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Abstract

In this article, we describe a project on the use of Virtual Reality Continuum (VRC) for applications in culture and heritage. Haw Par Villa, a local heritage site in Singapore, is selected to demonstrate the entire process of VRC-enhanced digitization from laser scanning to 3D mapping and to 3D prototyping, using Madam Snake White as an example. The objective of the research is to investigate an effective and integrated solution to developing VRC applications for culture and heritage. Efforts are made for fidelity in the 3D modeling of the existing heritage for multiple applications, with the aim to popularize them in a simple and effective manner. In particular, in the case of Madam Snake White, we investigate the feasibility and effectiveness of digitization, 3D mapping, and 3D printing. We also discuss the use of online and interactive Madam Snake White as VRC heritage. A small group of volunteers were invited to a trial and their feedback was positive. Future work includes the application of VRC-enabled heritage for humanities education in local schools.

I Introduction

Historical and cultural artefacts are worth preserving as they allow people to link themselves with the past, and thus to know their heritage. Each time a well-loved building is torn down, or a popular gathering place paved over, a strand of culture is frayed. Due to rapid urbanization and land scarcity, historical sites unfortunately have to be sacrificed to make way for development. Also, because of war and vandalism in parts of the world, much heritage has been lost to history.

Haw Par Villa, previously known as Tiger Balm Gardens, is a park built in 1937 by the Burmese–Chinese brothers Aw Boon Haw and Aw Boon Par, as a venue for teaching traditional Chinese values. During World War II, Japanese forces took over the villa and used it to watch over ships at sea. After the war, Boon Par's son added finishing touches to the park. In the 1970s and 1980s, the villa became a popular site for day trippers and school excursions, to experience the world's only eclectic Chinese mythological park of its kind.

Figure 1. Selected heritage and cultural works in Haw Par Villa, Singapore.

The original owners, the Aw family, struggled through many years of hardship, yet generously contributed to social and cultural works by building this theme park in Singapore and eventually donated it to the Singapore Government. Over the years, the park had been operated by a number of organizations. In 1985, the Singapore Tourism Board acquired the land and gave the park a facelift.

This wonderful Haw Par Villa has over 1000 tasteful scenes from Chinese legends, such as Jiang Taigong, Smiling Buddha, The Eight Immortals, Madam Snake White, and Ten Courts of Hell (see Figure 1).

This project seeks to make use of VRC to provide a feasible and effective solution to support the entire process of preserving digitally a historical site, in this case Haw Par Villa (Tan et al., 2016). The project has a second objective, in the long term to revitalize the heritage to allow people in future generations to experience it.

The third objective is to investigate the benefits of applying novel VRC for cultural heritage, specifically the use of VRC-enabled online and interactive Madam Snake White for young Singaporeans.

Madam Snake White (see Figure 2) is selected from a list of heritage and cultural works in Haw Par Villa in this research. This Chinese legend involving one gentleman and two snakes (one white and one green) tells a very popular love story. They overcome tremendous difficulties before managing to meet up together on the Chinese Valentine's Day (Lunar July 7) at the Broken Bridge near the West Lake in Hangzhou, China.

The rest of the article is organized as follows. Section 2 reviews the prior art. Section 3 describes the process of laser scanning the scene of Madam Snake White in Haw Par Villa, as an example. Section 4 presents the 3D mapping and reconstruction of the laser scanned objects. Section 5 discusses the applications of the digitized

Figure 2. *The Heritage Madam Snake White in Haw Par Villa and its digitization using a laser scanner.*

heritage for internet, 3D printing, and augmented reality. Section 6 concludes this research.

2 Literature Review

Ivan Sutherland (1963) pioneered the research of virtual reality. He wrote “The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked.” Jaron Lanier coined the term virtual reality in 1989 (Solman, 2013). The idea of the reality–virtuality continuum was proposed by Milgram and Kishino (1994). The first ACM SIGGRAPH conference on VRC and its applications in industry kicked off in 2004 (Brown & Cai, 2004).

