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Abstract. We describe a high-resolution, real-time 3-D shape measurement system based on a digital fringe projection and phase-shifting technique. It utilizes a single-chip digital light processing projector to project computer-generated fringe patterns onto the object, and a high-speed CCD camera synchronized with the projector to acquire the fringe images at a frame rate of 120 frames/s. A color CCD camera is also used to capture images for texture mapping. Based on a three-step phase-shifting technique, each frame of the 3-D shape is reconstructed using three consecutive fringe images. Therefore the 3-D data acquisition speed of the system is 40 frames/s. With this system, together with the fast three-step phase-shifting algorithm and parallel processing software we developed, high-resolution, real-time 3-D shape measurement is realized at a frame rate of up to 40 frames/s and a resolution of 532 $\times$500 points per frame. [DOI: 10.1117/1.2402128]

Subject terms: High resolution; real time; 3-D shape measurement; metrology; phase measurement; phase-shifting; structured light; range scanning.

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1 Introduction

High-resolution, real-time 3-D shape measurement for dynamically deformable objects has a huge potential for applications in many areas, including entertainment, security, design, and manufacturing. With the recent technological advances in digital imaging, digital projection display, and personal computers (PCs), it is becoming increasingly possible for 3-D shape measurement to be done in real time.

Among all the existing ranging techniques,[1] stereovision is probably the most studied. Traditional stereovision methods estimate shape by establishing spatial correspondence of pixels in a pair of stereo images. Recently, Zhang et al.[2] and Davis et al.[3] developed a new concept called spacetime stereo, which extends the matching of stereo images into the time domain. By using both spatial and temporal appearance variations, it was shown that matching ambiguity could be reduced and accuracy could be increased. As an application, Zhang et al. demonstrated the feasibility of using spacetime stereo to reconstruct the shapes of dynamically changing objects.[2] The shortcoming of spacetime stereo or any other stereo vision method is that matching of stereo images is usually time-consuming. Therefore, it is difficult to reconstruct high-resolution 3-D shapes from stereo images in real time.

Another major group of ranging techniques is structured light, which includes various coding methods and employs various numbers of coded patterns. Unlike stereovision methods, structured light methods usually use processing algorithms that are much simpler. Therefore, it is more likely for them to achieve real-time performance (measurement and reconstruction). For real-time shape measurement, there are basically two approaches.

The first approach is to use a single pattern, typically a color pattern. Harding proposed a color-encoded moiré technique for high-speed 3-D surface contour retrieval.[4] Geng developed a rainbow 3-D camera for high-speed 3-D vision.[5] Wust and Capson proposed a color fringe projection method for surface topography measurement with the color fringe pattern printed on a color transparency film.[6] Huang et al. implemented a similar concept but with the color fringe pattern produced digitally by a digital light processing (DLP) projector.[7] Zhang et al. developed a color structured light technique for high-speed scans of moving objects.[8] Since these methods all use color to code the patterns, the shape measurement result is affected to various degrees by the variations of the object surface color. In general, the more patterns are used in a structured light system, the better the accuracy that can be achieved. Therefore, these methods sacrifice accuracy for improved measurement speeds.

The other structured light approach for real-time shape measurement is to use multiple coded patterns but switch them rapidly so that they can be captured in a short time. Rusinkiewicz et al.[9] and Hall-Holf and Rusinkiewicz[10] developed a real-time 3-D model measurement system that uses four patterns coded with stripe boundary codes. The acquisition speed achieved was 15 frames/s (or a pseudo frame rate of 60 frames/s), which is good enough for scanning slowly moving objects. However, like any other binary-coding method, the spatial resolution of these methods is relatively low because the stripe width must be larger than one pixel. Moreover, switching the patterns by repeat-

