

Recent progresses on real-time 3D shape measurement using digital fringe projection techniques

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ABSTRACT

Over the past few years, we have been developing techniques for high-speed 3D shape measurement using digital fringe projection and phase-shifting techniques: various algorithms have been developed to improve the phase computation speed, parallel programming has been employed to further increase the processing speed, and advanced hardware technologies have been adopted to boost the speed of coordinate calculations and 3D geometry rendering. We have successfully achieved simultaneous 3D absolute shape acquisition, reconstruction, and display at a speed of 30 frames/s with 300K points per frame. This paper presents the principles of the real-time 3D shape measurement techniques that we developed, summarizes the most recent progresses that have been made in this field, and discusses the challenges for advancing this technology further.

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1. Introduction

With recent advancements of digital technology, real-time 3D shape measurement plays an increasingly important role in enormous fields including manufacturing, medical sciences, computer sciences, homeland security, and entertainment.

Over the past few years, real-time 3D shape measurement technologies have been advancing drastically rapidly. For real-time 3D shape measurement, the 3D shapes have to be acquired rapidly, processing quickly, and displayed in real time. Time-of-flight (TOF) is one of the technique that is commercially used. For this technique, a single camera is used to measure the time delay of modulated light from an active emitter. Based on TOF techniques, Canesta (<http://www.canesta.com>) and 3DV Systems (<http://www.3dvsystems.com/>) have developed real-time 3D range scanning camera that allows the data being acquired and processed in real time. However, the achieved depth accuracy is usually not high due to its fundamental limitations of this technique. For example, Canesta achieved depth (z) uncertainty of 0.3–1.5 cm depends on the measurement condition [1].

Stereo vision is another technique that is extensively used for 3D shape measurement. For this technique, two cameras viewing from different angles are used to acquire a pair of images at the same time. By finding the corresponding pairs from both images, 3D information can be extracted. For this technique, the data acquisition speed is fast (as fast as the camera can reach). However, because this technique hinges on detecting the

corresponding pairs from two camera images, which is difficult for objects without strong surface texture information. In addition, because finding the corresponding pair is a fundamentally difficult problem, it is very difficult for them to reach real-time 3D shape reconstruction.

Spacetime stereo is another technique that has potential for high speed 3D shape measurement [2–4]. To resolve the correspondence problem, a projector is used to project a sequence of active patterns for assistance. In a short period of time, a number of structured patterns are projected and captured by the camera. The correspondences between two camera pixels are identified based on the actively projected structured patterns. By using the active structured patterns, stereo matching can be done rapidly, thus this technique has the potential to achieve real-time 3D shape measurement. However, this technique has some drawbacks: (1) for any measurement point, the projector and two cameras must be able to “see” it. Therefore, it only measures the overlapping regions of the three devices, which is much smaller than any of them; (2) because stereo matching is utilized, it is very difficult for this technique to reach pixel-level resolution.

A structured light system is similar to a stereo technique in that it only utilizes two devices for 3D shape measurement. It replaces one camera of a stereo system with a projector to project structured patterns [5], which are encoded with codewords through certain codification strategies. From the captured structured patterns, the codewords can be decoded. If the codewords are unique, the correspondence between the projector sensor and the camera sensor is uniquely identified, and 3D information can be calculated through triangulation. To reach high-speed 3D shape measurement, the structured patterns must be switched rapidly, and captured in a short period of time. Rusinkiewicz and Levoy

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developed a real-time 3D shape measurement system based on the stripe boundary code [6,7]. The 3D data acquisition speed is 15 frames/s, because capturing each structured patterns takes $\frac{1}{60}$ s while four patterns are required to reconstruct one 3D model. Most of the structured light systems use binary patterns, where only 0 and 1 s are used for codification. The advantages of using a binary method are: (1) *simple*, the coding and decoding algorithms are very simple; (2) *fast*, because the processing algorithm is very simple, it can reach very fast processing speed; and (3) *robust*, since only two levels are used, it is very robust to the noise. However, it is very difficult for this technique to reach pixel-level spatial resolution at very high speed, because the stripe width must be larger than one projector's pixel.

To increase the spatial resolution without reducing the measurement speed, multiple-level codification strategies were proposed at the sacrifice of increasing the sensitivity level to noise. Pan et al. developed color N-ary method for 3D shape measurement [8]. This system can be used to measure neutral color objects very well. However, because the color patterns are used, the measurement accuracy is affected by the surface color. The extreme case of an N-ary pattern becomes a trapezoidal shaped pattern when the graylevel increment is 1. Huang et al. developed this algorithm which is called trapezoidal phase-shifting algorithm [9]. For this algorithm, the pixel-level spatial resolution is reached and the measured speed is high since only three patterns are required. However, it requires that the projector and the camera are in focus to alleviate errors induced by the image blurring or defocus, albeit it is less sensitive to this problem since the errors are canceled out to a certain degree due to the special design of the patterns. Triangular shaped phase-shifting methods were also proposed for high-speed 3D shape measurement [10]. Jia et al. has successfully demonstrated that this technique could be used to measure smooth objects at very high speed. For this technique, it suffers if the projector or camera is not in focus. Moreover, since only two images are used, which are not sufficient to solve the so called “phase”. This method also requires the neighborhood pixel properties to ensure the success of the measurement. Guan et al. proposed a composite method for real-time 3D shape measurement [11]. In this method, different frequency and orientation of fringes are encoded into a single grayscale image. The different phases with different frequencies

were obtain through demodulation. They have successfully demonstrated that this algorithm could perform the measurement well. However, the data quality is not very high since only 8-bit fringe images were used.

