

CHER-Ob: A Tool for Shared Analysis and Video Dissemination

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The study of cultural heritage involves many different activities, including visualizing digital data, analyzing information, and sharing results. Current technologies focus on providing better tools for data representation and processing, neglecting the importance of analysis and sharing. In this article, we present a software system, CHER-Ob, which offers powerful tools for evaluating and publishing the results of cultural heritage research. CHER-Ob provides the capability to visualize and add various types of annotations to data in a wide variety of formats. These annotations assist in the analysis phase and are used for sharing the results of a study. A written report can be generated and automatically illustrated using the annotations. In addition, an “animation scheme” is associated with each type of annotation. The schemes make it possible to generate an introductory video overview of an analysis by selecting preferences and annotations. A series of animated sequences of 2D and 3D objects will appear in a user-specified order in a video subtitled by annotations. The system is useful for integrating cultural and digital resources as well as for providing a method to author materials for disseminating cultural heritage findings to the public.

CCS Concepts: • **Computing methodologies** → **Graphics systems and interfaces**;

Additional Key Words and Phrases: Cultural heritage, video generator

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1 INTRODUCTION

Studies in cultural heritage rely on various processes including digitization, data processing, visualization, information collation, and dissemination. The successful completion of cultural heritage research depends on contributions of experts from various fields who may use different methodologies and terminology and who may collect different types of data. Therefore, effective interaction with information provided by experts from different fields in different forms is necessary for a holistic approach toward interpretation and preservation of cultural heritage.

However, current digital technologies for cultural heritage research are faced with three major limitations in terms of information interaction and cooperation:

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- **Management of Large-Scale Data and Projects.** An important attribute of cultural heritage projects is the use of information from previous research on the object or site, which often contains tens or hundreds of datasets in different formats. Researchers have to load datasets using custom tools for visualizing each type of data and manually link and maintain related files.
- **Lack of Analysis and Evaluation Methods.** Most digital technologies focus on data visualization but are poor in information display, analysis, and annotation, which are indispensable in cultural heritage research.
- **Documentation and Sharing.** Most digital analyzing tools fail to provide platforms for researchers to share results of their research in a formal way. In most cases, researchers use digital technologies only to visualize data, and they have to turn to other software for documentation that can be shared and propagated conveniently.

To address these problems, we developed an open-source software system, CHER-Ob (for “Cultural HERitage Objects”), which provides powerful analysis and evaluation functions for cultural heritage research. The main contributions of this work are:

- **Cultural Heritage Entity.** The “cultural heritage entity” (CHE) is introduced as the basic container of information about a cultural heritage object or site. CHEs serve as templates for researchers to build *projects* that address particular research questions. Using a hierarchical storage model, a CHE can maintain and manage all the data and related files.
- **Annotation System.** CHER-Ob provides annotation methods for various data formats. Multiple selection mechanisms and color encoding enable users to locate the area they want to annotate and differentiate annotations in different categories.
- **Automatic Report Generation.** CHER-Ob provides a function to generate a research report in PDF format, which summarizes the project information.
- **Animation Schemes.** Using computer graphics principles and theories of visual attention, an animation scheme is defined for each annotation/data type. This allows the production of an animated sequence for each user annotation.
- **Integrated Video Generator.** We build an integrated generator in CHER-Ob to produce introductory videos for cultural heritage projects. Several resolutions and video codec options are provided. Users are able to choose datasets and annotations to show in the video and specify their order. The sequences produced via individual animation schemes are integrated to smoothly transition between annotations in a single output video.

In short, the contribution of this work is an *integrated system* that allows users to visualize and annotate heritage data and produce a report or video summarizing their results. This article is a revised and extended version of the work described in Refs [37] and [41].

2 RELATED WORK

There are two major areas related to our work in cultural heritage—software systems for processing data and information organization and storytelling methods from various types of data.

Software Systems. Current systems mainly focus on image and geometry processing; however, they are too specialized and, in most cases, can only support a limited number of data formats. One of the most widely used digital processing software packages is MeshLab [8], which can handle various 3D visualizations and rendering; however, it is limited in its support for other data formats such as 2D images. The same applies to GNU Image Manipulation Program (GIMP) [18] and Graphite [26], which are designed only for processing 2D and 3D data, respectively. Reflectance Transformation Imaging (RTI) is an important method in cultural heritage research, but tools to process RTI data remain limited. RTIViewer [13] is useful only for a single RTI and cannot process

multiple RTIs simultaneously. InscriptiFact [7] supports the functionality of viewing multiple RTIs but provides limited options for annotating them. Tools such as webGLRTIMaker and webRTIviewer [14] make it increasingly popular to view RTI data online, which are useful for dissemination but not considered a substitute for RTI desktop apps due to the lack of annotating and bookmarking functionality in collaborative research. Hyper3D [17] is a software prototype system developed to support visualizations of various data formats but, by design, is a data viewer rather than an analysis and sharing tool. CHER-Ob is built on and extends the concepts used in Hyper3D.

There are some systems that provide analysis functionality for cultural heritage such as 3D Semantic Annotation (3DSA) [44], which is a web-based annotation system for 3D objects. However, 3DSA only works for 3D objects and the annotations cannot be exported into other formats or interact with other tools, creating difficulties in analyzing and sharing. 3D Heritage Online Presenter (3DHOP) [33] is another useful tool for web publication of 3D models with annotations and bookmarks, contributing significantly to the dissemination of 3D cultural heritage data. However, researchers who access the webpage play a passive role during the online exploration, limiting collaborative research. Other research efforts [11, 12] and systems [6, 32] gather and cluster information from a variety of cultural heritage collections as an inventory. They offer efficient search tools and classifiers but lack functions for interactive visualization and manipulation of heterogeneous data.

For sharing insights, automatic report generation is available in database software, with limited flexibility and without support for advanced visualization. Video production requires a high level of expertise and computational power (e.g., 3DS MAX) to create an animation from well-annotated cultural heritage data. Screen capture software has been used for video generation, but these clips require further processing with video editing software in order to enhance their communicative power, adding another level of complexity to cultural heritage projects. There are also attempts to interactively annotate 3D content in a virtual world [25] and automatically linking Wikipedia data to reconstructed geometry with navigation [34]. CHER-Ob is a step forward to better collect, visualize, and annotate heterogeneous data, enabling shared analysis and video dissemination.

Storytelling from Data. Classically, the result of the analysis of an object is a report that contains text and static screenshots. This essentially communicates the analysis as a very dry story. Arguably, to convey a message, video works better than text-based media in education [35], entertainment [16], and advertising [3]. Video comprises other mediums, presents quick and rich content, engages audiences, prompts shares, incites action, enhances social communication, enables convenient and accessible production, and reaches the widest range of viewers [9, 15]. One inspiring piece of research investigates user experience on a website for art and culture [40] and shows a strong interest among museum visitors in viewing streaming multimedia rather than in active interaction, namely “less clicking, more watching.” These findings encourage us to develop an introductory video generator for better dissemination of cultural heritage results in addition to generating a report.

As digital technologies are more accessible and broadly applied in cultural heritage research, it becomes an important issue to enrich the digitized data with cultural context such as historical notes, physical descriptions, stylistic analysis, and conservation information. A step further is to make the digitized data with cultural context known to the public so that more researchers can contribute public value to society and people can conveniently learn from state-of-the-art research. Among many efforts is storytelling from cultural heritage data [31]. For example, there is a storytelling-based application for an anthropomorphic guide to a historical site presented through a mobile device [27], where the basic structure of storytelling is merged with the requirements coming from the communication of the specific knowledge about the historical site. To provide exciting opportunities for individual users to take virtual journeys, interactive storytelling techniques are embedded within still and video panoramas captured by a spherical camera for cultural heritage sites such as Charles Church in Plymouth and the town of Launceston, UK [24]. Similarly, the Digital Longmen Project uses cultural heritage data to build a virtual reality (VR) system in order to offer an immersive experience [42], where it also optionally adopts a motion capture system to give users more degrees of freedom in storytelling. There are also research efforts to facilitate inspection of a virtual object by navigating over its surrounding space [30], intuitively controlling the

camera and automatically generating camera trajectories. This is one of the ideas that we adopt in CHER-Ob to automatically create explanatory videos based on well-organized heterogeneous data.

To summarize, the previous research in storytelling is inspiring, but the methodologies used are not easy to generalize to other topics or projects. To overcome this, we design a comprehensive scheme for a video generator to communicate results. We begin with an overview of the base CHER-Ob system, then provide details of video generation and show examples from two case studies.

