3D Reconstruction with Fisheye Images

Strategies to Survey Complex Heritage Buildings

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***Abstract*—Over the last few decades photogrammetry and laser scanning have been frequently considered valuable tools for creating three-dimensional models from which metric and radiometric information can be derived for the survey of cultural heritage buildings, reverse engineering, space exploration and other areas. However reconstructing old heritage buildings digitally may be a challenging task especially when the shape, geometry and volume of these buildings are intrinsically complex therefore requiring specific methods or ad-hoc solutions. Medieval castles are typical constructions that exhibit these kinds of features with inaccessible locations, bridges, wide areas followed by small and limited spaces, battlements, towers and walls occluded by vegetation. This variety of problems can prolong the time required to complete the tasks when using laser scanning or photogrammetry with conventional lenses. In this paper we present a research of use of fisheye lenses in photogrammetry, for capturing medieval castles' geometric and radiometric information of hard to reach places. We conclude that this reduces the total time needed to capture the same amount of information gathered with other instruments, it allows replacing the usage of Unmanned Aerial Vehicles (UAV) in low flight situations, makes the survey connection between areas of a building easier, reduces the total number of images and allows making a general fast survey. The castles illustrated in this paper are the Castle of Sesimbra and the Castle of The Convent of Christ, both in Portugal.**

***Index Terms*—Fisheye lens, photogrammetry, image-based modeling, 3D modeling, cultural heritage.**

I. Introduction

One of the fundamental questions when surveying buildings is related to the choice of the survey equipment while bearing in mind other aspects such as the complexity of said buildings, the financial availability, the surveyor's own experience, the weather conditions, the documentation to be produced, amongst others. This leads to multiple possible approaches when surveying due to the very particular characteristics of the scene or building. In this sequence the equipment must be chosen. Nevertheless it is advantageous to survey cultural heritage buildings in the most efficient way while maintaining (or raising) the level of effectiveness of the requested tasks. By efficiency we refer to the portability, cost, acquisition speed and user friendly conditions [1]. With these in mind one can plan ahead and bring to the field survey the required instruments. Occasionally the digital reconstruction of some buildings may be a difficult labor due to their physical configuration. This occurs most likely in old heritage buildings where the shape, geometry and volumes are intrinsically complex to capture with any regular survey equipment therefore requiring a of lot time to reach the desired goals. Medieval castles are good examples which show multiple space configurations: inaccessible locations, bridges, wide areas followed by small and limited spaces, battlements, towers and walls occluded by vegetation. All of these features pose a challenge for any surveyor since it demands constant planning and the use of additional help like helicopters, Unmanned Aerial Vehicles (UAV), cranes, telescopic poles, just to name a few [2], [3], [4], [5], [6]. We propose using fisheye photographs as a strategy to save time in surveys, providing at the same time good results in narrow spaces and connection between spaces.

This paper is structured as follows: In section II we discuss some related work that has been done with highly distorted images. The following section we present some practical cases while mentioning the potential application of fisheye lenses. In section IV the survey of the Castle of Convent of Christ is presented. In the last section we discuss the application of fisheye images and their possible future use.

II. Related Work

The application of fisheye lenses is uncommon probably due to the high amount of distortion, therefore a challenge for generating a 3D reconstruction. Indeed many papers refer to the mathematical equations, the complexity of the distortions and the difficulty of undistorting the images while keeping accurate geometric values. Kedzierski and others [7], [8], estimated that the deviation of the point location relative to point clouds produced with conventional lenses increased by 2 times or more while the accuracy lowered by 3 to 4 times. However, Stretcha et al. [9] concluded that fisheye lenses can have accuracy values within 10cms when photographing roughly at 15m distance and that smaller angle fisheye lenses offer similar results to conventional lenses. Georgantas et al. [10] reconstructed a complex modern interior stairwell with persistent lack of texture on the walls. In other works [11], [12], [13], panoramic spherical images were used instead of fisheye images to 3D reconstruct buildings and virtual tours.

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III. Fisheye Lens Versus Wide Angle Lens

A. Survey of Complex Elements

To compare the efficiency of fisheye lens (8mm) relative to the 18mm lens it was opted to survey battlements (Castle of Sesimbra) due to their complex configuration containing horizontal, vertical and oblique planes. To compare the effect of a wider field of view (FOV) in the horizontal axis it was decided to take an arc of photographs around each battlement with a total of 7 positions: 3 on the inside, 1 on top and other 3 on the outside. The average angle between each position was approximately 30º. This way a full coverage of the battlements could be achieved with both lenses and to only analyze the effects of the FOV (Fig.1a).

For the 18mm lens (Fig.1d) it was needed a total of 17 photographs per battlement, 2 for each position and they were taken in divergent directions with approximately 80º between their principal axes. It was additionally required 3 images from the top position to be able to cover the lower horizontal surface between the protruding elements.

For the 8mm lens (Fig.1c) the total minimum number of required images was 7, one for each position of the arc. The images were shot with their principal axis aimed for the center of said arc. The capturing of the side surfaces of the battlement was easy because of the high FOV and the 3D model was fully reconstructed.

