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Towards an Improved Method of Dense 3D Object Reconstruction in Structured Light Scanning

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Abstract

Optical three-dimensional shape measurement based on structured light has been widely used for 3D measurement in many different applications. Phase Shifting acquisition methods have been extensively used in these measurements, since they offer robustness against ambient light and reflections variation, but they need a phase unwrapping procedure and further phase-to-height conversions after complex calibrations. Although there have been different proposals last years, the design of an accurate and efficient 3D object reconstruction method is still an open issue. In this paper, we propose a new method of 3D object reconstruction that combines the benefits shown by Multi Phase Shifting and the potential of a phase-to-height mapping that uses implicit calibration. The performance evaluation, measured on virtual environments, show that the proposed method can efficiently deal with the sharp edges of the 3D reconstructed objects, removing the erroneous geometries, while it also avoids the need to geometrically calibrate the projector, a massive time consuming task that produces many problems related to the projector lens distortions. These results validate this proposal as an efficient method for 3D object reconstruction.

Key words: 3D object reconstruction, Physically based modelling

1 Introduction

Optical three-dimensional (3D) shape measurement based on structured light (SL) has been widely used for 3D measurement, machine vision, automated manufacturing, and industrial monitoring [13, 18, 5, 8, 3, 1]. These techniques offer the advantages of non-contact operation, full-field acquisition, high resolution and dense 3D reconstruction. SL

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techniques assume a projection of controlled illumination of the scene through one or more projected patterns onto the objects surface, commonly using DLP or LCD video projectors. Due to the differences in the object height, the projected pattern appears distorted when viewed obliquely. Therefore, the fringe pattern is modulated according to the objects 3D height and the angles formed between the illumination and the viewing axes. Projected light patterns have a characteristic structure (appearance) because projector image pixels are coded in a certain way. Detecting the same code on the pixels from a minimum of two cameras, or from one camera and one projecting device, the correspondence problem for a large number of points can be solved, leading to dense 3D surface acquisition after triangulation, for which the calibration of the camera(s) and/or projector(s) has to be known.

Different types of SL measurement methods have been developed [10, 12]. Among these methods, Phase Shifting (PS) acquisition methods have been extensively used [7, 11, 2]. Compared to other structured light techniques, PS techniques offer robustness against ambient light and reflections variation, due to the grayscale nature of the projected patterns [10]. Figure 1 shows the general procedure of 3D object reconstruction in the temporal domain based on SL [12].

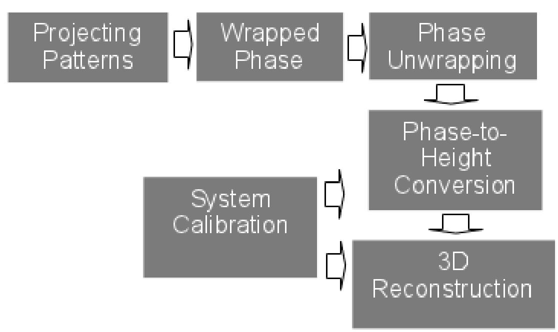

Figure 1: General procedure for the 3D reconstruction of objects of a structured light scanning system.

In these techniques, a sequence of periodic intensity patterns is projected onto an object or a surface, each of which is offset by a fraction of its period from the previous one, so that the entire period is covered. However, the demodulation of the acquired fringe patterns results in a so-called wrapped phase instead of the desired (unwrapped) phase. This raises the problem known as a *phase unwrapping* procedure (see Figure 1).

Many different methods have been proposed for unwrapping the phase [11, 2, 6]. Multiple Phase Shifting (MPS) methods use more than one frequency to cope with the uncertainty created in the extracted wrapped phase. Traditionally, three solutions have been adopted: temporal phase unwrapping, hierarchical approach and number-theoretical approaches. The

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first two create several relative phase maps, while the third one is based on the properties of relative primer numbers and divisibility of integers to create an absolute phase map [10]. Recently, an effective MPS method which provides high accurate reconstruction shapes has been proposed [11].

Once the unwrapped phase map is obtained, a relationship between the encoded phase and the height of the object should be established. This procedure is known as *phase-to-height conversion* (see Figure 1), and it requires a calibration procedure of the devices. Many calibration methods have been developed [19, 17, 15, 16]. One of these methods [16] uses implicit calibration, i.e., instead of explicitly computing the (interior and exterior) calibration parameters for the devices, a set of coefficients are calculated for a certain system configuration, and a mathematical model describes the relationship between these coefficients and the objects height. In this approach, a 3D calibration object is used, for which their heights in relation to a reference plane are known. The main advantage of this strategy is that the calibration method generates less computational workload than others [15], since the obtained coefficient parameters are independent of the image coordinates. Additionally, the calibration of the projector is not needed, thus avoiding the drawbacks of calibrating such devices (the projectors optics are normally behind of that of the cameras, so they are hardly accessible).

