J Vis (2018) 21:841–855
https://doi.org/10.1007/s12650-018-0492-4

REGULAR PAPER

Jiawan Zhang · Han Tao

On-site immersive visualization and rapid degradation annotation for mural degradation interactive analysis

Received: 31 August 2017 / Accepted: 5 November 2017 / Published online: 19 April 2018

Abstract On-site investigation is a natural efficient way to cognize tangible, while immersive visualization engages human senses to percept information from data. Hence on-site immersive visualization is able to provide a better stereo environment for enhancing the understanding of real scene and gathering insight. With the development of technology, optical see-through head-mounted devices can help researchers achieve the goals. However, worldwide ancient murals suffer from various degradations related to compound environmental factors, which requires interdisciplinary researches. And because of the importance of on-site investigation in heritage protection field, on-site visualization has to meet the requirements of relative professors. In this paper, we present a novel mixed reality, on-site immersive mural degradation visualization solution for analyzing relevance between degradation and environment data. And a rapid, simple, low-cost and interactive method of degradation contour annotation is provided to solve the data sparse problem of standard degradation data. To demonstrate the visualization solution and the annotation method, two application results with real data from Mogao Grottoes and domain-expert feedback are given. The solution is on-site, immersive oriented and integrates secure designs for heritages. Our solution is flexible and effective so that it can provide a better data analysis environment than conventional planar visualizations. It also provides a promising way to change work styles.

Keywords On-site visualization · Immersive environment · Heritage degradation · Degradation annotation

1 Introduction

On-site investigation is a natural efficient way of human to obtain information and derive knowledge. It enables people to optimize senses and interactions to cognize the objective presentations. To cognize imperceptible beings, people quantize and collect facts as data via sensors. And the immersive visualization is a widely-used method of engaging all human senses in data cognition with rich interaction and surrounding displaying. So as the combination, on-site immersive visualization is able to provide a better stereo environment to enhance the understanding of real scene and gather insight. Nevertheless, to our best knowledge, limited by technology, the fusion of on-site and immersive visualization has just a few works while those two have received impressive attention respectively.

Now we found that the ancient mural degradation analytics is fertile ground for on-site immersive visualization. Firstly, the degradation is a thorny problem to heritage protection. It damages global murals

J. Zhang (✉) · H. Tao
Tianjin University, Tianjin, China
E-mail: jwzhang@tju.edu.cn

H. Tao
E-mail: th8678@tju.edu.cn

severely and irreversibly all the time, urges comprehensive and interdisciplinary research. Degradations are symptoms of local matter interactions driven by geological, physical, chemical and biological factors together (Guo et al. 2009). Secondly, on-site investigation is a main part of heritage protection work, such as patrol, restoration and field study. Thirdly, the proper spatial expression is essential in degradation analysis. A lot of works against mural degradation demonstrate its significance.

Furthermore, mural degradation analytics needs a rapid method of degradation data acquisition. For safety, acquisition of degradation data must be non-contact and precise, which rules out many lightweight acquisition methods. Besides for specific reasons, the record update of degradation areas is annually. And it is too sparse to extract information. The present available measurements include manual photographing, the commonest method, and some precision focusing measurements, such as in (Zhang et al. 2012; Feng et al. 2016; Liang et al. 2014). But the manual photographing cannot avoid the errors from optical conversion and attitude change. And the more precise measurements are too arduous and time-consuming to take frequently.

We attempt to use mixed reality optical see-through head-mounted device (HMD) to implement the on-site immersive visualization. We employ the device for three reasons: (a) the mixed reality technologies are available to reconstruct environment model optically, and fuse the digital stereo view to real world properly; (b) see-through lens ensure the fidelity of natural vision, and the HMD is flexible and portable; (c) as becoming ubiquitous, consumer-level, this sort of HMD is one of the most compatible stereoscopic displays for daily life.

However, there are three challenges in visualization design and implementation: (a) how to provide a comfort on-site immersive visualization with binocular stereo vision (Stanney et al. 1999; b) how to meet the actual analysis demands within the existing technological limitations; (c) how to provide an easy-to-use, work-well degradation annotation method.

In this study, we present a novel mixed reality based, on-site immersive mural degradation visualization design for analyzing how the degradations work. It directly places digital stereo views in the heritage grottoes to visualize time-series data of degradation progressions and local monitors for intuitively expressing and simulating historical status. Customizable warning mechanism enables the interactive exploration of degradation-environment correlations. And we present a rapid and non-contact degradation annotation method. The annotation method, which results well in small-scale contour update, is handy while avoiding optical deviation in theory. Moreover the solution integrates some effective and executable secure designs against on-site work in heritage. The solution is flexible and effective to provide a better data analysis environment with on-site immersive visualization than conventional method. It also provides a promising way to change work style.

General descriptions of our contribution are listed below:

- A novel, on-site immersive visualization is designed with time-series data meeting actual demands from heritage protection field for interactive analysis of mural degradation-environment correlation. A set of design principles are applied to it for on-site immersive visualization on see-through HMD.
- Rapid mural degradation annotation method for contour updating.

2 Related work

2.1 On-site immersive visualization

As an approach to support decision and increase comprehension at the site, on-site visualization is highly applied to fields such architecture design, engineering and environment analysis. Owing to the absence of developed techniques, most of works concentrate on the framework of it. For planar display, such as in (Schattel et al. 2014; Kim et al. 2016; Liang et al. 2011; Nurminen et al. 2011). In binocular display type, Vlahakis et al. (2002) presented ARCHEOGUIDE for Olympia site guide, which achieve for real-time rendering restored sight of ruins on natural view with HMD at pre-determined positions. These works filled demands in accuracy, liveness and sense of reality with information or atmosphere of real scene. But they barely developed the analytical promoting potential of on-site visualization.

Immersive environment analytics is effective to attention concentration. It has been well explored in big data analysis field. Immersion is defined as “in the flow” (Mcmaster 1990) that is a positive and highly concentrated mental state for the current task. For immersive visualization, the task is information perception and analysis. Immersion can be built by surrounding images, sounds (Schettino 2015) and fined interactions (Ermi and Mayra 2005). To present immersive visualization, VR HMDs provide smaller field of view but better stereo feeling than CAVE-like displays. In Bobick et al. (1999); Cohen-Bendahan et al. (2015), immersive environment is used to improve task concentration with proper design.