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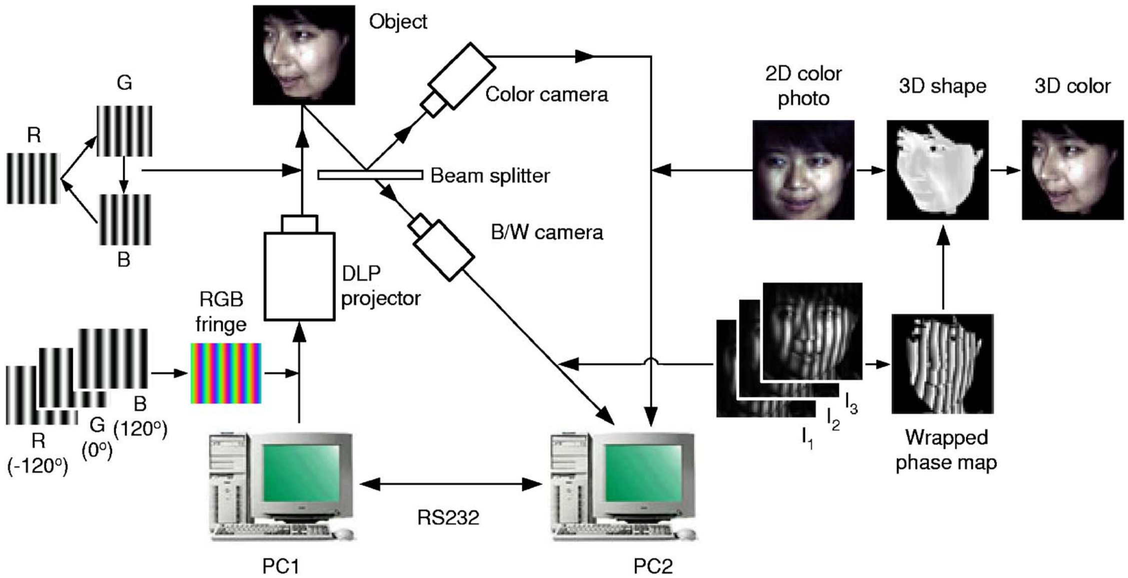

Fig. 1 Schematic diagram of our real-time 3-D shape measurement system. A color fringe pattern is generated by a PC and is projected onto the object by a DLP video projector (Kodak DP900). A high-speed B/W CCD camera (Dalsa CA-D6-0512W) synchronized with the projector is used to capture the images of each color channel. Then image-processing algorithms are used to reconstruct the 3-D shape of the object. A color CCD camera (Uniq Vision UC-930), also synchronized with the projector and aligned with the B/W camera, is used to capture color images of the object for texture mapping.

edly loading patterns into the projector limits the switching speed of the patterns and therefore the speed of shape measurement. Huang et al. recently proposed a high-speed 3-D shape measurement technique based on a rapid phase-shifting technique.[11] This technique uses three phase-shifted, sinusoidal grayscale fringe patterns to provide pixel-level resolution. The patterns are projected onto the object with a switching speed of 240 frames/s. However, limited by the frame rate of the camera used, the acquisition speed achieved was only 16 frames/s.

In this paper, we describe an improved version of the system developed by Huang et al. for real-time 3-D shape measurement.[11] This system takes full advantage of the single-chip DLP technology for rapid switching of three coded fringe patterns. A color fringe pattern with its red, green, and blue channels coded with three different patterns is created by a PC. When this pattern is sent to a single-chip DLP projector, the projector projects the three color channels in sequence repeatedly and rapidly. To eliminate the effect of color, the color filters on the color wheel of the projector are removed. As a result, the projected fringe patterns are all in grayscale. A properly synchronized high-speed black-and-white (B/W) CCD camera is used to capture the images of each color channel from which 3-D information of the object surface is retrieved. A color CCD camera, which is synchronized with the projector and aligned with the B/W camera, is also used to take 2-D color pictures of the object at a frame rate of 26.7 frames/s for texture mapping. With this system, together with the fast 3-D reconstruction algorithm and parallel processing software we developed, high-resolution, real-time 3-D shape measurement is realized at a frame rate of up to 40 frames/s and a resolution of 532×500 points per frame.

In Sec. 2, we discuss the working principle of the structured light system for real-time 3-D shape measurement. Section 3 describes the coding method. Section 4 explains the framework of the simultaneous 3-D data acquisition, reconstruction, and display system. Section 5 presents some experimental results, and Sec. 6 discusses the advantages of the proposed system. Section 7 summarizes the results obtained in this research.

2 Real-Time Structured Light System

Figure 1 shows the layout of the proposed structured light system for 3-D shape measurement, and Fig. 2 shows a picture of the developed hardware system. For the projection of computer-generated patterns, a single-chip DLP projector is used, which produces images based on a digital light switching technique.[12] The color image is produced by projecting the red, green, and blue channels sequentially and repeatedly at a high speed. Our eyes then integrate the three color channels into a full-color image. To take advantage of this unique projection mechanism using a single-chip DLP projector, we create a color pattern that is a combination of three patterns in the red, green, and blue channels, respectively. In the meantime, we remove the color filters on the color wheel of the projector to make the projector operate in a monochrome mode. As a result, when the color pattern is sent to the projector, it is projected as three grayscale patterns, switching rapidly from channel to channel (240 frames/s). A high-speed B/W camera, which is synchronized with the projector, is used to capture the three patterns rapidly for real-time 3-D shape measurement. An additional color camera is used to capture images for texture mapping.

