we designed in the *revealing flashlight*, we recall three characteristics involved in using a classical flashlight for illuminating an object. Note that these characteristics are interdependent, but we still separate them to clarify the parameter mapping of our interaction technique.

SPOT. This characteristic corresponds to the illuminated spot of the flashlight's lighting cone. Of course, a point on the object's surface is only illuminated and thus influenced by the flashlight when it is inside this spot. For an illustration, see Figure 7(a).

DISTANCE. This characteristic corresponds to the distance between the flashlight and the illuminated point on the surface. This distance influences the light intensity, and the shape and size of the spot. The closer the flashlight, the higher the intensity and the smaller the illuminated spot. For an illustration, see Figure 7(b).

ANGLE. This characteristic corresponds to the angle between the light direction (the incident light), and the normal of the illuminated point on the surface. In addition to the shape of the spot, this angle influences the intensity of the light in this point, defined by the cosine of the angle. The grazer the angle, the less the intensity, and the more ellipsoidal the illuminated spot. For an illustration, see Figure 7(c).

Recall that each of the two visualization modes described above involves various parameters. In the following, we describe how the three characteristics of the flashlight, captured by the 6 degrees-of-freedom input, are mapped to the parameters of the visualization modes. This mapping makes advanced 3D analysis accessible to the greater public with an everyday gesture, particularly thanks to the co-localization of the interaction and visualization space.

—The first characteristic called **SPOT** applies similarly to both visualization modes: it determines the location where the real artifact is augmented with geometrical information thanks to the superimposition of an expressive visualization. Hence, a user can easily specify the location of the object to inspect with additional virtual information.

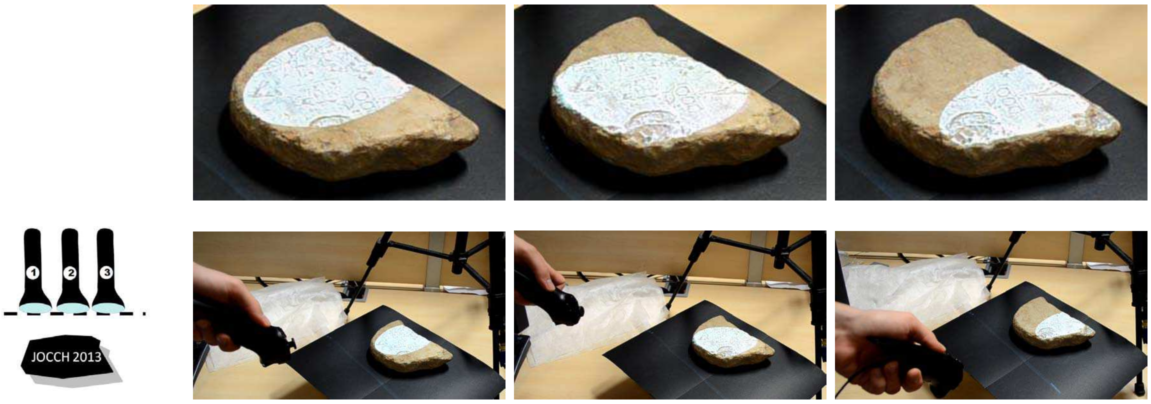
—The second characteristic called **DISTANCE** varies the intensity of the visualization. For the *curvature mode*, this consists in adjusting the involved *dist* parameter as described above and shown in Figure 5 (or alternatively the scale of the curvature analysis as shown in Figures 4). For the *Radiance Scaling* mode, this **DISTANCE** characteristic varies the intensity involved in the *Radiance Scaling* technique, as shown in Figures 6 and 7(b).

—The third characteristic called **ANGLE** influences the illumination intensity of the augmented visualization in both modes. The more perpendicular the angle to the surface normal, the more intense (in the sense of color saturation) is the superimposed visualization. The more grazing the angle, the less the augmentation is noticeable, and the more the real artifact "appears". Hence, the **ANGLE** characteristic can be considered as the blending parameter between the real object and the projected virtual information.

For visualization modes that involve more than three parameters, such as the *curvature mode*, there are further possibilities to adjust the additional parameters. For example, we can use the rotation of the "upvector", or use an additional controller in the other hand that would result in a bi-manual interaction. Note that the *revealing flashlight* goes well beyond the simulation of a classic flashlight, since we do not only steer the location of the spot to augment, but we also adjust various parameters involved in the expressive visualization modes.