The importance of cultural heritage preservation with the aid of innovative technology is increasingly recognized by individual nations and the United Nations (Falser, 2015; Hoffman, 2006; Carrozzino & Bergamasco, 2010). VRC applications in cultural heritage are not new. MIRALab at the University of Geneva investigated VRC applications in the Virtual Hagia Sophia project (Foni, Papagiannakis, & Magnenat-Thalmann, 2002) and the Ancient Pompeii project (Papagiannakis

et al., 2005). Mourkoussis et al. (2002) discussed the virtual and augmented reality for educational and cultural heritage applications in Poland. Ruiz et al. (2002) reported their effort on virtual reality application for archaeological Maya cities. Jacobson and Holden (2005) shared their works on the virtual Egyptian temple. Melotti (2011) looked into the use of VR in archaeological areas in terms of incessant representation or even reinvention. Kenderdine (2013) reported the digital representations of the Mogao caves at Dunhuang. Gutten-tag (2010) studied VR applications and implications for tourism. El-Razaz (2007) highlighted the importance of VR technology making culture more accessible to the wider public and in documenting, recording, and conserving cultural heritage. Reffat and Nofal (2013) elaborated how VR helps a museum curator to adapt a cultural proposal and the information about the artefacts based on the different visitor categories. Interactive virtual museums were discussed by many researchers (Bruno et al., 2010; Carrozzino & Bergamasco, 2010). Guarnieri, Pirotti, and Vettore (2010) examine web-based interaction for cultural heritage. Levoy et al. (2002) presented their 3D scanning work in the Digital Michelangelo project. El-Hakim, Beraldin, Picard, and Godin (2004) detailed the 3D reconstruction of large-scale heritage sites. Fiorillo, Jimenez, Remondino, and Barba (2012) discussed the 3D surveying and modeling of the archaeological area of Paestum. Micoli, Guidi, Angheleddu, and Russo (2013) presented a multidisciplinary approach to 3D survey and reconstruction of historical buildings.

Substantial efforts have been reported in the literature on the use of either VR or AR technology for digital heritage applications. Liu, Wang, Li, Lei, and Lin (2006) studied the key issues for AR-based digital reconstruction. We are interested to look into the possible digitization of Singapore’s cultural heritage. Madam Snake White is selected from the Haw Par Villa collection as an example to go through the entire process of digitization using the VRC. More specifically, we are interested to see the feasibility and effectiveness of VRC-enabled heritage digitization with possible sharing of the resources such as 3D models developed in the process including laser scanning and 3D reconstruction.

Table 1. The Specifications of FARO X330 Scanner

Resolution (mm)	Point (million)	Scan size (point)	Scan duration (hh:mm:ss)
1.534	699.1	40960 × 17067	01:58:00
3.068	174.8	20480 × 8534	00:32:43
6.136	43.7	10240 × 4267	00:11:15
7.670	28.0	8192 × 3414	00:08:40
12.272	10.9	5120 × 2134	00:05:53
15.340	7.0	4096 × 1707	00:05:14
24.544	2.7	2560 × 1067	00:04:32
30.680	1.7	2048 × 854	00:04:23
49.087	0.7	1280 × 534	00:04:12

3 Laser Scanning of Heritage Site

Laser scanning uses the principle of Light Detection and Ranging (LIDAR). Similar to RADAR, LIDAR uses a laser to illuminate a target and then analyzes the reflection. While RADAR uses radio waves or micro-waves, LIDAR uses light at or near the visible spectrum (390 nm to 700 nm). With the use of extremely narrow beams, laser scanning is capable of mapping objects to a high resolution at a relatively high speed.

3.1 The FARO Focus3D Scanner

Focus3D X330 from FARO is a high-speed 3D laser scanner used in this project for the detailed measurement and documentation. The system is suitable for large space and building captures, with the capability to perform scanning even in bright sunlight. With a range of 0.6 m up to 330 m, Focus3D creates detailed captures of its surroundings, with distance accuracy of up to about ± 2 mm. The measurement speed is up to 976,000 points/second with low noise, and the resolution of the integrated color camera is up to 70 megapixels. Several million of these (x, y, z) coordinates result in a complete 3D impression of its surroundings. Color scans are created simultaneously with the help of the integrated camera. The scan data are then stored on a Secure Digital (SD) card. Table 1 shows the specifications of the scanner.

