Real-time full-field 3-D surface-shape measurement using off-the-shelf components and a single processor

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Abstract

Phase-shifting fringe-projection methods have been increasingly used for three-dimensional (3-D) object surface modeling to permit full-field measurement. This paper presents a real-time full-field high-resolution 3-D surface-shape measurement system implemented with an efficient 3-D shape measurement pipeline and triangular-pattern phase-shifting based on off-the-shelf components, software synchronization and a single computer-processor. The system projects computer-generated fringe patterns with a triangular intensity profile onto an object via a Digital Light Processing (DLP) projector. The projected patterns are electronically shifted and a CCD camera synchronized with the DLP projector by software captures the images from another direction. The captured images are processed by a single computer to reconstruct the 3-D shape using triangular-pattern phase-shifting algorithms, and the model is displayed in real time. The 3-D shape acquisition system achieved a speed of 5.6 fps for an image size of 648×494 pixels using the two-step triangular-pattern phase-shifting method, without any hardware synchronization or dual processing.

1. Introduction

Various optical methods for three-dimensional (3-D) surface shape measurement have been proposed and developed, some reaching commercialization [1-3]. Applications include, 3-D object modeling and recognition, mobile-robot navigation, and environment modeling/mapping. Structured-light methods have been used to acquire full surface-geometry information. Point-by-point [4,5] and line-by-line [6,7] techniques require the projected light to be moved across the object surface by a scanning mechanism [8] equipped with accurate position sensors. These approaches are slow and not practical for real-time 3-D shape measurement. Multiple-stripe methods achieve faster data acquisition, but introduce the correspondence problem [9-11]. Multi-frame coded patterns, which carry coordinate information of the projected points without considering geometrical constraints, have alleviated the correspondence problem. Recently, full-field optical 3-D shape measurement techniques [12-14] have gained great interest in the field of computer vision and object modeling as the surface-geometry information is acquired over a region of a surface rather than just at a point or line. Compared with other techniques, it has the benefit of fast measurement speed as it does not require scanning over the whole object surface. Moiré interferometry [15] and fringe projection methods [16-18] are good representatives of this technique. The methods allow relatively simple image-processing algorithms to extract the 3-D coordinate information, and remain non-contact and noninvasive, and have potential for real-time 3-D shape measurement. White light is generally used in full-field systems. This is advantageous in avoiding the speckle problem and in being eye safe compared to use of laser light.

Several real-time 3-D shape measurement systems [14,19-26] have been developed, with some success and some limitations. Almost all the existing real-time 3-D shape measurement systems measure the 3-D object by projecting a structured-light pattern, capturing the distorted pattern images from another direction, and processing them using certain algorithms to retrieve the 3-D information of the object. Single-coded-pattern methods [14,19-23] usually use color patterns to retrieve the 3-D information of the object.

These techniques usually can achieve high acquisition speeds, but with low measurement accuracy due to the impact of the color of the object surface or the color coupling and intensity imbalance. Multiple-coded-pattern methods [11,24-26] project and switch a series of coded patterns rapidly onto the object, and the 3-D coordinates of points on the object surface can be calculated by processing the images captured from another direction. Phase shifting based methods [14,24-26] usually can achieve high measurement accuracy, but low measurement speed because of the complicated computation and more images required to retrieve the 3-D information. Dynamic structured lighting based method [23] and binary coding-based methods [11] usually suffer from the correspondence problem and low spatial resolution can be achieved. For most systems, much and often most of the processing time is spent on tracking of stripe boundaries or code points [11,23], phase calculations [14,19,24-26] and image processing. The type of pattern greatly affects system performance [27], and an efficient pattern can reduce the cost of computation. Also, the best selected design for an entire model-acquisition pipeline is vital to a real-time system. Therefore, for real-time 3-D shape measurement, it is not sufficient just to speed up projection and acquisition by means of efficient hardware. It is necessary to design efficient patterns and an implementation pipeline for fast manipulation and processing to increase the efficiency of the entire system.