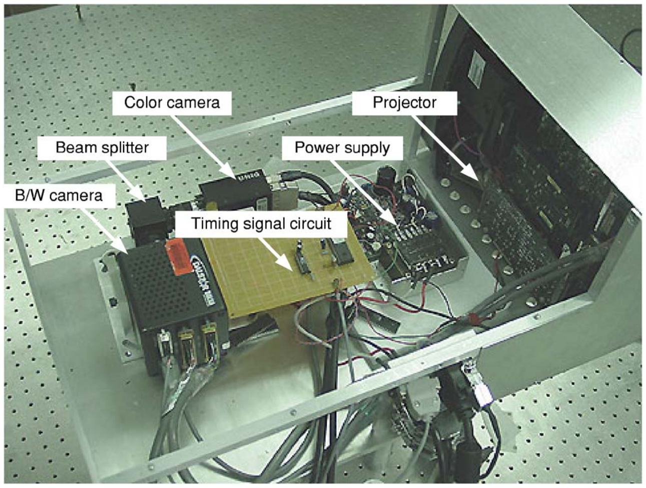

Fig. 2 Photograph of our real-time 3-D shape measurement system.

2.1 *Projector and Camera Synchronization*

Figure 3 shows the timing signals of our system. The projector trigger signal is generated externally by a microcontroller-based circuit. The internal timing signal of the projector is disabled. The projection timing chart indicates the sequence and timing of the projection of the color channels. The projection cycle starts with the red channel at the falling edge of the projector trigger signal. The camera trigger signal is generated by the same circuit, which guarantees its synchronization with the projector trigger signal. Because of the limitation in the frame rate of our B/W camera (maximum 262 frames/s), two projection cycles are needed for the camera to capture the three phase-shifted fringe patterns, which results in a frame rate of 40 frames/s for 3-D shape measurement. If a higher-speed camera is used, a maximum frame rate of 80 frames/s can be achieved. However, since the phase relationship between any two neighboring patterns is the same, any newly captured pattern can be combined with its preceding two patterns to produce a 3-D shape image. Therefore, the pseudo frame rate can be three times higher: 120 frames/s for the current system setup, and 240 frames/s if a higher-speed camera is used. Of course, any geometric changes on the object surface during the time when the three fringe patterns are captured may cause measurement errors. The color picture taken by the color CCD camera (Uniq Vision UC-930) can be mapped directly onto the 3-D shape once the correspondence of the two cameras is determined. To obtain 3-D and color information of the object simultaneously, multithreading programming was used to guarantee that the two cameras work independently and that the timing of image grabbing is determined solely by the external trigger signal.

2.2 *Texture Mapping*

For more realistic rendering of the object surface, a color texture mapping method is used. In the sinusoidal phase-shifting method, the three fringe patterns have a phase shift of $2\pi/3$ between neighboring patterns. Since averaging the three fringe patterns washes out the fringes, we can obtain a color image without fringes by setting the exposure time of the color camera to one projection cycle, or 12.5 ms. If the sinusoidal patterns are not truly sinusoidal due to nonlinear effects of the projector, residual fringes will exist. However, our experimental results show that such residual fringes are negligible and the image is in general good enough for texture mapping.

Since aligning the two cameras perfectly is difficult, it is necessary to perform coordinate transformation in order to match the pixels of the two cameras. For this purpose, we use projective transformation, which is good enough for texture mapping in this system. That is,

$$I_{\mathrm{bw}}(x,y) = PI_{\mathrm{c}}(x,y), \tag{1}$$

where I_{bw} is the intensity of the B/ W image, I_{c} is the intensity of the color image, and P is a 3×3 2-D planar projective transformation matrix. The parameters of the matrix P depend on the system setup, and only need to be determined once through calibration. Once the coordinate relationship between the two cameras is determined, we

