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Digital reconstruction of ancient Egyptian tombs

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Abstract: From the pyramids of Giza to the tombs of Thebes at Luxor, the glorious ancient Egyptian history has produced remarkable architecture. Sadly, tourists, numbering nearly four million per year, have taken a heavy toll on many of these ancient structures. Of particular concern are many of tombs located opposite Luxor on the western bank of the Nile. Digital reconstruction of these tombs has the potential of helping to document and preserve these important historical structures. Issues concernng new and unique problems involving the photographing and digital reconstruction of these tombs are addressed. Techniques for removing image distortions, recovering 3-D shapes and correcting for lighting imbalances are discussed. A complete reconstruction of the tomb of Sennedjem is shown.

Key words: tomb conservation; digital reconstruction; photographing

Approximately 5 000 years ago, Narmer unified upper and lower Egypt creating what is arguably one of the greatest civilizations of all time. From the pyramids of Giza to the tombs of Thebes, the glorious history of Egypt is enjoyed by nearly four million tourists each year. While the tourism trade bolsters the Egyptian economy, it has taken a heavy toll on many of its ancient monuments. Of particular concern are many of the Theban tombs on the western bank of the Nile, opposite modern Luxor (see Fig. 1[1] and Fig. 2). The delicate and vibrant colours found in the tomb paintings have survived for many millennia, but have recently seen significant deterioration partly due to the large number of visitors.

Fig. 1 Map of Egypt showing Luxor

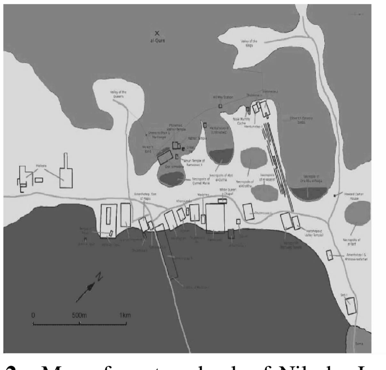

Fig. 2 Map of western bank of Nile by Luxor

Digital reconstruction of these tombs has the potential of helping to document and preserve these important historical structures while increasing general knowledge and interest (e. g., virtual museums). Reconstruction of these structures from photographs poses new and unique problems that this paper addresses. We have concentrated our initial efforts on the smaller tombs of artisans in "Deir el Medina" in western Thebes. These were the people who worked on the royal tombs in the valley of the Kings, located about a kilometre away.

In 1886, Mespero discovered a tomb which belonged to Sennedjem (designed tomb number one) in the "Deir el Medina" area. Together with his immediate family, they managed to survive in such a minuscule space, being undisturbed for over three millennia. It was a momentous occasion when the tomb was discovered still intact, not having succumbed to the fate of most royal and private tombs which were plundered in antiquity. A wire frame rendering of Sennedjem's burial chamber number one is depicted (see Fig. 3).

There are two photographs taken from each end of the chamber. The burial chamber, measuring 5. 12 m by

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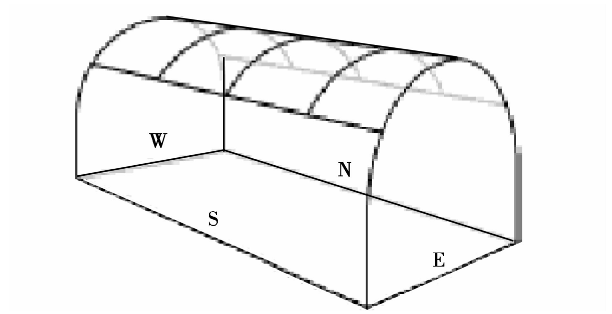
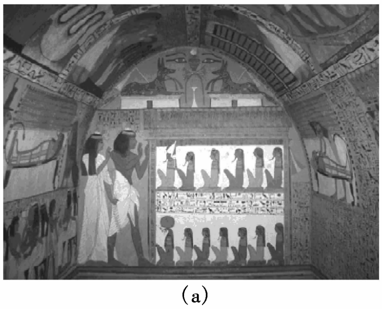
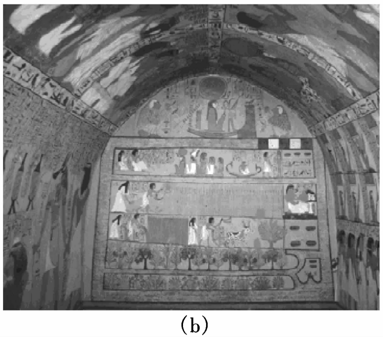