A new triangular-pattern phase-shifting approach [28], which combines the advantages of both traditional sinusoidal phase-shifting methods [16-18] and intensity-ratio methods [29,30], has recently been proposed. In this method, a triangular grey-level coded pattern is generated by computer software and used for projection. By applying newly developed decoding algorithms, an intensity ratio distribution can be obtained. The 3-D coordinates of the object can be obtained by applying an intensity ratio-to-height conversion algorithm, similar to the phase-to-height conversion algorithm [12,13,16-18] used in the traditional sinusoidal-pattern phase-shifting method. Compared with the traditional sinusoidal, trapezoidal [25], and previous linear-coded triangular [31,32] phase-shifting methods, this method involves less processing due to the combination of the simple computation of the intensity ratio and fewer images required to measure the 3-D object. This is advantageous when fast processing is important, as in real-time measurement. On the other hand, the extension [33] of the two-step triangular-pattern phase-shifting method to use additional steps with further phase-shifted images may be more appropriate for applications where higher measurement accuracy is required.

This paper describes a real-time full-field high-resolution 3-D shape measurement system developed using triangular-pattern phase-shifting. Furthermore, while most other real-time full-field measurement systems [11,14,24-26] rely on custom hardware and/or dual computers or processors, the real-time 3-D measurement system presented in this paper employs off-the-shelf components with no specialized hardware, circuits, or modifications to equipment, and only a single-processor PC computer. The system projects computer-generated fringe patterns with a triangular intensity profile via a DLP projector onto an object and the projected patterns are electronically shifted with high accuracy. A CCD camera synchronized by software with the video projector captures the images from another direction. The captured images are sent to the computer for processing to retrieve 3-D information with triangular-pattern phase-shifting algorithms. The reconstructed object is rendered and displayed on the monitor.

The remainder of this paper is organized as follows. Section 2 provides the decoding algorithms of the triangular-pattern phase-shifting method. Section 3 presents the working principle and implementation of the real-time 3-D shape measurement system developed. Section 4 presents measurement experiments. Section 5 compares the system with existing real-time systems, and the conclusion is given in Section 6.

2. Triangular intensity pattern phase-shifting algorithms

Triangular-pattern phase-shifting uses triangular intensity patterns shown in Figure 1(a) to reconstruct the 3-D object. The intensity equations used to generate the triangular pattern are formulated as follows:

$$I_i(x,y)=\begin{cases}\dfrac{2I_m(x,y)}{T}(x+\delta_i)+I_{\min}(x,y)+\dfrac{I_m(x,y)}{2} & x+\delta_i\in[0,\dfrac{T}{4}) \\ -\dfrac{2I_m(x,y)}{T}(x+\delta_i)+I_{\min}(x,y)+\dfrac{3I_m(x,y)}{2} & x+\delta_i\in[\dfrac{T}{4},\dfrac{3T}{4}) \\ \dfrac{2I_m(x,y)}{T}(x+\delta_i)+I_{\min}(x,y)-\dfrac{3I_m(x,y)}{2} & x+\delta_i\in[\dfrac{3T}{4},T)\end{cases} \tag{1}$$

