Precision Recording of Pompeian Standing Remains via Stitched Rectified Photography

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Abstract

Accurate recording of standing archaeological remains such as the walls of ancient Pompeii can be an extraordinarily time consuming process, especially when implementing traditional, hand-measured techniques. Such methods also suffer from considerable inaccuracy when dealing with walls or features greater than one or two meters in height. At the other end of the spectrum of possible methods, the use of 3D scanners for the recording of archaeological remains poses a different set of difficulties, including high costs and specific necessary expertise. Furthermore, the sheer volume of data produced by these methods can be so dense that preparation for basic analysis or publication can require considerable amounts of post-processing. However, the right tool for the job need not always be the most cutting-edge or expensive. This paper presents the results of research directed towards providing a simple and practical method for field recording and publishing standing archaeological remains that sits in between these two poles. The solution makes use of freeware Panorama Tools and Hugin, both originally designed for producing stitched panoramic images, in order to produce scaled, rectified records of architectural surfaces from multiple input photographs. The methodology presented in this paper has been tested in the working environment as a component of recent archaeological research conducted by the Via Consolare Project in the ancient city of Pompeii. It has been found that with appropriate controls and methodology, outputs can be significantly more accurate (+/- 3cm) than more traditional methods and may be produced in a fraction of the time spent in the field. It is hoped that these tools and methodology may be of use to other projects of archaeological research that face similar challenges and wish to explore low-end technologies as a potential solution.

Keywords: *photo rectification, Hugin, panorama tools, Pompeii, publication*

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1 PRACTICAL RECORDING IN POMPEII

The practice of field archaeology is at all times a compromise between two often competing goals: the accurate and comprehensive recording of archaeological remains and the practical production of meaningful results or interpretations. While digital technologies now offer the promise of ever-increasing accuracy and ever-growing volumes of data, it is not always necessary to use the latest or most powerful technology in order to achieve the often relatively simple goals of primary archaeological research. In the recent work of the Via Consolare Project, low-end, freeware-based solutions have been found to produce acceptable results both more cheaply and more quickly than traditional methods, facilitating the process of archaeological research and easing the movement towards publication of results in an appreciable and valuable way. Since 2005, the Via Consolare Project has undertaken a coordinated campaign of field research that aims to examine, document, and explain the process of urban and suburban development inside and outside ancient Pompeii through intensive study of two different areas of the city: the area outside the city gate known as the *Porta di Ercolano* and *Insula VII 6*, a city block close to the forum and the heart of the town. Taken together, these geographically distinct areas contain a wealth of information on the history of urbanization of Pompeii from its archaic beginnings in the plausible urban core generally referred to as the A*ltstadt*[1] until the moment of the eruption of Vesuvius in AD 79, including the 'suburban' areas[2] outside of the circuit walls. In order to uncover and record this information and to incorporate this data with previous research[3] into the early history of the site, the Via

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[1] Francis Haverfield, "Town Planning in the Roman World," paper presented at Town Planning Conference, London, England, October 10–15, 1910; Francis Haverfield, *Ancient Town Planning* (Oxford: Oxford University Press, 1913); Armin von Gerkan, *Der Stadtplan von Pompeji.* (Berlin, 1940).

[2] Tadashi Asaka, "Note on the Plan of the Villae Rusticae in the Vicinity of Pompeii," *Opuscula Pompeiana* 2 (1992): 25–53; Valentin Kockel and Bertold Weber, "Die Villa delle Colonne a mosaico in Pompeji," *Mitteilungen des Deutschen archaeo-logischen Instituts. Roemische Abteilung* (1983): 60–61.

[3] E.g. Maria Bonghi Jovino, ed., *Ricerche a Pompei: l'insula 5 della Regio VI dalle origini al 79 d.C.* (Roma: L'Erma di Bretschneider, 1988); Antonio D'Ambrosio and Stefano De Caro, "Un contributo all'architettura e all'urbanistica di Pompei in età ellenistica. I saggi nella casa VII 4, 62," *Annali dell'Instituto Universitario Orientale [Napoli]. Sezione di Archeologia e Storia Antica* 11 (1989): 173–215; Francesco Carocci et al., *Le Insulae 3 e 4 della Regio VI di Pompei: Un'analisi storico-urbanistica* (Roma: G. Bretschneider, 1990); Paolo Carafa and Maria Teresa D'Alessio, "Lo scavo nella Casa di Giuseppe II (VIII, 2, 38-39) e nel portico occidentale del Foro Triangulare a Pompei. Rapporto preliminare," *Rivista di Studi Pompeiani* 7 (1996): 137–152;

Consolare Project has carried out a diverse range of archaeological techniques, including geophysical exploration, primary excavation, 3D topographic survey, and extensive analysis accompanied by comprehensive documentation of surviving architectural remains and the developmental sequence that they reveal.[1] Of all of these techniques, the process of wall analysis and documentation often proves to be the most time consuming. Preserved remains are examined closely from all sides and the sequence of past events is reconstructed from the traces of construction events that each wall documents. A necessary step in the procedure is then to record the visible evidence from each and every wall surface, both in the form of detailed notes with an accompanying sketch and a detailed and accurate scaled drawing of each surface and the stratigraphic relationships that can be seen within it. These elements are an important form of the primary data collected in the field and facilitate not only the development of theories of construction sequence, localized phasing, and the general processes of urbanization, but subsequently play a central role in publication, since they may be arranged into architectural sections or integrated with surveyed architectural data.