On-site immersive visualization extracts features of on-site visualization and immersive environment analysis. Due to the technical threshold, there are sparse explorations on it. Some on-site visualizations are partial immersive. For example, Yapo, Sheng, and Nasman et al. (2010) traces multiple large-scale movable screens for custom projection to build a dynamic immersive environment for visualization. And Zollmann et al. (2012) presented an interactive visualization design of time-series data for building exterior display. The more immersive works still focus on the framework. Malkawi, Yi, and Chan et al. (2004) visualized computational Fluid Dynamics datasets of current room with gesture. The work is available with bearable latency and deviation while it efficiently and effectively reveals the indoor environmental situation. These works reveal the practicability and possible prospect of on-site immersive.

2.2 Culture heritage visualization

As the technologies increasing in recent years, Augmented reality, virtual reality, and even mixed reality widely used in culture heritage field. Colizzi, Pascalis, and Fassi (2007) visualized point cloud data of deteriorated heritage section to experts for diagnosis. The applications of these technologies enrich the ways for public to savor culture, strengthen interest and aid to cultural heritage conservation.

The conventional two-dimensional visualization for analysis against degradation has attracted considerable attention. RN45 designed an interactive multidimensional visualization to study the overall relevance of degradation in Mogao Grottoes on multi-scale. The deterioration risk analytic approach presented by Li et al. (2016) assembles variform analytic tool to assess the deterioration risk of ancient frescoes from multiple perspectives. These two works concentrate on the global relevance analysis of a heritage site. About single deterioration area analysis, Gordan et al. (2008) proposed a method of building surface deterioration visualization. It statistic assesses deterioration level and expresses with heat map.

2.3 Mural degradation data acquisition

The traditional acquisition of mural degradation data relies on the photos from artificial investigating routine. Then conservators manually annotate degradation areas according to photos and place them on file. It is obvious that it introduces uncertain deviations of lens distortion, illumination change and human cause. For now, many high-precision acquisition methods employ techniques such spectral imaging (Lu et al. 2015; Arnold 2014; Liang et al. 2014), RGBD scanning (Lawonn et al. 2017), and reference photo based camera relocalization (Feng et al. 2016), and joint image processing algorithms (Zhang et al. 2012, 2011) to get more precise, unified, pixel comparable image data. However, these approaches are auxiliary by specific equipments, for instance, camera orbits, electric tripods, imaging instruments and so on. Moreover these approaches require professional installment and operation. So owing to the possible risk during transport, as well as the high-cost on labor and time, these measurements can be carried out routinely but regularly.

3 Task analysis

In this section, we introduce a few points of degradation study, then analyze the demands from the stand point of professors and heritage protection field. Finally, a couple of tasks are summarized to conduct the design.

3.1 Degradation feature analysis

Degradations are the symptoms driven by microenvironment (Lawonn et al. 2017), and differentiate into many types damaging murals variously, such as flaking, blistering, cracking, efflorescence, hexapod and mold (Li et al. 2013). Besides human-made damage, the environmental factor is the main cause of degradation progression. According to the relevant reference works and opinions from professors, we found it is important to explore the relationship between degradation progression, environmental factors and spatial structure of heritage. The features and explanations as follow:

- *The factors of degradations are various and complicated*. Many reasons, such as substance transformation, environmental changes and biological forces, lead to degradation progression. About the complexity, for example, the water movement in rock is an important factor and can be influenced by raindrop, sun exposure, rock formation, and even ornamental plants irrigation. Likewise other factors such salt and vibration.
- *Factors influence each other*. According to physical, chemical, biological principles, there are interactions and correlations between factors. For example, inside the rock mass of some grottoes, the humidity and salinity have a close negative correlation.
- *Positions of degradations are information rich*. The concrete position and exact local environment provide clues for analyzing mechanisms. (a) Local material composition. The compositions of mural areas are different due to different ages, techniques and pigments. These differences can be ascertained by combining archaeological data and the positions of areas. (b) According to the known material movement patterns and surrounding information, the local conditions of degradations are estimable. (c) Positions bridge the real scenes and the theoretical distribution and evolution models from researches.

3.2 Professor behavior analysis

Our target users compose of scientists such as microenvironment researchers, geologists, chemists, and practitioners such as conservators, restorers. Based on the human cognition and our comprehension of actual conditions, we infer their possible typical behaviors during on-site analysis. We list the behaviors and detail them as follow.

- *Get an overview of current grotto*. As the interest points, degradations are immovable while the focus view angle of human is about 30°. They need an approach to keep feeling the interest points out of view.
- *Extract information from environment data*. Environment data is the basis of analysis. Only under the awareness of its tendency and features, professors can make deduction.
- *Update degradation records*. To make the comparison with recent environment change, professors need to capture the latest state of degradations.
- *Selective analyze degradation*. Professors want to focus on the detail information of degradations, such as the evolution process, history images and the correlations with environment factors.
- *Search for inspiration and testify hypothesis*. It is the core of the research works. Professors always need to confirm the accordance between the actual data and their models. They also always are in demands of new view of point to regard facts.

3.3 Safety analysis

About murals, the safety is the only propose of heritage conservation departments. Though professors will try their best to keep cautions, we should still help them to avoid accidents with design. Except for subject reasons, there are two extra possible points: (a) *The distance perception interfere* before professors adapt to the devices, and (b) *accidental contact caused by view interruption*.

3.4 Tasks

After general consideration of degradation features, professor behaviors and safety request, we compile a list of functional requirements of the visualization. The requirements improve our understanding of the problem and are used to guide our definition of functional points.

T. 1 *Deterioration-environment relevance analysis support: Is my presumption of degradation mechanism right? Could i customize relationship definitions and interact to explore it?* The visualization should help professor search inspirations, test and verify any possible hypothesis.

T. 2 *Spatial expression: Where are the degradations and sensors? How do their surroundings look like? Are there more details for my analysis?* The on-site visualization should show the positions where the data is got from to establish the relationship between data conception and real scene.

T. 3 *Comprehension of degradation progression: How did the degradation grow? How did environment change? Does the progression match my hypothesis?* There should be a way to examine the historical growing process of degradations and to feel the relevance with past environment.

T. 4 *To be on-site oriented and immersion oriented: What is its difference from 2-D visualizations, besides it is stereoscopic? Will it discomfort me? Did i concentrate more on the analysis with immersive experience than before?* The visualization should employ Human Computer Interaction knowledge about on-site visualization and immersive environment construction to provide an information-rich, intuitive, and handy analytical environment.

T. 5 *Convenient acquisition of degradation records: Did the degradation grow or not? Which part and what kind of degradation has grown? Can i record and add the slight change fast and precisely to the visualization?* A rapid and easy-to-use approach of degradation update should be furnished.

T. 6 *Accidence reduction: Am i about to touch the mural? Can i remove visual occlusions as I want?* The visualization design should consider about the possible negative effect of additional visual input on professors accidental risk, and try to reduce it.