$$I_m(x,y)=I_{\max}(x,y)-I_{\min}(x,y) \tag{2}$$

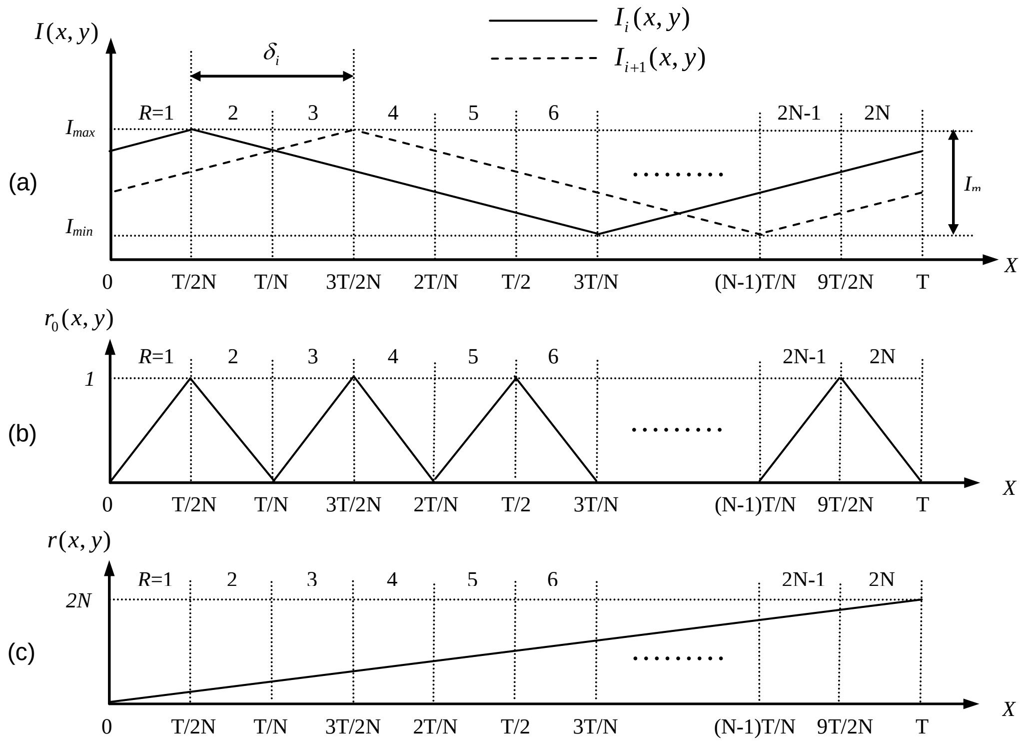

Figure 1. Triangular-pattern phase-shifting algorithm. (a) Two consecutive phase-shifted triangular intensity profile patterns, (b) intensity ratio as repeated triangles, and (c) intensity-ratio ramp after removal of the repeated- triangles.

where $I_i(x,y)$ is the intensity value of the *i*th phase shift triangular pattern at pixel (x,y) ; δ_i is the *i*th phase shift distance in the *X* direction; *T* is the pitch of the patterns; $I_m(x,y)$ is the intensity modulation, and $I_{\min}(x,y)$ and $I_{\max}(x,y)$ are the minimum and maximum intensities of the triangular patterns, respectively. To retrieve the 3-D information of the object, at least two samples are needed. These samples are taken at:

$$\delta_i = (i-1)\frac{T}{N} \qquad i = 1,2,......N,\ \ N \geq 2 \tag{3}$$

where *N* represents the number of shifting steps of the method. *N* = 2 is for the two-step method, 3 for the three-step, and 4 for the four-step method, etc.

The common equations for calculating the intensity ratio $r_0(x,y)$, essential for determination of the 3-D coordinates of the measured object, for different phase-shifting steps are summarized in Table 1.

After the operation by equations listed in Table 1 on the captured triangular pattern images, the triangular pattern is divided into different regions (Figure 1(b)), depending on the number of phase shifting steps. For two-step phase-shifting, it is divided into 4 regions; 6 regions for three-step; 8 for four-step; and 2*N* for *N*-step. For any phase-shifting method, the intensity ratio $r_0(x,y)$ has a repeated triangle shape with values ranging from 0 to 1. This shape can be converted to a ramp over the full pitch *T*, by applying the following equation:

$$r(x,y) = 2 \times round\left(\frac{R-1}{2}\right) + (-1)^{R+1} r_0(x,y)$$
$$R = 1,2,3,\cdots \tag{4}$$

where *R* is the region number (Figure1). The converted intensity-ratio ramp map *r*(*x*,*y*) shown in Figure 1(c), has values ranging from 0 to 4 for two-step phase shifting; 0 to 6 for three-step phase shifting; 0 to 8 for four-step phase shifting; and 0 to 2*N* for *N*-step phase shifting.