Fig. 3 Sennedjem's burial chamber

2.61 m with a vaulted ceiling of 2.40 m, is completely decorated. Nearly any photograph of this small room will contain significant distortions due to the curved ceiling, the inherent effects of perspective projection, and the wide-angle lens required to obtain a reasonable field of view (see Fig. 4(a)[2]).



(a)



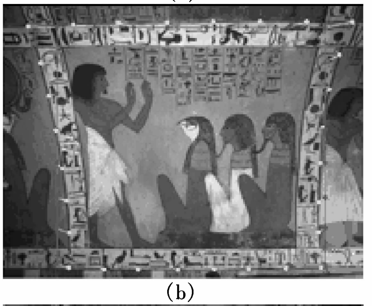
(b)

Fig. 4 The burial chamber of Sennedjem as viewed from each end

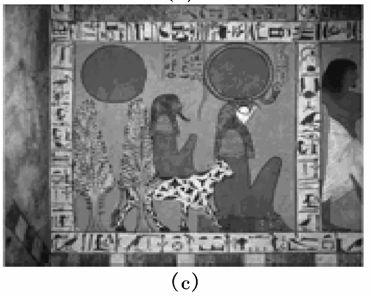
For example, there are two photographs taken from neighbouring panels on the curved ceiling. Given the small size of this room, these distortions are impossible to avoid. In the presence of these distortions, it is equally impossible to create a single large-scale seamless mosaic. This paper first describes an image-based technique for removing these distortions.

Combined with a simple technique for recovering the 3-D shape, we then reconstruct fully decorated virtual tombs. While not employed in the results presented here, we also propose a technique for automatically correcting the lighting imbalances that are typical of ash photographs. We hope to incorporate this technique in future reconstructions (see Fig. 5).

(a)



(b)



(c)

(d)

Fig. 5 Images from the curved ceiling before ((a) and (b)) and after ((c) and (d)) the removal of distortions

1 Tomb Image Distortions

Consider again the pair of images; these images were clearly intended to be rectangular in shape. However, due to the curved ceiling, these images contain significant distortions. Note that these panels neighbour each other on the chamber ceiling. That is, the right-most hieroglyph strip in Figs. 5(a) and (c) is the same as the left-most strip in Figs. 5(b) and (d). The goal is to seamlessly join these images, thus requiring the removal of these distortions. If we assume that the vertical and horizontal hieroglyph strips should be parallel, then these strips provide a convenient landmark for estimating the distortions. There are 30 points evenly spaced along the outer portion of the panel. These points are determined in a two step process. First, a small number of points (more than four) are manually selected anywhere along a horizontal/vertical portion of the hieroglyph strip that bounds the panel, making sure to choose the two points at either end of the strip. The fourth-order polynomial curves to these points, from which the equally spaced points are generated (see Fig. 5).

This process is repeated for each side of the panel. Also shown in Fig. 5 is the desired position of these 30 points, automatically chosen to be an equivalent number of equally spaced points along parallel horizontal-vertical lines passing through the average position of the specified distorted contour. By choosing these equally spaced points in the image, we are ignoring the surface geometry. As a result, a slight non-uniform compression is introduced in the resulting undistorted image. This effect seems to be qualitatively small.

2 Lighting

In addition to the distortions described above, the photographing of Egyptian tombs poses other challenges. The tombs are often poorly lit making it necessary to photograph with an ash, leading to non-uniformities in the lighting. A main contributor to these non-uniformities is the (approximately) quadratic falloff of light intensity as a function of distance[3]. As a result, when photographing, for example, a planar surface, the center of the image can be significantly brighter than the corners. The removal of these variations is critical to the creation of a seamless image mosaic. The results are obtained by manually adjusting for lighting and colour imbalances. Note in particular how the darkened corners have been corrected (see Fig. 6).