4 System construction

4.1 Data preparation

Data is the foundation, as well as the origin of all the information of a visualization. To ensure the universal applicability of the visualization, we should take the general available data as the analysis object.

Our purpose is to analysis relevance between degradation and environment. As our main reference target, Dunhuang Mogao Grottoes in China is one of the UNESCO world heritage sites. It preserves large amount of ancient murals suffering from deterioration problems. We format and utilize the degradation data and monitoring data in grottoes and make some necessary supplements for spatial expression.

Degradation data Conservators of Mogao Grottoes selected a couple of degradation areas in each grotto. These degradations are representative. The records of each degradation area are composed of photos with time stamps, and contours of each degradation type marked later. In this work, we select four degradation types: efflorescence, flaking, blistering, and cracking.

Sensor data Sensor data are collected by sensors in grottoes. Grottoes have different quantities, types of sensors without uniform placement. And due to the size, shape and physical characteristics of rock caves, there is often more than one sensor of each type set in a grotto for multi-point monitoring. Till now, the available common sensor types contain temperature, humidity and CO_2.

4.2 System overview

In this study, we propose a warning mechanism for revealing the degradation-environment relevance (T. 1). The stereo views of the visualization solution should be placed around the realistic position of their data sources (T. 2). Especially, the degradation view should locate to exact position for totally fitting the real contours of degradations (T. 2). Moreover, the views of degradations should reveal the deterioration progression (T. 3) fused with real murals (T. 4). A novel method of degradation annotation, which annotates degradations by contouring their area manually, is supported for the rapid acquisition of degradation data (T. 5). A few functions and details are aggregated in the solution for the safety of heritages and professors (T. 6). The usage scenario of this visualization solution is supposed at the inside of grottoes keeping murals. We referenced the design principles of on-site visualization and immersive environment and apply them to the solution for better assistance of on-the-spot analysis and investigations against mural degradations (T. 4). The visualization with optical see-through HMD provide professors a more intuitive, intent, handy analytical environment for degradation with better data support (T. 4). And it is also a tool for degradation recording and causes exploration.

The screen shot of the visualization solution in physical environment is given as Fig. 1a. And the illustration of degradation annotation is shown as Fig. 1b to indicate effect. As well as their runtime photo shot behind lens of HMD are shown as Fig. 2.

5 Degradation-environment relevance visualization

This part introduces the degradation-environment relevance visualization from four aspects: separate visualization views, the warning mechanism, overview radar, as well as the special interactive designs.

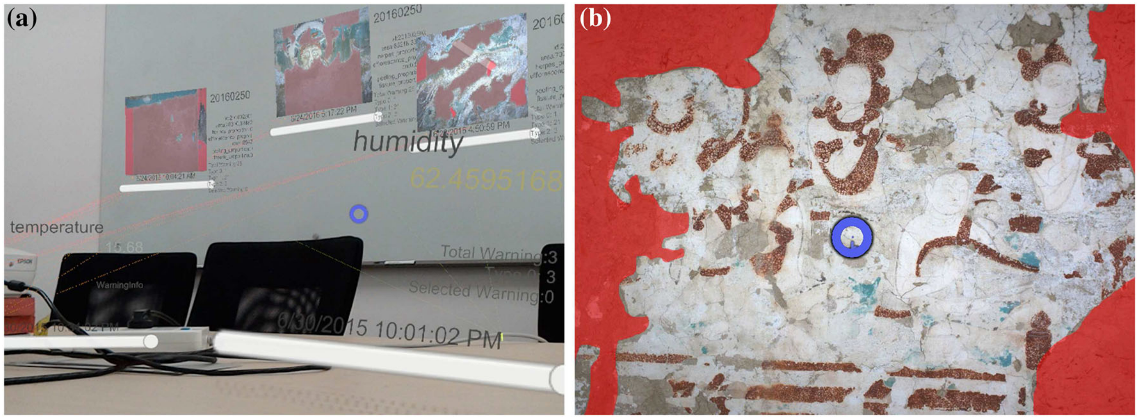

Fig. 1 **a** Part views of on-site immersive visualization in simulative running example. Warnings emitting from timeline reflect that how many customized patterns this sensor and linked degradations was involved in. And statistics of warning is provided. The photo is a screen shot of HMD synthesized automatically. The deviation from human eye is inevitable. **b** The mural is covered tightly with a virtual canvas. The latest contour is preloaded for annotation with a painting like interaction. Mostly degradations grow so slow that fringe modifications are able to meet the regular demands

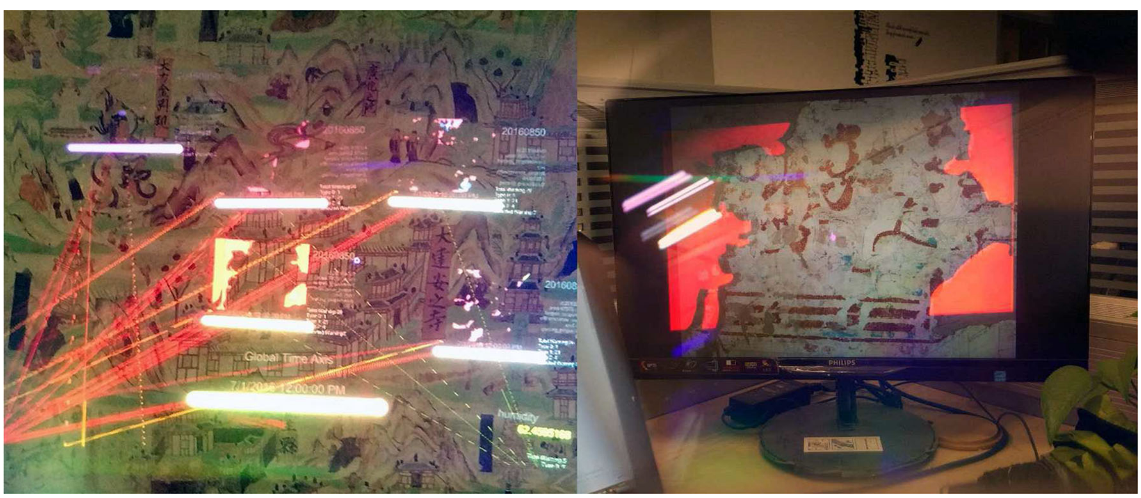

Fig. 2 Photos of on-site immersive visualization (left) in a scenario of partial real data, and a rapid annotation example (right) of an isolated image of mural for degradation interactive analysis, separately. The two photos were shot after single lens of binocular headset. The dazzles are caused by shooting devices in the former and ambient light in the latter

5.1 Views of degradations and sensors

Views of degradations and sensors in grotto are partly different from each other. They both visualize time-series data and have a time line respectively, but sensor view is simpler than degradation view.