When the binary, multiple-level, trapezoidal, or triangular shaped structured patterns are blurred to a certain degree, they all become sinusoidal in shape. Therefore, utilizing sinusoidal stripe patterns directly would be a natural choice. The technique that uses a projector to project sinusoidal patterns is called *digital fringe projection technique*, and if a phase-shifting algorithm is adopted, this technique is called *digital fringe projection and phase-shifting technique*. Digital fringe projection and phase-shifting method is essentially a special structured light technique with the structured patterns composing of sinusoidal stripes, which are then called *fringe images*. To reach high-speed measurement, a small number of fringe images are recorded and used for 3D shape measurement. In this paper, we mainly focused on real-time 3D shape measurement technique using the digital fringe projection technique, and especially on our recent explorations.

The paper is organized as follows. Section 2 explains the principle of real-time 3D shape measurement technique that uses a digital fringe projection and phase-shifting method. Section 3 details the real-time 3D shape measurement technique that we developed over the past few years. Section 4 presents the most recent advancements on this technology. Section 5 addresses some challenging tasks for the existing technologies, and Section 6 summarizes the paper.

2. Principle

2.1. Digital fringe projection system

Fig. 1 shows a typical digital fringe projection system. A computer generates the digital fringe patterns composing of vertical straight stripes that are sent to a digital video projector, the projector projects the fringe images onto the object, the object distorts the fringe images so that the vertical straight stripes are deformed because of the surface profile, a camera captures the distorted fringe images into the computer, and the computer then

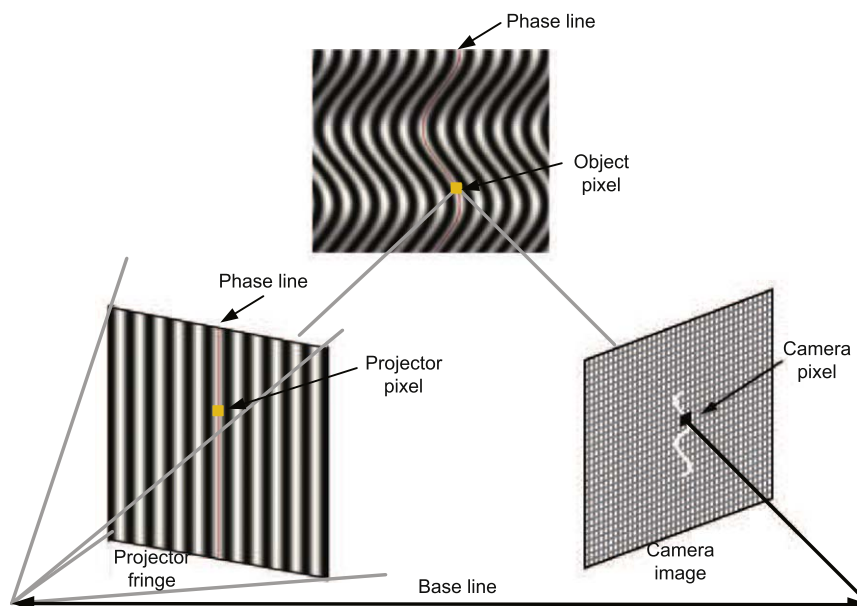


Fig. 1. Typical setup of a digital fringe projection and phase shifting system.

analyzes the fringe images to obtain 3D shape information based on the deformation using triangulation.

2.2. Phase-shifting algorithms

Phase-shifting methods are extensively utilized in optical metrology due to its advantageous features: (1) *point-by-point measurement*. Thus they can reach pixel-level measurement resolution; (2) *less sensitive to surface reflectivity variations*, therefore they can be used to measure very complex surfaces; (3) *less sensitive to ambient light*. They have less strict requirements for measurement conditions. A variety of phase-shifting algorithms have been developed, that include three-step, four-step, and least-square algorithms [12]. For real-time 3D shape measurement systems, a three-step phase-shifting algorithm is preferable, because the minimum number of fringe images are used to obtain 3D information. The phase shift is chosen as $2\pi/3$ because of its symmetric properties, and because of its less sensitivity to the nonlinearity errors. For this technique, three fringe images are utilized whose intensities can be expressed as

$$I_1(x, y) = I'(x, y) + I''(x, y) \cos[\phi(x, y) - 2\pi/3], \quad (1)$$

$$I_2(x, y) = I'(x, y) + I''(x, y) \cos[\phi(x, y)], \quad (2)$$

$$I_3(x, y) = I'(x, y) + I''(x, y) \cos[\phi(x, y) + 2\pi/3], \quad (3)$$

where $I'(x, y)$ is the average intensity, $I''(x, y)$ the intensity modulation, $\phi(x, y)$ the phase to be solved for. Solving Eqs. (1)–(3), we can obtain the phase

$$\phi(x, y) = \tan^{-1} \left[\frac{\sqrt{3}(I_1 - I_3)}{2I_2 - I_1 - I_3} \right], \quad (4)$$

and the texture or the 2D photograph without fringe stripes

$$I_t(x, y) = I'(x, y) + I''(x, y) = \frac{(I_1 + I_2 + I_3) + \sqrt{3(I_1 - I_3)^2 + (2I_2 - I_1 - I_3)^2}}{3}. \quad (5)$$

Eq. (4) only provides phase value with the range of $[-\pi, +\pi]$. If multiple fringe stripes are used, a phase unwrapping algorithm is necessary to obtain continuous phase map. This phase, often regarded as *relative phase*, is relative to one point on the phase map during phase unwrapping.