Since it was impossible to reach the designated positions with the camera, a telescopic pole (3,5m maximum extension) and remote shutter release were needed. Additionally, the camera was set to be fully automatic in sports mode (priority for fast shutter speed) because of the shakiness of the pole. This allowed the photographs to be sharp and the range of focus wasn't affected as small focal distances were being used.

The results demonstrate that fisheye lenses are capable of delivering same coverage with less than half of the needed images and time. The 3D reconstruction is also easier for there are no great angles between images or require the images to be shot with little deviation from the calculated position.

Nevertheless, a further study is required to check for any geometric inconsistencies.

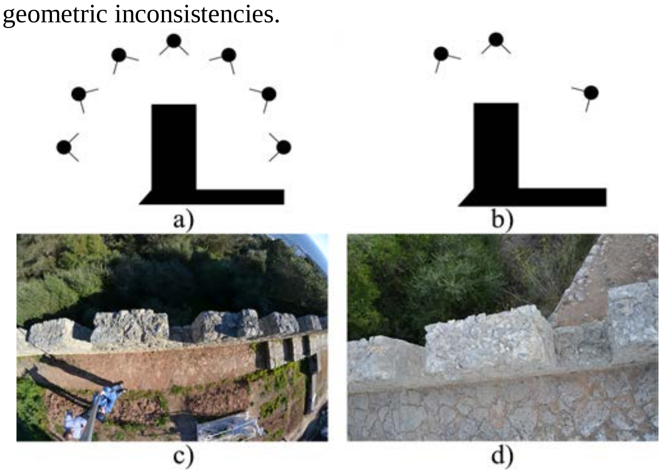

Fig. 1. a) Seven camera positions. b) Three camera positions. c) Fisheye image. d) Image taken with 18mm lens.

Yet, for practical reasons an additional investigation was conducted for surveying battlements in a more expeditious way. Instead of taking an arc of pictures it was preferred to take 2 or 3 photographs for the 3 specific positions (Fig.1b). This may increase the total number of images (a total of 6 or 9 per battlement) however it is more user-friendly and time saving. It was also possible to substitute the usage of UAVs in low flight condition for capturing these types of features. Similarly the application of Terrestrial Laser Scanning (TLS) would require the positioning of the instrument for each and every battlement to capture the sided faces therefore leading to a very time consuming task.

B. Transition of Areas and Narrow Spaces

Other possible applications of fisheye lenses are for capturing narrow or hard to reach places and make the transition between areas. We present a survey of the Castle of Tomar of an enclosed spiral staircase that completes two full 360º turn and is so narrow that only one person can climb it at a time (Fig.2a).

In the first experiment one row of images was taken while stepping down with the camera pressed to the surveyor's body. This procedure resulted in an incomplete 3D model without information on the ceiling, column and the step's risers. To solve this issue in the second experiment images were taken while climbing up the flight of stairs. It was needed 3 rows of images, one with the camera pointing a little to the right to capture the wall and stairs, another with the camera pointing to the left to capture the column and stairs and a last row to capture the ceiling. Overall 3 images were shot for every climbed step. Other photographs were also shot at the transition of the stairs in a convergent pivot around each jamb of the door. In the end 131 images were taken and a complete 3D model was generated (Fig.2b).

This experiment would be possible to accomplish with a wide angle lens however the total number of images would double or more just to generate a model with the same coverage. The usage of TLS in this case would also be a difficult task since one would have to adjust the legs of the tripod every time a new scan would be needed, not to mention the lack of maneuverability, the total number of scans and minimum distance for scanner operation. With the application of fisheye lenses one can survey spaces, which are too narrow for TLS or photogrammetry with any conventional lens, in a more efficient way.

Fig. 2. a) Fisheye lens versus 18mm lens (red limits). Notice the leg size relative to the width of the step. b) Camera positions.

C. Software Comparison

One of the most challenging tasks in the usage of the fisheye lens was to find the correct software to process the great number of unordered images while at the same time generating results with quickness and good geometric quality. For this purpose VisualSFM [14], [15], [16], PMVS [17], CMVS [18], CMPMVS [19], Apero/Micmac [20], [21] and Pix4D [22] were experimented and compared. The used hardware was an ASUS K56CB which has 8gb RAM, Intel Core i7 processor, Nvidia GeForce GT 740M and a SSD disk. For the comparison we chose an indoor space with three stone medallions each placed over a pedestal and in front of a planar wooden wall. The photographic camera, a Nikon D3100 with 14,2MP, was attached to a tripod and for each point of view 2 images were taken, 1 with the 8mm lens and the other with the 18mm lens. A total of 8 parallel points of view were considered. All the tests were carried out with maximized densification outputs (TABLE 1).