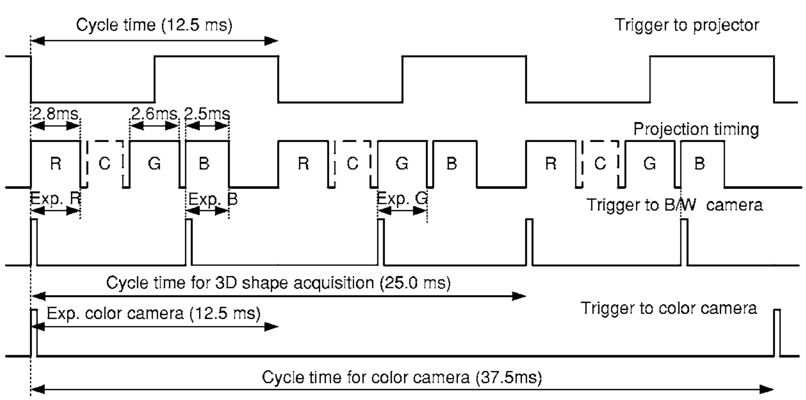

Fig. 3 System timing chart. The waveform at the top is the trigger signal to the projector, generated by a micro controller-based timing signal circuit. The second waveform from the top is the projection timing chart, where R, G, B, and C represent the red, green, blue, and clear channels of the projector. The clear channel is designed to enhance the brightness of the projected image. For the patterns used in this research, nothing is projected in this channel. The next two waveforms are the trigger signals to the B/W camera and the color camera, respectively.

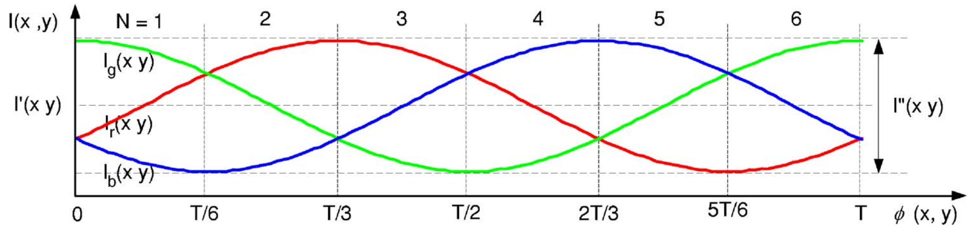

Fig. 4 Cross sections of the three phase-shifted sinusoidal patterns.

can identify the corresponding pixel of any 3-D image pixel in the color image for texture mapping.

It should be noted that we can also obtain a B/W image for the texture mapping by averaging the three phase-shifted fringe patterns. Since no additional images, B/W or color, need to be taken, this method is the fastest and is used in our experiment on high-resolution, real-time 3-D shape acquisition, reconstruction, and display.

3 Fast Three-Step Phase-Shifting Method

The proposed system provides us with the capability of projecting and capturing three coded patterns rapidly. In this research, we developed a fast three-step phase-shifting method that provides a real-time 3-D reconstruction speed and high measurement accuracy.

Sinusoidal phase-shifting method has been used extensively in optical metrology to measure 3-D shapes of objects at various scales. In this method, a series of phase-shifted sinusoidal fringe patterns are recorded, from which the phase information at every pixel is obtained. This phase information helps determine the correspondence between the image field and the projection field. Once this correspondence is determined, the 3-D coordinate information of the object can be retrieved by triangulation.

Many different sinusoidal phase-shifting algorithms have been developed. In this research, a new three-step phase-shifting algorithm similar to the traditional three-step algorithm[13] is used, which requires three phase-shifted images. The intensities of the three images with a phase shift of $2\pi/3$ are as follows (see Fig. 4 for the plots):

$$I_r(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) - 2\pi/3], \tag{2}$$

$$I_g(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y)], \tag{3}$$

$$I_b(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + 2\pi/3], \tag{4}$$

where $I'(x,y)$ is the average intensity, $I''(x,y)$ is the intensity modulation, and $\phi(x,y)$ is the phase to be determined.

Instead of calculating phase the $\phi(x,y)$ by an arctangent function as in the traditional phase-shifting algorithm, we developed a new algorithm to extract the phase by a direct intensity ratio calculation.[14] Similarly to what was done in our previously developed trapezoidal phase-shifting algorithm,[15] the sinusoidal fringe images can be evenly divided into six regions in one period ($T=2\pi$). Figure 4 shows the cross sections of the sinusoidal fringe patterns. We use the same equation developed for the trapezoidal phase-shifting method to calculate the intensity ratio. That is,

$$r(x,y) = \frac{I_{\text{med}}(x,y) - I_{\text{min}}(x,y)}{I_{\text{max}}(x,y) - I_{\text{min}}(x,y)}. \tag{5}$$

where $I_{\text{min}}(x,y)$, $I_{\text{med}}(x,y)$ and $I_{\text{max}}(x,y)$ are the minimum, median, and maximum intensities of the three patterns for point (x,y). The value of $r(x,y)$ ranges from 0 to 1 as shown in Fig. 5. The phase can then be calculated by the following equation:

$$\phi'(x,y) = \frac{\pi}{3}\left[2 \times \text{round}\left(\frac{N}{2}\right) + (-1)^N r(x,y)\right], \tag{6}$$

whose value ranges from 0 to 2π, as shown in Fig. 6. This equation provides the so-called modulo 2π phase at each pixel, whose value ranges from 0 to 2π. If multiple fringes are used, the phase calculated by Eq. (6) will result in a sawtoothlike shape, just as in the traditional phase-shifting algorithm. Therefore, the traditional phase-unwrapping algorithm can be used to obtain the continuous phase map.[16] This phase map can be converted to the depth map by a phase-to-height conversion algorithm based on triangulation. A simple phase-to-height conversion algorithm, which is used in this research, is described in Ref. 17. In this algorithm, surface height is considered proportional to the difference between the phase maps of the object and a flat reference plane, with the scale factor determined through calibration. Some complex but more accurate calibration methods are discussed in Refs. 18 and 19. Recently, Zhang and Huang developed an elegant and accurate algorithm for structured system calibration, which can significantly simplify the calibration.[20]

We can see from the nonlinearity of the curve in Fig. 6 that the phase calculation is not accurate, but has a small error. Theoretical analysis shows that the error is approximately 0.6%. Though this error is relatively small, it needs to be compensated for if accurate measurement is required.

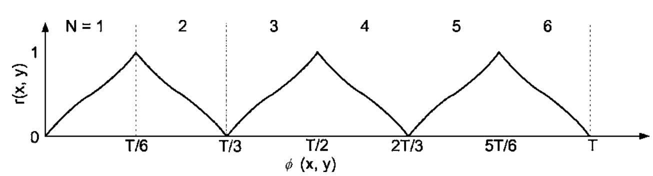

Fig. 5 Cross section of the intensity ratio map.

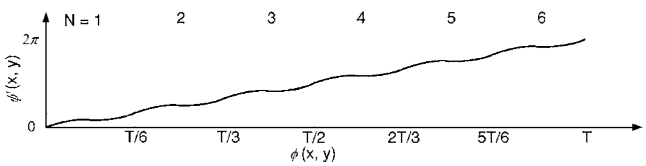

Fig. 6 Cross section of the intensity ratio map after removal of the triangular shape.

Since the ratio error is a systematic error, it can be compensated for by using a lookup table (LUT) method. In this research, an 8-bit camera is used. Therefore the LUT is constructed with 256 elements, which represent the error values produced by this processing algorithm. If a larger-bit-depth camera is used, the size of the LUT should be increased accordingly. Because of the periodic nature of the error, this same LUT can be applied to all six regions.

After error compensation, the reconstruction result using the proposed algorithm has similar accuracy to the traditional algorithm. But the improvement in processing speed is significant. In our experiment, we used an ordinary personal computer (Pentium 4, 2.8 GHz) for image processing. The traditional algorithm took 20.8 ms, while the proposed new algorithm took only 6.1 ms, which was 3.4 times less. With the implementation of this new algorithm in our real-time system, one 3-D reconstruction takes only approximately 12.5 ms, which makes real-time 3-D reconstruction feasible.

4 Real-Time 3-D Data Acquisition, Reconstruction, and Display

The system we developed could acquire and reconstruct 3-D data in real time. Our goal was to achieve simultaneous 3-D data acquisition, reconstruction, and display, all in real time. To reach our goal, parallel processing software employing a fast 3-D reconstruction algorithm is developed. This section discusses the framework of this real-time system.

Figure 7 illustrates the pipeline of real-time 3-D acquisition, reconstruction, and rendering system. The system includes three threads:

- *Acquisition*: A high-speed CCD camera captures fringe images in real time, and the fringe images are continuously sent to the computer.
- *Reconstruction*: A 3-D reconstruction algorithm based on the newly proposed fast phase-shifting algorithm is employed to generate 3-D models in real time.
- *Display*: The 3-D models are sent to the graphics card for display.

As has been discussed, the system is able to acquire 120 frames of 2-D fringe images per second. These 2-D images are then sent to the computer directly without any processing. Since the algorithm used in this research is the three-step phase-shifting algorithm, any three consecutive images can be used to reconstruct one 3-D model through phase wrapping and unwrapping. With the help of the fast 3-D reconstruction algorithm developed in this research, 3-D reconstruction can keep up with acquisition. For the current system, the typical reconstruction time for one frame is about 12.5 ms with a Pentium 4, 2.8-GHz CPU workstation. The reconstructed 3-D point clouds are then converted to 3-D geometric coordinates and sent to the graphics card for display.