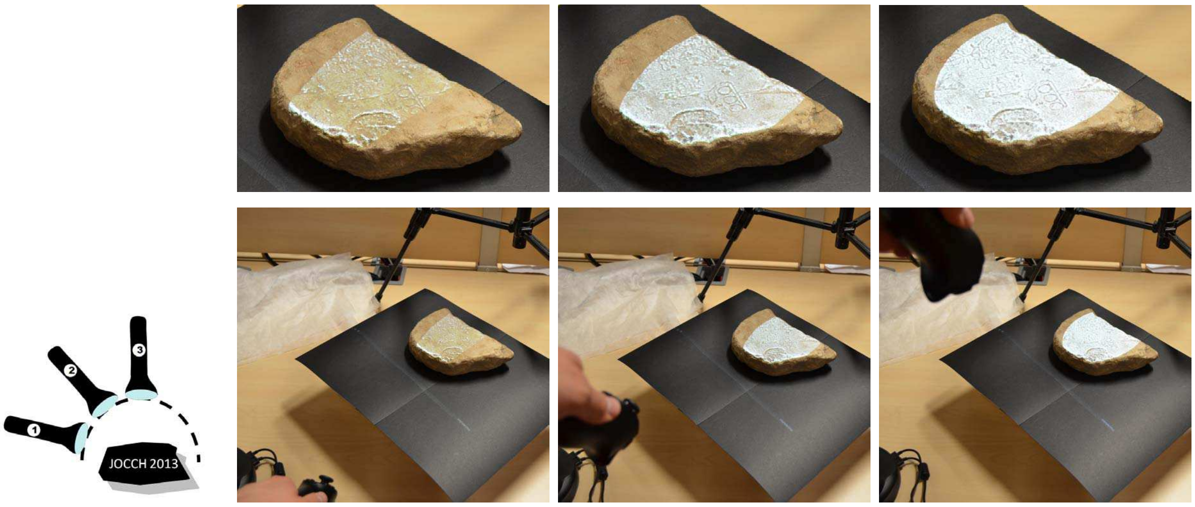
Our proposed interaction technique applies both to input by a physical prop that the user holds in his dominant hand (such as the *RazerHydra* in Figure 3(left)), and to finger pointing input (such as the optical tracker *LeapMotion* in Figure 3(right)). Note, however, that the finger gesture capture with the LeapMotion is limited to a rather small captured interaction volume, and so the variation amplitudes of the parameters **DISTANCE** and **ANGLE** are rather limited.

By using the physical prop, our interaction technique together with the prop can be considered as a tangible user interface (TUI) that perfectly reflects the definition of Ishii and Ullmer [Ishii and Ullmer 1997]: the prop *augments the real physical world by coupling digital information to everyday physical objects and environments*. A closer look to categorize this tangible user interface according to Fishkin's taxononomy



(a) SPOT: Illustration of different positions and orientations of the revealing flashlight to define the spot to illuminate.

(b) DISTANCE: Illustration of different intensities influenced by the distance of the revealing flashlight.



(c) ANGLE: Illustration of different angles between the direction of the revealing flashlight and the surface.

Fig. 7. Characteristics of the *revealing flashlight* and their impact on the visualization in the *Radiance Scaling mode*.

[Fishkin 2004] shows that, concerning the **embodiment** that represents how closely the input focus is tied to the output focus, the embodiment of the *revealing flashlight* is *nearby*. Moreover, according to the **metaphor** that describes the type and strength of analogy between the interface and similar actions in the real-world, the *revealing flashlight* has both the **metaphor of verb** appealing to the similar motion of the prop like moving a light source, and the **metaphor of noun** appealing to the similar shape of the prop as the shape of the *RazerHydra* resembles the shape of a classical flashlight.

5. USABILITY EVALUATION

The idea of the *revealing flashlight* came up during two collaboration projects between archeologists, museum directors, and computer scientists in 3D graphics. Starting from the early prototype design process, the researchers from the different fields were integrated in several design review meetings. In this section, we present usability evaluations for both application types: first, a preliminary user study of our new interaction and visualization technique for helping to decipher inscriptions as a curator work task, and second, user feedback from two exhibitions where visitors can interactively discover details.

5.1 Preliminary user study

5.1.1 *Overview.* For the usability evaluation of our new interaction and visualization technique for deciphering as a curator work task, we conducted a cognitive walkthrough based user study [Polson et al. 1992]. The users were in an exploratory learning mode. The aim of the cognitive walkthrough study is to see whether the users are able to use the interaction technique, and more precisely, whether they understand the effect of their actions, whether they find the available actions, and whether they learn from the provided feedback. Moreover, we made the following hypotheses:

H1. The *revealing flashlight* promotes the desire to observe and to understand a real artifact with augmented information about the geometric detail.

H2. The *revealing flashlight* is efficient for deciphering inscriptions on real artifacts.