3 BASIC SYSTEM OVERVIEW

CHER-Ob provides functions for analysis and annotation to meet the needs of cultural heritage research, which are different from the functionalities offered by current image and geometry processing tools. Because we aim at providing a system for cultural heritage professionals engaged in studies extending over many days or longer, we have taken the approach of long-term user engagement introduced by Shneiderman and Plaisant [38] for development and evaluation. Two of the authors (KA and EK) are conservation scientists who specified and continuously tested and evaluated the system, while the rest of the team was responsible for code development.

CHER-Ob supports visualizations and rendering of various data formats, including 2D images, 3D mesh models, computed tomography data, hyperspectral image, and RTI data. The principles of consistent user gestures for manipulating view and lighting introduced in its predecessor Hyper3D are used in CHER-Ob. CHER-Ob also uses the bookmark concept from Hyper3D, which allows the user to save and label a particular view of a project so that they can return to it later.

The CHER-Ob system is coded in C++, using Qt [10] Application Program Interface (API) for the user interface and the widely used The Visualization Toolkit (VTK) [36], Insight Segmentation and Registration Toolkit (ITK) [39], OpenExr [28] and RTIViewer [13] libraries for visualization.

3.1 Cultural Heritage Entity

To take full advantage of previous cultural heritage projects and efficiently manage files, CHER-Ob introduces the concept of a CHE (Figure 1). Representing previously existing knowledge, CHEs are collections of available information about a cultural heritage object or site. A CHE is different from a *project* in CHER-Ob. A project is defined as a study related to a CHE or CHEs that are focused on answering specific research questions. Researchers can build particular projects by importing information and data from one or more related CHEs, which include the basic data objects and previous expert knowledge. Serving as the main source of data, each CHE can be imported to different projects based on the needs of researchers to solve different problems.

During the development of a project (Figure 2), users explore the visualized objects and their metadata, add bookmarks, annotations, and new files, making use of search, sort, and filter options. The evolution of the project can be tracked using the navigation tool. The generation of new knowledge takes place in CHER-Ob projects while users examine, analyze, and interpret the data. Their names and timestamp in addition to evidence-based statements are important features that are tracked, protecting the intellectual rights of each contributor and preserving data provenance information. After the completion of a project, users may combine new data to the initial CHEs, share the research findings, and merge with other projects.

The CHE files are managed in a hierarchical model, where each object is a unit and related files are maintained by each object independently and separately. Each CHE consists of raw data, rendering and visualization information, previous annotations, and bookmarks. Additionally, each CHE is accompanied by its metadata, which includes 10 categories derived from the Getty Categories for the Description of Works of Art (CDWA) [4], i.e., “object/work,” “physical dimensions/measurement,” “creation,” “materials and techniques,” “stylistic analysis and descriptions,” “condition and conservation,” “analyses,” “related works,” “exhibition/loans and legal issues,” “image/audio documentation,” and a user-defined category labeled as “others/miscellaneous.” Information associated with both CHEs and projects are stored in XML format. One attribute may host multiple pieces of

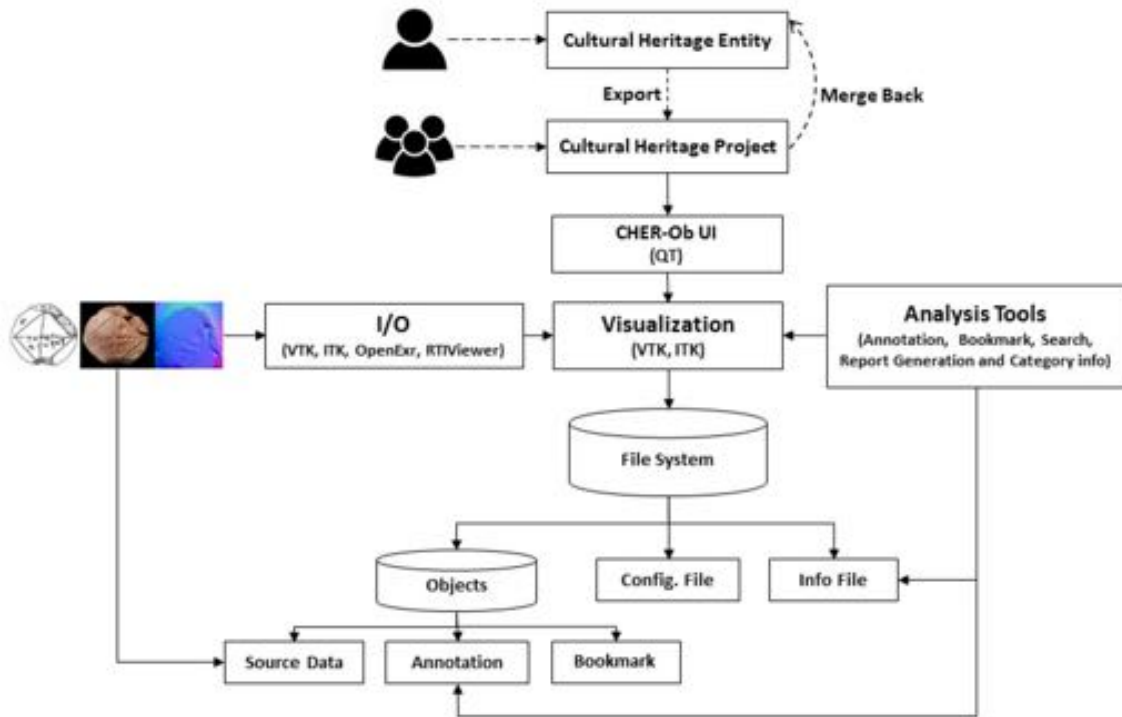


Fig. 1. CHER-Ob system architecture.

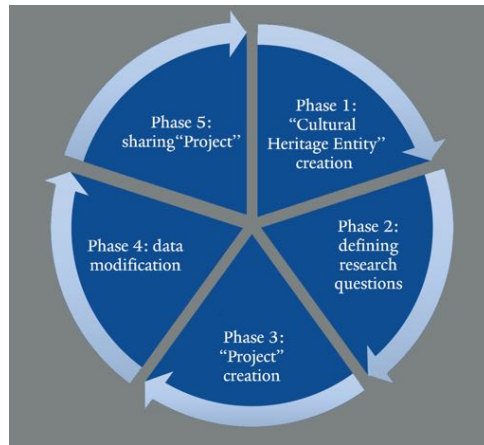


Fig. 2. CHER-Ob pipeline. In Phase 1, the user creates a CHE, providing the already existing information followed by Phase 2, where the research questions are defined, leading to a creation of a project in Phase 3. During the development of the project, in Phase 4, the data are modified and new information is added until its completion in Phase 5, where the project is shared.

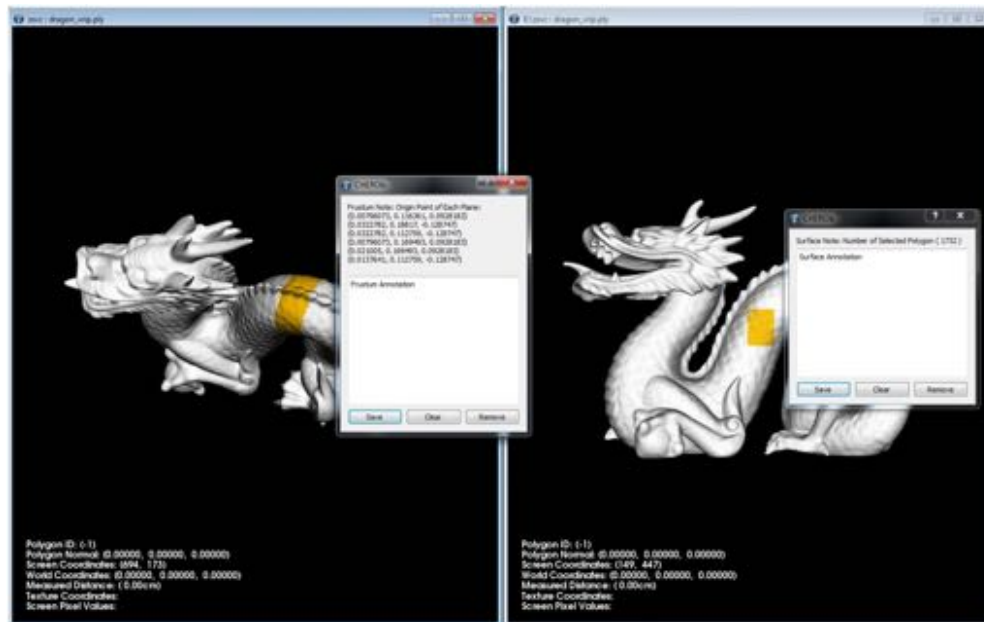


Fig. 3. Left: Frustum annotation. Right: Surface annotation. Frustum annotation selects part of the body behind the screen. Surface annotation selects surface skin.

information. For example, a CHE may have undergone more than one conservation treatment and been analyzed using different techniques.

