Digital Heritage Visualizations of the Impossible

Photogrammetric Models of Villa Foscari and Villa Pisani at Bagnolo

Takehiko NAGAKURA[1] / Daniel TSAI[2] / Diego PINOCHET[3]

[1,2,3] Massachusetts Institute of Technology

Abstract:

New digital capturing technologies can enable existing architecture to be seen as never before. This paper presents a photogrammetric modeling process and interactive representations of the Villa Foscari and the Villa Pisani at Bagnolo, two of Andrea Palladio's best known built designs. Palladio described them in his seminal work, The Four Books of Architecture (1570).Through the centuries, numerous studies have been made of his villas, most notably Bertotti Scamozzi's surveyed measurements and illustrations (1776). During the expeditions to each of these villas, the MIT team meticulously took photographs of the rooms on the piano nobile and of the building's exterior, and photogrammetrically processed them into models with accurate textures. When the pieces were combined in an interactive visualization environment, remarkable never before seen views of the villas were created, including a view of the fresco-covered ceiling vaults of the entire main floor looking up from the underground, as well as a side-by-side comparison of the two villas in miniature . Such photo-realistic representations extend a new insight into Palladio's design, architectural surfaces, tectonic solutions, and space.

Conventional drawings and models have been the media of designing, recording, and studying buildings throughout the history of architecture. Geometric models are virtual constructs added in the past half century. This paper presents the outcome of our recent experiments with digital capture, and uses them to exemplify how this latest, emerging media can inform and demonstrate architectural discourse, by delivering a sense of reality in the form of an analytical construct. In particular, it discusses engagement of photogrammetric models and an interactive game engine visualization tool in terms of (1) previously impossible viewing angles; (2) textures and details captured from a moment in reality; (3) compositing with traditional design media; (4) comparative methods of study, and (5) deployment in relevant technologies such as AR.

Keywords: Photogrammetric Model, Architectural History, Villas of Andrea Palladio, Digital Heritage, Interactive Viewing

Introduction

Photogrammetric modeling is a method of making a fully textured 3D model of an artifact from photographs. The recent use of low cost or no cost photogrammetric modeling software is becoming gradually accepted by the public, who use smart phone cameras and consumer digital cameras every day. Photogrammetry is also a potentially new tool for architectural scholars that allows convenient, simultaneous capture of architectural forms and textures. What impact does this emerging technological method have on the way we study architecture and spatial designs?

Fig. 1 – Photogrammetric model of Villa Foscari's fresco vaults viewed from below and in section. (Copyright: Nagakura, Tsai and Pinochet)

Between 2013 and 2015, MIT Department of Architecture conducted three workshops with short field trips to study a number of Renaissance buildings in Veneto, Italy. This paper describes (1) the on-site method deployed during these workshops to examine and to digitally capture two villas designed by Andrea Palladio, (2) the process of producing photogrammetric models, and (3) the outcome of interactive visual means derived from these processes (Fig. 1). It discusses the impact of this new type of heritage visualization for historians, designers, students of architecture, and others who have interests in the recording of buildings.

In a previous publication (Nagakura, Tsai and Choi 2015), the authors discussed four points peculiar to photogrammetric technology when applied to buildings: (1) The quality of the model depends on the technicality of the photographs and software such as the specifications of camera and lens, number and angles of the photographs sampled, and algorithmic implementations of the software used to process the photographs. (2) No two captures made at different times results in the same models. (3) The model represents its geometry by point cloud or mesh that has no discrete parts. For example, a window is not a discrete element from a wall but rather just a continuation of points or mesh triangles. (4) A photogrammetric recording exercise of a building usually produces many incomplete models of architectural parts, with some missing portions and overlaps.

This paper describes the actual use-case workflow in which the technology, as we adapted it in-house, was deployed for an academic project, where heritage buildings were recorded on site, and interactive visual representations were produced. Instead of analyzing the technology itself, this paper emphasizes the

significant outcomes. The reader is asked to examine the visual potential beyond the mechanics and the technical aspects: seeing architecture in a new way — not just as synthetic analytical construct, not as limited photorealism, but where the underlying designs can be revealed with the sense of architectural reality, with presence of details, materiality, phenomena, and time.

Palladio's Villas and the MIT workshops

Villa Foscari and Villa Pisani at Bagnolo

The case illustrated in this paper is our project that engaged the photogrammetric capturing of the Villa Foscari and the Villa Pisani at Bagnolo (Fig. 2), two villas designed and built by Andrea Palladio in northern Italy. An abundance of studies and descriptions of these villas throughout the history of architecture by many architects including Palladio himself makes them suitable vehicles to test the role of a new visual means in comparison to conventional representations.

Fig. 2 – Villa Foscari and Villa Pisani in photographs and as depicted by Palladio (top) and Scamozzi (bottom). The plans shown in the same scale illustrate Villa Foscari has a smaller footprint than Villa Pisani but is taller. Palladio's version as presented in his Four Books of Architecture shows his ideal and is different from the measured condition described in Scamozzi's drawing, which is also different from the present day recording.