On archaeological projects elsewhere in the city, the process of documenting ancient architecture has tended to evolve directly from standard excavation practice and thus is often accomplished by hand in precisely the same way that archaeological sections/profiles might be recorded. The method generally implemented involves plotting measurements by hand to points at right angles with a plumb bob from a horizontal line with a suspended measuring tape in order to trace the outline of the wall surface, key features, and details (see fig. 1).

While this system is certainly serviceable, it is not without problems. First, the considerable height of preservation of the walls at Pompeii can introduce significant inaccuracy in the final drawing, as only a small deviation from a perfect right angle creates an ever-increasing error the further the tape measure is extended from the base line. Second, these methods are costly in both time and resources. In order to ensure archival-quality results, the drawings must be plotted on permatrace or drafting film, and even a team of several experienced archaeologists working at an individual wall face can take many days to produce a final drawing of the surface.

Figure 1. *Students drawing a wall surface via the traditional method (Photo courtesy of the AAPP).*

When these factors are multiplied by the vast number of wall faces to be recorded in any group of Pompeian walls—the research areas covered by the Via Consolare Project include over 1700 wall surfaces—the costs in materials and time for such a method can easily become prohibitive. Furthermore, this type of drawing generally succeeds in recording only the most rudimentary information such as the primary phases as identified in the field, together with a few details. Other important elements, such as coloration, stone type, and even the alignments of individual building components can easily go unrecorded.

2 A DIGITAL METHOD

As the research of the Via Consolare Project began, it was clear that a new way of recording wall surfaces was necessary. At first, high-end solutions such as 3D scanning or photogrammetry were considered. Like most small archaeological undertakings however, the funds available in support of the Project's research are extremely limited. Work was therefore directed toward uncovering a low-cost and robust digital method to record the wall surfaces correctly, easily, and quickly, involving the use of freely available software that could be run on older laptops of the type most commonly available in fieldwork operations. After more than two years of evaluation and refinement, the Via Consolare Project now has a methodology that satisfies all of these requirements. The techniques and methodology that have been designed specifically for work in Pompeii are detailed below as a case study. It should be emphasized that in no way do the techniques presented below represent an advance in technology or the theory of photo-recording and should not be understood as such. Rather, they demonstrate that the impact of simple technologies and inexpensive solutions can often be as significant as cutting-edge developments on field archaeological operations.

Michael Fulford and Andrew Wallace-Hadrill, "The House of *Amaratus* at Pompeii (I, 9, 11-12)," *Rivista di Studi Pompeiani* 7 (1996): 77–113; Rick Jones and Damian Robinson, "Water, Wealth and Social Status at Pompeii: The House of the Vestals in the First Century AD," *American Journal of Archaeology* 109 (2005): 685–710; Filippo Coarelli and Fabrizio Pesando, *L'insula 10 della Regio VI* (Roma: L'Erma di Bretscheinder, 2006).

[1] Via Consolare Project Directors, "The Via Consolare Project Website," San Francisco State University, www.viaconsolareproject.org.

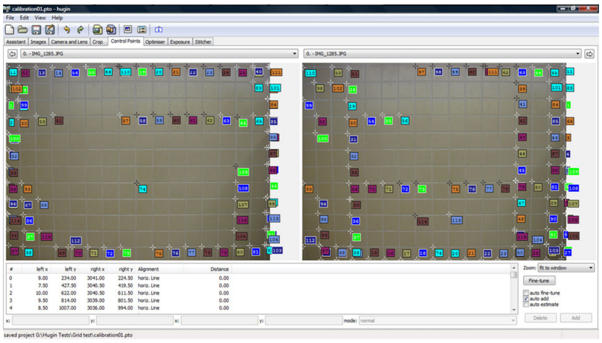
Panorama Tools is a suite of programs designed and made available by Professor Helmut Dersch of the Furtwangen University of Applied Sciences. Their primary purpose was to correct multiple types of lens distortion and, among other things, to provide a means for stitching these images into panoramic photographs.[1] A front-end for these tools known as Hugin[2] makes them much easier to use and also integrates them with a number of other helper packages. These include those designed to find matching points between images such as AutoPanoSift,[3] AutoPanoSift-C, and their relatives, which facilitate the process of aligning multiple photographs. In addition, Hugin now integrates Enblend, a plug-in that blends the results together without producing seams or artifacts between the images, and Enfuse, which allows photographs taken at multiple exposures to be combined into a single image that makes use of only the best exposed parts of each original.[4] Many of these programs are free for non-commercial use, and may be integrated immediately into a research project. It should be stressed, however, that the recording of archaeological surfaces was not the original or intended function of any of this software. Using guides and tutorials that were already available online, such as Bruno Postle's explanation of using Hugin in order to remove perspective distortion[5] and Joachim Fenkes' description of stitching long, flat rows of images,[6] it was possible to develop methods that permitted the correction of perspective or photo-rectification of planar-to-largely-planar architectural surfaces in a variety of archaeological situations. These implemented a variety of techniques ranging from single photographs to multiple rows of numerous stitched images.

