PRECISE 3-D MEASUREMENT USING UNCALIBRATED PATTERN PROJECTION

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ABSTRACT

Three-dimensional measurement methods using structured light projection enable accurate depth measurements by decoding the disparity between the projector-camera pair from an observed pattern. However, actual projection devices have various systematic error sources that distort the structured light pattern, directly affecting the accuracy of 3-D measurements.

We propose a new method of measuring depth that is not affected by the systematic errors in the projected pattern. In our method, the image of a pattern projected onto a plane is referenced to cancel errors. Based on the invariance of the cross-ratio under perspective projections, depth is obtained from the disparity determined on the referenced image.

In experiments, our method removed the systematic errors and improved the accuracy of depth measurement without any extra calibration or measurement.

Index Terms— Structured light, 3-D measurement, phase, systematic error, cross-ratio, invariants, calibration

1. INTRODUCTION

Recent progress in non-contact 3-D measurement technologies has been extending the availabilities and applications of 3-D models. For example, being able to take precise 3-D measurements in a short time means that 3D models of the human body, which cannot remain motionless for a long time, can be obtained. Numerous new applications in the medical, clothing, and biometrics industries are being proposed. The key to putting these proposals into practical use is developing 3-D scanners that can be inexpensively manufactured, calibrated, and maintained without sacrificing accuracy or speed of measurement.

Many commercial 3-D scanners based on active stereo using projection of structured light patterns are now available. They offer accurate and robust 3-D measurements by stereo with the projector-camera pair, because the disparity is accurately recovered by decoding the observed pattern of the structured light. Numerous methods using various patterns including slit scanning, gray codes, and sinusoidal fringe have been proposed. [9]

Since calibrating both the camera and projector is time consuming and tends to cause errors, numerous methods have been proposed to make calibration of the projector-camera pair more efficient. One method calculates the depth directly from measured phase by referring to the phases previously measured at known depths. [4] This does not require any model parameters of the camera and projector, and it makes possible highly accurate calibration of a 3-D scanner by a very simple procedure: merely locating a plane at three known depths and measuring the phases.

The problem with the conventional methods is that the actual projection device has various systematic error sources that distort the structured light pattern. These errors directly affect to the phase and 3-D measurements. Hardware improvements are limited and costly. Either extra measurement time or enormous calibration costs are required by the conventional methods to suppress the effects caused by the errors. [2][3][5]

We propose a new method of accurately measuring depth that does not require precise pattern projection and does not increase measurement time or calibration costs. In contrast to the conventional methods, our method does not assume a model between the decoded phase value and the disparity. The phase measurement of a plane is referenced to cancel the systematic errors in the pattern projection.

We also discuss our experiments quantitatively and qualitatively, comparing our method to the conventional method. The results show that our method removed systematic errors and improved accuracy of the 3-D measurements without additional measurement or calibration.

2. 3-D MEASUREMENT BY PATTERN PROJECTION

In this section, we review the conventional methods of 3-D measurement using pattern projection and efficient calibration. We show that the accuracy of the depth measurements using the conventional methods is affected by the systematic errors in the projected pattern.

2.1. Obtaining disparity by pattern projection

Figure 1 illustrates the geometries of the camera, projector, and target points. Let us suppose that there is a depth measurement for camera image pixel P'. The target and reference points on the line of sight are denoted by $\{P_i\}$. Here we consider only the target point (i=3). P_1, P_2 and P_4

are referred in the efficient calibration method described in the next section. The projector image pixel projected onto P_i, and its longitudinal position are denoted by P^*_i, and s_i, respectively. s_i is encoded as phase ϕ_i of the intensity pattern in the time series, which is projected through P^*_i, and the phase is decoded from the pattern observed at P'.

Various patterns, including sinusoidal fringe, slit, and gray codes, were proposed. In the methods using sinusoidal fringe projection with N-step phase shift, [2] s_i is encoded into intensities $\{I_i^{(n)}\}$ (n=0, 1,…, N-1) as

$$I_i^{(n)}{}_i = A + B \sin(\phi_i + 2\pi\, n/N), \tag{1}$$

Here, $\phi_i = 2\pi\, p^{-1} s_i$, and p is the pitch of the pattern on the projector image. The decoded phase ϕ'_i is obtained from the observed pattern as

$$\phi'_i = \arctan\{\Sigma_n I_i^{(n)} \sin(2n\pi/N) \,/\, \Sigma_n I_i^{(n)} \cos(2n\pi/N)\}. \tag{2}$$

An un-wrapping algorithm is used to recover the lost multiples of 2π in the decoding by equation (2) when multiple patterns are projected. [10]

In the method using a slit pattern, s_i is encoded as phase $\phi_i = p^{-1} s_i$ of the pattern, $I_i^{(n)} = \delta(n-\phi_i)$, where p is the scanning speed. ϕ'_i is obtained as the time when the pixel intensity peaks. In the methods using gray codes, s_i is encoded as the binary pattern representing the integer portion of $\phi_i = p^{-1} s_i$, where p is the resolution parameter.

