INFORMATION
Volume 16, Number 3(B), pp.2215-2220
ISSN 1343-4500

A Distance Measurement System Based on Structured Light Image

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Abstract

Distance measurement based on structured light image processing is computationally more efficient than conventional stereo image processing. In order to solve illumination noise problem of the structured light image processing, we propose an efficient image processing algorithm, i.e., the integration of sequential time-difference images with structured light modulation. The proposed algorithm involves only elementary operations such as integer subtraction and addition and is appropriate for hardware implementation. A distance equation and sensitivity analysis are also presented.

Keywords: ranging system, structured light, integration of time-difference images

1. Introduction

This paper presents a compact distance measurement system based on images acquired using laser structured light (SL). The SL imaging systems project light of a distinct frequency in a particularly structured pattern onto the environment [1]. Distance is computed from the distortion of the SL pattern, which is a function of the distance to objects. A SL imaging system avoids the computationally intensive correspondence problem of a conventional stereo vision system. The bulky laser and camera equipment and image processing time have discouraged the use of SL imaging in the past, but recent advancements in semiconductor laser equipment and faster processors have made this system more viable and economically feasible.

One of the disadvantages of a SL imaging system is its vulnerability to background illumination. In order to overcome this problem, we have developed an algorithm that can robustly extract a SL pattern from the source image [2][6]. The algorithm performs an integration of time-difference images with the modulated SL projection. Since this image processing algorithm involves elementary operations such as integer subtraction and addition, it is easy to implement in hardware. A ranging system based on SL imaging can simultaneously measure the distance to all points in wide direction corresponding to the field of view (FOV) of the camera. Therefore, SL imaging provides a fast and efficient solution to map a building and for the autonomous navigation of mobile robots [3][4].

2. Structured Light Imaging System

The distance measurement system based on SL imaging is shown in Fig. 1. This SL imaging system consists of a camera and an SL projection module with a vertical displacement. In images acquired using SL, the light pattern is distorted according to the distance of the reflecting object surfaces, and the distance can be computed from the distortion pattern and the extent of distortion [1]. A cylindrical lens can spread light stripes over a wider area, thereby speeding up the process of distance measurement [5]. However, such a lens lowers the light energy density by spreading the laser light. As a result, strong illumination noise can interfere with the extraction of the SL pattern from the image. Therefore, a special image processing method is required to improve the extraction of the SL pattern.

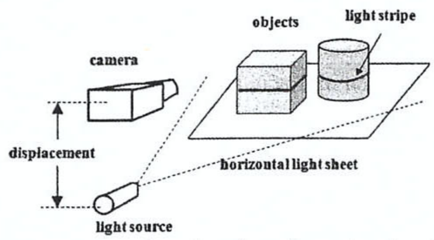


Fig. 1. Distance measurement system based on structured light imaging

An easy method for extracting an SL pattern is to obtain the difference between two images using SL modulation: one image is acquired with the SL on and the other without the SL. This is well-known technique to detect motion in a static background. A laser modulator is needed to use the image difference method. As mentioned before, when a point laser is converted into a line by a cylindrical lens, the energy density of SL is decreased. In order to enhance the weakened SL and make it resistant to background illumination, sequential integration of the time-difference images is proposed in this paper. This image processing method selectively emphasizes the SL pattern in the image. We demonstrate the effectiveness of this method through experiments in Sec. 5. The integration of a time-difference image requires sequential image frames that may undergo deterioration due to the afterimage effect in the case of non-static background. In order to mitigate this effect, we used a high-speed camera that can capture images at 200 frames per second (FPS) and developed a dedicated field-programmable gate array (FPGA) image processor for the camera. The 200 FPS image acquisition rate is much faster than the 30 FPS of a standard camera.

3. Distance Computation and Error Analysis

Distance computation is described in Fig. 2, where the symbols are explained.