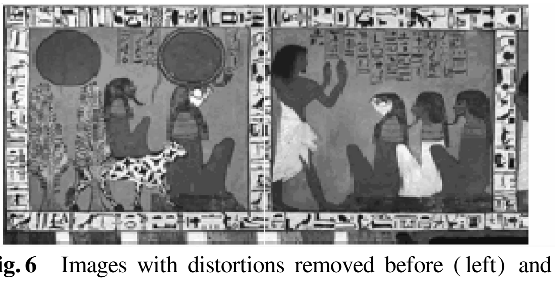


Fig. 6 Images with distortions removed before (left) and after (right) manual lighting and colour adjustments

In addition, for aesthetic reasons, we identified and digitally removed several modern-day blemishes in background areas. These manipulations were all performed in Photoshop. In future reconstructions, we propose a more automated process that employs a pair of photographs taken with the flash in different positions. Outlined below is a technique for estimating distance, and, hence, the amount of light attenuation, from such a pair of images. This idea was first proposed by Jarvis, but seems not to have been further explored in the computer vision community[4].

3 Geometry

The relatively simple structure of many ancient Egyptian tombs lends itself to a straight-forward technique for recovering their 3-D shapes. Many structures are rectangular at the base with a curved ceiling[5]. Since these structures have been thoroughly studied, the dimensions (length, width, height) are readily available. What remains to be determined is the curvature of the ceiling. This can be determined from a frontal-parallel view of either end of the structure. For example, in Fig. 4, concerning the views of Sennedjem's burial chamber as seen from each end, note that the curvature of the ceiling can be easily determined by simply tracing the contour of one or both end walls. This process can be semi-automated by first selecting a number of points along the contour of each end wall. For each wall, a higher-order polynomial curve is fit to these points, from which a dense sampling of points along each contour can be easily computed. In practice we found a reasonably dense sampling of points along the contour. As high as a tenth-order polynomial can be used. The final 3-D structure is then determined by directly outputting the shape of the contour in a format readable by a VRML (virtual reality modelling language) viewer[6]. There is a wire frame rendering of the recovered 3-D structure of Sennedjem's burial chamber. The curvature was determined as described above, and the proportions were determined from published measurements (see Fig. 7).

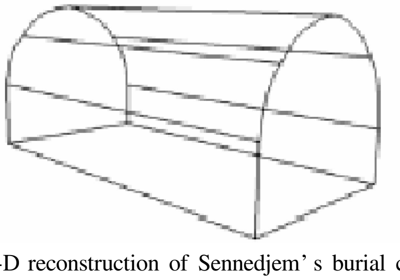


Fig. 7 3-D reconstruction of Sennedjem's burial chamber (shown in the same orientation as Fig. 3)

4 Reconstructing Sennedjem's Burial Chamber

There are sixteen photographs that provide full coverage of Sennedjem's burial chamber. These images were digitally scanned at 2 700 dpi from 35 mm slides. To reduce the demands on memory, each image (3 894 ×2 592 pixels) was sub sampled by a factor of two. The distortions were removed from each image, with the exception of the east and west end walls (which had virtually no distortions). In each image, horizontal and vertical markings were used to signify the distorted contour. The undistorted shape was automatically chosen to be a rectangle whose size was roughly that of the distorted shape[7]. After the distortions were estimated and removed, the aspect ratio of each image was adjusted as the images were overlaid, guided by the known chamber dimensions. Variations in global and local lightness-colour were corrected manually. For aesthetic reasons, we identified and digitally removed several modern-day blemishes in background areas[8] (see Fig. 8). These manipulations were performed in Photoshop.

Fig. 8 Original photographs of Sennedjem's burial chamber

The south, north, and the west-east walls became fully undistorted and seamed together. These undistorted images were then combined with a 3-D model of the burial chamber (see Figs. 9 to 11). Additionally, there are several views from the virtual chamber (see Fig. 12).