Absolute phase is the phase value that is relative to the pre-defined phases. In the digital fringe projection and phase-shifting system, the phase obtained from the computer generated fringe images can be regarded as the pre-known phases. To obtain absolute phase, at least one point on one connected patch must have the known phase value. A marker, such as a point, a line, or any other vivid features can be used as references to convert the relative phase to absolute phase. The marker is projected by the projector and captured by the camera. The software algorithm is then used to identify the marker points. Because the phase on the marker point is pre-defined, the relative phase needs to be shifted to ensure that the marker point phase is the same as the pre-defined value. Assume that the reference point on the computer generated fringe images has the absolute phase of 0, and on the camera image with the relative phase of ϕ_0 , the relative phase map can be converted to be the absolute phase map by the following equation:

$$\phi_a(x, y) = \phi(x, y) - \phi_0. \quad (6)$$

2.3. Phase errors reduction

Unlike traditional 3D shape measurement systems using phase-shifting method, where the phase shift error is drastic.

The digital fringe projection and phase-shifting method is not significantly affected by the phase shift error due to its digital fringe generation nature. However, because the projector is usually a nonlinear devices, the nonlinearity error is the dominant error source. Huang et al. proposed a technique that is to obtain the nonlinear gamma of the projector and then pre-distort the fringe patterns generated by the computer [13]. This technique reduces the errors significantly, however, the residual remains non-negligible. Zhang and Huang proposed a technique that can systematically reduce the nonlinearity errors completely by obtaining the gamma curve experimentally and analyzing the phase error in phase domain [14]. This technique can theoretically completely eliminate the errors caused by the nonlinear gamma of the projector. Because this type of error is systematic, the phase error look-up-table (LUT) which is a function of the phase can be created for error compensation. Moreover, similar technique can be used to correct the 2D photograph (texture image). However, the drawback of this technique is that it requires to obtain the gamma curve of the projector, which is a time consuming procedure. Besides, for some applications, the nonlinear curve might be difficult to obtain or even not possible. Zhang and Yau proposed a generalized method to alleviate the nonlinearity error of the system by analyzing the fringe images directly [15]. For this technique, a uniform white board is used as a calibration target to estimate the phase error caused by the nonlinearity of the projector, and to establish the LUT for error compensation. Because this technique does not require to obtain the nonlinear curve of the system, it can be applied to any measurement system that uses a phase-shifting technique.

2.4. System calibration

3D shape is carried on by the phase, therefore, 3D shape information can be retrieved from it. Conventionally, a reference plane is utilized, any measurement is relative to this reference plane [16,17], depth information (z coordinate) is proportional to the phase difference. However, the drawbacks of using a reference plane are:

- *Approximation*. Accurate coordinates for each point is very difficult to obtain.
- *Small range measurement*. The depth range must be very small relative to its distance from the hardware system. Otherwise, the approximation error is significant.
- *Inaccurate x and y coordinates*. This approach in general only obtains the depth z information, while x and y coordinates are ignored.

To avoid the approximation errors of the coordinate conversion, the system calibration has to be performed. Numerous system calibration techniques have been proposed [18,19], however, most of them are time-consuming and very difficult to achieve high accuracy. Legarda-Sáenz et al. proposed a method that uses absolute phase to find the marker center of calibration board for the projector by projecting a sequence of fringe patterns [20]. Through optimization, this method performed well in terms of accuracy. However, it requires the use of the calibrated camera to calibrate the projector, thus the calibration errors of the camera will bring into the projector calibration, which is not desirable. Zhang and Huang proposed a appealing method [21]. For this method, the fringe images are used as a tool to establish the correspondence between the camera pixel and the projector pixel so that the projector can “capture” images like a camera. By this means, the calibration of a structured light system becomes a well studied calibration of a stereo system. Since the projector and

camera calibration is independent, the calibration accuracy is significantly improved, and the calibration speed is drastically increased. Following their work, a number of calibration techniques have been proposed, which used various approaches to establish the relationship between the projector and the camera [22–25]. But essentially, they are the same. Once the system is calibrated, the xyz coordinates can be computed from the “absolute” phase, which will be addressed in the next subsection.

2.5. Absolute phase-to-coordinate conversion

Once the absolute phase map is obtained, the relationship between the camera image sensor and projector image sensor will be established as a one-to-many mapping, i.e., one point on the camera sensor corresponds to one line on the projector sensor with the same absolute phase value. This relationship provides a constraints for the correspondence identification of the camera-projector system. If the camera and the projector are calibrated in the same world coordinate system, and the linear calibration model is used for both the camera and the projector, the relationship between the camera image point and the object point in the world coordinates can be represented as

$$s^c\{u^c, v^c, 1\}^T = P^c\{x, y, z, 1\}^T. \quad (7)$$

Here s^c is the scaling factor, (u^c, v^c) the camera image coordinates, P^c is a 3×4 matrix that includes the camera intrinsic and extrinsic parameters, and (x, y, z) the object point in the world coordinate system.

Similarly, the relationship between the projector image point and the object point in the world coordinate system can be written as

$$s^p\{u^p, v^p, 1\}^T = P^p\{x, y, z, 1\}^T. \quad (8)$$

Here s^p is the scaling factor, (u^p, v^p) the projector image coordinates, P^p is a 3×4 matrix that includes the projector intrinsic and extrinsic parameters. Because the world coordinates from the point view of the camera and that of the projector, together with the absolute phase constraint, the world coordinates can be uniquely solved for [21].

P^c matrix can be obtained using a standard camera calibration software. The most popular method is to use a flat checkerboard method proposed by Zhang [26]. The system parameters can be estimated using the Matlab calibration Toolbox developed by Bouguet [27].

3. Real-time 3D shape measurement technique

As introduced in Section 1, in order to do real-time 3D shape measurement, 2D fringe images must be captured rapidly, and 3D shape must be reconstructed quickly, and the reconstructed 3D geometries must be displayed instantaneously in real time. Hence, it includes three tasks, acquisition, reconstruction, and display that must be completed simultaneously and quickly.

