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A high-speed 3-D image measurement method

Abstract With the recent popularization of digital cameras and projectors, practical applications of three-dimensional (3-D) image measurements based on intensity-modulation pattern projection are eagerly anticipated. Such an approach would permit a projection pattern to contain more measurement data, allowing 3-D data to be calculated with greater accuracy. However, to achieve a high level of accuracy using this approach, it is essential that an ideal observation pattern image should be obtained with a certain minimum number of stripes and a certain intensity distribution. To satisfy these requirements, an intensity correction method with two observation pattern images has previously been used. It is difficult to measure a fast-moving object in such calculations because the correspondence relation of the measured object is not established between the two photographic images, and consequently the pattern intensity is not corrected accurately. This study proposes an image analysis method for correcting intensity using an image synthesis technique that extracts precise stripes from a single observation pattern image. This analysis method allows 3-D shape measurements to be performed from a single projection pattern and a single image capture.

Key words 3-D shape measurement · Optimal pattern projection · Intensity modulation · Image synthesis

1 Introduction

Three-dimensional (3-D) shape measurement has a wide range of applications, including product quality inspection, face recognition, body surface evaluation, surgery simulation, and biomedical engineering modeling. Popular 3-D shape measurement techniques include stereo vision techniques, structured pattern projection, and the moiré method.

We have developed a 3-D shape measurement technique that employs optimal intensity-modulation pattern projection. It provides 3-D information from a single pattern projection. It is expected that it will be used in practical applications in the near future. However, if the target has complex color or surface reflection properties, it is necessary to remove the effects of these properties. This involves using another reference image to correct the intensity of the observed pattern. This measurement is difficult for a fast-moving object because the correspondence relation of the object is not determined between the two images, and thus the pattern intensity is not corrected accurately.

In this article, we propose a high-speed 3-D image measurement method based on optimal intensity-modulation pattern projection, in which a structured monochrome pattern is projected and a color image of the observation pattern is captured. We describe a method for analyzing the pixel intensity distribution to realize precise 3-D measurements. Unlike conventional methods, this method uses a single projection of a single captured image. The proposed method achieves not only a higher detection accuracy and faster computation in the analysis of the pixels in the intensity distribution, but also a better measurement of fast-moving objects since it requires only a single captured image.

2 Principle and method

Figure 1 shows a typical 3-D shape measurement system. The process for using this system is given below:

Step 1. Project the optimal intensity-modulation pattern onto the measured object.
Step 2. Capture the observation pattern image.
– **Step 3.** Perform color analysis of the observation pattern image.
– **Step 4.** Extract the observation pattern from the observation pattern image.
– **Step 5.** Correct for surface reflectance in the observation pattern image (Sect. 2 describes this technique and its principles).
– **Step 6.** Establish intensity correspondence between the stripes of the projection pattern image and the stripes of the corrected image.
– **Step 7.** Use triangulation to calculate the world coordinates in 3-D space based on the intensity correspondence relation.

This article focuses primarily on step 5. Steps 6 and 7 are described by Lu and Cho
and Cho and Lu.

In step 5, when the object has non-uniform reflectance, the stripe intensities of the observation pattern image are not necessarily in the same order as those of the projection pattern. In this case, it is necessary to correct the intensity distribution of the observation pattern image \( I(i, j) \) using the initial no-pattern observation image \( I_0(i, j) \) according to Eq. 1.

\[
I(i, j) = k \frac{I_0(i, j)}{I_2(i, j)} \tag{1}
\]

Here, \( I(i, j) \) is the intensity after image correction, \( I_0(i, j) \) are the coordinates of a pattern area pixel in the image, and \( k \) is a constant. Using the correction method, a regular pattern of stripes for measurement can be obtained. However, it is still difficult to measure a moving object. Therefore two observation images must be captured, which doubles the measurement time.

To realize 3-D shape measurement based on a single image, we propose an image analysis method that uses only a single captured image. This method entails generating \( I_2(i, j) \) from \( I_0(i, j) \) in Eq. 1. In a circular domain \( M \) centered on the observation point \((i, j)\), we perform the following processing:

\[
I_2(i, j) = \begin{cases} 
I_0(i, j) & (i, j) \in \text{no-pattern area} \\
\frac{I_{np}}{I_p} I_0(i, j) & (i, j) \in \text{pattern area} 
\end{cases} \tag{2}
\]

The radius of domain \( M \) (Fig. 2) is defined according to the width of the projection pattern in order to ensure that there are a sufficient number of pixels in the no-pattern area (which is two pixels wider than the projection pattern in this study). \( I_{np} \) and \( I_p \) are the average intensities of the no-pattern and pattern areas, respectively, in domain \( M \). We eliminate the effect of noise by determining the calculation range by applying a threshold to the average intensity based on an analysis of the intensity distribution histogram of domain \( M \) (Fig. 3). As in Eq. 2, when the observation point \((i, j)\) is a pixel in the pattern area, we calculate its approximate intensity in the projection before using the intensity information of the no-pattern area. We assume that most pixels have approximately the same intensity change when the pattern is projected onto an appropriate domain \( M \) (after excluding the effect of noise). Thus, we can use the average rate of change of the intensity \( I_{np}/I_p \) to calculate the observation point intensity prior to projection. Finally, we use this method to synthesize a no-pattern image \( I_2(i, j) \) in which there is a no-pattern area. We use this synthesized no-pattern image to perform a division calculation with Eq. 1, thereby avoiding the effect of reflectivity on the object surface color.

The resulting image is the corrected pattern image used to calculate the corresponding relation in step 6. The 3-D shape information is then calculated in step 7.