3 TESTING PANORAMA TOOLS AND HUGIN—SOURCES OF ERROR

Since Panorama Tools and Hugin were designed for panoramic photographic purposes and not specifically as rectification tools, at the outset it was uncertain whether the corrected images that they produced would be accurate enough to be useful for archaeological recording. Before they could be integrated into a long-term program of research, particularly as a replacement for a pre-existing technique, a period of testing and experimentation was undertaken, both at San Francisco State University and during the initial seasons of fieldwork in Pompeii. Results were monitored closely in order to identify any sources of error and to develop methods for overcoming these inaccuracies in field conditions. As a result, a formal methodology has been developed that can ensure consistent standards of accuracy in the output images produced by Panorama Tools and Hugin in a variety of field conditions, including the often difficult circumstances of working within Pompeian remains.

Sources of Error

One major step in this process was the identification of those factors that are the most important in reducing error and producing consistent results. The sources of error in Panorama Tools and Hugin are held in common with most photographic and photogrammetric techniques and include lens distortion, parallax, and non-planar qualities of the subject.



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2	10.00	622.00	3040.50	611.50	horiz. Line	0.00
3	9.50	814.00	3039.00	801.50	horiz. Line	0.00
4	8.50	1007.00	3036.00	994.00	horiz. Line	0.00

Zoom: fit to window

☐ auto fine-tune
☑ auto add
☐ auto estimate

mode: normal

saved project G:\Hugin Tests\Grid test\calibration01.pto

Figure 2. *Lens calibration calculation within Hugin using a tiled wall surface as the target.*

The distortions introduced through imperfections in lenses, specifically the complicated systems of optics involved in modern cameras, are numerous and well documented,[7] and need not be discussed here. Fortunately, many of them can be compensated for easily using Panorama Tools and Hugin.[8] The process of calculating the necessary correction values involves taking an image of a surface with many crossing parallel lines at right angles—such as a tiled wall—at roughly the same distance that the camera will be used to acquire images in the field. Guides are then added in the software along each of these straight lines and the whole is solved for Hugin's correction coefficients (see fig. 2). Once obtained for a particular lens, camera, and

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[1] Helmut Dersch, "Homepage of H. Dersch," HFU Furtwangen, http://webuser.hs-furtwangen.de/~dersch/.

[2] Pablo d'Angelo et al., "Hugin–Panorama Photo Stitcher," Sourceforge.net, http://hugin.sourceforge.net/.

[3] Sebastian Nowozin, "Autopano-sift: Making Panoramas Fun," Technische Universität Berlin, http://user.cs.tu-berlin.de/~nowozin/autopano-sift/.

[4] Andrew Mihal et al., "Enblend/Enfuse," Source forge.net, http://enblend.sourceforge.net/.

[5] Bruno Postle, "Hugin Tutorial—Perspective Correction," Sourceforge.net, http://hugin.sourceforge. net/tutorials/ perspective/en.shtml.

[6] Joachim Fenkes, "Creating Linear Panoramas with Hugin," Dojoe.net, http://www.dojoe.net/tutorials/linear -pano/.

[7] Sidney Ray, *Applied Photographic Optics : Imaging Systems for Photography, Film, and Video* (Boston: Focal Press, 1988), 93–97; Thomas Luhmann et al., *Close Range Photogrammetry: Principles, Techniques and Applications* (Hoboken: Wiley & Sons, Inc., 2006).

[8] Other methods include plug-ins for Photoshop, the Gimp, and MatLab.

focal length, the coefficients may be used to correct any image taken with the same lens at the same level of zoom.

Another important source of error in stitched rectified photography is caused by parallax, a phenomenon that occurs if a series of photographs is taken from horizontally or vertically shifted positions. As the optical center of the lens translates, its geometric relationship with each plane in the recorded scene also changes. This effect is most problematic in those areas where the surface to be recorded does not constitute a single plane that is exactly parallel with the movement of the camera.

By far the most important source of error, however, is non-planar features of the walls themselves. Hugin and Panorama Tools are capable of removing perspective distortion along a single, well-defined plane. However, most archaeological surfaces are not perfectly flat, but instead tend to lean outward or inward or have protrusions and indentations that deviate from the overall plane of the primary surface. Particularly pronounced cases of this situation are features protruding from a Pompeian wall surface such as wall scars or the remains of abutting walls. Such non-planar components will not only rectify incorrectly, but will also produce a "visual shadow" or gap in the data in areas that the camera cannot see (fig. 3). In extreme cases, the only way to overcome this phenomenon is to work around larger obstacles, dividing an extended surface into the largest visible zones and then stitching them together afterwards.