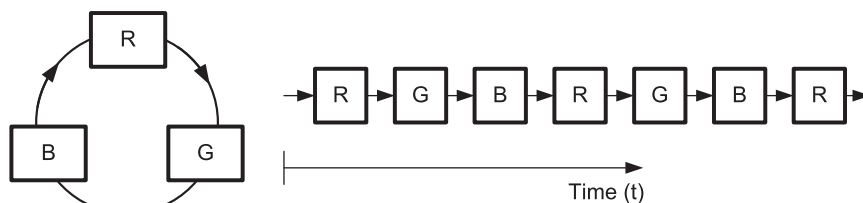


Fig. 2. Single-chip DLP projection mechanism. RGB channels are switches rapidly and repeatedly at very high speed.

3.1. Real-time fringe image acquisition

In order for high-speed 3D shape measurement, a natural choice is to use color by encoding three fringe images into red, green and blue (RGB) channels and capturing the color image using a color camera. Pan et al. extensively studied this technique by utilizing a 3-CCD color camera [28]. For this technique, one single color image is used to reconstruct one 3D model, the data acquisition speed is fast. However, like any other method using color, there are some unavoidable problems, such as color coupling problem and the problem related to object surface color. Therefore, the measurement accuracy is affected, to various degree, to the color of the object.

If all fringe images are projected in grayscale, they must be switched and projected rapidly so that they are captured in a short period of time. Switching the fringe images by software as that used in other systems [7,29] is limited by the graphics card speed and they can only reach 60 frames/s switching speed. We take advantage of the projection mechanism of the single-chip digital-light-processing (DLP) technology to reach fast image switching. For this technique, three primary color channels are projected sequentially and repeatedly which allows capture three color channel images separately if the camera is synchronized with the projector. Since the projector is projecting at its natural speed, the images switching speed is the fastest. Fig. 2 shows the projection mechanism of a single-chip DLP projector. The color wheel, which is composed of RGB color filters, is a circular disk that spins rapidly. The while light becomes color once it passes through the color wheel. By this means, the color light is generated. The digital micro-mirror synchronizes with the color light, reflects it, and form three color channel images. Therefore, the color channel images are output sequentially onto the screen. Because the projection speed is fast, our eyes cannot differentiate each individual color channels, instead only see a color image.

Fig. 3 shows the layout of the high-speed data acquisition system. Three phase-shifted fringe images are encoded as three primary color channels (RGB) of a color image. The color fringe pattern is sent to the single-chip DLP projector, that, when the color filters are removed, projects red, green, and blue channels rapidly and sequentially onto the object. A CCD camera, synchronized with the projector, is used to capture each color channel separately into the computer. Three phase-shifted fringe images are then used to reconstruct one 3D geometry through phase-wrapping, phase unwrapping, and phase-to-coordinate conversion steps. In addition, applying Eq. (5) to three fringe images will wash out the fringes and therefore will produce a texture image, which can be used for texture mapping purpose.

3.2. Real-time phase retrieval

The first two steps of 3D shape reconstruction are to wrap and unwrap the phase from the acquired fringe images. Therefore, these two algorithms play a key role for real-time 3D shape measurement. To boost the processing speed, Huang and Zhang developed a fast phase-shifting algorithm named “fast three-step

phase-shifting algorithm" [30]. They found that computing the phase, ϕ , using a standard function (e.g., *atan2* in C++) is too slow for real time applications. The algorithm introduced in this paper was to approximate the arctangent function with an intensity ratio calculation similar to that used in the trapezoidal phase-shifting algorithm [9]. And a small look-up-table is used to compensate the approximation error, which has been proven to be successful. By utilizing this algorithm, the processing speed is improved by 3.4 times faster.

Robust phase unwrapping, on the other hand, is very time-consuming since it involves a lot of computation as well as iterations. The processing time ranges from a seconds to minutes, and even to hours to process a standard 640×480 phase map [31]. Different phase unwrapping algorithms have been developed to improve the robustness of the phase unwrapping process, including the branch-cut algorithms [32–36], the discontinuity minimization algorithm [37], the L^p -norm algorithm [38], the region growing algorithm [39,40], the agglomerative clustering-based approach [41], and the least-squares algorithms [42]. However, they are generally too slow for high-resolution, real-time 3D shape reconstruction application. Some fast phase unwrapping algorithms, such as flood filling and scan line algorithms [17,43], can do real-time phase unwrapping, but they are very sensitive to the noise of the phase map. To solve the dilemma, Zhang et al. proposed a technique called "multilevel quality-guided phase unwrapping algorithm" [43]. For this

algorithm, the phase map are quantized into different quality levels. Within each level, a fast scan line algorithm is adopted. Because bad points are processed in later stages, the incorrectly unwrapped phase will not propagate extensively and thus will not drastically affect the whole phase unwrapping process. This algorithm is a good tradeoff between rapid but less robust and robust but time-consuming phase unwrapping algorithms. For measuring human face, where this system is mainly targeted at, this algorithm works reasonably well. Fig. 4 shows a typical measurement result of human facial expressions. It should be noted that because of the facial hair, the surface reflectivity variations are large, and the phase unwrapping is challenging. Our experiments demonstrated that even for this challenging object, this algorithm still performs very well by properly selecting the threshold and the number of levels to use.