In fringe projection phase-shifting methods, repeated fringe patterns are used in order to reduce sensitivity to image noise and increase resolution [16-18]. In the triangular-pattern phase-shifting methods, the repeated triangular fringe patterns result in the intensity ratio being wrapped into the ranges given above for the intensity-ratio ramp map. The unwrapped intensity-ratio distribution is obtained by removing the discontinuity of the wrapped intensity-ratio image with an unwrapping method [34] modified from that commonly used in the sinusoidal phase-shifting method. An intensity-ratio-to-height conversion algorithm [28], based on the phase-to-height conversion algorithm [12,13,16-18] commonly used in the sinusoidal phase-shifting method, is then used to retrieve the 3-D surface coordinates of the object from the unwrapped intensity-ratio map.

3. 3-D shape measurement system

3.1. Approach

By synchronizing the pattern projection and the image capture, a fast or real-time 3-D shape measurement system could be achieved. Hardware-based synchronization could achieve higher measurement speed, but a synchronization circuit board [14,24-26] is necessary and a more expensive system would be needed. Software-based synchronization has the advantage of being low cost, without requiring specialized hardware, circuits, or modifications to equipment. Through software-based synchronization 3-D shape measurement experiments, the efficiency of the patterns and the best algorithms can be tested and determined. Hardware-based synchronization can be implemented if further development to further increase measurement speed is necessary. To achieve real-time 3-D shape measurement by software, in addition to the synchronization between the pattern projection and image capture, the 3-D data acquisition, intensity-ratio wrapping and unwrapping calculations, 3-D coordinate calculation and 3-D object rendering should be carried out simultaneously to increase the measurement speed. Parallel processing software, which fully employs multi-thread programming techniques, was used.

Table 1 Equations of intensity ratio developed for triangular-pattern phase-shifting measurement.

Phase Step	Equation for $r_0(x,y)$
2	$r_0(x,y)=\left\|I_1(x,y)-I_2(x,y)\right\|/I_m(x,y)$ where $I_1(x,y)$ and $I_2(x,y)$ are the intensities for the two shifted triangular patterns, respectively.
3	$r_0(x,y)=\left[I_{high}(x,y)-I_{med}(x,y)+I_{low}(x,y)-I_{\min}(x,y)\right]/I_m(x,y)$ where $I_{high}(x,y)$, $I_{med}(x,y)$ and $I_{low}(x,y)$ are the highest, median and lowest intensities of the three shifted triangular patterns at the same position in the range of the pitch, respectively.
4	$r_0(x,y)=\left\|\left\|I_1(x,y)-I_3(x,y)\right\|-\left\|I_2(x,y)-I_4(x,y)\right\|\right\|/I_m(x,y)$ where $I_1(x,y)$, $I_2(x,y)$, $I_3(x,y)$ and $I_4(x,y)$ are the intensities for the four shifted triangular patterns, respectively.
5	$r_0(x,y)=\left[I_{high}(x,y)-I_{med1}(x,y)+I_{med2}(x,y)-I_{med3}(x,y)+I_{low}(x,y)-I_{\min}(x,y)\right]/I_m(x,y)$ where $I_{high}(x,y)$, $I_{med1}(x,y)$ $I_{med2}(x,y)$ $I_{med3}(x,y)$ and $I_{low}(x,y)$ are the highest, second highest, third highest, fourth highest, and lowest intensities of the five shifted triangular patterns at the same position in the range of the pitch, respectively.
6	$r_0(x,y)=\left[I_{high}(x,y)-I_{med1}(x,y)+I_{med2}(x,y)-I_{med3}(x,y)+I_{med4}(x,y)-I_{low}(x,y)\right]/I_m(x,y)$ where $I_{high}(x,y)$, $I_{med1}(x,y)$, $I_{med2}(x,y)$, $I_{med3}(x,y)$, $I_{med4}(x,y)$ and $I_{low}(x,y)$ are the highest, second highest, third highest, fourth highest, fifth highest, and lowest intensities of the six shifted triangular patterns at the same position in the range of the pitch, respectively.