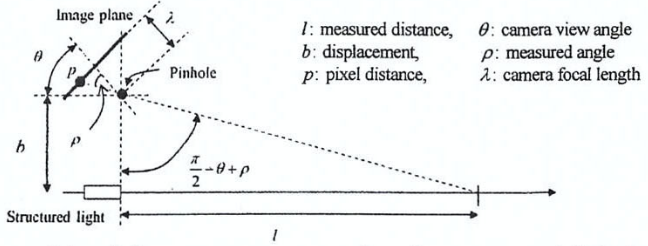


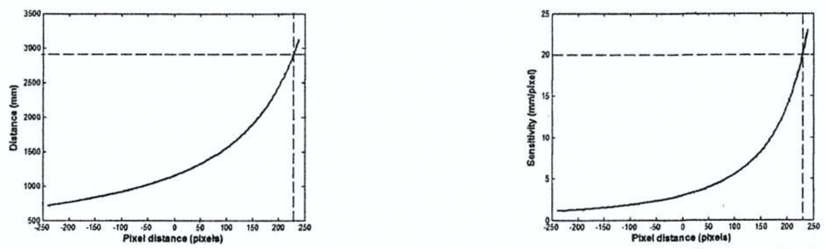
Fig. 2. Camera model and distance measurement based on structured-light imaging

Fig. 2 shows the side view, i.e. a vertical cross-section, of the system setup. The distance to the point that the SL is projected can be computed as

$$l = b\cot\left\{\theta - \tan^{-1}\left(\frac{p}{\lambda}\right)\right\} \tag{1}$$

Note that the distance depends on the displacement between the camera and the SL source. The image sensor is a two-dimensional regular grid of discrete photo sensors. Therefore, the quantization of pixel distance can introduce an error in the measured distance. The error sensitivity of the measured distance to the pixel quantization error is given by

$$\frac{\partial l}{\partial p} = \frac{b}{\lambda}\cdot\frac{1}{\sin^2\left\{\theta - \tan^{-1}\left(\frac{p}{\lambda}\right)\right\}}\cdot\frac{1}{1+\left(\frac{p}{\lambda}\right)^2}\ . \tag{2}$$



(a) Distance (b) Sensitivity according to pixel error

Fig. 3. Distance and sensitivity

Table 1. Parameter values for distance computation

Parameters	b (*mm*)	θ (°)	λ (*mm*)
Value	375.04	21.3	957.0

Fig. 3 shows the plot of distance (1) and error sensitivity (2) as a function of the measured pixel distance on the image plane. The parameters in the two equations assume the values listed in Table 1. Pixel 0 denotes the center pixel on the image plane. Fig. 3 (a) shows that about 230 pixels correspond to a distance of about 2.9 m. Fig. 3 (b) shows that the sensitivity is 20 mm at a pixel distance of 230 pixels, which implies that 1 pixel error in that region of the image causes a 20 mm error in the computed distance. In summary, our system has a less than 20 mm error when the distance is less than 3 m. If the displacement between the camera and the SL source is increased by a factor of two, the measurable distance and the error limit will be doubled as implied by (1).

4. Experimental Results

The SL-based distance measurement system developed in this study is shown in Fig. 4. The dedicated FPGA image processor performs all the image processing and sends only the data on the measured pixel distance to the host processor through a USB connection. In this manner, the computational burden on the host processor is reduced.

As stated before, we used a high-speed camera with a 640×480 image resolution and a 200 FPS acquisition rate. The time interval between two image frames is 5 ms. Therefore, the resultant distance measurement frequency is 10 Hz as the number of integrations of time-difference images is 10 using 20 image frames with SL modulation. For generating SL, we used a red semiconductor laser with a wavelength of 660 nm and a power of 5 mW, a cylindrical lens that spread the point laser into a line with a 90° width angle, and a laser on-off modulator synchronized with the camera image acquisition process.