3.3. Real-time 3D reconstruction and display

For real-time 3D shape measurement, the whole processing includes data acquisition, phase wrapping, phase unwrapping, coordinate calculation, and 3D rendering. It is very difficult for a single CPU to accomplish all these procedures. Parallel computation has to be adopted. However, because the data is so tremendous, the graphics card is heavily loaded for displaying the 3D points produced by the system, which is almost impossible

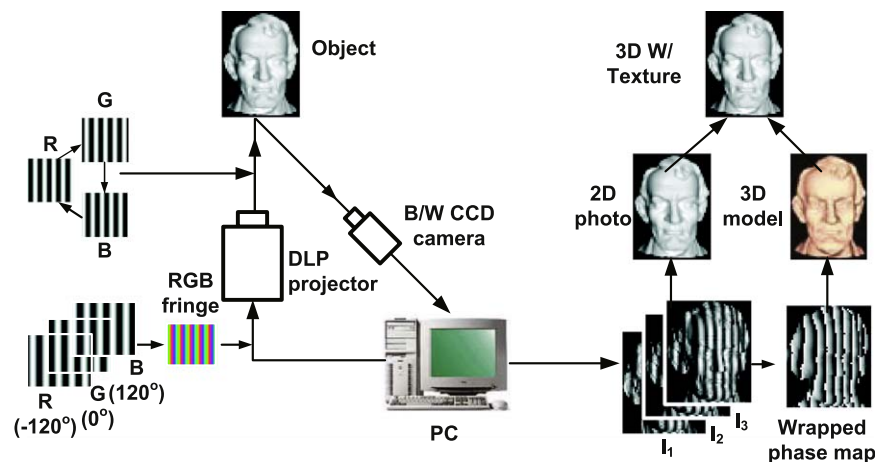


Fig. 3. Layout of the real-time 3D shape measurement system.

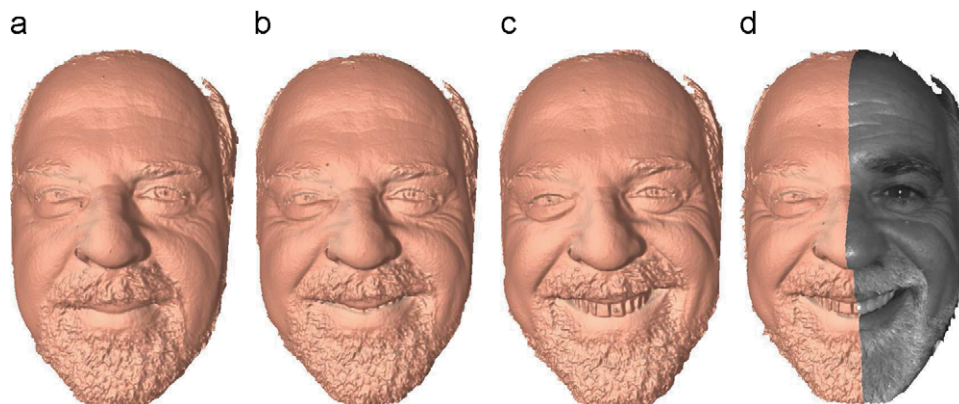


Fig. 4. Typical 3D reconstruction result using the multilevel quality-guided phase unwrapping algorithm. (a) Frame 1 rendered in shaded mode. (b) Frame 2 rendered in shaded mode. (c) Frame 3 rendered in shaded mode. (d) Frame 4 rendered in half shaded mode and half texture mode.

to transfer all data points to the graphics card for display with standard PCI bus. On the other hand, the absolute-phase-coordinate conversion is simple matrix operations, therefore can be computed by the most advanced graphics hardware technology, graphics processing unit (GPU).

Conventional GPU is a dedicated graphics rendering device. However, modern GPUs are very efficient at manipulating and displaying computer graphics, and their highly parallel structure makes them more effective than general-purpose CPUs for a range of complex algorithms. They are designed specifically for graphics and thus are very restrictive in terms of operations and programming. Because of their internal structure designs, GPUs are only effective at tackling problems that can be solved using stream processing. Similar to graphics rendering processing, the coordinate calculations are only smaller matrix operations, thus can be performed on GPU. Moreover, because the input data is phase point, the data passed to graphics card is only one third of the (x,y,z) coordinates, the PCI bus loading is drastically reduced. In addition, because the coordinates are computed on GPU, they can be rendered immediately without accessing CPU data. Thus, the rendering can be done very efficiently. Zhang et al. incorporated this technology into the real-time 3D shape measurement system and demonstrated that the processing speed increased drastically [44]. Fig. 5 shows an experimental result of measuring human face. The right figure shows the real subject, and the left shows the 3D geometry acquired and rendered on the computer screen at the same time. The simultaneous 3D data acquisition, reconstruction, and display speed achieved is 30 frames/s.



Fig. 5. Simultaneous 3D data acquisition, reconstruction, and display at 30 frames/s.

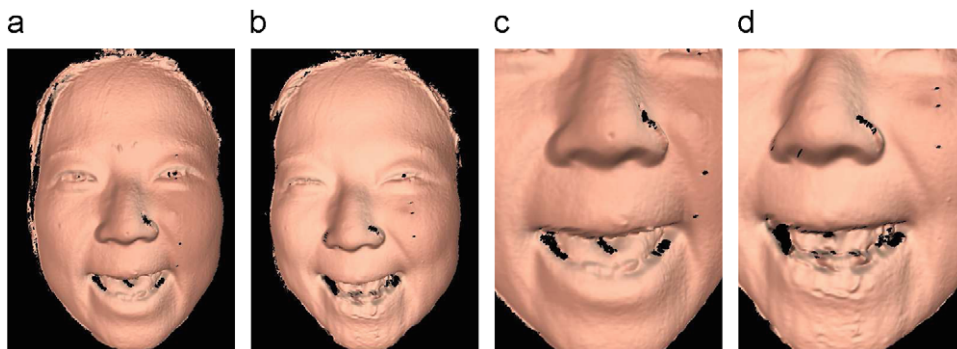


Fig. 6. Comparison between the measurement result of three-step phase-shifting algorithm and the 2 + 1 phase shifting algorithm. (a) 3D result using the modified 2 + 1 phase-shifting algorithm. (b) 3D result using three-step phase-shifting algorithm. (c) Zoom-in view of (a). (d) Zoom-in view of (b).