3.2. Implementation pipeline

To achieve real-time 3-D shape measurement, it is necessary to design an efficient implementation mechanism to integrate the hardware and software together to carry out fast processing. The entire measurement procedure includes several major processes. Each major process should be optimized and communicate with the others effectively to increase the entire processing speed.

The pipeline of the 3-D shape measurement system is shown in Figure 2. The measurement process includes several major steps. However, the time used in each step is different. To optimize the entire processing, the entire procedure should be separated into several groups. Each group that consists of one or more major steps can be implemented with a single thread. The entire procedure, shown in Figure 2, was separated into two, three, four and five groups and the initial testing indicated that four groups can achieve the highest measurement speed. These four groups are called: acquisition, wrapping, unwrapping, and reconstruction. The acquisition group consists of generating patterns, phase shifting, and capturing images; the wrapping group consists of intensity-ratio wrapping; the unwrapping group consists of intensity-ratio unwrapping; and the reconstruction group consists of 3-D coordinate calculation, 3-D object rendering and display. These four groups are implemented with the following four threads:

- Acquisition thread: this thread performs the pattern projection by the projector, phase shifting, and fringe pattern capture by camera continuously.
- Wrapping thread: this thread carries out the calculation of the intensity-ratio wrapping by applying phase-shifting algorithms to the images captured by the acquisition thread.
- Unwrapping thread: this thread is responsible for the intensity-ratio unwrapping by using the intensity-ratio unwrapping algorithm applied to the wrapped intensity-ratio map obtained by the wrapping thread.
- Reconstruction thread: this thread first performs 3-D coordinate computation by applying the intensity-ratio-to-height conversion algorithm to the unwrapped intensity-ratio distribution, acquired from the unwrapping thread, and then performs 3-D object rendering and display.

With the above configuration and implementation, the 3-D shape measurement system can perform 3-D shape measurement with the maximum measurement speed.

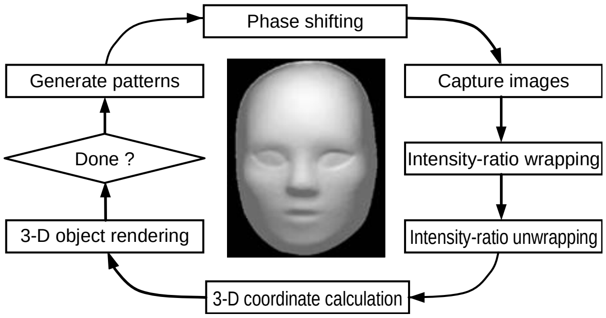

Figure 2. System implementation pipeline.

3.3. System setup

A schematic diagram of the experimental setup for the real-time full-field 3-D shape measurement system implemented by triangular-pattern phase-shifting is shown in Figure 3. The system consists of a computer (P4 3.04 GHz with 1 GB memory), a Digital Light Processing (DLP) projector (In Focus LP600, 8 bit), a CCD camera (Sony XCHR50, 8 bit), and a flat plate. The projector is used to project the computer-generated triangular fringe patterns onto the object surface. The CCD camera is used to capture images of the distorted triangular fringe patterns via a frame-grabber image-processing board (Matrox Odyssey XA) and the captured images are processed to retrieve the 3-D coordinates of points on the object surface. The system was calibrated [28] before performing any measurements. All experiments were performed using the same physical experimental system setup.

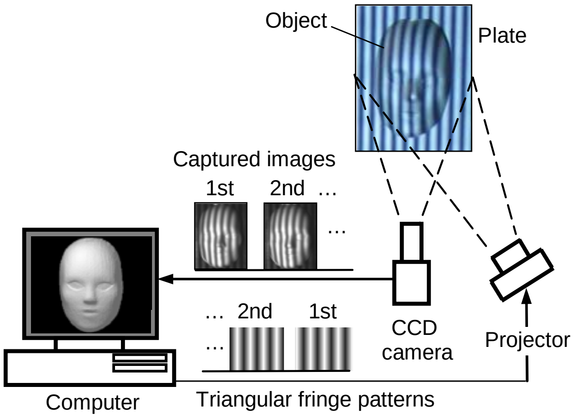

Figure 3. Schematic diagram of the 3-D shape measurement system based on triangular pattern projection.