Figure 3. Scanning effectiveness.

From Table 1, a plot for resolution-MPTS and resolution-duration is created in Figure 3. Based on the plot, a resolution of 7.67 mm is chosen for the digitization of the Madam Snake White for effective laser scanning.

3.2 Scanning the Scene

The Madam Snake White scene consists of three statues with a bridge. They were scanned from nine different viewpoints using the FARO Focus3D scanner, in order to cover the scene completely. This was due to the different poses of the statues (see Figure 4). For example, Madam Snake White's arm is angled toward the body, thus obscuring much of the body from the scanner. Similarly, the sides of the bridge obscure much of the lower half of the scene.

Figure 4. Nine scans from different views to capture Madam Snake White.

Each scan had a predefined range of scanning angles at a selected accuracy. Different time duration was taken to complete a scan depending on the accuracy in addition to the set-up time. A high accuracy scan (~ 2 mm) required about 20–30 minutes while a low one (5–10 mm) required 5–10 minutes.

4 3D Mapping

The point clouds from the different scans need to be stitched together to reconstruct the complete 3D model(s). Figure 5 illustrates the workflow for the processing of the point clouds, consisting of global registration, local registration and segmentation. Other techniques for point cloud processing, such as denoising, resampling and reconstruction, will be applied for further applications.

4.1 Multi-Scan Stitching

Given two point clouds from a set of scans, stitching is basically an estimate of a rigid transformation for aligning the two. This registration task can be divided into two subtasks: global registration and local registration. Global registration is to obtain a good initial alignment for arbitrary input poses (scans) of the same environment. Local registration is to refine the correspondences between the two globally registered scans and find the optimal transformations between them.

Figure 5. Workflow of point cloud processing.

For global registration, FARO offers a function to recognize markers (white balls) placed in the scene to calculate the rigid transformation among scans accurately and efficiently. However, it is difficult to obtain a perfect match from these calculations. The situation is worse if the scans are obtained in very different settings, for instance on different days or with unexpected marker movements. We implemented the Super4PCS algorithm (Mellado, Aiger, & Mitra, 2014) to solve the global registration by finding a congruent four-point set for each scan in point cloud form. In the situation of lacking or missing effective markers, Super4PCS could also help. In general, an efficient global registration will accelerate the alignment process and increase the convergence speed for the subsequent local registration.

Local registration focuses more on improving the accuracy of registration and resilience especially given a number of outliers and noise. Let $X = \{x_i\}$ and $Y = \{y_i\}$ be two point clouds. The Iterative Closest Point (ICP)

method formulates pairwise registration as two steps, including finding correct point correspondences in the input datasets (see Equation 1) and estimating a rigid transformation in global coordinates (see Equation 2):

$$\arg \min_T \sum_{i=1}^n \phi(Rx_i + t, y_i), \quad (1)$$

$$\arg \min_{R,t} \sum_{i=1}^n \phi(Rx_i + t, y_i), \quad (2)$$

where,

ϕ is the distance between two points;

R is constrained to the orthogonal group so that R and t will form a rigid transformation.

If ϕ measures the classical squared Euclidean distance in L_2 norm, the capability of ICP will be affected by noise and outliers. Various methods and heuristics have been developed to improve robustness using L_1 , L_p (Bouaziz, Tagliasacchi, & Pauly, 2013) and L_0 norm regularization. For a large number of input scans, parallel computing will help speed up the calculation. A binary tree could be built to organize scans hierarchically. A transformation matrix could be computed at each internal node based on two point clouds on children node pairwise. The final transformation of each point cloud is obtained by traversing from its leaf node to the root node.

4.2 Intelligent Segmentation

The min-cut based segmentation algorithm (Golovinskiy & Funkhouser, 2009) is applied in the work to recognize objects and shapes in a point cloud. It could be done during or after the registration. We first interactively select some points in the object of interest as seeds. The neighboring points are then merged to the object cluster, which is defined by color similarity and a smoothness constraint. The size of the cluster is grown iteratively to form a segmented object. The same segmentation algorithm can also be used to divide the point cloud into foreground and background parts.