Our experiments showed that a dual-CPU computer was necessary for this real-time system. One CPU handles the acquisition, while the other deals with the reconstruction and display. The reconstruction typically takes 12.5 ms of one CPU's time per frame. Therefore, only 12.5 ms is left for display, which is not enough for full-resolution (532×500 pixels) rendering. Experiments demonstrated that only $1/9$ of the points could be rendered in real time for the current algorithm. If a graphics processing unit (GPU) is utilized, full-resolution rendering in real time can be expected.

Three threads—the acquisition thread, reconstruction thread, and display thread—are used to realize real-time 3-D shape acquisition, reconstruction, and display. The acquisition thread is responsible for continuously capturing

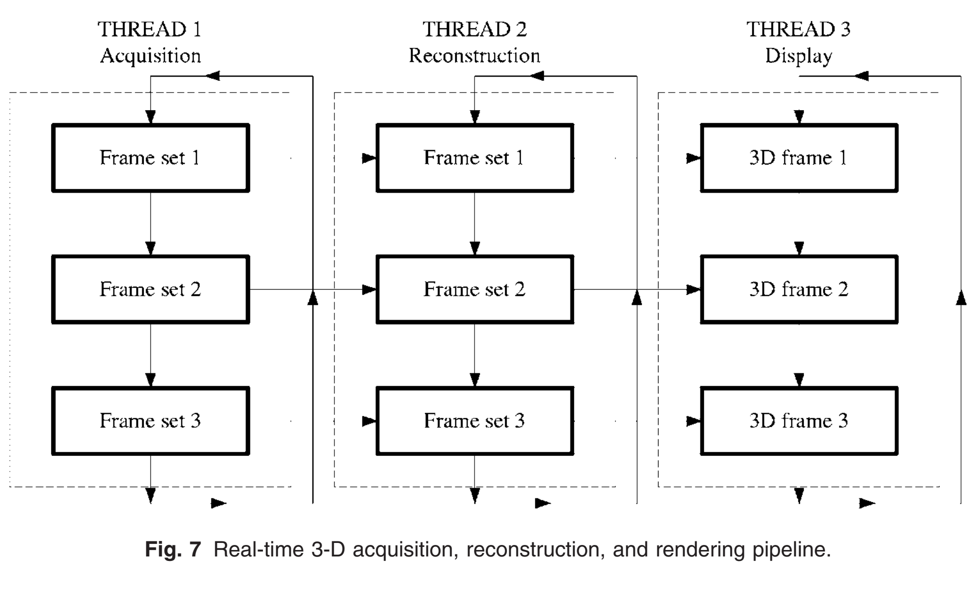

Fig. 7 Real-time 3-D acquisition, reconstruction, and rendering pipeline.