Even the less obvious errors caused by simple irregularities in the wall surface are best characterized as "visual shadow," since in both cases, the end result is a shift between the correct rectified location of a feature and the actual location where it appears on the final output image.

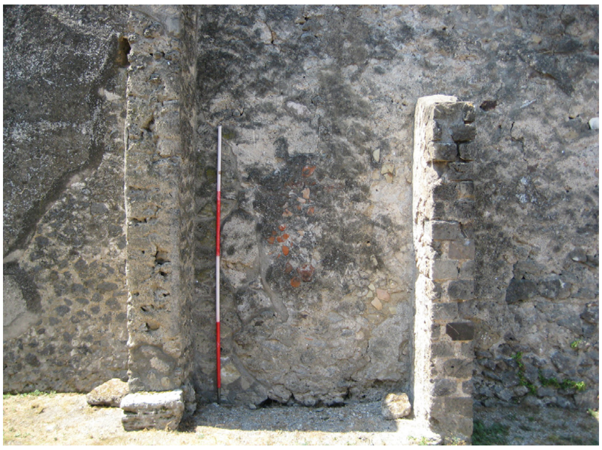

Figure 3. *A wall with protruding walls that will cause problems for rectification due to visual shadow errors.*

Methods of Minimizing Error

The errors caused by parallax or non-planar features of the wall surface may be kept to within predefined levels of tolerance by controlling carefully the angle at which the photographs are acquired, the degree of overlap between images that are to be stitched together, and the distance from which the subject is photographed. Since in sites with a large amount of preserved architecture it is not always possible to acquire photographs in optimal circumstances, in practice it is often necessary to find a compromise between several methods. While the challenges posed by these errors will be well-known to a technical audience familiar with photogrammetric methods, the generalized principles of error reduction that the Project has found empirically to be useful are described briefly below. These govern the choice of which of the three distinct methods of photo acquisition of the Project's field methodology to use in a particular field situation.

As long as the surface to be recorded is relatively flat overall, error in the end product can be kept to a desired minimum by controlling the angle at which it is photographed. By limiting the angle between the principal ray of the camera, the primary normal (the primary perpendicular ray) of the photographed surface, and the angle at which the surface is photographed (see fig. 4) to less than 30 degrees, the error for a surface with 5cm of planar variation is less than 2.89cm—certainly an acceptable margin for most archaeological applications in comparison to hand-drawn techniques.[1]

A second way of controlling error is to photograph a surface from a greater distance, either utilizing only a small fraction of the camera's field of view, or using a lens with a large focal length. It is important, however, to maintain appropriate image resolution for the needs of the end result. Furthermore, when taking a photograph at an oblique angle to the wall surface, it must be ensured that the furthest relevant detail in the photograph does not exceed this calculated distance, in order to ensure the minimum required level of accuracy. In the work of the Via Consolare Project, a standard of no less then 10 pixels-per-cm has worked well in ensuring that the resulting image does not lack significant detail for our purposes, but this standard will vary from project to project.

Finally, images may be taken at right angles to the wall surface and stitched into a photo-mosaic. This is especially useful if it is not possible to photograph the wall surface from an acceptable angle or from a distance that would overcome visual shadows. Parallax introduced by this method may be controlled by

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[1] The visual shadow size for a given wall may be calculated by the simple formula $\mathrm{TAN}(\mathrm{FOV}/2 + \varphi) * X$, Where: FOV = the camera's field of view, φ = the angle between the camera's principal ray and the surface normal and X = Maximum depth of non-planar objects on the photographed surface. Note that the units involved in this calculation are dependent entirely upon those used in the system and hence do not appear in the equation itself.

increasing the amount by which each photograph overlaps to such an extent that only a small fraction of each is used in the final stitched product. The primary instance of this approach in archaeological applications is when a surface must be recorded by a series of photographs taken along a line parallel to that surface, such a long, thin corridor (see Type Three Rectification below).