5.1.1 Sensor view

A single sensor view shows the values, position and tendency of a sensor. Sensor views are placed by their corresponding sensor entities and always rotate to face to professor. A sensor view is a timeline with a text panel for detail, as well as a line chart for tendency. For the numerical sense and distinguishing sensor type, the text color of value panel varies by the value according to the color table of each type.

5.1.2 Degradation view

A single degradation view reveals the growth progression of a degradation area. Degradation views cling to the degradations on the wall. A degradation view consists of a decorated timeline, a mask panel and a text panel for details such time stamp and statistics.

Timeline A timeline is decorated with a rectangle chart for abstracts of each record about the collection time, change of degradation types. An abstract is called a record frame. Frames are with uniform width. And each frame has four bars to represent four degradation types. The more a type of degradation change between two neighboring records, the fuller the bar of this type in frame of latter will be fill. If no change there is, the corresponding bar is completely blank, that is to say, totally transparent in the system.

Mask panel The mask panel (shown in Fig. 3) exactly overlaps the corresponding degradation area. The mask panel marks degradation regions with colors. It marks different type with different hue. Because black is showed as totally transparent in optical see-through devices, we paint recently deteriorated regions with saturate color, relatively, paint elder degradation regions with less saturated color. According to the value of timeline, the regions changed at that time will be highlighted.

5.2 Warning mechanism for relevance analysis

Warning mechanism is designed for observation of user-defined environment patterns. It enables professors to customize condition sets and interactive explore the frequency, occurrence, and positions of patterns. It is convenient to compare the theoretical and realistic states of involved degradations and environmental factors.

Warning mechanism transforms the pattern relevance of degradation to a warning sequence. The quantity, frequency, and occurrence time of warnings stamp on the degradation. With simultaneously visualization warnings in multiple, professors are able to construct general and temporal conceptions of degradations. Together with the progression visualization, it is available to reveal the insights of latent causes.

5.2.1 Warning mechanism definitions

Degradations do not effect on each other while factors multiply act on degradation areas. So we narrow down the range to relationships between single degradation, and single or multiple sensors.

In warning mechanism, degradations are associated to sensors nearby for environment data reference. These data references are the grounds for the warning judgement.

Data reference tragedy Degradation areas employ the nearest sensors different types as their environmental data sources. So every degradation area can own environmental data in types such approximate temperature, humidity, and CO_2. Though these sensor data are not exactly accurate to the areas, they still reflect environmental change tendency nearby the degradation areas.

Fig. 3 Mask panel is a major part of degradation view for progression visualization. Different type of degradation colored in respective tone. The more the region deteriorated recently, the more filled color saturated. Color lines represent warnings

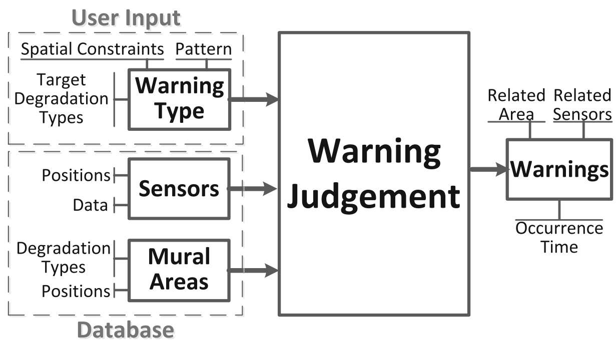

Fig. 4 Warning judgement data flow illustration

Warning judgement The warning is a notion to represent a detected instance of a warning type defined by professors. When professors consider that an environmental pattern may be relative to degradations, they can input the pattern and search instances in grotto. The corresponding degradation types are customized. The pattern in our solution is defined as a warning type. The judgement is shown as Fig. 4.

5.2.2 Expression

Now we have the warnings, which represent the pattern relations. For adequate utilization, we express warnings to solve following problems:

- *Where did the pattern happen?* Every warning marks itself at the warning time on timelines of all participant sensors.
- *Which degradation should be involved by the pattern?* Every warning also marks itself at the warning time on timeline of the degradation.
- *Which pattern is it?* Marks of warning in different type are colored differently.
- *How to find the correspondence between degradations and sensors?* Every mark on sensor timeline is linked to the corresponding degradation. Link colors are decided by warning types.

5.3 Overview radar

To keep the global awareness, we develop a radar component targeting event notification and tracking for on-site immersive environment. It should be in the eye shot all the time for lasting global concept providing; meanwhile it should not block visual information. The radar displays the tracking signs with news abstracts in a ring-like range around the border of display. The number of degradations and sensors per grotto is usually up to 20. Displays of their tracking signs are permanent only if they are out of view. While the tracking signs of warnings only appear when the warnings are emphasized. And once professors have seen the emphasized warning, this sign disappears and will not appear again even the warning is out of view.

In fact, our overview radar inspired by the ideas from the damage notification in First Person Shooting Games [18]. But we reconstruct it for adapting to our circumstance. The reconstruction includes the visual design for stereo display and the tracking algorithm for optical see-through HMD.

Stereo visual design For planar displays, the radars are shown as a UI component on the screen. But we cannot do so to human eye. Rationally endowing realistic forms of UI elements is a good method to employ metaphors. And it is also comfort people to avoid immersive sicks. Our radar looks like a set of automata in arrow shapes floating in front of people for position indication. To avoid occlusion, our radar is semi-transparent and can be hide by voice commands.

Stereo tracking The angle of focus view of human is about 30°. Furthermore, the display angle of our device is about 30 degrees horizontal and about 20° vertical. When sensors or degradation areas are out of this range, their tracking signs will be rendered. The positions of tracking signs is defined as below:

$$T' = O + r \cdot \amalg(OT - OT \cdot \vec{m}), \tag{1}$$

where T and T' indicate the position of target object and position of the tracking sign on the radar, respectively. O denotes the center of the radar. $\overrightarrow{m}$ presents the unit vector of HMD orientation. $\Pi(x)$ represents the normalization of x. The r is the distance between O and T'. r is not a constant. Tracking signs of further objects will be smaller and much peripheral.

5.4 Interaction

5.4.1 Global play mode

Global play mode presents a process that seems like that the time of grottoes flies by. It brings out a temporal overall conception to professors. Global play mode is a cavern global data browser to reappear the whole grotto evolution with historical data. It plays back all the timelines of degradation and sensors fast and simultaneously, to show the deterioration processing of diseases and warning occurrences.