Anyway, the phase is designed to be linear to s_i and is decoded from the observed intensity pattern. If the camera, projector, and parameter p are calibrated, the position of P^*_i is obtained from ϕ'_i and the epipolar line of P'. The depth of P_i is obtained by stereo with the projector-camera pair.

2.2. Phase-to-depth mapping revisited

The phase-to-depth mapping directly calculates the depth from the phase using the measurements of the reference points. [4] Based on the invariance of the cross-ratio under a projective transformation, we give a different derivation of the method. This is the key to developing our new method.

Since the mapping from $\{\mathrm{P}^*_i\}$ to $\{\mathrm{P}_i\}$ is a perspective projection, the cross-ratio of the distances in 3-D space between $\{\mathrm{P}_i\}$, denoted by $C(\{\mathrm{P}_i\})$, is equal to that of the distances between $\{\mathrm{P}^*_i\}$, denoted by $C(\{\mathrm{P}^*_i\})$. Therefore,

$$C(\{\mathrm{P}_i\}) = (\overline{\mathrm{P}_1\mathrm{P}_3}\;\overline{\mathrm{P}_2\mathrm{P}_4}) \,/\, (\overline{\mathrm{P}_2\mathrm{P}_3}\;\overline{\mathrm{P}_1\mathrm{P}_4}) = C(\{\mathrm{P}_i^*\}). \tag{3}$$

It is obvious that the cross-ratio between depth coordinates $\{z_i\}$ of $\{\mathrm{P}_i\}$, denoted by $C(\{z_i\})$, is equal to $C(\{\mathrm{P}_i\})$; and the cross-ratio between $\{s_i\}$ is equal to $C(\{\mathrm{P}^*_i\})$. Therefore,

$$C(\{z_i\}) = C(\{\mathrm{P}_i\}) = C(\{\mathrm{P}^*_i\}) = C(\{s_i\}), \tag{4}$$

where $C(\{z_i\}) = \{(z_3-z_1)(z_4-z_2)\} \,/\, \{(z_3-z_2)(z_4-z_1)\}$.

The conventional methods assume that the encoding and decoding of the phase by equations (1) and (2) are perfectly implemented and that ϕ'_i is linear to s_i. Thus, they find the cross-ratio between the decoded phases to be equal to $C(\{s_i\})$. Substituting this to equation (4) leads to:

$$C(\{z_i\}) = C(\{\phi'_i\}). \tag{5}$$

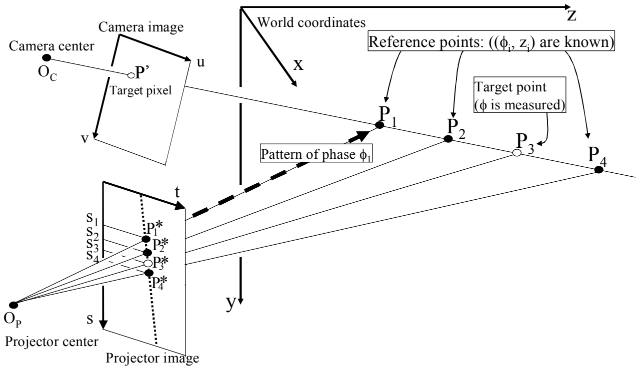

Figure 1: Geometry of camera, projector, target and reference points in 3-D space.

Phase-to-depth mapping [4] is derived by solving this equation for z_3.

$$z_3^{-1} = a\, \phi'^{-1}_3 + b \tag{6}$$

Mapping parameters a and b are determined by the regression to the reference measurements $\{z_i, \phi'_i\}$ (i=1, 2, 4). Therefore, depth z_3 can be directly calculated from phase ϕ'_3. This makes it possible to omit the calibration of the model parameters of the camera and projector. It is sufficient to obtain the three sets of measurements $\{z_i, \phi'_i\}$ for each pixel of the camera image, which is simply implemented by measurements of a plane located at the three known depths.

2.3. Problem of systematic errors in pattern projection

The conventional methods described above assume that the waveform of the projected pattern is accurate and that disparity is successfully decoded. However, the intensity and geometric profile of the structured light pattern projected by an actual device is distorted by the designed waveform of equation (1) due to numerous sources of systematic errors, including nonlinearity and hysteresis of the intensity synthesizer, the phase shifter and geometric distortions. There is a limit to which these errors can be reduced by improving the device, which increases the hardware cost. This is not a problem particular to the phase shift method. Even when another pattern is used, systematic errors in the projected pattern induce nonlinear errors in the decoded phase, which directly affects the depth measurements.