H3. The *revealing flashlight* facilitates establishing the link between the real artifact and its virtual 3D representation.

Fig. 8. Egyptian stele to decipher.

In order to test these three hypotheses, 7 subjects participated in the user study, 6 men and 1 woman, aged from 23 to 41 years, 29 years in average. They were not paid. More than half of the subjects had no experience with deciphering inscriptions using 3D.

The subjects' task was to decipher inscriptions in an Egyptian stele (Figure 8) with the *revealing flashlight* in the visualization mode *Radiance Scaling*. For a comparison with a more classical exploration technique, every subject explored the stele in the following two modes:

Revealing flashlight mode. The subject uses the *revealing flashlight* to inspect the object. This means that he can choose the location to augment, and "feel" the influence of the other involved visualization parameters.

Real/Meshlab mode. The subject analyzes the real object, and in parallel he can use the *Meshlab* software [Cignoni et al. 2008] with the *Radiance Scaling* technique. Consequently, the user has to switch between the real object and the screen.

We are aware that these two modes are fundamentally different, and that we do not perfectly isolate the testing of only one variable. However, our aim in this first cognitive walkthrough study is to test the general acceptance and usability of the *revealing flashlight* - but we find it still useful to retrieve the users' feelings with respect to an alternative inspection mode.

Each subject explored the artifact in both modes. To avoid learning effects, we ensured that the order was counterbalanced (within-subjects design). More precisely, the subjects' tasks were as follows. Each subject inspected the object in each mode during 2 minutes. After the first pass, we showed the subject a list of 5 very similar patterns where only one actually belongs to the artifact (Figure 9), and the subject had to decide which pattern it was. Moreover, the subject had to estimate the real diameter size (in centimeters) of the pattern on the artifact. The second pass of the subject in the other mode is similar, but of course a different pattern had to be inspected. In addition, we asked the subject the distance between the two patterns (in centimeters). The aim of this task was to demonstrate the difference of a subject's analysis with and without the *revealing flashlight*, in terms of deciphering capacity, and in terms of real object understanding (with the distance question).

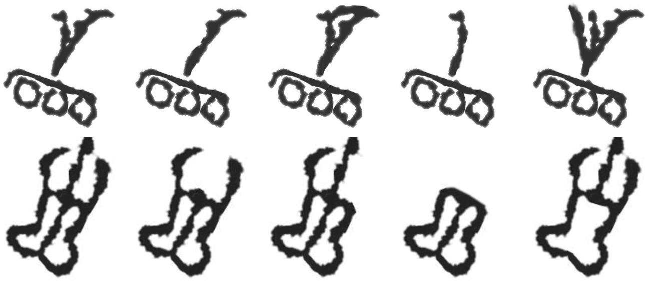


Fig. 9. The two series of very similar patterns. Here, the leftmost pattern is the correct one. For the presentation of the patterns to the user, the order is shuffled.

At the end, the subject had to fill out a questionnaire to provide a qualitative and subjective feedback. For example, we asked the subjects about their preferred inspection mode, and how they feel about the inspection with the *revealing flashlight*.

5.1.2 *Results of the user study.* Among the 7 subjects, 3 subjects identified the correct pattern in the *revealing flashlight* exploration mode, and 3 subjects in the *Real/Meshlab* mode as well. We are aware that the task for the subject was difficult since during the exploration, the subjects did not know which pattern they should look at more precisely. However, the task was motivating for all the users, especially in the second pass of each subject in the other exploration mode, since they were challenged by the difficulty of the task.

When it comes to determining the actual size of the patterns, both exploration modes generate similar results. However, when we ask the users the distance between the two patterns, the results in the *revealing flashlight* mode are much closer to the reality of 8.3cm distance: the subjects that completed in this mode responded with 7.7cm in average, compared to 4.3cm in the **Real/Meshlab** mode. We explain this superiority of the *revealing flashlight* mode that simultaneous inspection keeps the notions of space and distances, unlike on a screen.

According to the qualitative answers, the subjects highly prefer the use of the *revealing flashlight* (6 out of the 7 subjects). They stated that they find it easy-to-use, easy-to-learn, highly interactive, and practical to make the link between the real and the virtual object. Moreover, the *revealing flashlight* mode makes it possible to focus on a particular area of the object with the maximum attention and concentration, without being bothered by the rest of the object, thanks to the spot emitted by the *revealing flashlight*. Among the individual remarks, during the experiment, one subject claimed: ”It’s more clear with the flashlight. I like it. I prefer the flashlight, we can focus!”.