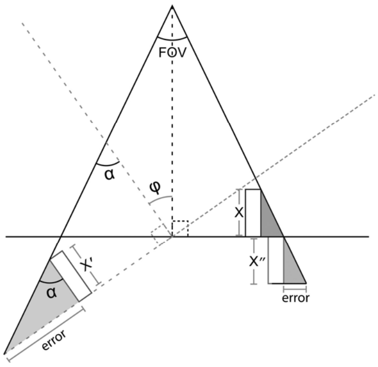


Figure 4. *Diagram of angles involved in photographic rectification and their effects on non-planar aspects of the subject surface. Error is marked in grey.*

4 METHODS

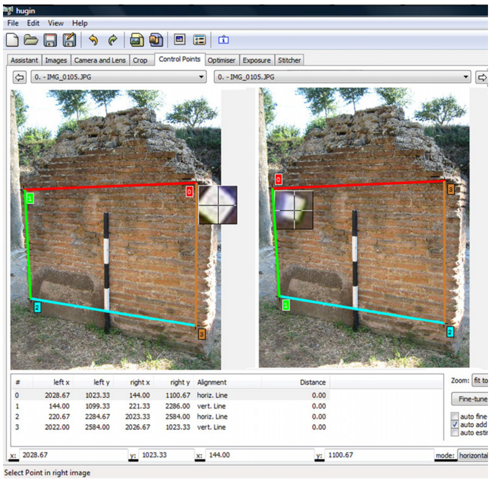
Since the arrangement of preserved standing walls at Pompeii rarely provides optimum conditions for taking photographs of wall surfaces, it has been necessary to develop three related but independent techniques in order to work around particular environmental challenges posed by the architecture of Pompeii itself, while applying controls designed to produce results of a standardized quality and to minimize the sources of error discussed above. This means that even in situations where the camera cannot be positioned at a sufficient distance from the surface to be photographed, such as when access is blocked by other architectural features, or in cases where the surface is larger than will fit comfortably within a single photograph, as in most walls in Pompeii, it is nevertheless possible to produce accurate, rectified photographs of their surfaces. For convenience of reference, the various methods have been termed Type One, Two and Three.

Preparing the Surface for Photography

Prior to the acquisition of photographs, the wall or surface to be rectified was in all cases provided with a grid of control points at strict right angles and parallel lines. While the surface itself need not be aligned with the horizontal or vertical planes of the camera's viewpoint, it is essential that a minimum of two sets of parallel lines meeting at right angles be present on the surface to be rectified. For floors or other surfaces, the same might be achieved by two sets of lines simply arranged at right angles to each other. The Project followed a consistent system of marking one or more "squares" of points affixed to the wall faces such that parallel lines might be traced between them on the photographs taken of their surfaces (see fig. 5). It was found to be particularly important that these points be arranged in conjunction with the planning of photography, so that the spacing ensures that the central or base photograph of each sequence will have at least two sets of parallel lines visible within it. The precise spacing required is a function of the particular method type implemented and varies most greatly with the distance from which the walls are to be photographed.

Type One Rectification: Single Photograph

The simplest and most straightforward method of Panorama Tools and Hugin photo rectification involved only a single photograph of the wall surface. This method was employed when a wall surface was sufficiently small or the environment surrounding it was free of visual obstacles so that it could be photographed with a single shot according to two requirements. First, the photograph had to contain two visible sets of parallel lines marked with points representing the plane of the surface to be rectified. Second, as discussed above, it was necessary that the angle between the normal of the surface and the principal ray of the lens not be overly oblique. In the case where this was not possible, the "Type Two" method was implemented as described below. After photography, the image was opened in Hugin. Lens correction values were applied to the image and then the horizontal and vertical lines marked on the walls were marked in the image as "vertical and horizontal control points" (see fig. 5). The image was processed[1] and saved as final output (see fig. 6).



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2	220.67	2284.67	2023.33	2584.00	horiz. Line	0.00
3	2022.00	2584.00	2026.67	1023.33	vert. Line	0.00

x: 2028.67 y: 1023.33 x: 144.00 y: 1100.67 mode: horizontal

Select Point in right image

Figure 5. *Control points connected with horizontal and vertical lines in Hugin. (The lines have been added for illustration).*

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[1] Guides to the process are published online at: www.viaconsolareproject.org.

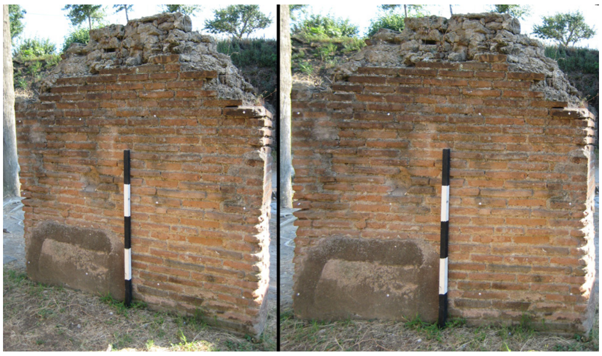

Figure 6. *Original image and rectified result of a wall surface using Type One method.*

Type Two Rectification: Tripod-Mounted Rotation with Multiple Photographs

Type Two rectification involved taking a number of photographs from a single fixed point, stitching them together, and then rectifying the combined result. It was employed when a wall surface was too large to fit within a single shot at the desired distance, or if it was not possible to move to a sufficient distance from the wall surface to be able to compose a photograph that included the entire wall surface. This may be because there was not enough physical space for the camera and photographer, because the view was blocked by other walls or vegetation, or simply because moving the camera further away would have produced an image of insufficient resolution. Photographs were taken from a camera mounted on a tripod and fitted with a leveling device such as a dumpy level tribrach so that it would rotate in a perfectly level plane. A special camera mount designed for taking panoramic images was fitted onto the tribrach, allowing the camera to be set up such that the focal point of the lens was situated precisely over the center of rotation to minimize parallax error. This method is the same as that used for producing panoramas and QTVR panoramic images.[1] The mounting for the camera also permitted the camera to rotate up and down around the center of the lens, so that areas of interest above and below the rotation level could also be acquired. It was found that image overlap of at least a third was sufficient to permit accurate stitching, and that it was necessary to rotate the camera through less than 30 degrees in any one direction to keep "visual shadows" to an acceptable minimum (see fig. 6).