Palladio is known as the pre-eminent Renaissance architect, who influenced his contemporaries as well as generations of architects to follow. James Ackerman (1966, p19) stated at the outset of his book on Palladio:

> *All over the western world, hundreds of thousands of houses, churches and public buildings with symmetrical fronts and applied half-columns topped by a pediment descend from the designs of Andrea Palladio. He is the most imitated architect in history, and his influence on the development of English and American architecture probably has been greater than that of all other Renaissance architects combined.*

Palladio's influence was achieved through his built projects around the Veneto region and through The Four Books of Architecture, in which he described his design principles with drawings of his architectural projects and those of ancient architecture that he surveyed. One of the later architectural scholars who studied Palladio's work was Bertotti Scamozzi (1786), who extensively traveled to visit Palladio's built works, measured them, and published his findings. His publication includes shaded drawings of buildings and components with carefully added shadows as well as line drawings with measurements (Fig.3). Shaded drawings are sometimes used to compare variations of building components, and shaded and line drawings are often composed in the same page to make sense about the three dimensionality, proportions, and details. This style takes after Palladio's use of compositions of line drawings in his treatise, where he described not only his own designs but also ancient architecture that he studied in Rome. One widely known

example of this architectural tradition of surveying a building and meticulous graphical depiction is the compilation of studies by French students published by Hector d'Espouy (1905), where Scamozzi's shading by hatching is replaced by continuous shading by ink wash. The architectural components in this later case show more photographic sense of reality (Fig. 6).

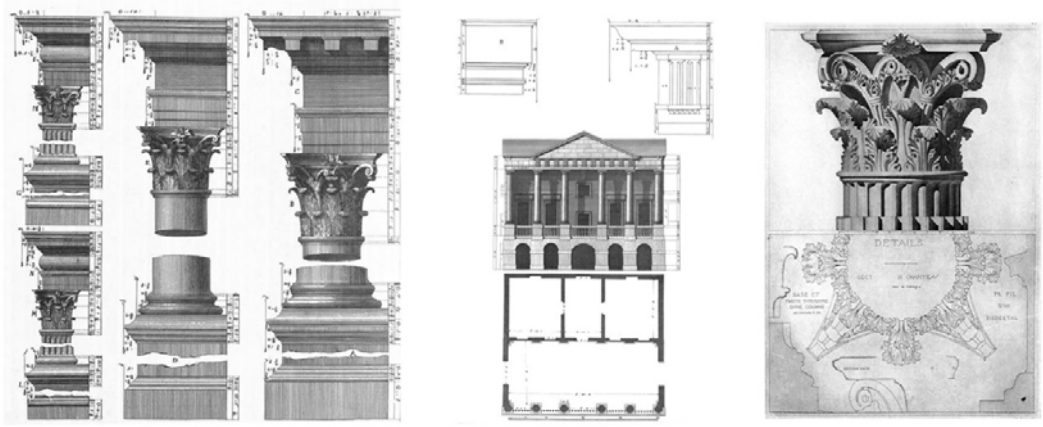

Fig. 3 – Illustrations from *The Buildings and Designs of Andrea Palladio.* Bertotti Scamozzi drew variations of column orders he measured in Teatro Olimpico (left), and composed line drawings and a shaded one for Loggia Valmarana (middle). Image on the right is a drawing of a Corinthian capital from the Temple of Minerva composed with ink wash and lines in d'Espouy's compilation.

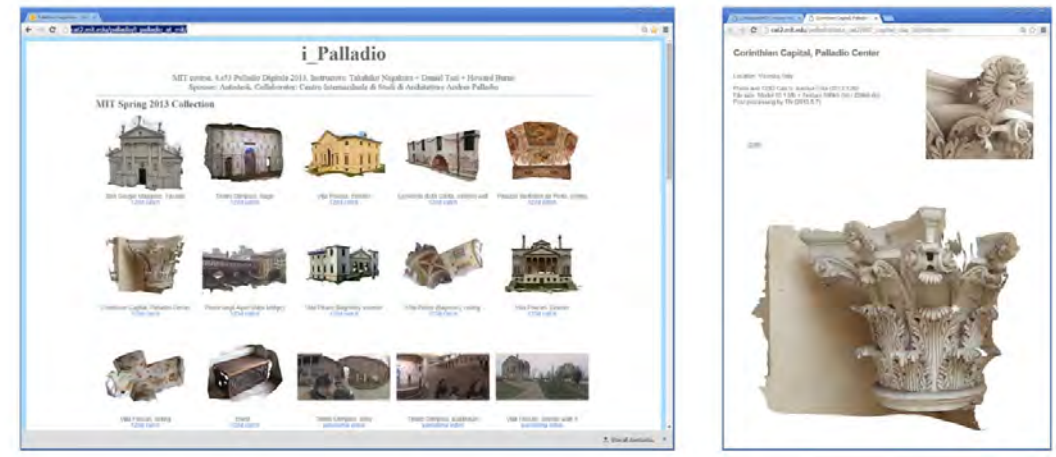

Fig. 4 – MIT i_palladio website at http://cat2.mit.edu/Palladio including photogrammetric models and panoramic videos collected on the sites of Palladio's buildings. The Corinthian capital is a capture of a floor exhibit at the Palazzo Barbaran Da Porto, which houses CISA Palladio. (Copyright: Nagakura and Tsai)

Palladio's designs of the villas was his attempt to bring the spatial sense and tectonic motif of ancient Roman architecture into the lives of the 16th century establishment in the Veneto region, who needed country residences to oversee their agricultural productions and as retreats from their congested urban lives. A typical villa he developed has rooms arranged symmetrically on a grid of 3 by 3 or 3 by 5 bays, with a temple-like loggia in the front and vaulted ceilings over major chambers. For economical building with ancient motifs, he employed creative tectonic systems such as brick columns plastered to look like a stone monolith, plastered brick wall added with large masonry groove patters, and wood beams shaped to stone entablature. Through collaborations with contemporary painters, many interior surfaces were embellished with fresco paintings that depict lives and stories in ancient times. Many villas were similarly situated near

water traffic from the urban centers with the façade facing the water, and a large courtyard behind to help production operations with crops and animals.