Even though only seven subjects participated, this preliminary user study qualifies our solution to be effective and easy-to-use and learn, and we think we can validate the three hypotheses. The feedback motivates us to conduct a more extensive user study for a more formal validation of our assumptions, and to test more variables with different tasks.

5.2 Feedback from public exhibitions

We installed two setups of the *revealing flashlight* at public exhibitions. In the first setup, we highlight geometric surface detail of the Isis bust by using finger pointing input, in both visualization modes. The Isis bust is a 1/5 scale reproduction from one of the colossal statues that was found at Alexandria’s Lighthouse and acquired by photogrammetry. The exhibition was part of the demonstration session at the annual conference of the Francophone Human-Computer Interaction Association (see Figure 10).

The second setup is slightly different to the ones described before, since it does not deal with geometric detail, but we superimpose texture information over a relief fragment from the wall of a Mastaba, a type of ancient Egyptian tomb. This fragment was originally colored, but all the original pigmentation has been lost. We use the revealing flashlight to interactively superimpose the lost colors. Our setup only implements the **SPOT** characteristic and maps texture information instead of geometry. It was on display in a 6 month-long exhibition in the Allard Pierson Museum in Amsterdam (the Netherlands), shown in Figure 11. In a 10 day user evaluation period, among the 42 subjects (21 men and 21 women, of all ages) that tested the *revealing flashlight* and replied to the questionnaire, 34 (81%) found that it is a positive addition to the exhibition offer. It is also interesting to note how the subjects learned to use the *revealing flashlight* and how their attention was captured (Table II).

The museum director was very pleased. He stated that the presence of a computer is completely hidden during the interaction, and this makes it possible to focus on the artifact, without being distracting by some type of new technology. Moreover, he liked that the virtual information layer is integrated almost seamlessly, and that non-3D experts may reason directly in the real-world.

In both venues, the exhibition visitors were enthusiastic about the revealing flashlight. For example, they pointed out that it is rare to be able to interact with real cultural artifacts in exhibitions.

6. CONCLUSIONS

In this article, we have presented a new interaction and visualization technique in spatial augmented reality that helps to reveal the detail of a real artifact thanks to a superimposition of precise geometric information

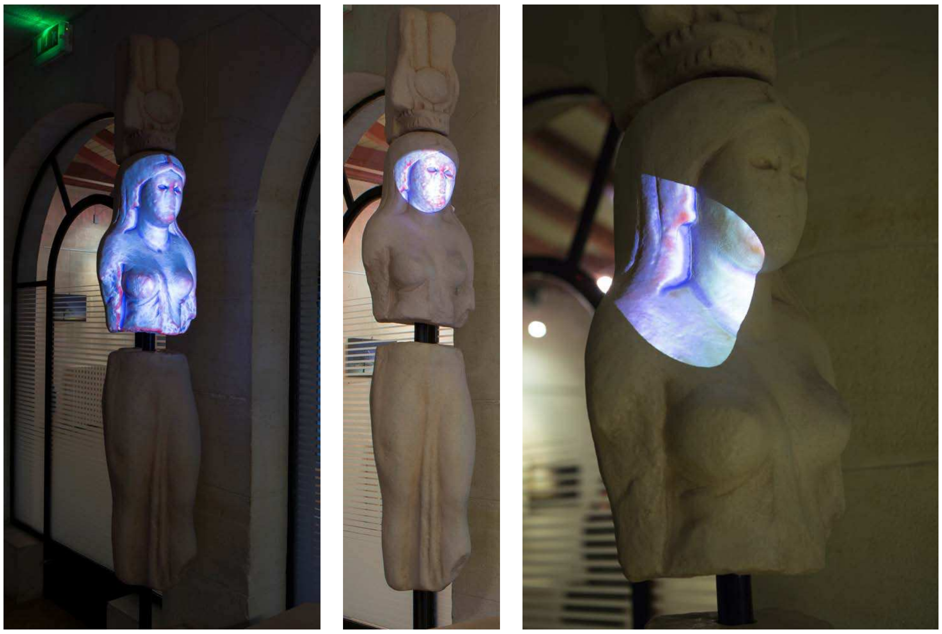


Fig. 10. The demonstration session at the annual conference of the Francophone Human-Computer Interaction Association, with and without the interaction technique (Photos © Inria/MS).

Table II. Feedback from the Allard Pierson Museum: How the visitors learned to use the *revealing flashlight* .

How the visitors learned to use the *revealing flashlight*	Percentage
I read the instructions.	42%
I tried until successful.	23%
I saw somebody else using it.	15%
A museum employee explained how to use it.	15%
I didn't manage to use it.	6%

obtained from a prior 3D acquisition of this object. The main advantage of our technique is to have a direct link between the real object and the virtual object, thanks to the use of spatial augmented reality and an effective interaction technique. Our user study highlights the importance of being able to focus on a particular area of the object. In addition, it shows that our interface is easy to use.