Warning emphasis Tracking signs of warnings will pop up to draw attention when warnings alarm and are out of view. And marks and lines of emphasized warning will be highlighted for easily finding.

Manipulation The mode is controlled with voice commands and gestures. The passing through speed is scalable for both detail and general examination. The main controller is a global timeline moving along with the HMD attitude. The global timeline should stays by hand as well as avoid unexpected occlusions. The moving strategy is also adopted by other frequently-used interfaces.

5.4.2 Safety designs

To meet the safety requirement from heritage protection field, we add a few on-site immersive environment oriented secure details to our visualization solution.

Hide all Hide all is a movement shortcut to hide all of the holography. Sometimes, the virtual objects blocks physical targets while professors cannot remove the hinder or take off headset immediately. We design that professors can hide or show all of the holography by quickly, slightly shaking head, or more exactly, move head with a fast linear or angular velocity. The reasons are following: (a) the mechanism is convenient, space free and intuitive, as well as hard to trigger by mistake. (b) Constrained by display and hardware technique, people are not recommended to move and turn fast because of the decrease of display quality and possible vertigo. (c) Furthermore, there is no reason to move fast in grottoes, unless accidents happening such overbalance.

Hand detection The distances between gesture hands and murals are under supervision for timely reminding. The function is based on depth detection supported by machine vision. To build the distance awareness naturally, once the distance is less than threshold, the whole display turns red gradually. The reddish tone will get deeper along with the hand distance cutting down. And an alarm will break off the operation and last until professor complete posture adjustment. The design largely avoids accidental touches led by analysis concentrating, as well as conduces to good usage habit formation.

Interact-oriented expression One of the main reasons for accidental touch is users subconscious touching or pointing interaction purposes. We solve the problem in two ways: (a) Our solution should seem touch-forbidden intuitively. For example, the degradation mask panel is interaction free. (b) On the other hand, all the frequently-used interactive objects (e.g. the timelines of degradation views) are placed further than other visualization objects.

6 Rapid degradation annotation

The rapid degradation annotation is designed for fast, simple, subjective contour update of a degradation area. Since human judgement is the essence of degradation annotation, the method utilizes on-site immersive environment to remove the intermediates between human senses and targets. With human decision, it decreases the influences from light condition difference, shooting angle and imaging error. Firstly, compared to conventional annotation method, our method skips the manual photo capturing and annotation data conversion. Manual photo capturing introduces photo perspective distortions including camera attitude change and lens distortion. Secondly, the received data is WYSIWYG (what you see is what you get). Professors modify degradation contour on the virtual canvas covering the physical mural. So they can modify and survey the contour freely until they accept it. Moreover, the contour is native digital data. So it is lossless that the storage and recurring process of the confirmed contours.

We introduce the details in three parts: the usage process, visual design, and interaction.

6.1 Annotation process

The annotation process is illustrated in Fig. 5. We also introduce the process by dividing it in following steps:

- *Load data:* System loads the contour data collected last time in target type and degradation area. If there is no historical data of the degradation area, the default result is a blank mask.
- *Show contour mask:* System locates degradation area exactly and visualizes the contour as the cling mask.
- *Revise contour:* Professor modifies the contour by coloring the loaded mask manually, to revise the mask to fit the current deterioration situation.
- *Save data:* System saves the latest contour in standard format and takes a synthetic photo for reference. An optional mixed reality video is available as extra archive for judgement supporting. Current disease attitude and collect time will be saved simultaneously.

6.2 Degradation location

The precision of degradation attitude is one of the determinants of our degradation annotation method. Our locating method is based on Vuforia, which is a mobile AR toolkit providing the function that recognizing and tracking images physically existing in virtual three-dimensional space. However, the delay and deviation of the function is perceptible. And HMDs with high portability are usually poor in performance. They cannot afford the computation of full real-time feature recognition. This aggravates the problem that how to provide an available location solution in a close-distance usage scenario.

We solve the problem by a mixed location strategy. Simultaneous Localization And Mapping method are employed for spatial position maintenance. The technique is capable to support the fundamental spatial location, while it prefers a wide perspective for more scene features. Its spatial position maintenance performs just acceptable on small-scale and in short time. But the maintenance result will shift severely if the camera attitude changes a lot. We apply feature recognition to fix the location discontinuously. And the reference of feature recognition is offered by user interactively. It enables that professors calibrate the contour mask position as they want. So the solution gets a subjective satisfied location through human interaction, and then holds it by SLAM and feature recognition alternatively, to meet the requirement on accuracy and stability of relative position between mask and physical degradation.

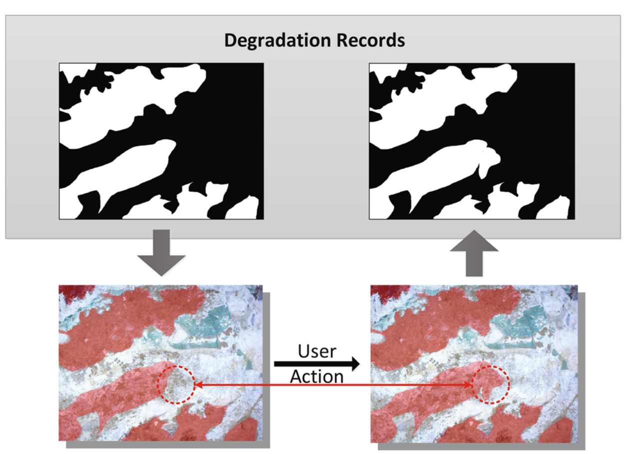

Fig. 5 Data flow of degradation annotation method. Previous contour is loaded when user begins annotation for reducing workload. Then save the revised contour

6.3 Interaction

6.3.1 Basic operation

Generally, gesture and voice commands are available for controlling. Annotating contour with degradation annotation is experienced like the marking action of the conventional method, besides that professors are marking degradation on real murals rather on photos. There are switchable painting tools for mask drawing, pen and eraser that are stroke changeable. The movement of pen point is controlled by gesture and the speed rate is changeable, too.

6.3.2 Precision enhancement design

Pen point move mapping For precision, the pen point moves with the projection of offset of gestures. If we use gaze (an imaginary beam emits from the point between the eyebrows) or a beam from fingers or hand as the pen point on the mask, any slightest body vibration will be magnified to make a big difference, owing to the distance from head or hand to mural. So professors will approach murals unconsciously. Moreover, head movement is hard to be accuracy, and depth perception based gesture tracking cannot be as precise as with gyros. The movement mapping between gesture and pen point is defined as :

$$O_p = \begin{bmatrix} o'x' \\ o'y' \end{bmatrix} \cdot (O_h - o'), \tag{2}$$

where $o'x'y'$ represents the coordinate system of the plane where target mural is on. O_h indicates the hand offset in world coordinate system, O_p denotes the pen point offset in $o'x'y'$. The offset of pen point is the projection of three-dimensional absolute offset of gesture on the plane where the mural is.