With a basic proportional scheme to give each building component an appropriate measurement and relationships among them, Palladio developed the characteristics of his villas into an overarching system of design principles that governed all of his published designs, although many built versions have compromised solutions to different degrees. The Villa Pisani at Bagnolo (1542) was one of his early villa designs preceded by Villa Godi (1537), his first, and a few other early villas. The Villa Foscari (1558) was a later work before he embarked on institutional commissions such as his work on San Giorgio Maggiore in Venice. Our project captured both villas into photogrammetric models (Fig. 4), developed derivative digital representations, and tested their usefulness in studying how each of these villas followed Palladio's principles, as well as how they were different in order to accommodate the specificity of the context and program of architectural design.

MIT Workshops

At MIT's Department of Architecture, a workshop on digital heritage was held for three consecutive years between 2013 and 2015. Each workshop was run by an instructor team of experts in visualization, digital tools, and architectural history, and included a field trip to Veneto, Italy to survey Renaissance architecture for about a week during the Spring break in March. Villa Foscari was visited one day during the 2013 workshop and three days during the 2014 expedition. Villa Pisani was had been visited one day in 2013, three days during the 2014 workshops, and one day during the 2015 workshop.

The case presented in this paper is a product of the work of the architecture students in these workshops, who are not specially trained as surveyors, historians, or archaeologists. The workshops had nine students in 2013, ten students in 2014 and five students in 2015. They went through only a short in-class training on using capturing tools in advance of the field trip, and practiced using them on site while they learned and captured these villas for the first time in their lives. Thus, the nature of the work on discussion is mainly a rapid sampling through taking photographs with low cost consumer devices such as digital cameras and smart phones, and different from that of professional surveying and modeling done on construction sites with a professional laser scanner. The time spent for capturing each villa was approximately three to four hours per visit. On these two villa sites, the workshop members gained full access to the interior and the exterior of the buildings including permission to fly drones, thanks to the generous arrangement provided by the villa owners.

Capturing Method and Workflow

Each of the three MIT workshops proceeded in the following manner.

A. Preliminary study

Conventional 3D models were made from plan, section, and elevation drawings described in Book 2 of Palladio's Four Books of Architecture as well as Scamozzi's book. Discrepancies between the descriptions in the two sources have been identified and discussed. Book 1 of the Four Books was examined to study Palladio's building components and compositions, and attempts were made to take advantage of recent advances (Aubin 2013) in Building Information Modeling software and to create a catalogue of parametric architectural components. The catalogue was incomplete but helped with accelerating production of the villa and palazzo models as Palladio's design system disposes well defined components and their assembly. The

drawings and 3D models prepared in this preliminary stage became a place holder for captured fragments and their composite visualizations later.

B. Fieldwork

On the sites of the villas, numerous sets of photographs were taken to produce photogrammetric models. Each set requires overlapping photographs taken from different angles. Palladio's villas do not have a large portion of reflective or transparent surfaces, and the villa's aging materials reduce any repetitive design motifs. These are very suitable conditions for a photogrammetric algorithm to work efficiently and properly. The following notes itemize the typical processes and findings during these workshops:

1. Photo count: Less than a dozen photographs can produce a convincing model for a simple object such as a door handle (Fig. 7, top). Less than 70 ground-based photographs can produce a model showing a local condition (Fig. 7, bottom) or schematic exterior model of a villa. A few thousand photographs of the building exterior taken on the ground and from the drone produced a fairly detailed model of the building (Fig. 11).

2. Lighting: For a well-lit interior space or exterior surfaces, a consumer digital camera or high-end smart phone cameras produced decent models. The photogrammetric algorithm does not work well with blurred or dark photographs, and the depth of a focal field also needs to include the surfaces to be modeled. Therefore, a dark interior space benefits from a full-frame digital SLR camera with a high quality fast prime lens. A tripod may be used instead to allow a longer exposure, but it is inconvenient for taking a sequence of shots while changing the angles each time. HDR shooting option, if available and feasible, would be helpful.

3. Lens: A middling wide-angle prime lens within the range of 20-35mm can efficiently produce overlapping shots for photogrammetric models of architecture. A fish eye lens or an action cameras such as a GoPro or a drone-embedded camera may be used, but it usually requires appropriate correction with a software filter during the process of photogrammetric modeling. While cell phone cameras have increased in quality, our models derived mostly from consumer digital cameras as well as digital SLR photographs when available.

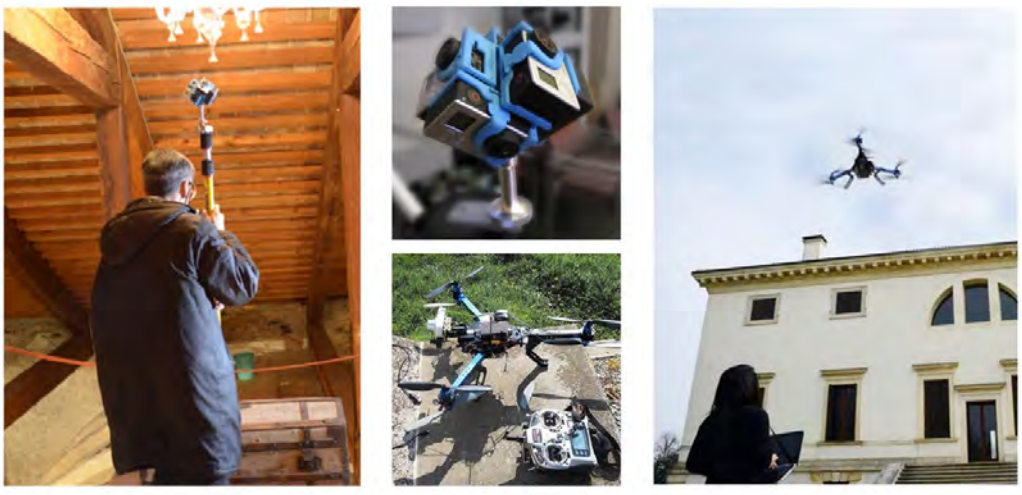

Fig. 5 – MIT Workshop on the sites of Palladio's villas with drones, poles, and panoramic video device. (Copyright: Nagakura and Tsai)