4.3 Resampling

Quite often, the scanning files are large. When a great number of large scans are used for stitching,

resampling is necessary. This is because there are often substantial redundant and duplicate points among these scans. The large data sets of scans can make rendering and further processing difficult and time consuming. Resampling is a technique widely used to tackle the redundancy problem. To reduce the file size, down-sampling the point cloud using different resolutions for different applications is a practical solution. The bounding box of the point cloud is partitioned into a grid of 3D voxels. The size of each voxel, defined by the user, determines the resolution of the down-sampled point cloud. The points in each voxel are resampled or approximated with their centroid, which is controlled by a user-defined sampling rate. If the number of points contained in a voxel is less than a predefined threshold, these points could be regarded as noise. Also, a statistical outlier removal method based on the distribution of distance from a point to its neighbors could be applied to denoise the point cloud.

4.4 Surface Reconstruction

The obtained point cloud could be used for rendering, animating, and other processing directly. For many applications, the surface mesh representation is preferred. The surface reconstruction from oriented points is a classic problem (Kazhdan, Bolitho, & Hoppe, 2006; Calakli & Taubin, 2011; Kazhdan & Hoppe, 2013). A typical approach is to compute a 3D indicator function χ (defined as 1 at points inside the model, and 0 at points outside), and then to extract an appropriate isosurface. It can be formulated as a spatial Poisson problem: compute the scalar function χ whose Laplacian (divergence of gradient) equals the divergence of the vector field $\vec{V}$,

$$\Delta \chi \equiv \nabla \cdot \nabla \chi = \nabla \cdot \vec{V}.$$

Figure 6 shows the mesh model of Madam Snake White, which is reconstructed from the point cloud data captured by the laser scanner in Haw Par Villa. The reconstructed mesh model can be used for various applications such as 3D printing and analysis (Cai, Loh, Nee, & Miyazawa, 1998).

(a)

(b)

Figure 6. (a) The mesh model of Madam Snake White reconstructed from point clouds. (b) A simplified mesh model of Madam Snake White.

5 Digital Heritage Using Internet, 3D Printing, and Augmented Reality

In this section, we describe a few heritage-related applications of the reconstructed mesh models, which include internet visualization, 3D printing, and augmented reality.

5.1 Online Virtual-Reality Heritage

A virtual Haw Par Villa can help promote the physical heritage. The 3D reconstructed models, however, may have to go through a number of postprocesses before they can be readily used for online display. This is due to the consideration of internet bandwidth. Simplified models with reasonably fine details are highly desired. Figure 7 is a complete 3D reconstruction of Madam Snake White used for online visualization.

Figure 7. Online visualization of Madam Snake White.

Figure 8. 3D-printed Madam Snake White model.

People can view this 3D digital model from different viewpoints by rotating and translating it on the web.

5.2 3D Printed Heritage

3D printing sometimes is referred to as real-virtuality. The same 3D reconstructed models can be used for 3D printing after reformatting and postprocessing. This can be done using the STL mesh generator. Likely, the STL formatted mesh model will go through processes such as the creation of a thickened surface model to reduce the material usage and thus the cost. Additional structures may be generated to support 3D printing. Figure 8 shows a 3D printed model of Madam Snake White.

Figure 9. An initial trial with Madam Snake White, from left to right: (a) the Augmented Reality app; (b) the AR model; (c) the feedback outcome.

5.3 Promoting Culture and Heritage with the Aid of VRC

Using the 3D printed models of Madam Snake White, an augmented reality application has been developed for Android smartphones. The development of this application demonstrates the entire process of using VRC. The digital models and animation of Madam Snake White make interactive manipulation and visualization of the object possible and flexible. Thus, the static Madam Snake White can become an interactive storytelling tool with enhancements using multimedia such as (folk) music, narration, and animation (Figure 8[b]). For instance, the app can allow users to learn the background information behind the 3D models, and trigger an animated story easily. The models and animations are kept in a server online enabling anyone to access the digital heritage anywhere anytime. This VRC-enhanced interactive approach has the potential for young people to learn heritage such as Madam Snake White.

An initial trial with Madam Snake White was conducted with 13 young people (see Figure 8[a]). Overall, response in using the AR technology for culture and heritage application is positive (see Figure 8[c]).