4. Recent progresses

After developed the first real-time 3D shape measurement system using a digital fringe projection and phase-shifting algorithm [45], we, as well as Prof. Huang's group from Stony Brook, have made tremendous progresses on improving this technology. The vast majority of our efforts have been devoted to reducing the errors caused by motion, extending the measurement range, and acquiring color texture simultaneously. This section will summarize these most recent progresses.

4.1. Motion error reduction

The assumption of the measurement is that during the period of three fringe images being captured, the object is motionless. However, in practise, it is very difficult to ensure it for dynamically deformable objects. Therefore, motion will bring some errors to the system. Some attempts have to be done to reduce the errors caused by motion.

Zhang and Yau tried a phase-shifting algorithm called modified 2 + 1 phase-shifting algorithm to alleviate the errors caused by motion [46]. For this technique, instead of using three fringe images, it utilized two fringe images with a phase shift of 90°, together with a uniform illuminated image. Three fringe images are

$$I_1(x, y) = I'(x, y) + I''(x, y) \cos[\phi(x, y) - \pi/2], \quad (9)$$

$$I_2(x, y) = I'(x, y) + I''(x, y) \cos[\phi(x, y)], \quad (10)$$

$$I_3(x, y) = I'(x, y). \quad (11)$$

From these equations, the phase can be calculated

$$\phi(x, y) = \tan^{-1} \frac{I_1(x, y) - I_3(x, y)}{I_2(x, y) - I_3(x, y)}. \quad (12)$$

The two fringe images are captured successively to reduce the data acquisition time. Since the uniform illuminated image is not very sensitive to the movement, this technique can reduce the measurement error due to motion.

Fig. 6 shows a comparison between the result using a three-step phase shifting algorithm and that using the modified 2 + 1 phase-shifting algorithm. The subject was asked to speak at similar speed during the experiments so that similar motion can be introduced around the mouth region. Figs. 6(a) and (c) show the measurement results by the proposed 2 + 1 phase-shifting algorithm. Figs. 6(b) and (d) show the measurement results by the three-step phase-shifting algorithm. This experiment shows that the new algorithm indeed can reduce the error caused by motion drastically. However, it should be noted that the technique has

larger random noise, therefore, phase unwrapping is more difficult.

Reduce the number of images for 3D reconstruction will increase the measurement speed. Fourier method, proposed by Takeda and Mutoh, that only uses a single image for 3D shape measurement is the best choice [47]. Guo and Huang implemented this method to the digital fringe projection system [48]. However, for the object with drastic surface reflectivity variations, this technique encountered significant problems. The same group then proposed a method that uses two images, one fringe image and one uniformly illuminated image to alleviate the problems caused by surface reflectivity variations. This technique is called modified Fourier method [49]. The reason of using a flat image instead of another fringe image is the same as the method proposed by Zhang and Yau [46]. The intensity of two images used are

$$I_1(x, y) = I'(x, y) + I''(x, y) \cos[\phi(x, y)], \quad (13)$$

$$I_2(x, y) = I'(x, y). \quad (14)$$

By applying Fourier transform to the difference image $I_1 - I_2$, they obtained decent result. Fig. 7 shows a comparison between the result using a three-step phase-shifting algorithm and that using the modified Fourier method. The subject was also asked to speak at similar speed during the experiments so that similar motion can be introduced around the mouth region. This experiment clearly demonstrated that the modified Fourier method can measure much faster motion than three-step phase-shifting algorithm because only a single fringe image is used to encode the phase value. This is encouraging since the number of fringe images required for 3D shape measurement is reduced, which means that the measurement speed can be increased drastically by applying this technique. At the same time, since only one single fringe image is used, some merits of the traditional phase-shifting algorithms are lost, for example, the robustness to surface reflectivity variation. Moreover, for this technique, the phase noise is much larger and the phase unwrapping becomes even more challenging.

4.2. Measurement range extension

A single camera and a single projector can only measures the region that the camera and the projector can “see”. To increase the measurement range, Zhang and Yau attempted to use multiple cameras with a single projector [50]. For this system, each camera captures only a part of the 3D shape. The 3D data pieces are registered with the assistance of the absolute phase [51], and then merged together using a technique called “Holoimage” [52]. Here only a single projector is utilized, absolute phase is unique, therefore, they should be aligned whichever camera acquires it. By implementing this technique, 3D shape measurement range can be extended to the whole area where the projector can project fringe images onto.

4.3. Simultaneous color texture acquisition

Real-time 3D shape measurement is not limited to optical metrology, where the texture, the photograph of the object, may not be very vital. With the recent advancements of real-time 3D shape measurement techniques, they have been applied to numerous fields including medical sciences, homeland security, and entertainment. For many fields, such as entertainment and medical sciences, the color texture is vastly essential to providing more information or enhancing better visual effect. Thus, obtaining precisely aligned color texture and 3D geometry in real-time is very important.