In this paper, we propose an improved method of 3D object reconstruction by combining the benefits shown by Multi Phase Shifting [11] and the potential of the improved algorithm for phase-to-height mapping [16], thus resulting in an improved method from both the reconstruction accuracy and the computational effectiveness points of view. The performance evaluation results, measured on virtual environments, show that the proposed method can efficiently deal with the sharp edges of the 3D reconstructed objects, removing the erroneous geometries, while it also avoids the need to geometrically calibrate the projector, a massive time consuming task that produces many problems related to the projector lens distortions. These results validate this proposal as an efficient method for 3D object reconstruction.

The rest of the paper is organized as follows: Section 2 describes in detailed the proposed method. Next, Section 3 shows the performance evaluation of the proposed method. Finally, section 4 shows some conclusions remarks and future done to be done.

2 A New Method for 3D Object Reconstruction

In this section, we describe the proposed method for 3D Object Reconstruction in Structured Light Scanning. In our approach towards an effective 3D reconstruction method, we have included two recently proposed techniques that improve two of the steps shown in Figure 1: the phase unwrapping and the phase-to-height conversion.

The implemented method of phase unwrapping is based on the one described in [11],

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which makes use of Multiple Phase Shifts (MPS) patterns. According to their authors, the algorithm is robust to objects with sharp discontinuities and depth changes, and it provides better accuracy in 3D reconstruction than standard Phase Shifting. On the other hand, the method of phase-to-height conversion that we have used is the one described in [16], which provides a phase-to-height mapping with a calibration method that makes use of a 3D reference object. The main advantage of this method is that it uses an implicit procedure, avoiding the need to geometrically calibrate the projector, a massive time consuming task that produces many problems related to the projector lens distortions. Another advantage of this method is that it allows a more flexible system configuration than basic measurement systems in phase measuring profilometry [14, 20, 9], since the reference plane does not need to be orthogonal to the camera optical axis and both the camera and the projector can be located at different distances to the reference plane.

Compared to the method described in [11], our proposal adds less computational workload, since the calibration method is much less complex than than traditional calibration methods based on the computation of the spatial and geometric properties of the camera and the projector. However, in order to perform MPS, the PS method should be applied twice, and therefore it may generate more computational workload than the one shown in [16]. Concretely, the steps of unwrapping and phase-to-height conversion can be split in three different parallel processes performing different tasks. The tasks to be performed are the following ones:

- Process 1: Projection, capturing and storing images.

  Task 1: Projection, capturing and storing (in hard disk) of the images with the first period of the periodic intensity pattern for the reference plane.

  Task 2: Projection, capturing and storing of the images with the second period for the reference plane.

  Task 4: Projection, capturing and storing the images with the first period for the calibration object.

  Task 6: Projection, capturing and storing of the images with the second period for the calibration object.

  Task 9: Projection, capturing and storing of the images with the first period for the object to be reconstructed.

  Task 11: Projection, capturing and storing of the images with the second period for the object to be reconstructed.

- Process 2: Computing of the wrapped phase

  Task 3: Computation of the wrapped phase (using the PS algorithm) for the images gathered in task 1.

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Task 5: Computation of the wrapped phase for the images gathered in task 2.

Task 7: Computation of the wrapped phase for the images gathered in task 4.

Task 10: Computation of the wrapped phase for the images gathered in task 6.

Task 12: Computation of the wrapped phase for the images gathered in task 9.

Task 14: Computation of the wrapped phase for the images gathered in task 11.

- Process 3: Computing of the object height

Task 8: Computation of the absolute unwrapped phase (using the MPS algorithm) for the phases computed in tasks 3 and 5.

Task 13: Computation of the absolute unwrapped phase for the phases computed in tasks 7 and 10.

Task 15: Computation of the seven calibration parameters from the unwrapped phases computed in tasks 8 and 13.

Task 16: Computation of the absolute unwrapped phase for the phases computed in tasks 12 and 14.

Task 17: Computation of the object height with the seven parameters computed in task 15 and the unwrapped phases computed in tasks 8 and 16.

Task 18: Computation of the cloud of points from the object height computed in task 17.