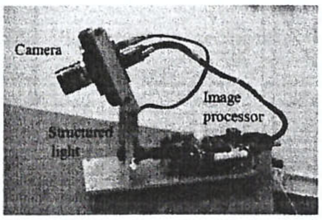
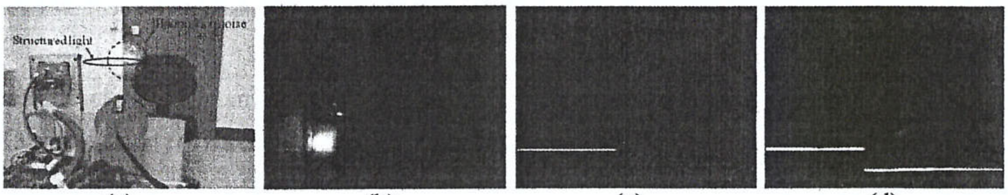


Fig. 4. SL-based distance measurement system

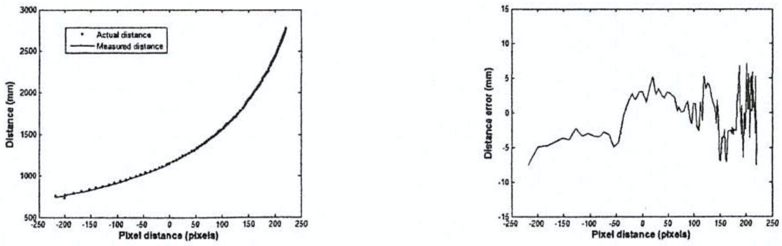
In order to verify the robustness of the proposed system against illumination noise, we carried out the following experiment. Fig. 5 (a) shows the setup where the lines in bold ellipsoids represent the SL, and the bright light in the dotted circle is a flashlight applied to the SL as an intentional source of illumination noise. At the center of the flashlight, illumination intensity is about 1100 lux and that of ambient light is about 400 lux. The original image acquired by the proposed system with the SL ON is shown in Fig. 5 (b). It is difficult to extract the SL pattern from this image since the illumination noise is stronger than the SL. Fig. 5 (c) shows that the time-difference with SL modulation removes the background flashlight in the image. However, a part of the SL pattern is still too weak to be extracted from this image. The strength of the SL pattern depends on the object distance and the reflectivity of the object material. As shown in Fig. 5 (d), in accordance with the integration of the sequential time-difference images, the SL pattern becomes clear enough to be extracted from the image. This result demonstrates the robustness of the proposed system against environmental illumination noise.

From the measured pixel distance and the calibrated system parameters, we can compute the distance data using (1). Fig. 6 (a) shows the comparison between the actual distances and the distances computed from the measurement. Fig. 6 (b) presents the corresponding distance errors. As shown in these figures, when the measured pixel distance is within 230 pixels, the approximate measurable distance range and the error bound are ~3 m and 10 mm, respectively. As explained in Fig. 3, when the measured pixel distance exceeds 230 pixels, the sensitivity of distance to pixel error is over 20 mm. We thus limit the range of high-confidence distance measurement to [0, 3] meters. It is possible to set the measurable distance by the displacement and the camera view angle with reduced accuracy, as stated before.



(a) (b) (c) (d)

Fig. 5. Results of experiment to verify the robustness of the proposed system against illumination noise: (a) Experiment setup, (b) Original image, (c) Difference image, (d) 10^{th} integration of difference images



(a) Distance (b) Error

Fig. 6. Result of distance measurement

6. Conclusions

In this paper, a distance-measurement system using SL image is developed. In order to compensate for the low energy density of the SL stripe spread by a cylindrical lens, an image processing algorithm based on the difference of modulated SL images and their sequential integration is developed. A compact FPGA image processor for a high-speed camera is also implemented in order to accelerate the integration of the time-difference image processing algorithm, thereby reducing the computational burden on the host computer. This system has markedly improved the performance of SL pattern extraction and made the extraction robust to background illumination noise, as verified through our experiments.

7. Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2009-0073417).

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