The first image in each sequence was taken with the camera at precisely 90 degrees to the wall surface and with the camera in the level position containing at least one complete "box" of control points. This acted as a control image and formed the anchor around which all other images could subsequently be re-projected. The Project found that other images, especially those at some height, did not necessarily need to contain control points, but that additional sets of parallel lines of points allowed the rectified end result to be checked internally for accuracy.

Figure 7. *Original images and stitched rectified result of a wall surface using Type Two method.*

The images were initially processed in Hugin largely as for Type One. Matches between the images were then located by means of a key-point automatic matching helper program, such as AutoPano-Sift or AutoPano-Sift-C. The final output was produced through rectifying and stitching the image into a single corrected result (see fig. 7).

Type Three Rectification: Multi-Stage Processing with Multiple Photographs

Type Three rectification involved the combination of the previous methods into an approach suitable for capturing the surface of a long vertical surface that could not be photographed within accuracy tolerances using either of the previous two methods. Narrow corridors were the primary example of this type. The method is a variant on Type Two that results in a number of overlapping flat surfaces. When combined, these images document the wall surface in great detail. Due to the specialized nature of the Type Three method and because it was found to produce a rather large number of photographs, both set-up for photography and final processing was significantly more time consuming than for the first two methods. It was therefore only undertaken where other techniques were not practical. Furthermore, this method was not found to be suitable for walls or surfaces with pronounced deviations from the rectified plane, such as abutting wall remnants. In such circumstances, the individual parts of the surface on either side of each obstruction were rectified separately using either via Type One or Type Two and then joined by hand in image processing software.

An important requirement of this method was that a large number of overlapping images had to be taken from points at precisely 90 degrees to the wall surface. These images needed to overlap each other to such a degree that only the central part of each image was

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[1] Michael, Anderson, "QTVR and the Preservation of Pompeii Regio VI," in *Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 30th Conference*. (Heraklion: Hellenic Ministry of Culture, 2003): 21–27.

utilized, minimizing error from planar deviation and parallax. The exact amount of overlap depended upon the degree to which out-of-plane objects produced parallax error in a given surface. The Project found that a minimum overlap of three-quarters of the imaged area for Type Three rectification was generally appropriate. In preparation for photography, a measuring tape was arranged parallel with the wall surface, running along the ground at either a set distance from the wall or at the maximum workable distance in close quarters. At regular, measured distances along the tape, a tripod with camera mountings as described in Type Two rectification above was erected and leveled. The initial photograph of each set-up was akin to the anchor image in Type Two rectification and similarly needed to be taken at 90 degrees to the wall surface from a perfectly level tripod and to contain at least two sets of parallel and perpendicular control points. For this reason the positioning of these points on the wall required some advance planning. Further images were then acquired by rotating the camera up and down in order to photograph the entire height of the wall at that location. Unlike Type Two, in this method it was not necessary to rotate the camera horizontally, since the lateral extent of the surface was recorded through the process of moving the tripod and camera parallel to the wall surface. After the wall had been photographed at one location, the process was repeated, shifting the tripod setup one step down the tape.

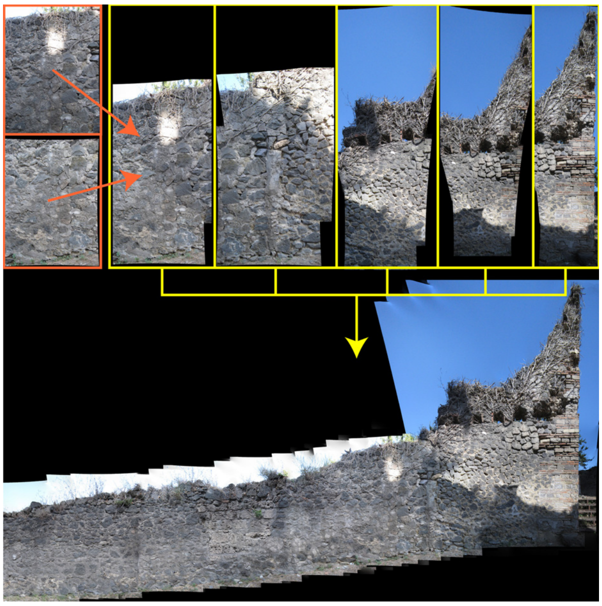

Figure 8. *Original images, first stage processed images, and final stitched rectified result of a wall surface using Type Three method.*

Photographs were then combined and processed in the way that a series of photos might be spread out upon a table surface, with areas overlapping each other. This was accomplished by means of "tricking" Hugin and Panorama Tools' processes into treating the images as though they were acquired with a number of different lenses, the principal centers of which differed widely in lateral and vertical translation, as described by Joachim Fenkes.[1] Processing therefore proceeded in two phases. First, the images from each individual tripod set-up were processed independently according to the Type Two method. The resulting output images from each set-up were then put through a final stitch so that they were aligned into a long flat surface rather than a projection (see fig. 8).