4. Coverage: To cover surfaces at a significant height, different types of drones were tested (Fig. 5). A large drone is capable of carrying a high-end camera of choice but costly, and remotely monitoring the camera is difficult. Mounting a camera also needs consideration for eliminating vibration. A small consumer drone with an embedded camera such as DJI Phantom was an effective alternative that the workshop deployed with a decent result. Setting the camera to time-lapse mode allowed a single person to operate the drone and to

sample photographs. Software for a programmed flight is not as useful for capturing a single architecture with complex details unlike doing a typical, large scale archaeological site.

5. Mobile Rig: Using a monopole with a remote camera is convenient for capturing parts of interior spaces such as a small floor and the top of closets. The workshops used a few Mr. LongArm products that extends up to 12 feet (Fig. 5).

6. Progression through Space: Covering a large area in one sweep is one strategy while making part by part or room by room captures for later assembly is another. A good practice is to discuss this among the team while scouting the site before the sampling session.

7. Measurements: Laser measurements were used to record major dimensions of the building. They were used to scale the photogrammetric models later.

8. 360 Video: Panoramic video recording made on the site (Fig. 5) was very useful for checking the conditions and contexts of the villas back in the lab.

9. Difficult Spaces: For a tiny space like a staircase, an RGBd scanning tool such as Kinect was a convenient alternative.

C. Photogrammetric Data Processing

The next step after taking photographs is to process the photographs into 3-dimensional mesh model and photographic texture. Each set of photographs was processed through one of three photogrammetric modeling software packages: (1) Autodesk 123D Catch was used to process small sets of seventy or less photos. The software is cloud-based and the required internet access is not always available in the field. However, it is free and convenient for each workshop participant to generate a small model of a building component without much training. (2) VisualSFM and MeshLab are public domain tools. The sifting algorithm of the first application produces a point cloud from a photographic set and the second application converts the point cloud into a mesh model with a texture map. Learning the operation and adjustment of these (free) applications requires extensive training. The advantage lies in the capacity to process thousands of photos at a time, and to operate without connection to the internet. One use is for testing time-lapse shots from drone data in the field, if a laptop with high-end GPU is available. (3) Photoscan is a commercial package widely used by recent archaeological projects. On a high-end CPU with sufficient RAM, a large volume of photographs can be processed with professional results. The workshop used this application to create a final visualization of some difficult parts of the buildings, such as the roof and for an exhibition model.

Once the meshed models are generated with texture maps, 3D graphics software such as 3D Studio and Rhino were used to clean up the irregular or unnecessary parts of the raw mesh and to optimize the mesh density. In most cases, the face count of each mesh is kept approximately under 50,000. This size is convenient for a model to be used on the internet or for incorporation into various interactive visualization applications. Each model is scaled, rotated, and positioned appropriately in a single coordinate space with reference to the schematic geometric model of the villa prepared earlier.

D. Interactive Visualizations

The models captured from villas have been incorporated and delivered in the following types of interactive visualization venues:

1. Online catalogue of individual captures
2. Representations combined and edited within a game engine visualization environment

3. Application of visualization tools including AR, VR, and projection mapping

On the internet, a website (Fig. 5) titled i_Palladio (2013) has been created to visually host the database of each model with information about recording date, location, processing software, author, and other annotations, which are compiled in an associated xml file. WebGL-based GUI on the page allows interactive panning and spinning of the model, although the internet bandwidth limits each model to be a reasonably small mesh size with texture data, which is typically only sufficient for a building component or a schematic exterior.

On the other hand, more complex interactive representations have been created on Unity3D platform, a game engine environment, by editing multiple photogrammetric models together sometimes with additional drawings and geometric models. This method typically produces an application package of a significant size, which is not appropriate for instant online distribution, but can include a crafted, choreographed representation enabling a design of a multifaceted way of seeing architecture. The captured models can also be further processed and deployed in other emerging visualization platforms such as augmented and virtual reality systems.

Digital Heritage: Representations and Significance

The following examples illustrate and discuss various interactive visualizations of the two villas, created through the use of models captured on sites. The spirit of careful surveying and visualizing important architecture and the methods of three dimensionally describing surfaces of each component and editing them for sensible representations takes precedence in the conventions developed by Palladio, Scamozzi, d'Espouy, and others in the history of architecture.