4. 3-D shape measurement experiments

First, the measurement of a flat plate at a depth of 25 mm was carried out with the triangular-pattern phase-shifting method for different number of phase-shifting steps using optimal values of pitch [33] of the triangular fringe patterns to test the measurement accuracy of the system. The measurement accuracy determined with respect to ground truth depth and reported as a RMS value based on all image pixels was 0.66, 0.62, 0.42, 0.31, and 0.29 mm for 2-, 3-, 4-, 5- and 6-step phase shifting. The measurement accuracy increases with an increase in the number of phase-shifting steps. The minimum measurement error is RMS 0.29 mm for the six-step method.

In the real-time 3-D shape measurement experiment, a human facial expression measurement was carried out with the triangular-pattern phase-shifting method with different number of phase-shifting steps. The optimal value of pitch [33] of the pattern was chosen to generate the triangular pattern for each method. Figure 4 shows a human facial expression measurement procedure with the two-step triangular-pattern phase-shifting method. In this figure, (a) is a photo of the subject; (b) is one of the captured triangular-pattern fringe images of the two-shifted triangular pattern; and (c)–(e) are renderings of the reconstructed 3-D object. A sequence of dynamic human facial expression measurements by the two-step triangular-pattern phase-shifting method was recorded, and is shown in Figure 5. The measurement speed is approximately 5.6 fps. It is noted that during measurement, the subject was intentionally changing the expression and the facial expression was reconstructed by the system. The experiment results demonstrated that the 3-D shape measurement system can measure a slowly deforming surface in real-time.

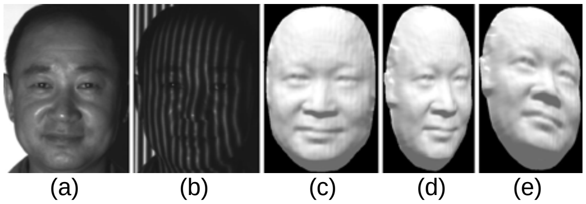

Figure 4. 3-D shape measurement of a human face with the two-step triangular-pattern phase-shifting method. (a) 2-D photo, (b) Captured triangular fringe image, (c) – (e) Reconstructed 3-D model.

Figure 5. Sequence of measurement results of human facial expressions with the two-step triangular-pattern phase-shifting method.

Triangular-pattern phase-shifting methods with different number of phase-shifting steps were also tested with human facial expression measurements. Figure 6 shows the result with the six-step method. The measurement speeds were 5.2, 4.8, 4.5, and 4.2 fps for the 3-, 4-, 5-, and 6-step methods, respectively. The more steps used in the triangular-pattern phase-shifting method, the slower the measurement speed was; however, the measurement accuracy increased with more phase-shifting steps. This can be seen by the smother surfaces obtained when more steps are used.

Figure 6. Sequence of measurement results of human facial expressions with the six-step triangular-pattern phase-shifting method.

5. Discussion

The most significant real-time 3-D shape measurement systems developed so far have been those developed by Rusinkiewicz [11], Huang [14], and Zhang [25]. In Rusinkiewicz's method, a structured light pattern consisting of many vertical stripes was used for projection, and a variant of the iterative closest point (ICP) algorithm was used to perform alignment. Four frames of projected patterns were captured and used to decode the range information using a complex algorithm. The method allows the users to rotate an object by hand and fill holes in the model in real time. The projector was synchronized to an NTSC camera by hardware. A dual-CPU system with Intel Pentium III Xeon processors running at 1.0 GHz was used to carry out image grabbing, stripe-boundary detection, matching, 3-D coordinate calculation, 3-D object rendering, and display. The system operates at a speed of 60 Hz with lower quality results. High quality measurement results could be achieved with offline registration and surface reconstruction with noise of about 0.1 mm that depends on the quality of camera and digitizer used.