Stability of input and mask The annotation needs a trigger to start to and stop drawing. We employ an extra gadget, a portable clicker, as the input device of the trigger. To operate, professor should control pen point with one hand, and click with the free hand. The clicker is small and with an elastic band to put on the fingers. Because of the trigger should not cause unnecessary movement of pen point, and should be clear and immediate. Gestures conflict the former, and voices conflict the latter. The clicker increases the tracking stability of pen point. On the other hand, mask should not move when professor is drawing. So feature recognition is suspended during drawing operations.

7 Application and discussion

With the development of techniques, advanced instruments will come to us, which should be consumer-level portable HMDs that completely afford large computation and high precision. Despite they have not yet. We tried to lessen the affects due to the lack of performance, data and real scene, so as to test our work objectively.

In this section, the application results of visualization solution, as well as two tests of our annotation method are given separately. And feedback from domain experts is summarized at the end of the section.

7.1 Degradation environmental relevance analysis

Unfortunately, our solution cannot exert itself due to the data shortage. The reasons are as follow: (a) Our solution is designed on the precondition of data abundance while the quality degradation records are sparse and small in size. Quality acquisitions are carried annually and just employed in a few years. (b) The spatial data is absent. Relative positions between entity objects is a significant basis of the warning mechanism. Furthermore, the spatial expression cannot be exerted. (c) The environment data cannot be distinguished spatially. Environment data in same type are mixed together without sensor identification. It dents the spatial sense further. (d) From the usage aspect, tendency plays a vital role in a time-series visualization analysis. Our present available degradation data are insufficient to form tendency.

Hence, we recomposed an integrated dataset reasonably with real data, and then simulated an analysis of degradation environmental relevance with the dataset and our visualization solution, shown in Fig. 6. The adopted environment and degradation data is sampled from the cave No. 25 of Mogao Grottoes in the period from July 2014 to June 2015. In detail, the data includes the grotto temperature, humidity and CO_2 data from

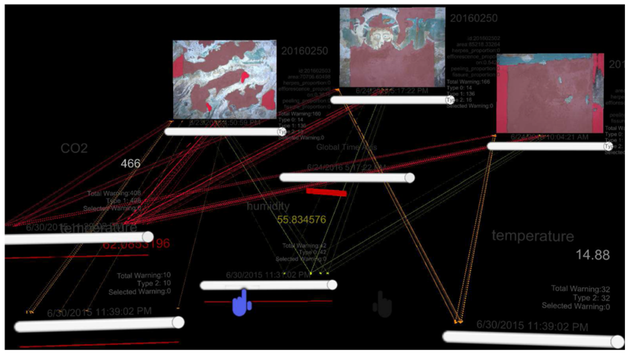

Fig. 6 On-site immersive visualization ran on simulative dataset. Customized line colors represent different warning types. Red, orange, and green lines denoted high humidity, high temperature, and high CO_2 air content warnings respectively

two, two and one sensor respectively. Despite unaware of the exact positions, we learn that the degradations are on the same wall. Moreover, since the fasteners are forbidden, sensors in heritage sites are usually placed on the ground or platforms. Thus the five sensors in simulation are scattered on platforms.

Degradation progression First of all, we looked over the degradation progression to seek interest points. We found the efflorescence dominates these three degradation areas. All of them are spread wide and stale, except for the left area, which is deteriorated recently (Fig. 6). Though recent environment data is lacking, the degradation progression visualization is capable to show the type, range of degradation, as well as speed, process of progression(T. 3).

Insight extraction And then, we sought information from warnings relationships. We highlighted the high values of temperature, humidity and CO_2 with warning types respectively (the transparentness of lines in Fig. 6 are different). In common sense, high temperature and humidity usually have negative impacts on heritage preservation. By the warning distribution on the timelines of degradations, we found the warning about CO_2 are very dense during March to August. The temperature warnings of the left one are spread all the year, while the others are narrowly contributed in July, which is similar to the efflorescence situation. So we could concentrate on the relevance of efflorescence and temperature (T. 1). And if more degradation areas are available, the lateral comparison can help professors to identify potential causes (T. 1).

General situation understanding The global play mode and radar unite to help professors to establish an overall concept. Warning sounds offer an immersive experience to perceive patterns on the spot. We found out the spatial and timely distribution of warnings with sounds. And besides prompts these visually, global radar also reveal the degradation areas and sensors not involved, which provides another aspect for analysis. Professors can concentrate on a few targets and quest the global relevance of them. Or they can browse the overall situation with the radar and global play mode (T. 4).

Safety assumptions Owing to the lack of data and real scene, the safety functions cannot exert themselves. Expected effects are listed: Hand detection will avoid introducing extra risks from gesture operation. The risk deriving from analytical concentration is weakened by interact-oriented expressions. The hide all function will help professors to get real vision timely, to reduce the possibility of overbalances and facilitate working procedure of professors.

7.2 Annotation test

We tested the degradation annotation method in two experiments: accuracy of location test and the speed and accuracy of contour modification test. The former focuses on the deviation of stereoscopic imaging to testify the availability of the method, and the latter is aimed at input interaction design. The device limitations should be excluded, such as performance lack and the location deviation caused by sensor precision and specific technologies. We think the relative fields are promising, and these limitations will be overcome in near future. So we just need to testify the process. Our experimental design purposes are: (a) Test the process availability. (b) Check validity of the interaction design. (c) Remove the interference factor as much as possible.

7.2.1 Location accuracy

The accuracy of localization decides the feasibility of the whole process. The experiment will be carried on an HMD called HoloLens. It has a built-in computer that provides flexible mobility to fit for daily life while its limits the performance in a relatively low level.

To avoid the situation disturbing results and focus us on the location accuracy, we scatter 10 small circles with a point at the center each. Only centers will be marked with our annotation method for reducing computation. We get a few people familiar with the operation of the HMD, and taught them the usage of our method. The case picture is shown as Fig. 7a, of which physical size is 34.5 $\times$ 26.0cm. It was printed out and cling on a board to close to real scene.

One of the test results is shown as Fig. 7b. The average physical deviation (the average distance between centers of circles and centers of strokes) is 10.388 mm. Whereas user paints according to the mixed reality presentation, the deviation consists of two parts, the deviation produced in annotation process, as well as the registration offset between virtual views and real scene.