3.2 Annotation System

To help cultural heritage professionals keep track of their own thoughts and share their perspectives, CHER-Ob provides powerful features for evaluation and annotation. The annotation system provides different modes for 2D and 3D data, in addition to general annotation that applies to the whole object. The annotations, applied to different data types, are categorized according to widely used standards, which enable efficient search leading and are not limited to the generation and display of notes for a particular data type.

Since the annotation is based on selection, multiple annotation methods are offered due to the different selection mechanisms. For 2D images and RTI, points, and rectangular or polygonal areas can be selected based on pixels. For 3D models, vertices, surfaces, or frusta (volumes) can be selected. Taking into consideration the complex geometries of 3D models in cultural heritage research, CHER-Ob distinguishes surface selection from frustum selection (Figure 3). Surface mode only selects the surface in a user-specified rectangular area on the screen, such as a small patch on the object surface, while frustum mode selects the entire volume within a user specified window, such as the body of a sculpture including invisible surfaces on the other side. Rectangular windows are convenient to specify. Free-form areas could be included in future systems. The background is black by default for users to focus on the object, but users can change the background to another color if necessary, e.g., when the object is mostly dark.

Apart from selections, color encoding is supported for annotation to represent metadata categories mentioned in Section 3.1. All the notes can be saved or removed based on the needs of user. The notes are saved as text files with metadata, user information, and optional associate images in a *Note* folder for each object. Using text and standard image formats make it possible to easily export notes to other applications. The annotation text is searchable and annotations can be filtered by categories.



Fig. 4. Four types of maps in the geographical tab with markers for the location of cultural heritage objects. From left to right: basic map, terrain map, satellite map with labels, and satellite map without labels.

The system is not designed for multiple users to annotate the same CHE simultaneously. Locks on data or a versioning system are possibilities for future work.

3.3 Incorporating Other Information

In addition to annotation on 2D and 3D objects, it is also necessary to incorporate other information in a cultural heritage project, such as geographical information, spectral distributions, and distance measurement and comparison of two RTIs under varying lighting conditions.

In order to integrate the function of geographical information and enable CHER-Ob to connect to popular geographic information system (GIS) tools in cultural heritage research, we design a tab for geographical information using Google maps APIs (Figure 4). Google maps APIs provide web-based interactive methods to display and mark a map in JavaScript. Since CHER-Ob is an open-source platform implemented in C++ using Qt and VTK libraries, we design a Qt-supported QWebView window that is used to view and edit web documents. Note that accessing geographic information is the only function that requires network access in CHER-Ob. This makes it possible to display an online map in the software. Users can simply interact with the map just as people do in a browser, including dragging to change visible locations and scrolling to zoom in or out. We are also able to call JavaScript functions by calling C++ wrapper functions, which is very helpful for adding geographical information to cultural heritage objects. When the annotation mode is on, users are able to make different types of notes on an object, as well as mark its location on our map. Each object has a longitude and a latitude stored in the CHER-Ob .xml project file, which can be read and updated if necessary. For the simplicity of user interface, we design a “Mark Center” button that sets a marker in the center of the map to avoid the confusion that the user wants to drag but not to mark when clicking on the map. Every time the user updates the geographical marker for an object, the software saves a screenshot of the current map—this retains the information for when the network is not accessible. Since there are usually many cultural heritage objects in a project, the marker of the current active object bounces for a better distinction. These APIs also offer four different styles, i.e., map, terrain, satellite, and satellite with labels. Researchers may want a certain style of map based on their interests such as urban planning and geomorphology.

CHER-Ob is also able to inspect spectral information on an object. The software can plot a reflectance histogram of different wavelengths on the right panel when a user clicks on a point of a 2D image or a textured 3D model. We see the reflectance in RGB channels for standard imagers and textures, but hyperspectral imagers can detect a much broader range of electromagnetic radiation beyond human vision. Hyperspectral data captured



Fig. 5. Part of report generated by CHER-Ob.

from cultural heritage artifacts can assist researchers in analyzing the condition of cultural heritage objects by plotting spectral histograms in CHER-Ob. Since spectrum inspection is based on individual points, CHER-Ob is also able to export the spectral information to point notes.

Distance measurement is another powerful tool in CHER-Ob, especially for 3D objects. The user can select two points on a 3D mesh model after turning on the measuring mode, and then a line segment connecting these two points in 3D will be rendered with its computed distance. For example, the user can perform several measurements of length, width, and height to understand and document the scale of a cultural heritage object. CHER-Ob also supports distance measurement on multiple 3D objects so that researchers can compare measurements interactively using our interface. Although we find that measuring line segments is able to help users understand the scale, in the future, more functions such as measuring polylines and geodesic distance may be useful additions.

Multiple RTI images may be loaded into CHER-Ob. User-specified changes in illumination direction are applied to all RTIs simultaneously. This mimics setting all of the artifacts on a surface together and moving a single light source to explore similarities and differences.

3.4 Report Generation

For the purpose of sharing and publishing, CHER-Ob is designed to support automatic report generation, which can summarize the output of a project or CHE (Figure 5). A report includes information such as user name, data of creation and descriptions, and details of each object that contain screenshots of the raw data, properties, and annotations. To display 3D objects comprehensively, screenshots from six directions (front, left, right, top, bottom, and back) are taken by changing the camera position. For every object, the catalog information is saved in the local file system as an XML file along with images and text files. When an object is imported into CHER-Ob, its information is read into memory, updated by users, and then prepared to generate a PDF report using Qt library.

To clearly match each annotation to the area where it is annotated, the screenshots are labeled with numbers (annotation IDs). For 2D images, the annotated area can be easily located by using the 2D coordinates of the

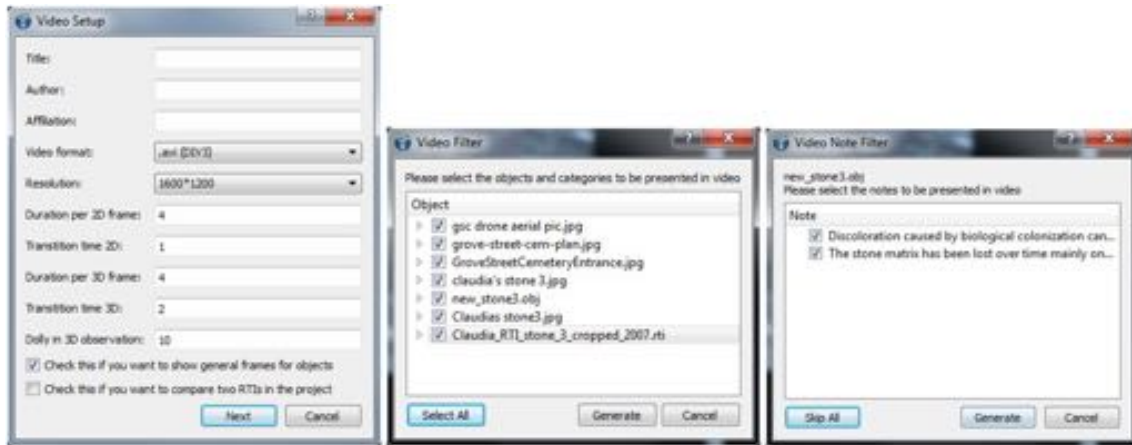


Fig. 6. Left: Video setup dialog. This is the first step to generate introductory videos, where many parameters can be specified according to different needs. Middle: Video object filter. Entries are draggable in this dialog, so users can select and reorder objects in the video more conveniently. Right: Object note filter. Entries are also draggable, so users can select and reorder notes of each object in the video more conveniently.

selected pixels. For 3D models, the center point of the selected surface or volume is calculated and projected to the object surface in each direction. If the center point is visible from the current camera position, it is assumed that the selected area can be seen in this screenshot and the annotation IDs are labeled on the center point with 2D image coordinates transformed from 3D world coordinates. Although it is effective in localizing the notes, a shortcoming is that the label may occlude useful information on the object. This is one motivation for creating a video generator to break through the limitations of static reports.