For illustration purposes, Table 1 shows a schematic view format of the dependencies among the tasks performed by each process. This view assumes that time passes from left to right, and the dependences among tasks are represented as empty cells within the same row. Thus, a sequential implementation would consist of a single row with a length of 18 tasks, and and a parallel implementation could benefit from overlapping the three processes as shown in Table 1.

Process P1	2	4	6	9	11					
Process P2		3	5	7	10	12	14			
Process P3				8		13	15	16	17	18

Table 1: Distribution in processes and tasks for the proposed 3D object reconstruction method

As Table 1 shows, the execution of the proposed algorithm on multi-core processors can overlap different tasks, reducing the required execution time accordingly.

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3 Performance Evaluation

In this section, we present the performance evaluation of the proposed method. In order to avoid possible errors due to the quality of the devices (e.g. lens distortion), we have performed the experiments in a virtual scenario. We have tested different system configurations, such as camera/projector distance to the reference plane, rotations, parallel vs. cross-optical axes, etc. We present in this paper the results for the configurations shown in Table 2. As 3D reference calibration objects, we have used 3 boxes of different heights.

	camera			projector		
	X-axis	Y-axis	Z-axis	X-axis	Y-axis	Z-axis
position:	100	0	1000	0	0	1000
rotations:	0	185	0	0	180	0
FOV:	30			40		
Far:	1100			1100		

Table 2: Camera and projector settings

One restriction of the MPS method is that the least common multiplier (lcm) of the two projected periods should be greater than the width of the projected image. In this sense, we have tested different combinations, finding the best results for the wave period of 32 and 45 pixels (denoted as T32 and T45, respectively). In our case the the width of the projected image was 1280 pixels, lower than the the lcm of 32 and 45, that is 1440.

We have compared different options in our proposal, in order to select the best combination of elements in the 3D object reconstruction method. Concretely, we have considered different patterns to be projected, and different phase unwrapping techniques for each configuration. We have used the PS technique [11] for achieving a wrapped phase, as well as the phase-to-height method proposed in [16], in all the configurations considered. For the phase unwrapping step, MPS [11] was used in configuration 3, while the standard 2D unwrapping algorithm (2DM) described in [4], which uses a single relative phase map, was used in configurations 1 and 2. Table 3 shows the combination of these elements that are included in each of the three configurations considered for evaluation purposes.

		Conf. 1	Conf. 2	Conf. 3
Projected pattern	32 pix.	X		X
	45 pix.		X	X
Phase Unwrapping	2DU	X	X	
	MPS			X

Table 3: Camera and projector settings

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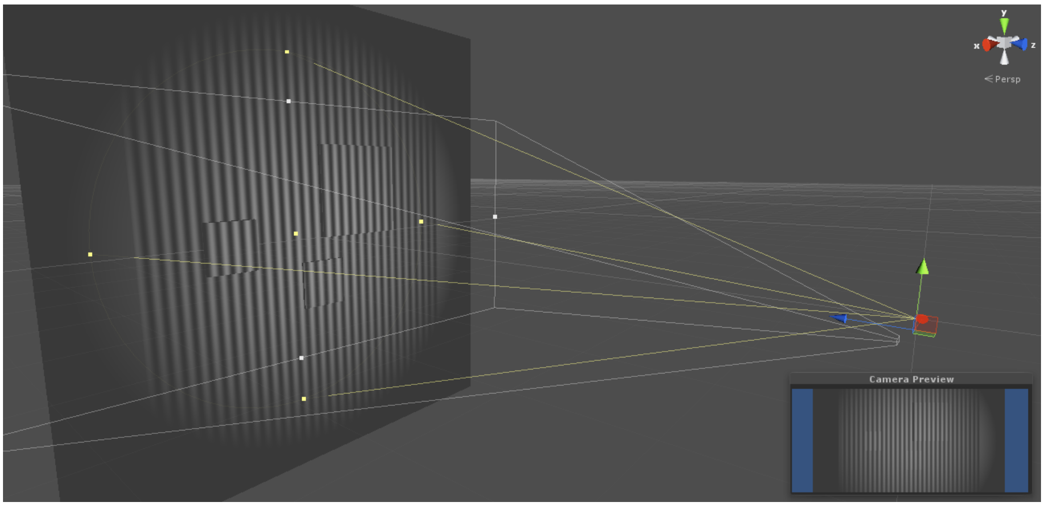

Figure 2: Arrangement of elements in the virtual scenario.

Figure 2 shows an scheme of the location and arrangements of the camera and projector in the virtual scenario in order to project and capture the considered intensity patterns. Also, figure 3 shows a snapshot of the projected patterns (with period of 32 pixels on the left side and with period of 45 pixels on the right side) on the virtual 3D boxes.