Those errors produce the phase errors of sinusoidal functions with spatial frequencies that are integer multiples of the projected pattern frequency. [3] For a method to be robust to these high frequency errors, many observations are required, which increases measurement time. [2] While numerous methods have been proposed to compensate for the errors by using nonlinear fitting [6] or local regressions [5] for the phase-to-depth mapping, a large amount of calibration data is required.

3. DEPTH FROM DISPARITY ON IMAGE OF PLANE

3.1. Obtaining disparity on image of reference plane

In this section, we propose a new method of accurately measuring depth without being affected by the systematic errors in the projected pattern. We show that the cross-ratio $C(\{P^*_i\})$, which is needed to obtain depth by equation (4), is obtained by referring to the phase measurements of a plane. Since the model between the phase and the disparity (positions of $\{P^*_i\}$) is not used, our method is not affected by the systematic errors in the phase.

During calibration, the reference plane is installed and the phase is measured. The phase measured at pixel (u,v) in the camera image is denoted by $\Pi(u,v)$. As shown in Figure 2, the intersection between projection ray $O_PP^*_i$ and the reference plane is denoted by P''_i, and the camera image of P''_i by P'_i. The mappings from $\{P^*_i\}$ to $\{P''_i\}$ and $\{P''_i\}$ to $\{P'_i\}$ are perspective projections. Since the cross-ratio is invariant under perspective projections, the next equation consists of:

$$C\{P^*_i\}=C\{P''_i\}, \text{ and } C\{P''_i\} = C\{P'_i\}. \qquad (7)$$

Thus, $C\{P^*_i\}$ can be obtained by determining the positions of $\{P'_i\}$. Since $\{P'_i\}$ lies on line l_e, which passes target pixel P' and the epipole of the projector, P'_i is determined by searching where $\Pi(u,v)=\phi_i$ on l_e. However, this requires calibration to determine the epipole.

If projection of another pattern, whose phase varies along the lateral direction, is available, the positions of $\{P'_i\}$ are determined by the two phases. In this case, the epipole need not be known.

3.2. Extension to omit the epipole calibration

In this section, we extend our method to omit the epipole calibration in cases using the single pattern projection. We show that a feature of the widely used pattern leads to this extension, which enables us to use a projector that is not able to generate complex patterns.

Here, we assume that the projection pattern satisfies the following two conditions: phase contour Φ^*_i, which is a set of projector image points through which the pattern of the same phase ϕ_i is projected, forms a straight line and; all contours $\{\Phi^*_i\}$ are parallel or intersect at a single point. These conditions are acceptable for many of the existing 3-D scanners because the patterns used in those systems are uniform in the lateral direction. As illustrated in Figure 3, the phase contours of the pattern projected on the reference plane, denoted by $\{\Phi''_i\}$, and the camera image of $\{\Phi''_i\}$, denoted by $\{\Phi'_i\}$, are perspective images of $\{\Phi^*_i\}$. Therefore, $\{\Phi''_i\}$, and $\{\Phi'_i\}$, are straight lines crossing at a single point.

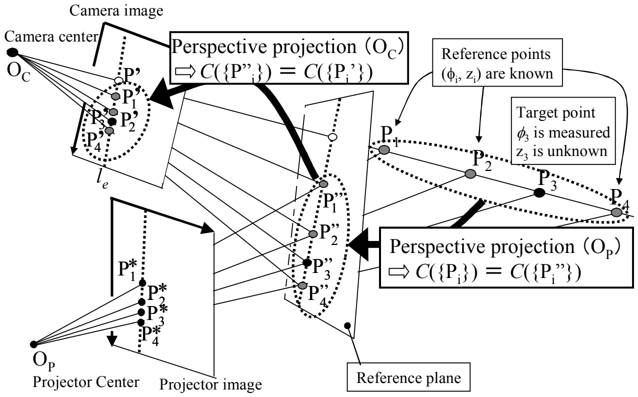

Figure 2: Cross-ratio of depths between $\{P_i\}$ is equal to cross-ratio of distances between image points $\{P'_i\}$.

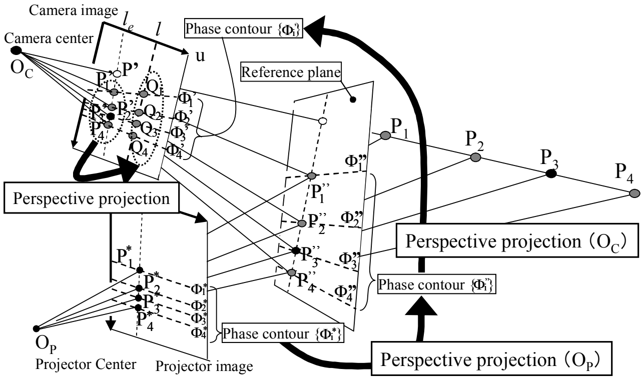

Figure 3: When projection pattern is uniform in lateral direction, Q_i is point of P'_i transformed by perspective projection. Therefore, cross-ratios are invariant.