4 VIDEO GENERATION

In this section, we elaborate on the methodology of our CHER-Ob integrated generator for introductory videos. The videos are “introductory” in that they give a convenient overview of data, rather than being polished cinematic products. The organization of cultural heritage data and associated information described in the previous section is used in the design of our video generator. Users can specify overall parameters for the video such as resolution and format. We define animation schemes using computer graphics algorithms and insights from theories of human attention. Schemes are defined for six different types of notes in both 2D and 3D. The capability for spectral, distance, and side-by-side RTI information is also provided.

4.1 Organization and User Dialog

As just described, CHER-Ob projects make use of CHEs as the basic container of cultural heritage information. Each CHE has some digitized data, such as 2D images and 3D models. These data are linked to associated information including general annotation, a list of notes on different parts, illustrative pictures, and so on. In our generated introductory videos, we expect to cover the basic content in a CHER-Ob project in an efficient way, starting with several dialogs.

To enable users to customize videos according to various needs, we first design a video setup dialog (Figure 6). The information of title, author, and affiliation is extracted from the project, but the user can also modify how they appear in the video. We provide three different video formats, i.e., .avi, .mp4, and .wmv. By providing these options users are able to create videos that are portable and compatible with their own working environment. We also provide three different options for video resolution, i.e., 800×600, 1600×900, and 1600×1200, covering



Fig. 7. 2D animation scheme for point notes (left: CHER-Ob interface, right: video frame). A highlighted circle centered on the note’s position is presented in video frames with subtitles at the bottom.

common aspect ratios of 4:3 and 16:9. Lower resolution videos are quicker to generate and easier to spread via smartphones and tablets, while higher resolution ones are of better quality and more suitable for official publication. The last few parameters are the duration time for each 2D or 3D frame and the transition time between 2D or 3D frames. Keyframes remain static for a certain period of time as specified so that viewers can have the appropriate amount of time to appreciate each object. The transition time is relevant to the animation scheme and makes it more viewer friendly in terms of visual perception. Dolly in 3D observation describes how far the camera is from the object. Users are also able to choose if they want frames that show general annotation to appear in the introductory video.

After the video setup dialog, users select the data objects to be presented in the generated video. A list of all objects in the CHER-Ob project is shown to users with a “Select All” button that can easily gather all of them. Then for each object, users are able to decide the notes to be presented in the generated video in a dialog with the name of the current object at the top. The “Skip All” button skips remaining dialogs of notes and generates the video with default preferences. Note that in both object filter and note filters, entries in the tree widget are draggable. Therefore, it is convenient for users to select and reorder content in the introductory video.

The video writer in OpenCV takes images frame by frame in order to make a video. In addition to the title frame where the project name, authors, and affiliation are listed on a black background, object frames have a layout that the object appears in the middle, subtitles are shown in a darkened region at the bottom, and in the bottom right corner is either a geographical screenshot in a general frame or an associated image in a note frame. More examples are shown in the following sections.

4.2 Animation Schemes

We define an animation scheme for each annotation/data type combination—that is, the scheme for generating a sequence of frames. The final video is formed from these sequences in the order specified by the user.

First, we discuss the animation schemes for 2D cultural heritage objects such as images and RTI data. The general frame of a 2D image is the resized original image with the general annotation as subtitles. The intensity of the original image is reduced by 30% in the subtitle region. For RTI data, we change the light azimuth from 0 to 2π with a fixed elevation to produce frames with the general annotation, so viewers can appreciate different appearances of the object under changing lighting conditions. After the general frame is finished, 2D note frames are generated using the following scheme.

Since there are three different types of notes on a 2D cultural heritage object in CHER-Ob, i.e., point note, surface note, and polygon note, we need to draw the viewer’s attention to a specific region on the image. The region of interest (ROI) to be presented in a video is defined according to the type of note (Figures 7, 8, and 9).



Fig. 8. 2D animation scheme for surface notes (left: CHER-Ob interface, right: video frame). A highlighted rectangle encircling the note area is presented in video frames with subtitles at the bottom.



Fig. 9. 2D animation scheme for polygon notes (left: CHER-Ob interface, right: video frame). A highlighted circle centered on the polygon’s center of an adaptive radius is presented in video frames with subtitles at the bottom.

We decide to use a circle of radius that equals $1/20$ of the image height for point notes so that it has a noticeable size. A rectangle ROI identical to the rectangle used for annotation is used for surface notes. We also use a circle to represent polygon notes whose center is the center of all polygon vertices and radius is the longest distance from the center to one of polygon vertices. Inspired by attention models in psychology, specifically that higher spatial resolution and luminance attract attention [43], we keep the original resolution within the note ROI and perform bilateral filtering to blur background and maintain spatial context.

Bilateral filtering preserves edges and reduces noise to make a better smoothing result. Performing this on the background produces an illusion of lower resolution on the non-ROI region. Bilateral filtering may have little effect on images with little noise, so we also reduce the intensity of the non-ROI region by 30% to enhance contrast. Therefore, our 2D animation scheme is expected to draw people’s attention to annotated regions. A smooth transition between 2D keyframes is implemented by image interpolation to make the video more aesthetically pleasing.

The animation scheme for 3D cultural heritage objects requires another approach (Figures 10, 11, and 12). 3D frames are generated by manipulating properties of the VTK camera, primarily the camera position P_c and focal point P_f . For the general frame, we rotate the 3D model by 360° and then elevate the virtual camera to the top for a bird’s-eye view with the general annotation as subtitles to deliver a better sense of 3D geometry in the video. There are three different types of notes for 3D mesh models, point notes linked to a triangle, surface notes linked to a set of triangles, and a frustum note linked to all the triangles covered in a frustum. Our intuition is



Fig. 10. 3D animation scheme for point notes (left: CHER-Ob interface, right: video frame). The camera looks toward the note's center from a distance along the triangle normal with subtitles at the bottom.



Fig. 11. 3D animation scheme for surface notes (left: CHER-Ob interface, right: video frame). The camera looks toward the note's center from a distance along the normal of center triangle with subtitles at the bottom.

that we prefer to inspect parts of a 3D object from directly above, so we need to compute mesh normals. Given a triangle with the coordinates of three vertices, the normal vector can be computed using the cross product.

For 3D point notes, we set the focal point to be the center of the selected triangle and set the camera position to be a point a distance from the focal point along the computed triangle normal. For 3D surface notes, we set the focal point to be the center of all selected triangles and set the camera position to be a point a distance from the focal point along the normal of the triangle on which the focal point is projected. For 3D frustum notes, we set the focal point to be the center of the selected frustum and set the camera position so that it rotates ϕ (0 to 2π) around the frustum for a full view. The distance from the focal point to decide the camera position is specified by the dolly parameter λ in video setup dialog. The set of indices of vertices on all the selected triangles is denoted by S , e.g., $|S| = 3$ for a 3D point note because only one triangle is selected. Annotations and associated images are put in the subtitle region to explain details of the 3D cultural heritage object.

$$\text{Point: } P_f = \sum_{i \in S} P_i / |S|, \quad P_c = P_f + \lambda \vec{n} \quad (1)$$

$$\text{Surface: } P_f = \sum_{i \in S} P_i / |S|, \quad P_c = P_f + \lambda \vec{n}_j \quad (2)$$

$$\text{Frustum: } P_f = \sum_{i \in S} P_i / |S|, \quad P_c = P_f + \lambda \vec{v}_\phi \quad (3)$$

Proj(P_f) is in triangle j



Fig. 12. 3D animation scheme for frustum notes (left: CHER-Ob interface, right: video frame). The camera looks toward the note’s center from a distance and rotates around the object with subtitles at the bottom.

Smooth camera transition is implemented by spherical linear interpolation (Slerp) of camera positions and focal points between two consecutive 3D keyframes. Compared with linear interpolation (Lerp), Slerp is more capable of keeping track of the camera motion so that users can better understand the relative positions of notes. For example, it is less likely for the camera to penetrate an object using Slerp. Denoting the relative coordinates of two 3D points to the object’s center of mass as p_0 and p_1 , the spherical linear interpolation is computed as follows given a parameter $t \in [0, 1]$, where $\cos \Omega = p_0 \cdot p_1$:

$$p(t) = [\sin((1-t)\Omega)p_0 + \sin(t\Omega)p_1] / \sin\Omega \quad (4)$$

4.3 Other Information Types

Other types of information described in Section 3.3 can be included in videos (Figure 13). For example, geographical information can be presented with the general annotation of a cultural heritage object by showing the screenshot of the map with markers at the corner.