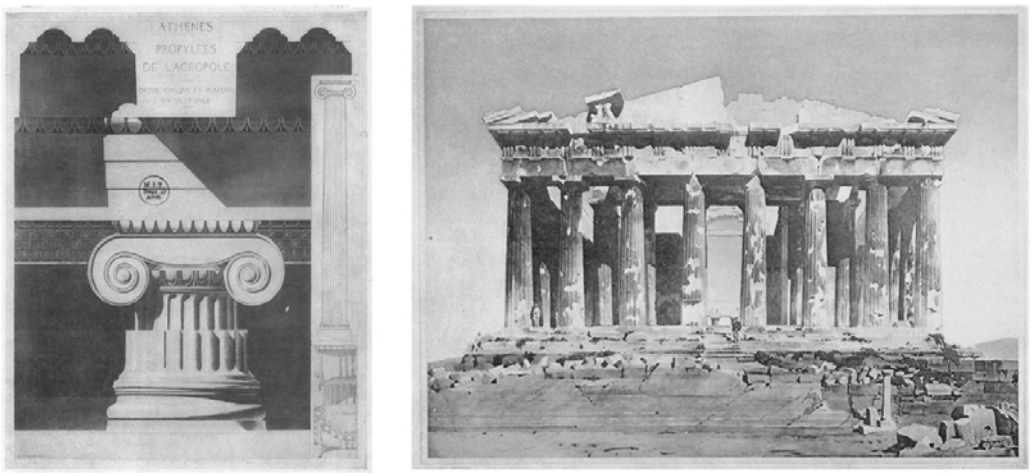

Fig. 6 – From d:Espouy's compilation, Ionic column with surrounding details of Propylea (left) and Parthenon (right) at Acropolis.

A. Small artifacts and building components with materiality and details

1. A door handle of Villa Poiana (Fig. 7, top)

This digital capture of a wooden door and iron handle is made from less than a dozen photographs sampled at Villa Poiana (1548), another villa designed by Palladio. From afar, the objects seem unremarkable. Its surfaces, however, can be studied at an extreme close up at different angles, where the high resolution texture sampled directly from the photographs provides a sense of the real wood grains and the subtle geometric pattern of the metal work. The model also shows aging of the materials as well as wearing and weathering of the surfaces, and evokes a sense of passing time since its construction. Despite the simplicity

of the overall form, achieving such an intimate visualization is difficult with conventional geometric modeling and texture mapping methods.

Fig. 7 – Captured models of a door handle at Villa Poiana and a column base of Villa Fosacri's loggia (Copyright: Nagakura, Tsai and Pinochet)

2. A base of column supporting the façade pediment of Villa Foscari (Fig. 7, bottom)

The captured fragment around a column base bears as a target of archaeological examination. On the steps are observed circular marks of lost balustrade posts. Attached to the base is a broken piece of handrail stone. The base is made of impaired stone and the column is made of brick layers with some remains of a plaster finish which reveals its tectonics and indicates its intended completion. Also observed is a black cap for an electronic plug modifying the podium base to fit into a contemporary life style.

3. Vaulted ceilings covered with frescoes inside the piano nobile of Villa Foscari (Fig. 8)

This captured model faithfully reproduces the design of fresco paintings by Battista Franco and Giambattista Zelotti on Palladio's design of the cross vault form. Interactive viewing allows the close-up examination of figures and artifact details in the painting, and continuous zooming out shows how the painted image covers the ridges of the cross vault, turns the corners of the hall, wraps around the window frame beneath, and converges onto a single octagonal image at the top. The viewing point can be pulled further down to the

imaginary level below the floor to command a view including the ceilings of adjacent rooms (Fig. 8, bottom). Moving the viewpoint around lets a viewer experience how well the illusive three dimensionality created by painterly method works on the flat geometry (Fig. 8, top). The photogrammetric model also captures the role of the windows and architectural surfaces around them in illuminating the frescoes by letting natural light in and bouncing it gradually deeper into the space (Fig 8, middle).

Fig. 8 – Vaulted ceilings covered with fresco in Villa Foscari. (Copyright: Nagakura, Tsai and Pinochet)

B. Composite representation

Multiple captures and conventional drawings such as plan, elevation and section can be composed and arranged in the shared coordinate space for interactive viewing. This is a work of curation to make sense out of individual media by relating them.

1. A door model composed of captures from two sides (Villa Pisani main hall and northeast chamber) (Fig. 9)

This example shows an interactive examination of both sides of a door and the wall around it at the Villa Pisani. One side of the main hall with the high vaulted ceiling has a glorified cornice on the door frame. The other side is used as dining and kitchen space with a modest door frame. The example illustrates the duality of these architectural components which are designed to have different details and conditions appropriate to serve the space on each side delimited by them.

Fig. 9 – A door model in Villa Pisani interactively viewed from two sides (Copyright: Nagakura, Tsai and Pinochet)

2. Villa Pisani's main vault captured from the attic above and floor below (Fig 10, right)
Another example that allows examination of two sides of a spatial divider shows the tectonic system behind the brick vault seen from the attic as well as that covered by plaster and fresco painting from the main hall below. This model is composed of two captures.

3. A captured built-in sink composed with measured drawings (Fig 10, left)
This example combines photogrammetric models with elevation and section drawings found in the Media Library archive at the Palladio Foundation in Vicenza. Such a representational method helps to analyze three dimensional conditions with measured projections, where each drawing understood as a projection of the three dimensional artifact. The drawings decode the design of a real object, while the real object decodes how the drawings' needs read.