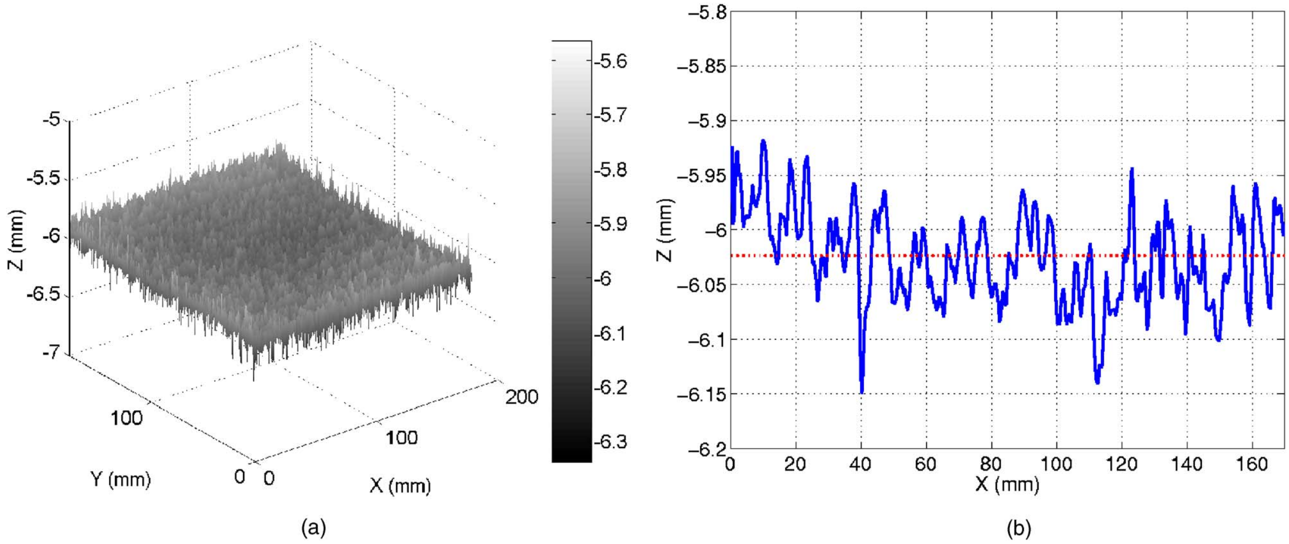

Fig. 8 Measured result on a flat board with a smooth surface. The measured area is 260×244 mm, and the noise is 0.05 mm rms. (a)3-D plot. (b) One example cross section.

fringe images from the camera. The reconstruction thread takes in the fringe images passed over by the acquisition thread, reconstructs the 3-D shape, and then passes the data to the display thread, where the 3-D shape is rendered. At any moment of time, if the acquisition thread is capturing frame set i (three image frames), the reconstruction thread is processing the immediately previous frame set $i-1$, and the display thread is rendering frame set before that $(i-2)$. Between the acquisition thread and the reconstruction thread, or the reconstruction thread and the display thread, there is always a delay of one frame. During the process, no frame of data is stored or remains in the memory for more than the time for acquiring three frames. That is, the fourth frame overrides the first frame, and so on.

5 Experiments

After calibration, we first tested the measurement noise of the system. Figure 8 shows the measured results on a flat board using the sinusoidal phase-shifting algorithm. Since the surface is very smooth, the variations shown in the results are largely due to the noise of the system, which measures approximately 0.05 mm rms for the whole measured area (260×244 mm).

We then measured human faces to test our system's capability of capturing 3-D dynamic facial changes. Figure 9 shows the results. During the acquisition, the subject was asked to smile, so that facial changes were introduced. The experimental results demonstrate that the system is able to measure moving objects with good accuracy. Figure 10 shows eight of the frames of the reconstructed 3-D models of a male and a female subject. It can be seen that detailed facial expression changes have been successfully captured. As an application, this type of high-quality models are being used for the tracking, learning, and transferring of facial expressions.[21]

In this research, we used a Dell Precision 650 workstation, with dual CPUs (2.8 GHz) and 1 Gbyte of memory, to accomplish simultaneous acquisition, reconstruction, and display. Figure 11 shows the experimental environment setup for our real-time 3-D system. To display the real-time result, an additional projector is utilized to project the computer screen onto a white board on the side of the subject. Figure 12 shows one image of a video sequence recorded during the experiments. The left image is a human subject, while the right image is the image generated by the computer in real time.

6 Discussion

The proposed real-time 3-D shape measurement system has several advantages over systems based on other methods:

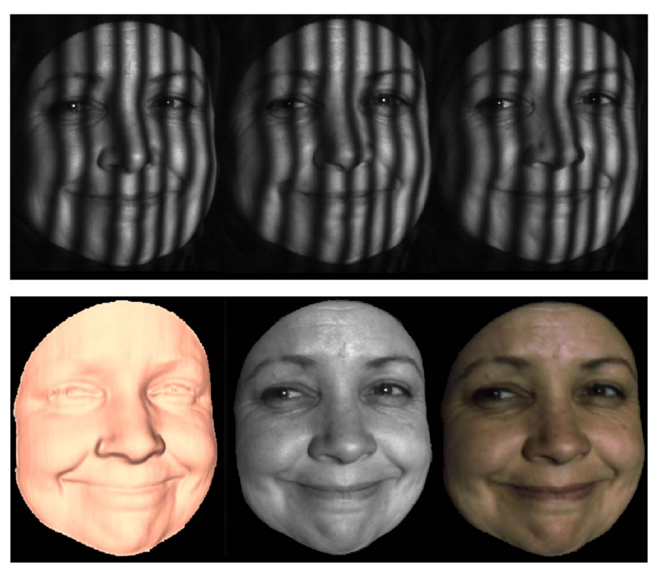

Fig. 9 Shape measurement of a human face. First row shows three phase-shifted fringe images. Images in the second row from left to right show 3-D shaded model, 3-D model with B/W texture mapping, and 3-D model with color texture mapping, respectively.