To include spectral information in our automatically generated videos, the user can simply export the spectrum inspection to a 2D point note on an object with the histogram screenshot as its associated image. The content of the point note is set using the spectral information about the reflectance in a channel with a specific wavelength along with necessary comments. After that, the video generator can highlight the picked position in the way that 2D point notes are animated with spectral information in the subtitle.

During the video generation, if there is an active distance measurement, a line segment with its distance in centimeters will be rendered in every frame of the object, including both frames of general annotation and individual 3D notes. Therefore, viewers are able to better understand the scale of the object as well as its notes given the rendered distance.

Thus far, we only have animation schemes for a single object, but it is also interesting to explore the difference between two objects in a cultural heritage project. In particular, instead of comparing two static images, we enable the functionality to compare two RTIs under varying lighting conditions in the video generator. If the user checks the box of RTI comparison in the video setup dialog, we will have an additional series of frames after it finishes generating the animation of notes for each individual RTI, which put two downscaled RTIs side by side and generated the video with varying lighting directions. The number of frames is decided by the duration of 2D general annotation frames. Although users are able to compare multiple RTIs in the interface by adjusting the lighting direction, it helps more people appreciate the appearance of cultural heritage objects by presenting them under different lighting conditions in the form of video that is easy to disseminate.



Fig. 13. Upper left: A frame from an animation with geographical information, where the general annotation and the map screenshot are shown at the bottom. Upper right: A frame from an animation with spectral information, where the reflectance values in different wavelength channels are shown in the subtitle with a histogram at the corner. Lower left: A frame from an animation with distance measurement on a 3D model. Lower right: A frame from an animation with RTI comparison under different lighting conditions.

5 CASE STUDIES

As described in Section 3, the system was developed with two cultural heritage specialists continually evaluating the capabilities in their projects. The use of CHER-Ob is demonstrated using two of these projects as case studies, different in terms of scale and nature. The first case study concerns the condition assessment of a stone in the the historic Grove Street Cemetery in New Haven, Connecticut, while the second one compares three cuneiform tablets from Yale Babylonian Collections.

5.1 Grove Street Cemetery

Grove Street Cemetery (GSC) was known originally as the New Haven Burying Ground. It is located on the outskirts of the Yale University campus, in the city of New Haven. It was designated a National Historic Landmark in 2000. GSC is also one of the earliest burial grounds to have a planned layout, with plots permanently owned by individual families, a structured arrangement of ornamental plantings, and paved and named streets and avenues.

Conservation work at the site currently does not match the importance of the cemetery itself. To express the urgent need of a conservation project, some pilot studies have been conducted and the results were shared with the stakeholders. Since the stakeholders are not from the conservation related backgrounds, it is necessary to present the expert views to non-expert stakeholders by using mainly visual tools. Thus, the visual weathering

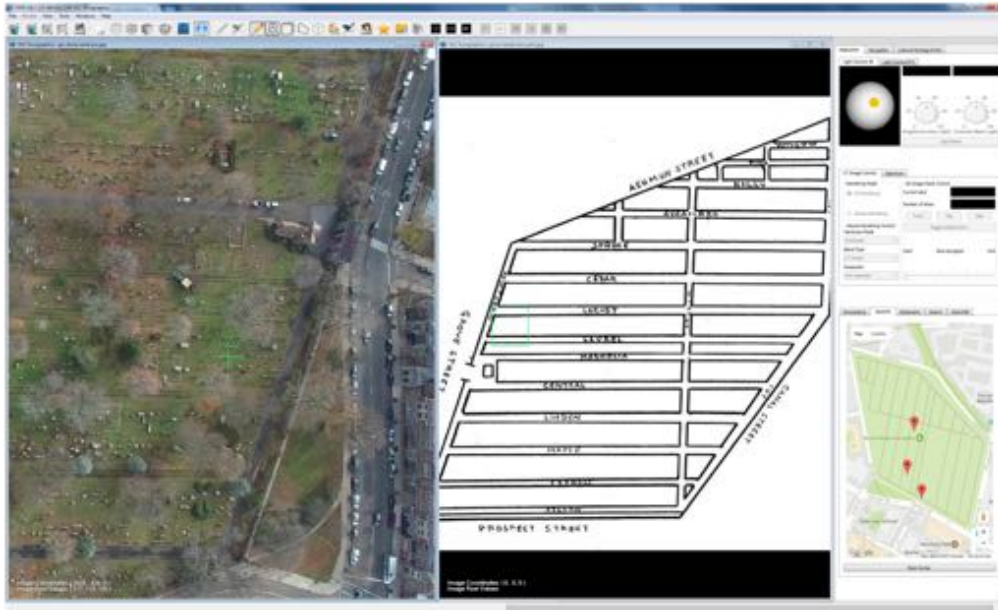


Fig. 14. A screenshot from CHER-Ob showing the plan and aerial photograph of Grove Street Cemetery and active GeoInfo tab for reference.

forms of stones were expressed in different images, 3D models of tombstones were generated, and RTI were captured and processed for detailed surface views of the tombstones.

A cultural heritage entity named Grove Street Cemetery was created (Figure 14) in CHER-Ob and a tombstone was selected to showcase (Figure 15). The project Tombstone C3 Project (Figure 16) was created with the available information in the Grove Street Cemetery CHE file. The Grove Street Cemetery in CHER-Ob included various 2D images and digitized plan drawings of the GSC and the selected tombstone in particular. Ultrasonic velocity (UPV) measurements of the tombstone were also taken for the condition assessment of the tombstone as a part of the Tombstone C3 Project. The results were depicted and comments were added to the images with the help of annotation tools.

The Grove Street Cemetery and the images were marked in the GeoInfo tab for future map reference to make finding the tombstone in the cemetery easier for project team members. The GeoInfo tab locates the cultural heritage object in question, which is needed when the CHE is a heritage site, building, monument, group of buildings, and monuments. The GeoInfo function makes it possible to connect other GIS-based software or tools, which are popular in cultural heritage research. This information is also valuable when CHE and projects created by different users are at different locations. Also, it helps locate and orient images taken by different people. The plan drawing from the literature and aerial photographs of the cemetery from different time eras can be used to indicate the location of the tombstone. However, the orientations of the various drawings and photographs are different and it is difficult for third parties to comprehend the differences, especially if they are not present at the time of the capturing of the images or creating the CHE in CHER-Ob. In this case, the GeoInfo tab is the source of objective reference for the orientation and location of the object.

A video was generated from the C3 project. It begins with the overall context of the cemetery and then focuses on information about the specific tombstone. Geographical information is also shown in the video with a map screenshot at the bottom right corner of the frames. A summary of the generated video is shown (Figure 17). The generated video can be found in the supplementary material.

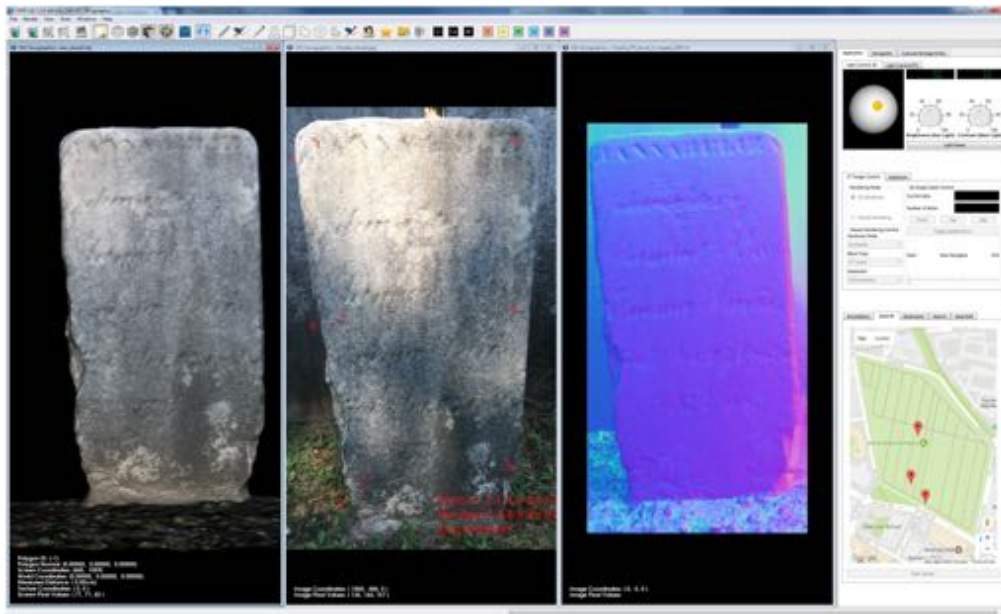


Fig. 15. A screenshot of CHE in CHER-Ob with 3D model, 2D image, and RTI of the tombstone.