Enblend and Enfuse

Type Two and Type Three rectification methods also introduced the use of an additional helper program that is designed to produce seamlessly stitched input images. While Panorama Tools and Hugin do what they can to correct for errors in the input images, nevertheless some small degree of difference remains prior to final stitching. Normally the most noticeable difference is in exposure levels, but the Project has found that even the most carefully collected set of images will also have small errors of orientation and alignment. Enblend uses a context-specific method of blending in order to produce a seemingly perfect result with only occasional blurring, noticeable discrepancies of exposure, or object misalignments. At the same time, Enfuse can resolve multiple, overlapping images of differing light exposures in order to produce a composite image that includes only the best exposed areas. The internal workings of Enblend and Enfuse are both described in detail by their authors in their respective websites.[2] Since the emphasis of the present research was upon the accuracy of the resulting images, however, it is important to note that both processes involve some degree of shift or alteration to the input images geometries and therefore introduce their own errors. Empirically, the research of the Via Consolare Project has yet to experience any worrying errors introduced through the use of these programs, and the resulting smoothly-stitched images, when examined, have remained accurate in terms of shape and location to the tolerances described above. Nevertheless, Enblend and Enfuse can occasionally produce unexpected results, especially with particularly poorly acquired image sets.

5 RESULTS

In order to examine the quality of the results produced by these methods, the three output rectified images have been combined with outlines of the wall surfaces and details acquired using a Leica TPS 805Power Total Station (see figs. 9, 10 and 11). Visual comparison suggests that the results are quite similar, and in no case deviating beyond what might be expected from traditional hand-drawn and hand-measured methods.

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[1] Joachim Fenkes, "Creating linear panoramas with Hugin," Dojoe.net, www.dojoe.net/tutorials/linear -pano/.

[2] Andrew Mihal, et al., "Enblend/Enfuse," Sourceforge. net, http://enblend.sourceforge.net/.

At first glance the Type Three rectification comparison presented in figure 11 appears to deviate significantly along the top surface. This is because the surveyed outline traces the northern face of the wall while the photograph presents the southern face and therefore some deviation should be expected between these faces. Upon closer examination, it may be observed that features such as abutting walls present on the opposite side are reflected clearly on the photographed surface, in the correct position and at the correct scale.

Figure 9. *Comparison of Type One result with surveyed surface outline.*

Figure 10. *Comparison of Type Two result with surveyed surface outline.*

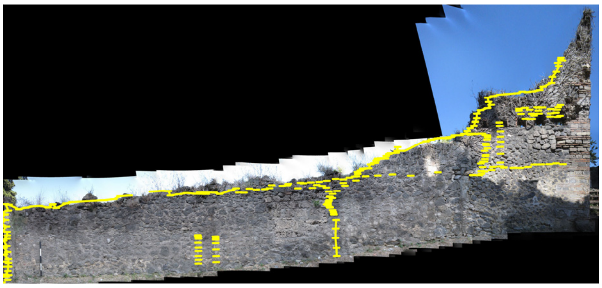

Figure 11. *Comparison of Type Three result with surveyed surface outline.*

In the Type Two rectification comparison shown in figure 10, it may also be noted that the barrel vaults, which project toward the camera and hence do not constitute a part of the rectified plane, nevertheless do align very well with the surveyed outline at the point where they meet the wall surface.

Comparison with Other Potential Methods

Perspective correction or photo rectification with Hugin and Panorama Tools has a number of distinct advantages over other potential methods. Compared to the traditional hand-measured approach, it is both considerably faster and more accurate, producing an end result that not only records each surface in much greater detail, including the particular coloration, position, and even texture of each stone, but also achieves this in a fraction of the time in the field. Conservative estimates have suggested that this method is roughly twenty times faster than traditional methods including the post-processing of images. If post-processing is performed during the off-season, then this method saves even more time in the field. Following the guidelines as suggested above, it is possible to minimize error in stitching and rectification in order to produce flattened wall surface images that are accurate to ±3–4 cm even for relatively uneven surfaces. Using traditional hand-drawn methods, these same surfaces have experienced much greater degrees of recording error, sometimes in excess of ±10cm.