Let us choose an arbitrary straight line l on the camera image, and determine points $\{Q_i\}$ on l so that the phase of Q_i is equal to that of P_i, i.e. $\Pi(Q_i)=\phi_i$. Here, the mapping from $\{P'_i\}$ to $\{Q_i\}$ along phase contours $\{\Phi_i\}$ is a perspective projection, and the cross-ratio of the distances between $\{Q_i\}$ is equal to the cross-ratio of the distances between $\{P'_i\}$. Consequently along with equation (4) and (6), $C(\{P_i\})$ is equal to $C(\{Q_i\})$.

This demonstrates that we can choose an arbitrary line, determine $\{Q_i\}$ where $\Pi(u,v)=\phi_i$ on it, and calculate $C(\{Q_i\})$, which is equal to $C(\{P_i\})$. Therefore, l_e and the epipole need not be known.

4. EXPERIMENTAL RESULTS

Our method was applied to a 3-D scanner that uses sinusoidal fringe projection. [8] The benefits of our method were evaluated by comparing them to the results of the conventional method [4] using the same inputs.

Table 1: Depth measurement accuracy.

	Conventional	Proposed
RMS error in depth [mm]	0.137	0.125

4.1. Experimental setup

The 3D scanner used in the experiments consisted of a camera and a projector equipped with film and mechanisms for phase shifts. The sinusoidal pattern was printed on the film so that the transparency of the film varied as a sine function along the longitudinal direction. The film was shifted by the mechanisms by a quarter of the pitch of the printed pattern to implement four-step phase shifts. [2] However, there actually exist systematic errors in the transparency and the phase shifts, so that the observed pattern was systematically distorted from a sine function.

The origin of the coordinates of the measurement was 760 mm from the camera. Following the conventional calibration method, a plane was located at three positions z=0, 99, and 198 mm orthogonal to the z-axis, and the phases were measured to obtain reference point data. The phase measurements obtained at z=99 mm were used as $\Pi(u,v)$ in our method (see section 3.1), which means that no extra calibration was conducted. The positions of $\{P'_i\}$ in Π were determined up to the sub-pixel level by linear interpolation. The resolution of the camera image was 480∗640 pixels and the field of view was about 250∗330 mm at z=150 mm.

4.2. Improvement of depth measurement accuracy

For the quantitative evaluations, the measurements of a plane were taken at seven positions from z=1.5 to 181.5 mm in 30–mm intervals. The measurements were repeated five times at each position. Table 1 shows the average RMS error for measured depth. Our method reduced the error by 10% in comparison with the conventional method, although both methods used exactly the same data as inputs.

4.3. Qualitative evaluation: human face measurements

Figure 5 shows the results for measurements of a human face. The image of the projected pattern is shown in the left column, and the images in the center and right column shows the computer graphics rendered by flat shading from the 3-D models calculated by the conventional method [4] and our method, respectively. The result of the conventional method exhibited systematic errors that look like stripes. These errors were successfully removed by our method, although both methods use exactly the same data as inputs. Note that our method is not a smoothing technique: the ‘stripes’ in the conventional method image were removed, but random noises were not.

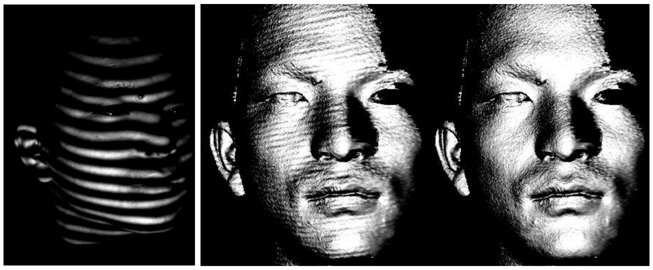

Figure 4: (left) Image of a projected pattern, (center) graphics generated from resulting 3-D models by conventional method, and (right) proposed method.

5. SUMMARY

We have proposed a new method of taking precise 3-D measurements without requiring precise pattern projection. In our method, the phase image of the pattern projected onto a plane is referenced to cancel systematic errors. Based on the invariance of the cross-ratio under perspective projections, depth is obtained from the disparity which is determined on the referenced phase image. Since the measurement of a plane is already included in the standard calibration procedures of the conventional methods, our method does not incur any extra calibration costs.

The results of our experiment showed that our method removed systematic errors in the resultant 3-D shape data and reduced the depth measurement error by 10% as compared with the conventional method, without any extra calibration cost or extra measurement time.

6. REFERENCES

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