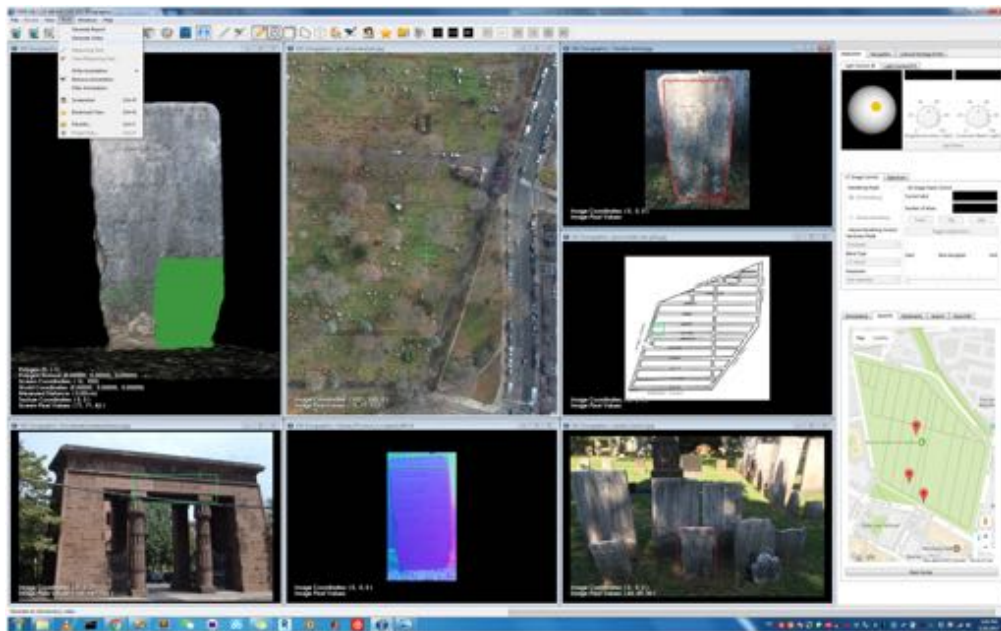


Fig. 16. A screenshot of the Grove Street case study also showing the video generation tool.

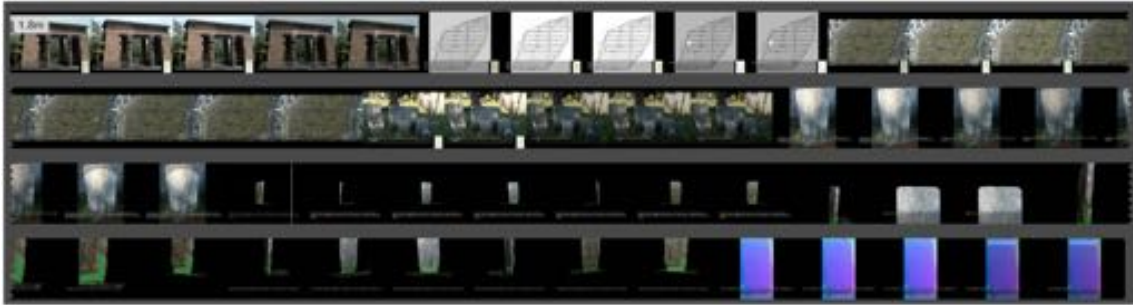


Fig. 17. A summary, showing a sparse sampling of frames, of the video generated for the Grove Street Cemetery project. The video is included in supplementary material.

5.2 Babylonian Cuneiform Tablets

Babylonian cuneiform tablets are among the most interesting historical documents of human history, since they are one of the oldest versions of written communication. Cuneiform tablets are mainly kept in museums or university collections around the world. Hundreds of thousands of text cuneiform are read, translated, and interpreted by scholars who are trained to read and translate the lexical, religious, literary, and administrative texts they contain in order to shed light on our perception of the Babylonian Civilization. The Yale Babylonian Collection has approximately 45,000 cuneiform tablets, cylinder seals, and other artifacts. However, the number and fragility of the artifacts make the collection almost impossible to exhibit to a wider audience. It is even difficult to make them accessible to the researchers around the world to study on them.

The “Babylonian Mathematical Tablets” project in CHER-Ob aims at bringing the information held by three cuneiform tablets in the Yale Babylonian Collections that contain geometric representations to a younger generation, especially with the help of the video generator in CHER-Ob. The project was created using available 3D models, RTI, and 2D images of the tablets. The details of how the CHE and the project in CHER-Ob were developed are as follows. First, three CHEs—“YBC7289,” “Area of Circle,” and “Calculation of Trapezoid Tablet”—were created by classifying information for each cuneiform tablet into eight categories: object/work, physical dimensions/measurements, creation, materials and techniques, stylistic analysis and descriptions, condition and conservation, exhibition/loans and legal issues, and documentation.

Then, the project “Babylonian Mathematical Tablets” was created by merging three CHEs, where the comparative analysis and visualizations are introduced for different tablets. While showing them all together it is also possible to select only one object and work individually on a particular case. In mathematical tablets, the only texts to be translated are the numbers that are common in all three tablets. To facilitate understanding the marks, a drawing of the number table was also added to the project. Additional drawings and images with annotations on 3D models were used to clarify the translations where necessary (Figure 18).

Different visualizations of the tablets can be retrieved using bookmarks and by using the textual search tools. Once the project was complete (Figure 19), the video generator tool was used to make an explanatory video. An overview of the video by sparsely sampling the frames is shown (Figure 20), and the full video is provided in supplementary material. The video shows each tablet in turn, with annotations and with a side-by-side RTI visualization. A casual user can use the video slider as a scroll bar to examine the three tablets without having to load the full project.

5.3 Observations

The two case studies illustrate that a wide range of data can be collected and used to study and document cultural heritage objects in CHER-Ob. With the design of CHE and functionalities of annotation, bookmarking, and

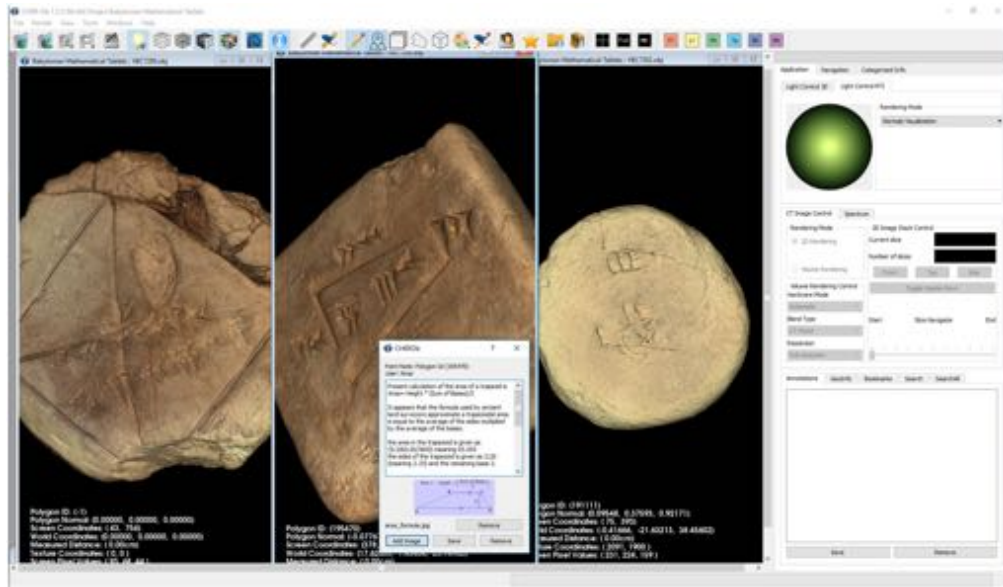


Fig. 18. A screenshot from CHER-Ob showing the three tablets. Users can annotate the 3D model of Trapezoid’s Area Calculation Tablet with text and an associated image.