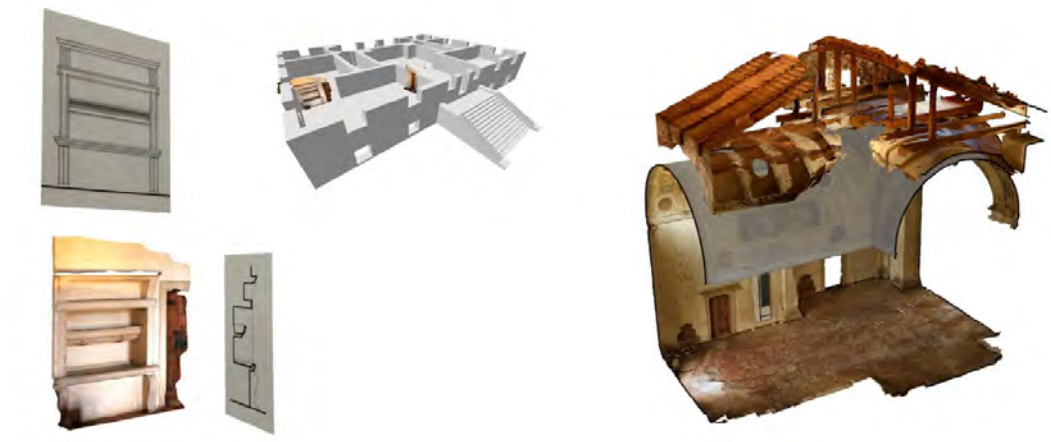

Fig. 10 – The Cross Vault and a Sink at Villa Pisani (Copyright: Nagakura, Tsai and Pinochet)

C. Comparative visualization
A custom interface with dual viewports comparing 2 villas side-by-side was developed. Each 3D villa model is a complex composite construct of captured data. While the viewer interactively operates on changing the view angle, zooming in and out, turning on and off the architectural components such as roofs and ground, and sectioning the building model, the operations simultaneously take effect in the two views and allows the two villas to be examined side by side. The following examples show the way this means is used to demonstrate the similarities and the differences between the Villa Foscari (left viewport) and the Villa Pisani (right viewport), as was summarized by the text in the previous section.

Fig. 11 – Comparison of site and room layout of Villa Foscari (left) and Villa Pisani (right) (Copyright: Nagakura, Tsai and Pinocet)

1. Villa Pisani and Villa Foscari: Sites and exterior (Fig. 11, top)

This comparative view of the full capture of the site and the building exterior reveals the shared characteristics of the villa sites and Palladio's master plan strategy for placing a building on each.
- Each site is adjacent to the waterway, which was used for transportation from the city.
- Each villa is placed near the waterway with a small open space in-between and a large rear courtyard.
- The courtyard is flanked by a *barchesse* to support agricultural production and house animals.
- Each villa has a rectangular profile.
- The main building façade is located on the side of the waterway as approach was made directly from it.
- The façade accommodates a loggia in the center with a pediment over it.
- Each villa has a basement, piano nobile and a story above. (The Villa Foscari also has a small mezzanine.)
- Villa Foscari's piano level is set higher to keep the basement above the ground and high water level.
- The component vocabulary for windows, roofs, moldings, and many other details are shared.
- The loggia support is different: the Villa Foscari has an Ionic order, while the Villa Pisani uses arched piers.
- The Villa Foscari exterior has a large masonry-groove pattern. Villa Pisani has white walls with partial rustication.

2. Villa Pisani and Villa Foscari: room layout (Fig. 11, bottom)

This view of the horizontal sections of the villas allows a comparison of interior organizations.

- The villas share a 3 x 5 bay grid with transformations of merged bays allowing a cross vault and larger rooms.
- Each villa has a symmetrically arranged plan.
- The Villa Pisani has a loggia inset on the grid, while the Villa Foscari loggia is projected out of the grid.
- The Villa Pisani uses circular steps for the main entrance, while the Villa Foscari uses two sets of angular stairs.
- Windows and doors are placed to penetrate through all walls between the opposite sides of the building.

3. Villa Pisani and Villa Foscari: ceilings (Fig. 12)

Further observations on the ceiling and interior space can be made by these comparative views.

- In the middle of each villa is placed a main hall that has a cross vault with fresco painting.
- The Villa Foscari's periphery rooms are all vaulted with fresco, while the Villa Pisani has five rooms with flat ceilings.

- The Villa Foscari rooms have fresco walls, while the Villa Pisani rooms, except for one room, have white walls with some paintings hung.