The registration offset is inevitable but negligibly small compared with annotation deviation. It is assured by the stable attitude keeping of device and the accuracy of feature recognition algorithm. The device as the usage platform is a mixed reality HMD, of which the SLAM module performs well in self-localization within small range movement. So that the relative attitude of virtual objects can be kept stable. Moreover, the initial attitude of virtual canvas is confirmed with feature recognition and is fine adjustable by users.

The deviation from annotation process is the vast majority of the whole deviation. This is principally because the location algorithm is incompatible with headsets. The absent of track prediction of camera lead to the non-fluency of the location output. Human heads cannot be absolutely stable. From users' view, the mask was keeping slightly trembling that interferes user operation. This problem can be solved by process optimization that the location adjustment module is invoked actively rather passively. Nevertheless, besides the deviation caused by the location module, this precision fulfills requirements in the usage scenario (T. 2).

7.2.2 Speed and accuracy of interaction

In this test, we focus on the efficiency of the input interaction of the degradation annotation method. In fact, our design is equal to place a paint board like canvas on the mural. So it is the key point of our work that how to draw the contour handy and exactly with proper interaction. The performances of interaction in speed and accuracy are tested here.

Similarly, to reduce the computation, we cut down the render operations by reducing mask resolution, while it coarsens the drawing results. And the location influence is removed by displaying the sample picture (Fig. 8a) together with mask and deactivating the location module. We select a sharp-edged color lump as the annotation target. the sample picture is extracted from the degradation records of Mogao Grottoes. The test takes HoloLens as platform, too.

The annotation result is shown as Fig. 8b. The red area was stroked first, and then filled by color. The whole process took within one minute. The marked area is 5.16 cm^2, and the contour length is approximate to 193.8 mm. From the test result, we can get that the accuracy and efficiency of the interaction design in the annotation method can fit the usage scenario well. With the subjective factor ruled out, the contour matches the selected color lump well. And the time cost is rational to the degradation annotation. Degradation grows slow, so mostly the update workload is small. The speed and quality of the annotation fulfill the requirement (T. 5).

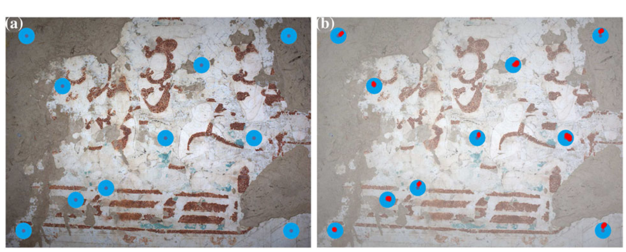

Fig. 7 **a** The case picture used in the test of Location Accuracy. The physical size is 34.5 $\times$ 26.0 cm. Average distance between centers of circles and centers of strokes is 10.388mm. The volunteers are told to mark all of the ten centers of the circles out. **b** The comparison of case picture and test result. Red points are the annotation results.

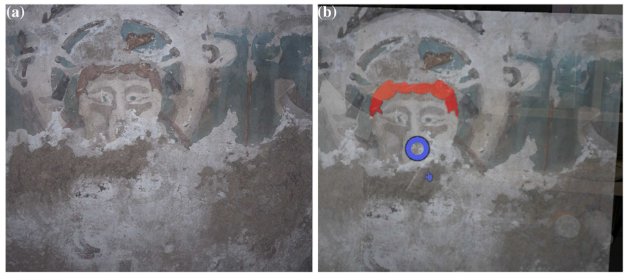

Fig. 8 **a** The case picture used in the test of Speed and Accuracy of Interaction. The display size in physical world is 18.8 × 18.8cm. **b** A screen shot of test result in running application. The red area was marked, of which area is 5.16cm^2. The contour length is approximate to 193.8mm. The shown annotation result cost within one minute in total

7.3 Expert feedback

We invited a heritage preservation expert and a visual analytics expert to experience our solution and annotation method. The usage scenario is same as we mentioned above. Then we collected their feedback in single interviews. The feedback is summarized as follows:

- The on-site visualization of degradation and environment data is intuitive and novel. It combines the mixed reality with heritage protection and is convenient to observe data and real scene simultaneously.
- The solution is able to provide the visual analytic support to heritage protection professors. It is able to play a part in degradation mechanisms analysis in the future.
- The annotation is natural and optical error avoided. As a positional annotating method, it is more accurate than traditional methods. And comparing to the other annotation methods, the on-site annotation is more intuitive to professors.
- The navigation tool is necessary and has a certain effect. But the further optimization is needed.
- User training for our solution is needful. Even the principal reason is the great difference between traditional operations and mixed reality operations.
- The beautification of user interface is available.

8 Conclusion and future work

In this paper, we synthetically study the problem of ancient mural degradation with degradation field knowledge and work procedure of heritage professors, and come to rational requirements analysis. Guided by this, a novel on-site oriented and immersive oriented visualization solution is designed for professors to explore degradation mechanism on the spot. This visualization combines with spatial expression, natural interaction and real scene details to offer an information-rich, intuitive and handy analytical environment to optimize work style. Moreover, a proven feasible, rapid, contact-free annotation method is designed to simplify the update of mural degradation standard data. Some safety designs directing at this usage scenario is integrated to protect murals and user. Real application results of the visualization and the annotation method are provided to testify the significance and availability of the design, which is also confirmed by feedback from experts.

In the future, we plan to enhance the on-site immersive visualization on interaction design and improve existing functions. We are also planning to optimize the location algorithm and interaction to get a better result. And more functions of painting-like contouring will be added, such as undo, select, and contour prediction. As well as more experiments with abundant data and complete real scene are in plans to test our solution. We will attempt to overcome the limit of performance by reducing demands to fulfill the portability.

Acknowledgements The authors wish to thank Prof. Xin Tong, Dr. Yue Dong, Microsoft Research Asia, for discussions with us. We appreciate Xudong Wang, Bomin Su, Xiaowei Wang and Bolong Chai and all the Dunhuang Academics, for providing us the Dunhuang Mogao wall painting survey data. We also thank the anonymous reviewers for their helpful suggestions and comments. This project is funded by Microsoft Research Asia through grants "Holo-Heritage: Dunhuang Cultural Heritage Conservation Research and Development based on Microsoft Hololens".