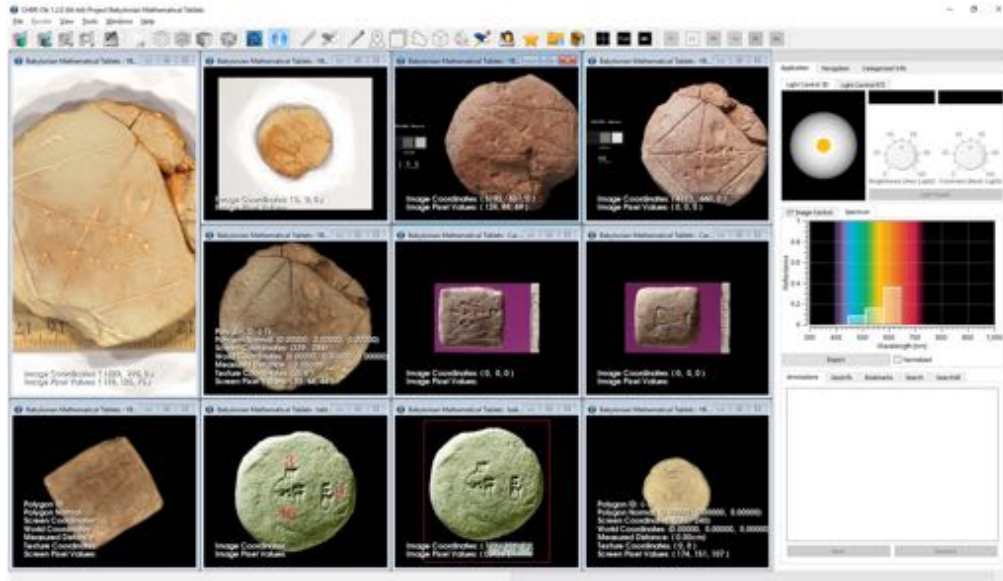


Fig. 19. A screenshot of the developed CHER-Ob project for the tablet case study. The project has evolved with the collaboration of multiple researchers over time.



Fig. 20. A summary, showing a sparse sampling of frames, of the video generated for the tablet project. The video is included in supplementary material.

navigation, heterogeneous data for cultural heritage research can be well organized and studied in CHER-Ob. As a CHER-Ob project evolves with collaborative analysis, the view of data can become quite complex and difficult to interpret by someone other than the project authors. The production of a video can give a quick overview of a project. The videos produced are simple and do not explain a project fully as stand-alone productions. However, they are quite useful in person-to-person presentations of a project as a powerful means of effectively disseminating cultural heritage research to non-experts.

6 DISSEMINATION AND USER FEEDBACK

The CHER-Ob system was initially released in 2016, with subsequent updates including the animation generator in 2017. The release was announced by means of various cultural heritage Listservs. The releases included source code, executables, a “quick start” guide, and sample datasets. To introduce the software, presentations and tutorial sessions that included users downloading and experimenting with the software were made at a series of cultural heritage events [2, 19–22].

Typical positive comments received from attendees included:

- the system introduces new ideas not available in commonly used viewers and other systems
- this helps make sense of material presented in cultural heritage courses
- this will help in completion of their research
- the video generator will be useful in public engagement

Common negative comments and suggestions that will direct future development included:

- the system requires effort to learn and use
- loading of large data files is too slow
- the annotation should be more compatible with the annotation in RTI VIEWER
- the system should be integrated into other cultural heritage software
- a web-based version of the software would be valuable

Since the release, the software has been used in studies by other heritage professionals [5, 29]. Additionally, individual authors of the system have used CHER-Ob in subsequent cultural heritage projects. EK worked with a group that used CHER-Ob for the comparative analysis of 2D and 3D visualizations of rock art pictographs [23]. HR and ZW used the video generator to illustrate at-risk sites in the Middle East for Project Anqa (Figure 21) [1]. In these practical applications, the system was further tested. We found that users usually make less than 20 annotations on each object, which CHER-Ob is able to handle without delay and which does not seem to be



Fig. 21. A summary, showing a sparse sampling of frames, of the video generated for Project Anqa.

a limitation. On the other hand, a limitation that was found was that requiring a user to enter a distance for a dolly to render 3D frames resulted in the need for multiple iterations in generating a video.

7 CONCLUSION

We have presented an open-source system, CHER-Ob, which provides an efficient platform for researchers to analyze the objects/sites and share their results with others. CHER-Ob uses the basic idea of a CHE that contains the data objects for a particular entity. CHEs are combined in projects that are used to explore particular research questions. CHER-Ob supports visualizations of various data formats, multiple annotation methods, automatic report, and video generation.

The introductory video generator integrated CHER-Ob is in particular a unique new tool that enables dissemination of cultural heritage projects in a more convenient manner. The design takes data of various formats and their associated annotations in cultural heritage research as input and generates introductory videos according to different needs. Users need only to specify some parameters and select the objects and annotations in the order to be rendered in the video. The video is then generated automatically, using insights into human attention and computer graphics animation techniques. Through two case studies, we have demonstrated that the videos, though simple, can be used to provide context for data and a convenient way to browse information.

The CHER-Ob system with sample data and documentation is publicly available at <http://graphics.cs.yale.edu/site/cher-ob-open-source-platform-shared-analysis-cultural-heritage-research>. Windows and Mac executables are available. The full source can be obtained at <http://github.com/WeiqiJust/CHER-Ob>. The open source project is continually under development to respond to user suggestions and bug reports.

Directions for future work include improving performance for large datasets using progressive loading, including video as an input data type for viewing and annotation, developing a versioning system, and including cinematic techniques to create high-quality output video. As a long-term vision of the future development, we would like to adapt CHER-Ob functionalities to more standards in cultural heritage research, implement a web-based platform for visualizing, annotating, and exploiting heterogeneous data, and design more intelligent interfaces to facilitate dissemination in the form of storytelling from experts to the general public.