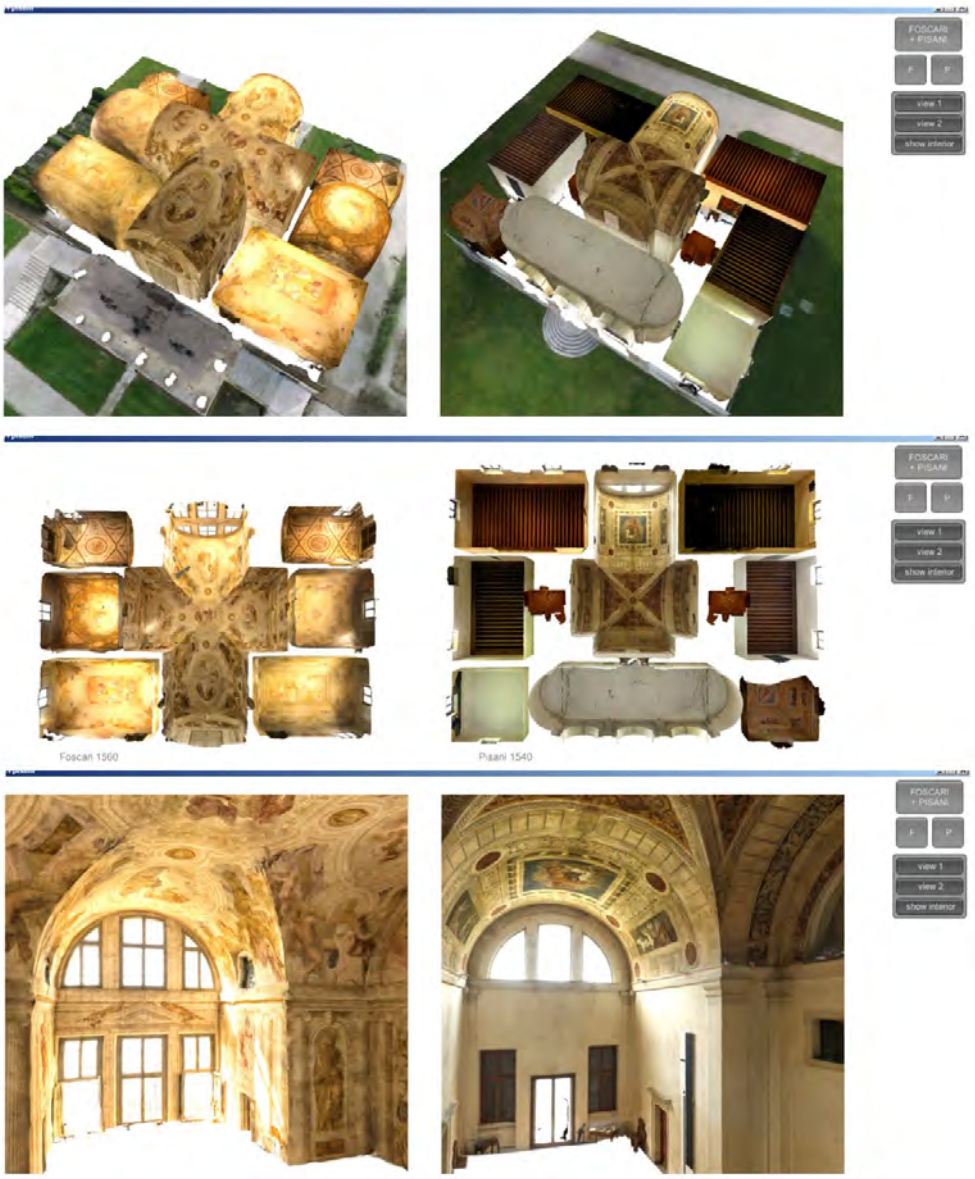

Fig. 12 – Comparison of ceiling structure and texture of the Villa Foscari (left) and Villa Pisani (right). Images on the top show the ceiling textures mapped on the reversed side and seen from above. (Copyright: Nagakura, Tsai and Pinochet)

4. Captures of windows motif variations in Villa Pisani (Fig. 13)

All the main floor windows in the Villa Pisani are designed similarly with built-in seats. However, examining the windows in the captured room models reveals that there are two types of seats: one with a volumetric form (Fig. 13, bottom) and the other with a slab and post (Fig. 13, top). The capture-models also show different present day usage and condition around these window.

Fig. 13 – Villa Pisani window variations (Copyright: Nagakura, Tsai and Pinochet)

5. The Passage of time: The Brion Vega Cemetery steps and the Fraternity Corner Wall

Each photogrammetric capture samples a visual moment of architectural reality. Captures of the same location at different times can inform an historian, designer, preservationist, and facility manager about ephemeral conditions and chronological transitions of a building.

Fig. 14 – Entrance of an MIT fraternity sampled before and after the column restoration (left), and Brion Vega Cemetery exterior captured at two different times in the same day (right). (Copyright: Nagakura and Tsai)

D. Deployment with AR, VR, 3D printing, and Projection Mapping

The captured models can also be applied with other technology platforms to produce different visual experiences. For example, a photogrammetric model showing a part of the building can be used as digital augmentation to a physical model of an adjacent part. A team from the MIT workshops produced an exhibit of the Villa Foscari through this method as shown in figure 15. [Reference here] A VR environment with a head mounted display (HMD) device can take advantage of a photogrammetric capture to make a compelling immersive experience for the audience. A photogrammetric model's surface mesh can also be modified to make a volumetric enclosure by appending some side surfaces, and then be 3D-printed into a physical model. In addition, it can be made into a part of a projection mapping exhibit by projecting the image of the photogrammetric model back on to its surface.

Fig. 15 –Multirama AR, Oculus Rift VR, and Projection Mapping (Copyright: Nagakura, Tsai and Pinochet)

Conclusion

This paper described the photogrammetric sampling of two Renaissance villas, and use of the resulting models in architectural representations. It showed examples of visualizations that allow interactive examinations of architectural components, composite representations of multiple media, and comparative methods of study.

With careful processing and thoughtful designs, these representations made from photogrammetric models allow us to view and to talk about architectural designs in ways previously impossible with conventional representations alone. They allow historians and architects to bring the architectural *specimen* from the site back to the lab for further analysis, and then present and share them in classrooms. By presenting photo-realistically textured, detailed forms and their relationships interactively, analytically and from impossible vantage points, a learning experience delivered becomes different from what an on-site visit and lecture provides, as well as what a class room lecture with textbooks and slides provides. Digital heritage in this use-context acts simultaneously to preserve architectural phenomena and to analyze underlying architectural design.

Photogrammetric models digitally bring miniature reality to the screens of desktop computers and mobile devices. Representations using these new digital means adds significantly to the tradition of architectural studies in the line of what Palladio and Scamozzi were exploring in their respective publications.

Acknowledgements

The case presented in this paper derived from the MIT workshops: Palladio Digitale 2013-2014 and Digital Heritage 2015, as well as a UAV research project in 2014 with funding from Autodesk, Singapore University of Technology and Design, and MIT Department of Architecture, Daniel Tsai, and Evelynn Doone. The workshops were made possible in collaboration with Professor Howard Burns, President of the Scientific Committee of CISA Palladio, whose scholarship the authors owe a great gratitude, admiration, and respect. Special acknowledgment to Professor Antonio Foscari, Director Guido Beltramini of CISA Palladio, Professor Terry Knight, Joanne Tsai, and Manuela Bedeschi, the owner of the Villa Pisani at Bagnolo. Thanks to Joshua Choi for creating Unity visualizations, Victor Leung for assembling and operating drones, and all other students who participated in these workshops with excellence.