Huang [14] presented a high-speed 3-D shape measurement system that uses a color sinusoidal fringe pattern to measure the 3-D object. When the color sinusoidal fringe pattern is sent to a modified DMD-based projector with the removal of the color filter, three gray-scale sinusoidal fringe patterns with a 120-deg phase shift are obtained. The 3-D information of the measured object is obtained by applying traditional sinusoidal-pattern phase-shifting method. The data are processed offline with the measurement resolution of 1 mm on a measurement area of 250 × 180 mm^2. Because the computation of phase involves a time consuming arctangent function, Zhang [25] presented an improved method, called trapezoidal-pattern phase-shifting method, to further increasing the processing speed. In this system, two Pentium 4 computers with 2.8 GHz processing speed were used, one for pattern projection and the other for image processing. The synchronization between projection and acquisition was implemented with a self-designed circuit board. By projecting three phase-shifted trapezoidal patterns with a modified DLP projector, the 3-D object is reconstructed by intensity ratio-to-height conversion instead of phase-based calculation at each pixel, and less processing time is required. For an image size of 532×500 pixels, the processing time needed was 4.6 ms compared to the sinusoidal-pattern phase-shifting method, which needed 20.8 ms to process. The total processing time for 3-D shape reconstruction was about 24.2 ms per frame. Specialized hardware and two computers were necessary.

The speed of a real-time 3-D shape measurement system depends on the processing algorithms, the speed permitted by the hardware, and the efficiency of communication between hardware and software. The processing algorithms play a critical role. The measurement system developed in the present paper has a measurement speed of 5.6 fps for measuring an object with the size of 368 × 280 mm^2 for the two-step method with an image size of 648×494 pixels, which seems slower than the systems described above [11,14,25]. However, it is noted that this system is based on a single-CPU computer, software synchronization only, and without any modification of hardware. This is major difference from the other systems described above. The most important feature of the proposed triangular-pattern phase-shifting method developed in this research is that the minimum number of measurements (sample images) that are required to reconstruct the unknown 3-D object is two, which is less than the number of measurement requirements of the systems described above [11,14,25]. It should be appreciated that each measurement, includes the image acquisition and computation on every pixel of an image, so the reduction of one image or phase-shifting step is a highly significant reduction of demand for processing. Furthermore, the coding and decoding algorithms to retrieve the 3-D information of the measured object are simpler than any methods described above. These two points suggest that with the same experimental setup including hardware synchronization, the two-step triangular pattern phase-shifting method would have the highest measurement speed. Synchronization of the pattern projection and image acquisition using hardware, to enhance the efficiency of the implementation mechanism developed in this paper, is anticipated for future work.

Even under the same number of phase-shifting steps, the triangular-pattern phase-shifting methods are expected to be faster than the sinusoidal-pattern phase-shifting methods with similar resolution. This is due to the sinusoidal-pattern phase-shifting methods involving a time consuming computation of non-linear functions to calculate phase (arctangent function for phase-shifting with more than two steps and arccosine for two steps [35]), while only linear computation is involved in the triangular-pattern phase-shifting methods. Trapezoidal-pattern phase-shifting [25] can only be applied with three phase-shifting steps.

6. Conclusion

An efficient 3-D shape measurement pipeline was proposed. Using this pipeline and the triangular-pattern phase-shifting method, a high resolution and real-time 3-D shape measurement system has been developed based on software synchronization, off-the-shelf components and a single-computer-processor. The measurement speed of 5.6 fps for measuring an object of size of 368 × 280 mm^2 was achieved by the two-step method. More accurate measurement can be achieved with more phase-shifting steps with lower measurement speed. A system with higher measurement speed could be achieved, using more advanced hardware found in other systems.

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