To solve this problem, we recently developed a technique that allows capturing the color texture and the 3D geometry simultaneously [53]. In this technique, we take advantage of one of the merits of the phase-shifting algorithm, pixel-by-pixel phase retrieval, to realize simultaneous color texture acquisition. This technique is successful because:

- *White light alleviates absorption problem.* If color is used, the object color will affect the measurement accuracy. For example, for a red object, the green and blue light will be

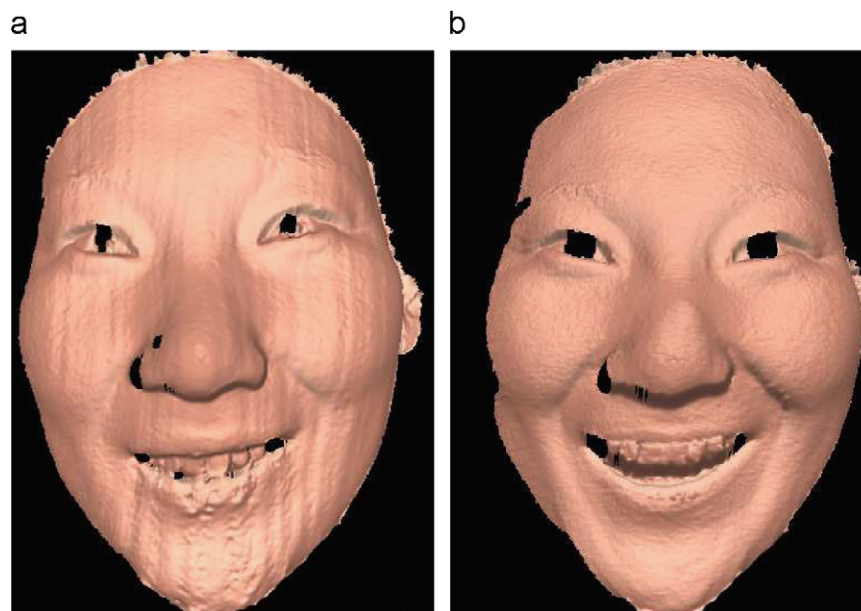


Fig. 7. Comparison between the measurement result of three-step phase-shifting algorithm and the modified Fourier method. (a) 3D result using three-step phase-shifting algorithm. (b) 3D result using modified Fourier method.

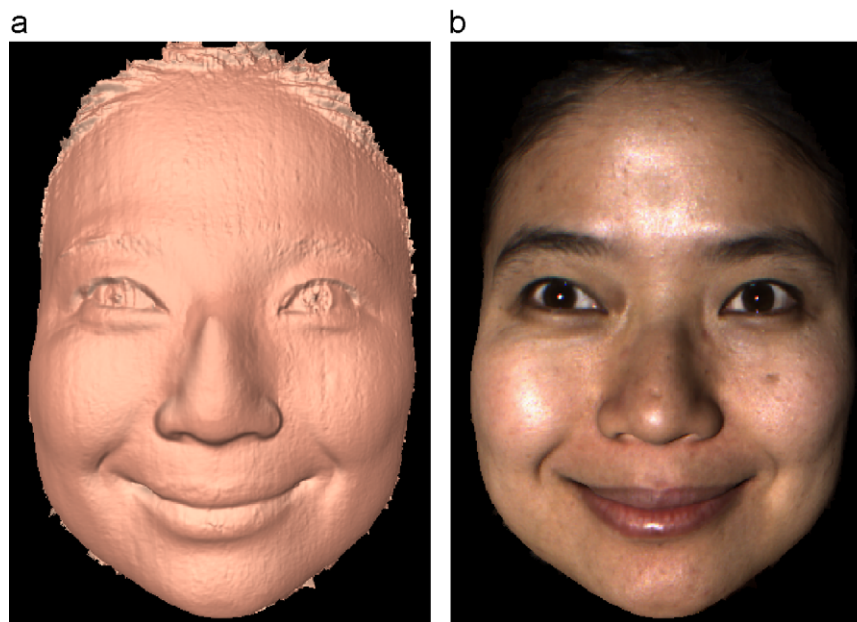


Fig. 8. Simultaneous color and 3D geometry measurement. (a) 3D geometric shape rendered in shaded mode. (b) The corresponding color texture acquired at the same time.

absorbed, thus the information carried on by these color channels will be lost. Instead of projecting color fringes, black-and-white (B/W) fringe images are used to alleviate this problem. Because the white light covers a wide range of spectrum, at least a part of the light projected by the projector will be reflected by the object and captured by the camera.

- *Phase-shifting algorithms are less sensitive to local surface reflectivity variations.* From Eq. (4), it is clear that (1) the phase calculation is point by point, (2) the numerator and denominator take the difference of fringe images, and (3) the division will cancel out the reflectivity coefficient. Therefore, theoretically, the phase should not be affected by the reflectivity of the object. However, in reality, because of the digitalization problem, the noise will play some role with a result of larger noise.

Thus, a single-chip color camera, or a 3-CCD color camera can be used to capture the reflected fringe images and perform the measurement. In addition, because applying Eq. (5) to three images will wash out the fringes, a B/W texture image can be generated. The texture image can be converted to color texture image by using a demosaicing algorithm (if a single-chip color camera is used), or taking each color channel intensity from the corresponding sensor. In our research, we used a single-chip color camera, which can produce high quality 3D geometry as well as color texture simultaneously. Because the single-chip color camera does not increase the cost significantly. This technique is essentially obtain the color texture for free. Of course, the noise of the data is larger and phase unwrapping is more challenging. Fig. 8 shows a typical measurement result of the human face by implementing this technique.

5. Challenges

To extend their applications to other fields, and to enhance their performances, real-time 3D shape measurement techniques have to increase the measurement speed, range, and capabilities.

Miniaturizing the real-time 3D shape measurement system will also be essential to enabling this technology enter into ordinary consumers. The challenges are huge, but the future is promising. In this section, we will address the paramount challenges facing the real-time 3D shape measurement techniques. It seems that the ultimate challenge is the fringe projection speed that is mainly limited by the current hardware technologies.