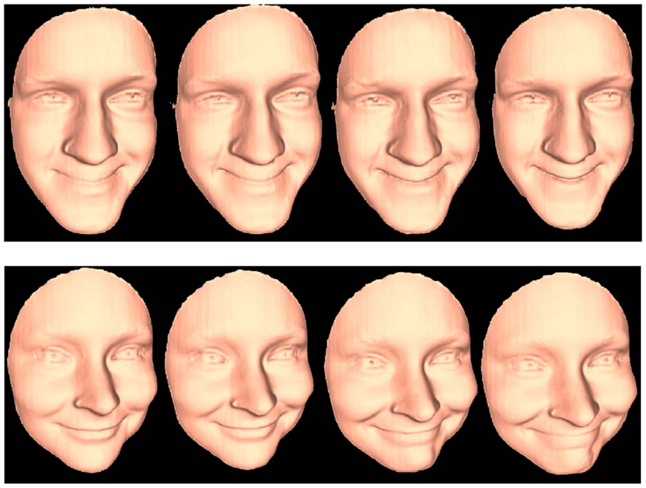

Fig. 10 Facial expression measurement results using our system.

Fig. 12 Experiment on real-time 3-D shape acquisition, reconstruction, and display.

1. *High resolution*: The phase-shifting method employed in this research provides a pixel-level resolution, which is much higher than that of stereovision or binary-coding methods.
2. *High acquisition speed*: Our real-time 3-D system has achieved a speed of up to 40 frames/s with grayscale texture mapping. With color texture mapping, the speed is reduced to 26.7 frames/s due to the limited frame rate of the color camera. The acquisition speed is already faster than that achieved by most of the other methods proposed. In the future, the acquisition speed can be further improved if a faster camera is used; the maximum achievable 3-D shape acquisition speed is 120 frames/s, which is determined by the projector.
3. *High processing speed*: With the fast phase-shifting algorithm, the processing time for 3-D shape reconstruction is reduced to approximately 12.5 ms per frame with a Pentium 4, 2.8-GHz PC.
4. *Large dynamic range*: Since the sinusoidal phase-shifting method is insensitive to the defocusing of the projected pattern, a relatively large depth can be measured, provided that the fringe visibility is good enough.
5. *Simultaneous 2-D and 3-D acquisition*: This is one of the unique features of the sinusoidal phase-shifting method. From the three phase-shifted fringe images, 2-D and 3-D information can be obtained simultaneously.
6. *Color tolerance*: Unlike those real-time systems based on color-coded structured light methods, this system uses B/W fringe images. Therefore the object color does not affect the measurement accuracy.
7. *Real-time acquisition, reconstruction, and display*: Since the phase-shifting algorithm is a pixelwise computation algorithm that does not require the computationally intensive stereo matching, high-resolution, real-time 3-D reconstruction is possible. Being able to achieve real-time 3-D shape acquisition, reconstruction, and display at high resolution is one of the most important advantages of the system.

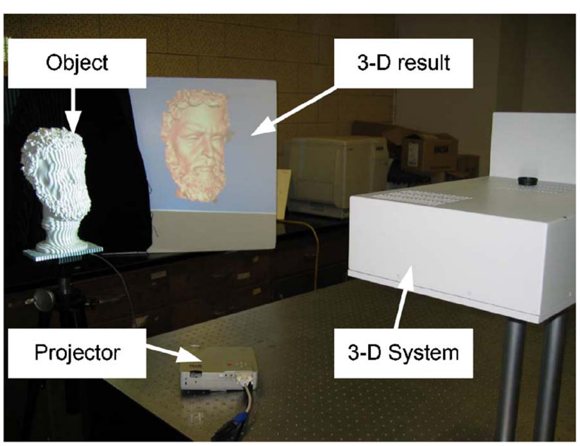

Fig. 11 Experimental setup for real-time 3-D shape acquisition, reconstruction, and display.

7 Conclusions

A high-resolution, real-time 3-D shape measurement system has been developed. The 3-D shape acquisition speed can be up to 40 frames/s for the current setup, or 120 frames/s if a higher-speed camera is used. A fast three-step phase-shifting algorithm was proposed for fast 3-D shape reconstruction. Using it with the fast 3-D shape reconstruction algorithm and the parallel processing software developed in this research, we realized simultaneous 3-D shape acquisition, reconstruction, and display at a frame rate of 40 frames/s and a resolution of 532×500 pixels per frame. The system is able to acquire dynamic 3-D models with B/W and color texture mapping. The noise level was found to be 0.05 mm rms in an area of 260×244 mm. This real-time 3-D shape measurement system has potential applications in many different fields, such as computer graphics, medical diagnostics, plastic surgery, industrial inspection, reverse engineering, and robotic vision. If infrared light is used; this system can also be used for security checks in homeland security applications.

Acknowledgments

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