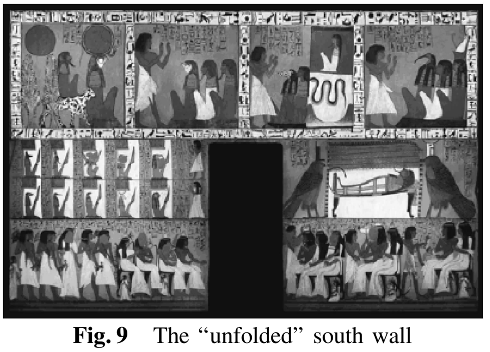


Fig. 9 The "unfolded" south wall

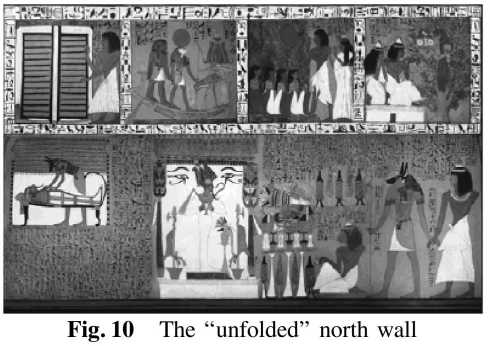


Fig. 10 The "unfolded" north wall

Fig. 11 The west and east walls

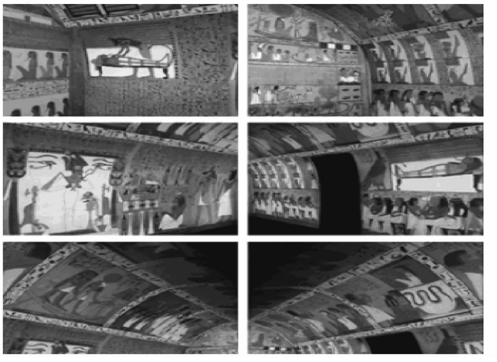


Fig. 12 Views from the virtual chamber

5 General Idea

For several millennia, the remarkable pyramids, temples, statues, and tombs of ancient Egypt have remained symbols of this civilization's fascinating history[9]. Over the past few decades, these structures have seen significant decay partly due to the ever increasing number of visitors. Digital reconstruction of these structures can help document and preserve these important historical monuments, which in the long run will bolster tourism.

This paper has particularly focused on the task of digitally reconstructing tombs. With respect to the general reconstruction of architecture, these tombs pose new problems and simplify others. At the outset, when photographing in these small tombs (often 2 to 3 m wide and high), it is nearly impossible to avoid significant distortions from the decorated and highly curved ceilings. We have proposed an image-based technique for removing these distortions in the absence of the 3-D structure or intrinsic-extrinsic camera parameters. This technique estimates the distortions by exploiting as fiducial markings the ubiquitous horizontal and vertical hieroglyphic text. This approach should prove to be particularly useful when working from archival photographs.

Photographing in these small tombs is further complicated by poor lighting, making it necessary to photograph with ash. These photographs suffer from the classic problem that the ash does not uniformly illuminate the scene. The removal of these variations is critical to the creation of a seamless image mosaic. The recent addition of protective glass along the walls has created further complications. In particular, reflections from the ash and from the opposing wall yield substantial artifacts in the photographs. With regards to this, it is hopeful that our earlier work on the removal of reflections may prove effective.

The relatively simple structures of many tombs greatly simplifies the recovery of their 3-D structures[10]. Many structures are rectangular at the base with a curved ceiling. The curvature of the ceiling can be easily determined from a frontal-parallel view of either end of the structure. Since these structures have been thoroughly studied, the base dimensions are readily available. The digital reconstruction of ancient Egyptian structures poses new and unique problems that this paper has only begun to address.

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古老埃及陵墓的数字建构和保护

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摘要：从吉斯的金字塔到底比斯的陵墓，古老埃及的璀璨历史就体现在这些著名的建筑上. 不幸的是，每年近四百万的旅游者给上述古建筑，尤其是那些位于尼罗河西岸的陵墓带来了沉重的负担. 用数字化技术帮助建立起传统陵墓的资料库，以便更好地保护这些重要的历史建筑. 同时通过重建一个数字陵墓的例子，讨论了运用照片图像及数字建构技术应注意的新问题，例如需要消除图像的变形、矫正三维模型和调整光线的平衡等问题，来达到真实的数字感观.

关键词：陵墓保护；数字建构；照片技术

中图分类号：TU984. 11^{+}4