Figure 4 depicts the 3D reconstructed cloud of points for the three considered configurations. This figure shows that in configurations 1 and 2 erroneous geometries are produced at the edges of the boxes, like in most of the PS-based methods. However, the third configuration can deal with the sharp edges of the 3D reconstructed object, removing the erroneous geometries, These results validate configuration 3 as the most efficient one, and we have selected this one as the proposed method.

4 Conclusions and Future Work

In this paper, we have proposed a new method of 3D object reconstruction that combines the benefits shown by Multi Phase Shifting [11] and the potential of the improved algorithm for phase-to-height mapping in phase measuring profilometry [16]. The performance evaluation, measured on virtual environments, show that the proposed method can deal with the sharp edges of the 3D reconstructed objects, removing the erroneous geometries. Since it also avoids the need to geometrically calibrate the projector, a massive time consuming task that produces many problems related to the projector lens distortions, these results validate this proposal as an efficient method for 3D object reconstruction.

As a future work to be done, we plan to perform an exhaustive computational evalua-

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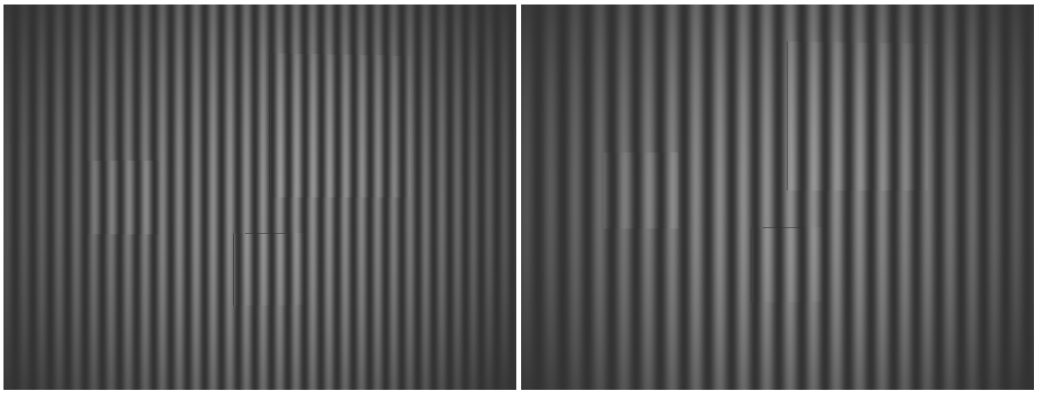

Figure 3: Projected patterns on the virtual 3D boxes.

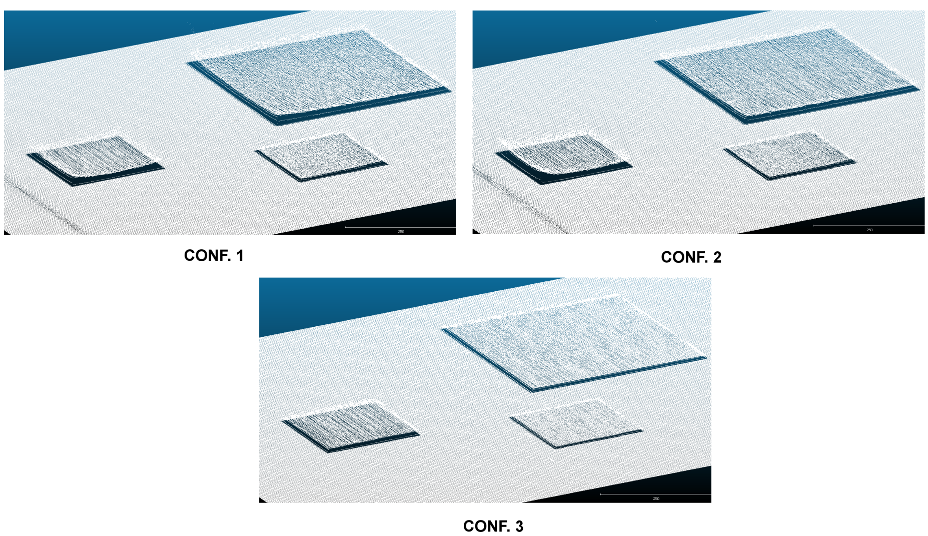

Figure 4: Visualization of the 3D cloud of points achieved by each of the three configurations.

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tion, in such a way that the proposed implementation can properly exploit the parallelism available in current multi-core processors.

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