For the group of images taken with the 18mm lens all of the previously listed software was tested. The most noticeable differences are the processing time, number of 3D reconstructed points, coverage and noise. The software that reconstructed with the least coverage was VisualSFM+CMVS/PMVS with some noise on the wall. Pix4D has more or less the same noise level as the previous software although it can reconstruct a lot more 3D points when compared for the same time interval. When processing with CMPMVS, despite the fewer 3D points, there is more coverage and the points are more precise (lower re-projection error) and there is clearly less noise. However it takes a lot more processing time. Apero/Micmac produces the most visually satisfying results. The coverage is very good considering one must choose an image from which the 3D points are projected. When more than one image is selected the processing time greatly increases.

For the group of 8mm lens only the fisheye supporting software were used. In fact, when using fisheye lenses one has to consider the various mathematical models to undistort the images. Particularly fisheye images have high radial distortion and other significant distortions that may lead to high systematic errors. Thus an accurate calibration is needed. Pix4D uses self-calibration, supports equidistant fisheye camera model and standard perspective camera model. To generate trustworthy calibration results a ring of divergent pictures was taken in an enclosed space and compared to a conventional lens with known parameters. The resultant model didn't show any noticeable discrepancies or disproportions.

Between Pix4D and Apero/Micmac two major differences can be identified. The former can process data a lot faster while the latter (with FishEyeEqui model) has less noise at the cost of processing time. This was done with a small set of images but when thousands of images are used Apero/Micmac's processing time increases beyond any useful time frame, at least with the used hardware, and images have to follow the photogrammetric rules.

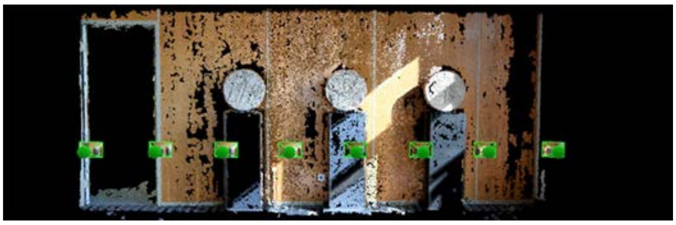

Fig. 3. Position of the cameras.

TABLE I.

18mm	Points (M)	Time (minutes)
VisualSFM+CMVS/PMVS	1.8~	18~
VisualSFM+CMPMVS	1.5~	70~
Apero/Micmac	2.9~	90~
Apero/Micmac	-	600~
Pix4D	15.5~	42~
8mm		
Apero/Micmac	1.25~	90~
Pix4D	10~	47~

Moreover we intend to access the geometric quality of the reconstructions using TLS survey as reference, and further explore the integration of these methods with others.

IV. CASTLE OF THE CONVENT OF CHRIST

The Castle of the Knights Templar of Tomar is part of the site of Convent of Christ which is in the Unesco World Heritage list. The Keep of the Castle of Tomar is considered one of the oldest keeps in Portugal. The Castle is not open to the public and there is only a survey at 1:1000 scale, and there is a need to produce better documentation to support further studies. This site was chosen for being interesting to test the application of the studied methods for its challenges.

For this purpose the experiences acquired earlier were employed and assessed in the main case study, allowing to accelerate the planning and photogrammetric acquisition. Three lenses were employed (8mm, 18mm and 50mm), a telescopic pole, remote shutter release plus straps for the wiring and a checklist with most of the demanded areas. A total of 6930 images with 14,2MP were shot in order to make the batters, bridges, transition between spaces, the interiors of the keep, the inside and outside faces of the wall plus their battements and arrow slits, among other features.

This methodology was successful and yielded very good results at the first try with the Pix4D software (fig.4.). In the near future we intend to continue applying this methodology.

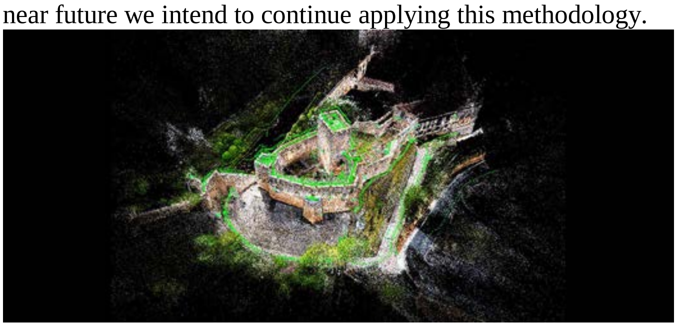

Fig. 4. Sparse reconstruction of the Castle of Tomar.

V. Conclusion and Future Work

In this paper we have presented the application of fisheye lenses to illustrate their potential for the survey of complex features in heritage buildings. Three isolated experimental cases were shown to demonstrate the differences between a wide angle lens and an ultra-wide angle lens. The usage of the latter proved to be favorable for 3D reconstruction purposes since the quantity of images could be reduced while keeping the same coverage and easing the photographic acquisition. Furthermore, what stands out the most is that these kinds of lenses are very good for capturing protruding elements, narrow spaces, indoor spaces, transition between spaces and in some cases to replace the usage of additional equipment such as helicopters and UAVs in low flight conditions.

Additional work is being done to evaluate the geometric quality of the 3D models by using TLS survey data as reference. Also we are exploring the integration of these methods with others.

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