5.1. Simultaneous multiple-object shape measurement

The real-time absolute coordinates measurement system developed by Zhang and Yau [54], as well as our previously developed real-time systems [17,44,46], are limited to measure a single connected component where the marker is located, and smooth surfaces without step-height beyond $\pi/2$ between neighboring pixels. These are universal problems for 3D shape measurement system where a conventional spatial phase unwrapping algorithm is adopted. How to measure multiple objects simultaneously in real time becomes interesting. One solution is to use multiple markers, however, how many markers to use? Of course, the best solution would be to obtain absolute phase for each point without any markers to perform the measurement point by point. Multiple-wavelength phase-shifting algorithms can accomplish these tasks by increasing the number of fringe images used [55–59]. For these techniques, the minimum number of three frequencies are required [59], where at least nine fringe images are used. However, it reduces the measurement speed since more fringe images are required.

5.2. Ultra fast 3D shape measurement

The fastest speed 3D shape measurement system that uses three fringe images is 60 frames/s [46], which is sufficient to measure slow motion. However, to measure faster motion, for example, a beating rabbit heart, 300 frames/s speed might be mandatory. However, the projection speed of a digital video projector limits the data acquisition speed. The current digital display video projector typically projects at a maximum speed of

120 frames/s. A much faster projector is needed to boost the projection speed. Of course, if a multiple-wavelength technique is utilized, a faster projection system is almost mandatory for real-time 3D shape measurement.

5.3. Real-time panoramic 3D shape measurement

White light is used for 3D shape measurement to avoid the problems induced by color. However, for panoramic 3D shape measurement, white light will bring trouble. In order to measure real-time 3D shape from different angles, multiple camera-projector pairs have to be used. If all the projectors use white light, cameras cannot differentiate where it comes from, thus, the measurement cannot be performed properly. As addressed previously, using different spectrum of light for different projectors is not the ultimate solution because the measurement accuracy will be affected by the surface color. It seems that switching the projectors ON/OFF rapidly might be possible. The mechanical or optical shutters can be used for slow speed, but when the speed goes up to KHz, the ON/OFF switching becomes very challenging.

5.4. 3D shape measurement system miniaturization

Current real-time 3D shape systems using fringe projection techniques are relatively large, how to reduce the size and weight of the system is very important, especially when the technology is ready to go to consumer level. 3D shape measurement system based on a time-of-flight technique, a laser range scanning technique, or a stereo vision technique has already had miniature version of the system. The challenge for the fringe projection system is to reduce the size of the projector. Conventionally, the projector uses a Halogen lamp that generates tremendous heat. Moreover, the projector size is also very large. In recently years, projector companies including Mitsubishi, Samsung, Dell, LG, and Hitachi have launched their LED projectors, comparing with their Halogen lamp counterparts, these projectors are usually much smaller, which can be used to miniaturize the real-time 3D scanning system, although the output light intensity of the LED projectors is low at present. With the breakthrough of LED technologies, led by the Luminus, the high brightness LED projectors might come to the market shortly.

5.5. Real-time shiny parts measurement

Shiny parts are very common in manufacturing especially before surface treatments. How to measure shiny parts using optical methods itself is a very challenging problem. We recently proposed a technique that can measure shiny surfaces by multiple exposures [60]. The measurement speed is drastically reduced. Hu et al. proposed a technique that measure the shiny surfaces from different angles [61], this technique might be a good solution for real-time measurement purpose. However, the challenges for implementing this technique are essentially the same as those for the panoramic 3D shape measurement techniques. If real-time panoramic 3D shape measurement technique is realized, this problem can be easier to be solved for by measuring the shiny areas from different viewing angles.

5.6. High surface reflectivity range 3D shape measurement

Due to the artistic features or materials used, the object surfaces are diffuse but have large reflectivity variations. This type of surface differs from shiny parts in that the surface is diffuse, but it is difficult to measure these objects because the contrast of the

surface is very large. Zhang and Yau proposed a technique, that is called high dynamic range scanning technique, to deal with this time of objects [62]. The basic idea of this method is that by using multiple exposures and a phase-shifting method, different points are measured with different exposures so that the whole surface can be measurement completely, albeit it takes longer to perform the measurement. However, it remains challenging for any real-time measurement system to measure this type of objects at very high speed.

5.7. Accuracy evaluation

In manufacturing, the measurement accuracy is usually much more vital than the measurement speed. It is very important to evaluate the accuracy of the real-time 3D shape measurement system. It usually assumes that the object is motionless when the measurement is performed. However, for dynamically changing objects, this assumption might cause problem. Therefore, it is important to know how the motion will affect the measurement accuracy. For stationary object measurement, the accuracy of an optical system can be compared with that of a higher precision surface contact measurement system (e.g. CMM). It is well known the CMMs cannot perform high accuracy measurement in real time. The challenging problem now becomes to establish a standard for real-time 3D shape measurement so that the real-time optical system can be compare with. Unfortunately, there is no such system in exist.

5.8. Application exploration

This technology itself will not go much further without exploring its potential applications. We have successfully worked with computer scientists to explore its applications in computer vision and computer graphics [63,64], with medical doctors to investigate its potential value in diseases diagnosis [65], and with entertainment industrial colleagues to apply this technology to music video [66]. There are far more application to explore. Building the bridge between this technology and other fields is essential to driving the technology developments and to increasing their values. We expect that this technology will be used in more applications including homeland security, medical sciences, manufacturing, entertainment, and many more.

6. Conclusions

Real-time 3D shape measurement is increasingly important with its applications expanding rapidly to diverse areas. Rapid progresses have been made over the past few years, but challenges remain tremendous. This paper has presented the real-time 3D shape measurement techniques that we have developed over the past few years, explained the most recent efforts towards advancing this technology further, and addressed the challenges that we are facing or will encounter. We hope that this paper has guided the readers to know the state-of-art technologies in this field and motivated them to work on the challenging tasks.

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