6 Conclusions

This article describes a project on the use of virtual-reality continuum for culture and heritage applications. In particular, we discuss the case of Madam

Snake White at Haw Par Villa in Singapore. Laser scanning technology is applied to digitize the objects in the villa. 3D mapping is then conducted to reconstruct the digital 3D models of the objects from the captured point clouds, through the processes of multiscan stitching, segmentation, and simplification. Emphasis is placed on leveraging on the VRC to develop a shared platform for culture and heritage applications. Efforts are made on digitization of existing cultural heritage using laser scanning, processing of point cloud data, and 3D printing of digitized cultural heritage in an integrated manner.

The great advantage of laser scanning is its high accuracy. We can generate models with very fine detail. However, this high-resolution model requires substantial time to develop from initial scanning to stitching and meshing. When the meshed models are used for online visualization, 3D printing, and augmented reality, model simplification is often desired in order to make these applications feasible. On the other hand, low resolution and fast scanning may cause a significant loss of detail which is difficult, if not impossible, to recover in postprocessing. This work investigates the possible trade-off of laser scanning resolution, processing time, and meshed model detail by taking possible heritage applications into consideration. In Figure 3, we selected the resolution of 7.67 mm for our scanning of the Madam Snake White. The time required was about 9 min to complete one scan. It took about 80 min to do 9 scans. This took advantage of avoiding recharge of the scanner battery. The average number of points for each scan is

Table 2. Modeling of Madam Snake White and Its Polygon Numbers and Processing Times

Madam Snake White	# of vertices	# of faces	Processing time
Reconstructed mesh model (Fig 6[a])	184,171	338,115	2 min 131'54" for reconstruction
Online mesh model (Fig 6[b] & Fig 7)	21,996	42,263	4'14" for simplification
3D printing model (Fig 8)	1,014,345	338,115	1' for export to STL file
AR mesh model (Fig 9[b])	11,427	21,131	5'56" for simplification

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Figure 10. VRC-enabled digital heritages.

around 13 million, making 118,305,121 points for a total of 9 scans. To align these 9 scans, it takes 1 min 30 sec for global stitching and 2 hr 4 min 56 sec for local stitching. The point cloud after stitching and denoising only contains 9,540,109 points and 2,597,543 points after intelligent segmentation. For applications in online visualization, 3D printing, and augmented reality, model simplification is required. Different simplifications are conducted given the initial scanning resolution of 7.67 mm. Table 2 shows the polygon number and processing time of the Madam Snake White.

In summary, we report a case of how VRC can be used for heritage preservation. The 3D models reconstructed from laser scanned point cloud are used to create a digital heritage of Madam Snake White for online visualization, real-virtuality 3D printings, and augmented reality (see Figure 10). In this example, we demonstrate the effectiveness of VRC-enabled digitization of Madam Snake

White with a focus on the trade-off between digitizing accuracy and processing speed. Compared to the previous efforts reported in the literature, we emphasize the integrated solution for the digitization of heritage sites.

This is a piece of preliminary work with a number of future directions. First, there are missing parts with laser scanning for the areas that are hidden or beyond the reach of the laser. It is interesting to combine other techniques such as Unmanned Aerial Vehicles (UAV) together with photogrammetry (The Art of Photogrammetry, 2015; Radosevic, 2010). Remote-controlled drones, such as the DJI Phantom, can be programmed with preset GPS coordinates of the site and with flight routes mapped out. The drone would fly the preset routes and take multiple images of the park from the air to generate the general model of the park using photogrammetry. The cost of such a setup would be relatively low, as programmable drones with high-resolution cameras are now widely available in the market, thanks to the growing interest in aerial photography. Handheld depth imaging can also be used to capture those areas difficult for the laser to reach. Second, due to the huge data size, parallel processing using the latest GPU hardware should be attempted to speed up the computing process for multiscan stitching, segmenting, and rendering. Third, the quality of the surface reconstruction can be further enhanced (Kazhdan & Hoppe, 2013). In addition, the geometric modeling techniques (Ye, Cai, Chui, & Anderson, 2002) can be used to restore artefacts damaged by filling holes and so on.

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