References

Arnold D (2014) Computer graphics and cultural heritage, part 2: continuing inspiration for future tools. IEEE Comput Gr Appl 34(4):70–79. https://doi.org/10.1109/MCG.2014.65

Bobick AF, Intille SS, Davis JW, Baird F, Pinhanez CS, Campbell LW, Ivanov YA, Schutte A, Wilson A (1999) The kidsroom: A perceptually-based interactive and immersive story environment. Presence Teleop Virt Environ 8(4):369–393

Cohen-Bendahan CCC, Beijers R, van Doornen LJP, de Weerth C (2015) Explicit and implicit caregiving interests in expectant fathers: do endogenous and exogenous oxytocin and vasopressin matter? Infant Behav Dev 41:26–37. https://doi.org/10.1016/j.infbeh.2015.06.007

Colizzi L, Pascalis FD, Fassi F (2007) 3d visualization and virtual reality for cultural heritage diagnostic. Conserv Sci Cult Heritage Hist Tech J 7(1):629–639

Ermi L, Mayra F (2005) Fundamental components of the gameplay experience: analysing immersion. In: Digital games research conference 2005, Changing Views: Worlds in Play, June 16-20, 2005, Vancouver, British Columbia, Canada

Feng W, Tian FP, Zhang Q, Sun J (2016) 6d dynamic camera relocalization from single reference image. In: Computer vision and pattern recognition

Gordan M, Dancea O, Vlaicu A, Stoian I, Tsatos O (2008) Computer vision based decision support tool for hydro-dams surface deterioration assessment and visualization using fuzzy sets and pseudo-coloring 3:207–212

Guo Q, Wang X, Xue P, Zhang G, Fan Z, Hou W, Zhang Z (2009) Research on spatial distribution and relations of salinity and moisture content inside rock mass of low-layer caves in Dunhuang Mogao Grottoes. Chin J Rock Mech Eng 28(SUPPL. 2):3769–3775

Kim W, Kerle N, Gerke M (2016) Mobile augmented reality in support of building damage and safety assessment. Nat Hazards Earth Syst Sci 16(1):287–298. https://doi.org/10.5194/nhess-16-287-2016

Lawonn K, Trostmann E, Preim B, Hildebrandt K (2017) Visualization and extraction of carvings for heritage conservation. IEEE Trans Visual Comput Graphics 23(1):801–810. https://doi.org/10.1109/TVCG.2016.2598603

Li H, Zhang J, Sun J (2016) A visual analytics approach for deterioration risk analysis of ancient frescoes. J Vis 19(3):529–542. https://doi.org/10.1007/s12650-015-0327-5

Li J, Zhang H, Fan Z, He X, He S, Sun M, Ma Y, Fang S, Zhang H, Zhang B (2013) Investigation of the renewed diseases on murals at mogao grottoes. Heritage Sci. https://doi.org/10.1186/2050-7445-1-31

Liang H, Lucian A, Lange R, Cheung C, Su B (2014) Remote spectral imaging with simultaneous extraction of 3d topography for historical wall paintings. ISPRS J Photogramm Remote Sens 95:13–22. https://doi.org/10.1016/j.isprsjprs.2014.05.011

Liang X, Lu M, Zhang JP (2011) On-site visualization of building component erection enabled by integration of four-dimensional modeling and automated surveying. Autom Constr 20(3):236–246. https://doi.org/10.1016/j.autcon.2010.10.002

Lu D, Wang Z, Zhang D, Sun M (2015) System for hyperspectral data analysis, visualization and fresco deterioration detection. In: IEEE International conference on multimedia big data, pp 312–317

Malkawi A, Srinivasan R, Jackson B, Yi Y (2004) Interactive, immersive visualization for indoor environments: use of augmented reality, human–computer interaction and building simulation. In: Information visualisation, eighth international conference, pp 833–838

Mcmaster T (1990) Flow: the psychology of optimal experience (book). Library Journal

Nurminen A, Kruijff E, Veas E (2011) Hydrosys - a mixed reality platform for on-site visualization of environmental data. In: Lecture notes in computer science (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics), vol 6574 LNCS, pp 159–175. https://doi.org/10.1007/978-3-642-19173-2-13

Schattel D, Tonnis M, Klinker G, Schubert G, Petzold F (2014) On-site augmented collaborative architecture visualization. In: ISMAR 2014 - IEEE International Symposium on Mixed and Augmented Reality - Science and Technology 2014, Proceedings, pp 369–370, https://doi.org/10.1109/ISMAR.2014.6948493

Schettino P (2015) Re-defining the concept of immersion in digital immersive environments: patterns emerging from qualitative data analysis and theoretical comparison with previous theories on immersion. In: 2015 Digital heritage international congress, digital heritage 2015, pp 409–412, https://doi.org/10.1109/DigitalHeritage.2015.7419536

Stanney KM, Kennedy RS, Drexler JM, Harm DL (1999) Motion sickness and proprioceptive aftereffects following virtual environment exposure. Appl Ergon 30(1):27–38. https://doi.org/10.1016/S0003-6870(98)00039-8

Vlahakis V, Karigiannis J, Ioannidis N, Tsotros M, Gounaris M, Sticker D, Daehne P, Almeida L (2002) 3d interactive, on-site visualization of ancient olympia. In: Proceedings - 1st international symposium on 3D data processing visualization and transmission, 3DPVT 2002, pp 337–345, https://doi.org/10.1109/TDPVT.2002.1024080

Yapo TC, Sheng Y, Nasman J, Dolce A, Li E, Cutler B (2010) Dynamic projection environments for immersive visualization. In: 2010 IEEE Computer Society Conference on Computer Vision and Pattern Recognition - Workshops, CVPRW 2010, pp 1–8, https://doi.org/10.1109/CVPRW.2010.5543463

Zhang J, Kang K, Liu D, Yuan Y, Yanli E (2013) Vis4heritage: visual analytics approach on grotto wall painting degradations. IEEE Trans Visual Comput Graphics 19(12):1982–1991. https://doi.org/10.1109/TVCG.2013.219

Zhang Y, Zhang Z, Sun M, Ke T (2011) Precise orthoimage generation of Dunhuang wall painting. Photogramm Eng Remote Sens 77(6):631–640

Zhang Y, Hu K, Huang R (2012) Bundle adjustment with additional constraints applied to imagery of the dunhuang wall paintings. ISPRS J Photogramm Remote Sens 72:113–120. https://doi.org/10.1016/j.isprsjprs.2012.06.008

Zollmann S, Kalkofen D, Hoppe C, Kluckner S, Bischof H, Reitmayr G (2012) Interactive 4d overview and detail visualization in augmented reality. In: ISMAR 2012 - 11th IEEE international symposium on mixed and augmented reality 2012, science and technology papers, pp 167–176, https://doi.org/10.1109/ISMAR.2012.6402554