This method also has a number of distinct advantages in comparison to top-end techniques such as 3D scanning or close-range photogrammetry. It is more cost-effective than either, requiring only a simple digital camera, basic tools for temporarily marking the wall surfaces, and free software. The camera employed by the research of the Via Consolare Project was a humble Canon SD1000, and given appropriate calibration, most current cameras should produce similar or better results. The Panorama Tools and Hugin rectification methods also require little equipment to transport and maintaining the necessary devices in field conditions is not taxing. While it could be argued that this particular advantage is also shared by close-range photogrammetry, freely available systems for performing the necessary calculations on unordered sets of uncalibrated images are not yet widely available or reliable enough for field implementation—though it is to be hoped that this may change in the near future. While some of the inaccuracies and challenges of the stitched rectified photographic methods presented above are not faced by comprehensive 3D scanning, nevertheless visual shadows are just as problematic to 3D scanners and photogrammetry of all types and can only be solved through multiple, often time-consuming, set-ups. Of course, these stitched rectified photographic methods can in no way compete with scanning and true photogrammetry in terms of high-definition 3D information such as dense point clouds representing the surface geometry, but ultimately this is a question of using the right tool for the right job. The low cost, ease, and simplicity of Hugin and Panorama Tools mean that it has been possible to record almost all of the walls in the Via Consolare Project's study areas during the past two years, which would likely not have been possible using either laser scanning or photogrammetry, even if the Project could have afforded them. Furthermore, high-definition point clouds must be processed by large, powerful computers and require additional work for conversion into tools that are easily published, archived, or presented in a traditional manner. The methods described above were accomplished on low-end laptops in the field and produced results that can be used immediately for both traditional analysis techniques and for publication.

Uses, Conclusions, and Future Directions

After completion of any of the above methods of stitched rectified photographic recording, the resulting image file may be processed further in order to produce a scaled vector image of the wall surface (see fig. 12). Such a tracing may include important details of materials or, in the case of the research of the Via Consolare Project, the major phases of the wall as identified in comparison to the sketches made during field study. This scalable vector image subsequently may be integrated with surveyed data or may be used for primary measurement and finding the precise location of features of interest, assisting greatly in the process of analysis and sequencing when away from the field. Vectors and rectified image files may also be combined in 3D restorations, GIS analysis, AutoCAD plans, or architectural sections for the purposes of publication, archiving, and continued research.

The methodology that has been presented here is neither a technological innovation nor the panacea for archaeological recording problems, but nevertheless provides an example of a low-end solution to real-world archaeological challenges that is both simple and easy to learn (see fig. 13). It is hoped that it will be of use to other projects facing the challenge of recording standing architecture and might also be used to record mosaic or *opus sectile* floors or similar flat surfaces such as ceilings. Indeed, the methods presented above will see further refinement and adaptation in the summer of 2009 with the Oplontis Project (http://oplontis.cch.kcl.ac.uk: 51525/) for recording finely decorated plaster surfaces. The Via Consolare Project is currently investigating further ways in which these methods may be applied to the recording of excavated deposits. While such surfaces tend to be more pronounced in their three-dimensionality and therefore present a host of new challenges, including extreme parallax errors, perhaps it will soon be possible to suggest a Fourth Type of stitched rectified photographic recording to augment previous work on this topic.[1] The freeware Hugin and Panorama Tools, in combination with low-end hardware and the methodology presented in this paper, present a robust and powerful technique facilitating and improving the process of traditional archaeological documentation and analysis of standing architecture and preserved structural remains.

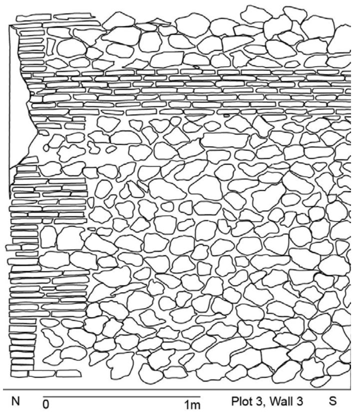

Figure 12. *Scaled, vectorized, rectified wall image with stones, phases and details traced.*

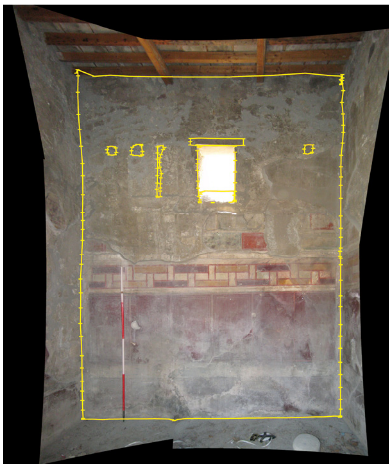

Figure 13. *Comparison of rectified wall surface with surveyed wall outline demonstrating use for stitching well-preserved wall painting.*

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[1] Geoff, Avern, "The Orthographic Approximation–A Simple Geometrical Model for Avoiding Perspective Error in Constructing Photomosaics," in *Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 31st Conference*, BAR International Series 1227 (2004): 405–408.

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