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REFERENCES

- [1] Saima Akhtar, Goze Akoglu, Stefan Simon, and Holly Rushmeier. 2017. Project Anqa: Digitizing and documenting cultural heritage in the middle east. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 42 (2017), 1.
- [2] Kiraz Akoglu. 2016. CHER-Ob: An open source Software for the Integrated Shared Platform for Cultural Heritage Experts. Presented at *LAWDYN Digital Antiquity Research Workshop 2016 at ISAW* (Institute for the Study of The Ancient World), 02 December 2016 (program: <http://isaw.nyu.edu/library/blog/digital-antiquity-research-workshop-2016-at-isaw>).
- [3] Osei Appiah. 2006. Rich media, poor media: The impact of audio/video vs. text/picture testimonial ads on browsers' evaluations of commercial web sites and online products. *Journal of Current Issues & Research in Advertising* 28, 1 (2006), 73–86. DOI: <http://dx.doi.org/10.1080/10641734.2006.10505192>
- [4] Murtha Baca, Patricia Harpring, College Art Association, et al. 2006. *Categories for the Description of Works of Art*.
- [5] A. Baron Tacla. 2018. For a Digital Archaeology of Coins? A RTI project on Celtic coins kept at the BnF in L'Antiquité à la BnF. Retrieved March 15, 2018 from <https://antiquitebnf.hypotheses.org/1746>.
- [6] Marc Bron, Titia van der Werf, Shenghui Wang, and Maarten de Rijke. 2014. A social bookmarking system to support cluster driven archival arrangement. In *Proceedings of the 5th Information Interaction in Context Symposium (IiX '14)*. ACM, New York, NY, 295–298. DOI: <https://doi.org/10.1145/2637002.2637046>
- [7] Marilyn Lundberg Bruce Zuckerman and Leta Hunt. 2017. InscriptiFact. Retrieved from <http://www.inscriptifact.com>.
- [8] Paolo Cignoni, Massimiliano Corsini, and Guido Ranzuglia. 2008. Meshlab: An open-source 3D mesh processing system. *Ercim News* 73, 45–46 (2008), 6.
- [9] Brenna Clarine. 2016. 11 reasons why video is better than any other medium. Retrieved from <http://www.advancedwebranking.com/blog/11-reasons-why-video-is-better>.
- [10] Matthias Kalle Dalheimer. 2002. *Programming with Qt: Writing Portable GUI Applications on Unix and Win32* (2nd Ed.). O'Reilly & Associates, Inc., pub-ORA:adr. xviii + 499 pages.
- [11] Karl Grieser, Timothy Baldwin, Fabian Bohnert, and Liz Sonenberg. 2011. Using ontological and document similarity to estimate museum exhibit relatedness. *Journal on Computing and Cultural Heritage (JOCCH)* 3, 3 (2011), 10.
- [12] Mark Hall, Paul Clough, and Mark Stevenson. 2012. Evaluating the use of clustering for automatically organising digital library collections. In *International Conference on Theory and Practice of Digital Libraries*. Springer, 323–334.
- [13] Cultural Heritage Imaging and ISTI Italian National Research Council Visual Computing Lab. 2013. RTIViewer. Retrieved from http://culturalheritageimaging.org/What_We_Offer/Downloads/rtviewer/RTIViewer_Guide_v1_1.pdf.
- [14] Visual Computing Laboratory ISTI CNR initiative. 2014. WebRTIViewer. Retrieved from <http://vcg.isti.cnr.it/rti/webviewer.php>.
- [15] Andreas M. Kaplan and Michael Haenlein. 2010. Users of the world, unite! The challenges and opportunities of social media. *Business Horizons* 53, 1 (2010), 59–68.
- [16] Clare-Marie Karat, Claudio Pinhanez, John Karat, Renee Arora, and John Vergo. 2001. Less clicking, more watching: Results of the iterative design and evaluation of entertaining web experiences. In *Proceedings of IFIP TC 13th International Conference on Human-Computer Interaction*. IOS Press, Amsterdam. 455–463.
- [17] Min H. Kim, Holly Rushmeier, John French, Irma Passeri, and David Tidmarsh. 2014. Hyper3D: 3D graphics software for examining cultural artifacts. *Journal on Computing and Cultural Heritage (JOCCH)* 7, 3 (2014), 14.
- [18] Spencer Kimball and Peter Mattis. 1998. GIMP, the GNU image manipulation program. Retrieved from <http://www.gimp.org>.
- [19] Eleni Kotoula. 2017. CHER-Ob (Cultural HERitage-Object): An open source platform for shared analysis in cultural heritage research. Presented at CAA 2017-UK Chapter, Winchester, UK. 4-5 March 2017.
- [20] Eleni Kotoula. 2017. CHER-Ob for Cultural Heritage Research: Unsleben Jewish cemetery case study. Presented at *Digital Cultural Heritage: FUTURE VISIONS*, London, UK, 13-15 November 2017.
- [21] Eleni Kotoula and Kiraz Akoglu. 2016. Beyond Digitization: CHER-Ob for Analyzing Cultural Heritage Datasets. Presented at *CAA D GR Chapter December 2016, (Computer Applications and Quantitative Methods in Archaeology - Greece)*.
- [22] Eleni Kotoula, Kiraz Akoglu, and Zeyu Wang. 2017. An introduction to analysis using CHER-Ob. Workshop presented in *Computer Applications and Quantitative Methods in Archaeology (CAA'17)*.
- [23] Eleni Kotoula, David W. Robinson, and Clare Bedford. 2018. Interactive relighting, digital image enhancement and inclusive diagrammatic representations for the analysis of rock art superimposition: The main Pleito cave (CA, USA). *Journal of Archaeological Science* (2018).
- [24] Karol Kwiatek and Martin Woolner. 2009. Embedding interactive storytelling within still and video panoramas for cultural heritage sites. In *Proceedings of the 15th International Conference on Virtual Systems and Multimedia*. IEEE, 197–202.
- [25] Christine Lehmann and Jürgen Döllner. 2013. Annotating 3D content in interactive, virtual worlds. In *Proceedings of the 18th International Conference on 3D Web Technology (Web3D'13)*. ACM, New York, NY, 67–70. DOI: <https://doi.org/10.1145/2466533.2466552>
- [26] Bruno Lévy. 2008. Graphite. Retrieved from <http://alice.loria.fr/index.php/software.html>.
- [27] Vincenzo Lombardo and Rossana Damiano. 2012. Storytelling on mobile devices for cultural heritage. *New Review of Hypermedia and Multimedia* 18, 1–2 (2012), 11–35. DOI: <http://dx.doi.org/10.1080/13614568.2012.617846>

- [28] Lucas Digital Ltd. 2009. OpenEXR. Retrieved from <http://www.openexr.com/>.
- [29] Michael Maggen and Moshe Caine. 2017. Heritage imaging solutions for the real world. In *Proceedings of the 15th Conference on Culture and Computer Science*.
- [30] Luigi Malomo, Paolo Cignoni, and Roberto Scopigno. 2016. Generalized trackball for surfing over surfaces. In *Proceedings of the Conference on Smart Tools and Applications in Computer Graphics*. The Eurographics Association. DOI: <https://doi.org/10.2312/stag.20161368>
- [31] Bob McKercher and Hilary Du Cros. 2002. *Cultural Tourism: The Partnership Between Tourism and Cultural Heritage Management*. Routledge.
- [32] David Myers, Alison Dalgity, Ioannis Avramides, and Dennis Wuthrich. 2012. *Arches: An Open Source GIS for the Inventory and Management of Immovable Cultural Heritage*. Springer Berlin, Berlin, Germany, 817–824. DOI: https://doi.org/10.1007/978-3-642-34234-9_87
- [33] Marco Potenziani, Marco Callieri, Matteo Dellepiane, Massimiliano Corsini, Federico Ponchio, and Roberto Scopigno. 2015. 3DHOP: 3D Heritage Online Presenter. *Computers & Graphics* 52 (2015), 129–141. DOI: <https://doi.org/10.1016/j.cag.2015.07.001>
- [34] Bryan C. Russell, Ricardo Martin-Brualla, Daniel J. Butler, Steven M. Seitz, and Luke Zettlemoyer. 2013. 3D Wikipedia: Using online text to automatically label and navigate reconstructed geometry. *ACM Transactions on Graphics* 32, 6, Article 193 (Nov. 2013), 10 pages. DOI: <https://doi.org/10.1145/2508363.2508425>
- [35] Wolfgang Schnotz. 2002. Commentary: Towards an integrated view of learning from text and visual displays. *Educational Psychology Review* 14, 1 (01 Mar. 2002), 101–120. DOI: <https://doi.org/10.1023/A:1013136727916>
- [36] William J. Schroeder, Martin Kenneth, and William E. Lorensen. 2006. *The Visualization Toolkit* (4th ed.). Prentice Hall.
- [37] Weiqi Shi, Eleni Kotoula, Kiraz Akoglu, Ying Yang, and Holly Rushmeier. 2016. CHER-Ob: A tool for shared analysis in cultural heritage. In *Eurographics Workshop on Graphics and Cultural Heritage*. The Eurographics Association. DOI: <http://dx.doi.org/10.2312/gch.20161404>
- [38] Ben Shneiderman and Catherine Plaisant. 2006. Strategies for evaluating information visualization tools: multi-dimensional in-depth long-term case studies. In *Proceedings of the 2006 AVI Workshop on BEyond Time and Errors: Novel Evaluation Methods for Information Visualization*. ACM, 1–7.
- [39] Senate Johannes Taka and Subhadra Srinivasan. 2011. NIRViz: 3D visualization software for multimodality optical imaging using visualization toolkit (VTK) and insight segmentation toolkit (ITK). *Journal of Digital Imaging* 24, 6 (2011), 1103–1111. DOI: <http://dx.doi.org/10.1007/s10278-011-9362-5>
- [40] John Vergo, Clare-Marie Karat, John Karat, Claudio Pinhanez, Renee Arora, Thomas Cofino, Doug Riecken, and Mark Podlaseck. 2001. Less clicking, more watching: Results from the user-centered design of a multi-institutional web site for art and culture. *Museum and the Web* (2001), 23–32.
- [41] Zeyu Wang, Kiraz Akoglu, and Holly Rushmeier. 2017. An introductory video generator for disseminating cultural heritage. In *Eurographics Workshop on Graphics and Cultural Heritage*. The Eurographics Association, 83–92.
- [42] Zeyu Wang, Xiaohan Jin, Dian Shao, Renju Li, Hongbin Zha, and Katsushi Ikeuchi. 2017. *Digital Longmen Project: A Free Walking VR System with Image-Based Restoration*. Springer International Publishing, Cham, 191–206. DOI: https://doi.org/10.1007/978-3-319-54427-4_15
- [43] Yaffa Yeshurun and Marisa Carrasco. 1998. Attention improves or impairs visual performance by enhancing spatial resolution. *Nature* 396, 6706 (1998), 72–75.
- [44] David Yu and Jane Hunter. 2014. X3D fragment identifiers—Extending the open annotation model to support semantic annotation of 3D cultural heritage objects over the web. *International Journal of Heritage in the Digital Era* 3, 3 (2014), 579–596.

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