References

Ackerman, J. (1966) *Palladio*. New York: Pelican Books.

Agisoft, (n.d.) *PhotoScan*. [online] Available at: <http://www.agisoft.com> [Accessed 7 January 2016].

Aubin, P. (2013) *Renaissance Revit: Creating Classical Architecture with Modern Software*. Charleston: G3B Press.

Autodesk, (n.d.) *Autodesk 123D Catch: Generate 3d model from photos*. [online] Available at: <http://www.123dapp.com/catch> [Accessed 7 January 2016].

Bertotti Scamozzi, O. (1786) *The Buildings and Designs of Andrea Palladio*. Translated by Emiliabianca Pisani., 1786. New York: Princeton Architectural Press.

Changchang Wu, (n.d.) *VisualSFM: A Visual Structure from Motion System*. [online] Available at: <http://ccwu.me/vsfm/> [Accessed 7 January 2016].

CNR research center, (n.d.) *MeshLab* [online] Available at: <http://meshlab.sourceforge.net> [Accessed 7 January 2016].

Burns, H. and Beltramini, G. (2008) *Palladio*, Catalog of the exhibition, Venezia: Marsilio.

d'Espouy, H. (1905) *Greek and Roman Architecture in Classic Drawings*. Translated by Henry Hope Reed., 1999. New York: Dover Publications.

Mr. LongArm, (n.d.) *Mr. LongArm Utility Handle* [online] Available at: <http://www.mrlongarm.com> [Accessed 7 January 2016].

Nagakura, T., (2013) *i_palladio*. [online] Available at: <http://cat2.mit.edu/palladio/i_palladio_at_mit> [Accessed 7 January 2016].

Nagakura, T., Tsai, D, and Choi, J. (2015) *Capturing History Bit by Bit: Architectural Database of Photogrammetric Model and Panoramic Video.* eCAADe 2015.

Nagakura, T. and Sung, W. (2013) *Augmenting Architecture through Ramalytique:A Tablet to See the Lost in Translation*. Video clip presentation. [online] Available at: <http://cat2.mit.edu/ramalytique> [Accessed 10 January 2015].

Palladio, A. (1570) *The Four Books on Architecture*. Translated by Robert Tavernor and Richard Schofield., 1997. Cambridge, Massachusetts: MIT Press

Palladio Museum, (n.d.) *Media Library*. [online] Available at: <http://www.palladiomuseum.org/mediateca> [Accessed 7 January 2015].

List of Figures and Captions

Fig. 1 – Photogrammetric model of Villa Foscari's fresco vaults viewed from below and in section. (Copyright: Nagakura, Tsai and Pinochet)
Fig. 2 – Villa Foscari and Villa Pisani in photographs and as depicted by Palladio (top) and Scamozzi (bottom). The plans shown in the same scale illustrate Villa Foscari has a smaller footprint than Villa Pisani but is taller. Palladio's version as presented in his Four Books of Architecture shows his ideal and is different from the measured condition described in Scamozzi's drawing, which is also different from the present day recording.
Fig. 3 – Illustrations from *The Buildings and Designs of Andrea Palladio.* Bertotti Scamozzi drew variations of column orders he measured in Teatro Olimpico (left), and composed line drawings and a shaded one for Loggia Valmarana (middle). Image on the right is a drawing of a Corinthian capital from the Temple of Minerva composed with ink wash and lines in d'Espouy's compilation.
Fig. 4 – MIT i_palladio website at http://cat2.mit.edu/Palladio including photogrammetric models and panoramic videos collected on the sites of Palladio's buildings. The Corinthian capital is a capture of a floor exhibit at the Palazzo Barbaran Da Porto, which houses CISA Palladio. (Copyright: Nagakura and Tsai)
Fig. 5 – MIT Workshop on the sites of Palladio's villas with drones, poles, and panoramic video device. (Copyright: Nagakura and Tsai)
Fig. 6 – From d:Espouy's compilation, Ionic column with surrounding details of Propylea (left) and Parthenon (right) at Acropolis.
Fig. 7 – Captured models of a door handle of Villa Pisani and a column base of Villa Fosacri's loggia (Copyright: Nagakura, Tsai and Pinochet)
Fig. 8 – Vaulted ceilings covered with fresco in Villa Foscari. (Copyright: Nagakura, Tsai and Pinochet)
Fig. 9 – A door model in Villa Pisani interactively viewed from two sides (Copyright: Nagakura, Tsai and Pinochet)
Fig. 10 – The Cross Vault and a Sink at Villa Pisani (Copyright: Nagakura, Tsai and Pinochet)
Fig. 11 – Comparison of site and room layout of Villa Foscari (left) and Villa Pisani (right) (Copyright: Nagakura, Tsai and Pinocet)
Fig. 12 – Comparison of ceiling structure and texture of the Villa Foscari (left) and Villa Pisani (right). Images on the top show the ceiling textures mapped on the reversed side and seen from above. (Copyright: Nagakura, Tsai and Pinochet)
Fig. 13 – Villa Pisani window variations (Copyright: Nagakura, Tsai and Pinochet)
Fig. 14 – Entrance of an MIT fraternity sampled before and after the column restoration (left), and Brion Vega Cemetery exterior captured at two different times in the same day (right). (Copyright: Nagakura and Tsai)
Fig. 15 –Multirama AR, Oculus Rift VR, and Projection Mapping (Copyright: Nagakura, Tsai and Pinochet)