There is a wide variety of applications of our approach, especially for cultural heritage. As shown by the user study, archeologists and museum curators have a powerful tool to inspect cultural artifacts and might improve their knowledge about them while staying focused on their actual task. For example, they can decipher hardly visible inscriptions in eroded stones. Moreover, we have shown that museum and exhibition visitors can explore real artifacts and gain additional information on demand without touching the often fragile and precious objects themselves. This represents a completely novel interactive experience that is naturally shared with the other museum visitors thanks to the spatial augmented reality. Our system can be easily extended to project meta-information such as text and images for annotating cultural artifacts as well, in addition or replacement of long and painful-to-read museum labels. With the increasing availability of 3D printers, nowadays real objects can be reproduced from virtual objects, and the *revealing flashlight* can be used even if the real object is not available, by replacing it with a printed copy of the original object.

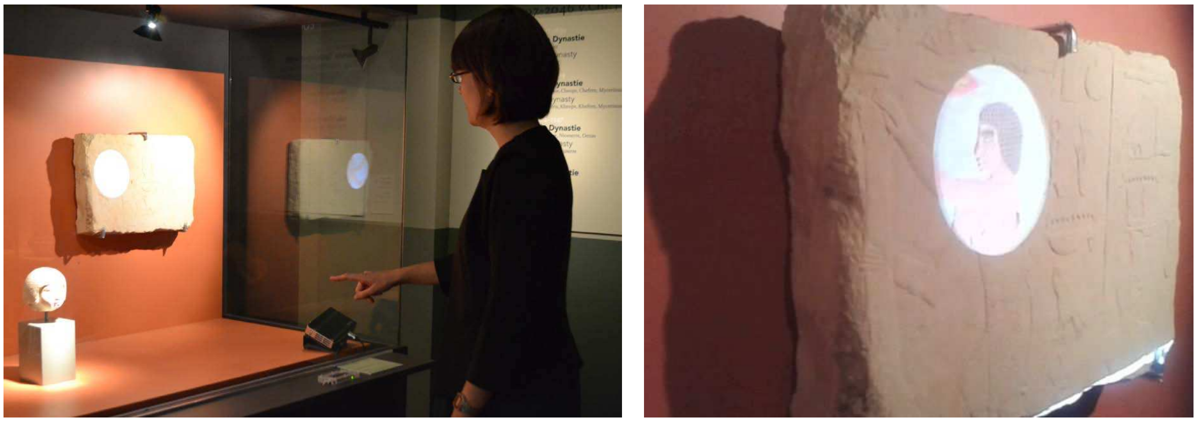


Fig. 11. The *revealing flashlight* at a temporary exhibition in Amsterdam (Photos by Christie A. Ray, Allard Pierson Museum).

Compared to the *context-aware light source* [Wang et al. 2010], the *revealing flashlight* interaction and visualization technique is conceptually different: since we acquire and analyze the 3D geometry of the artifact in a preprocess, we are not constrained by the resolution of a camera or limited time for the analysis. Moreover, we run our analysis in 3D object space at multiple scales, and not only in 2D. This is particularly important for inspecting archeological artifacts, since they contain details that are difficult to identify due to aging effects such as erosion. Finally, we do not depend on a real light source and hence exploit the full freedom to map the 6 degrees-of-freedom input to the parameters of the visualization that augments an artifact.

There are several avenues for future work. For the moment, the real object is augmented without taking into account the lighting of the environment. In the future, we want to automatically analyze the ambient lighting in order to have a consistent brightness and shadows, for example by estimating the number, position, and intensity of the surrounding light sources. This might further improve the legibility of artifacts. Concerning the interaction techniques itself, we plan to study two-handed interaction in order to adjust additional parameters, by using asymmetric bi-manual interaction [Guiard 1987].

Acknowledgements

We are grateful to Robert Vergnieux for borrowing the stele relief from his private collection, and his team Archeovision for borrowing the buddha reproduction. We thank Wim Hupperetz, Merel van der Vaart and Christie A. Ray from the Allard Pierson Museum in Amsterdam for the kind cooperation and gathering museum visitors' feedback, as well as the use of the "Wall of Mastaba" relief fragment. The Isis bust was acquired and reproduced within the ANR SeARCH project, grant ANR-09-CORD-019 of the French Agence Nationale de la Recherche. This project has received funding from the V-MusT.net Network of Excellence (European Community's Seventh Framework Programme under Grant Agreement 270404).

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