2008 10th Intl. Conf. on Control, Automation, Robotics and Vision
Hanoi, Vietnam, 17–20 December 2008

Auto-focusing Technique in a Projector-Camera System

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***Abstract*—Projector-camera system has been researched for years and it has become more and more popular in 3D vision and many other applications. However, with pre-determined position of projector's lens, projector based researches were not able to deal with the scenes that have objects with different distances from the projector. In this paper, we present a projector auto-focusing technique based on local blur information of the image that can overcome above limitation. The algorithm is implemented on projector-camera system, in order to focus the pattern which is projected by projector on all objects in the scene sequentially. The proposed algorithm first obtains a blur-map of the scene on the image by using a robust local blur estimator, and then the region of interest is decided by thresholding the obtained blur-map. Since the main light source is provided by projector, the proposed auto-focusing algorithm achieves a good performance with different light conditions.**

Keywords—auto-focusing, projector-camera, blur estimation, blur-map.

I. INTRODUCTION

Recently, a projector-camera system, which uses one or multiple projectors and cameras, is commonly used in many research applications such as structured light based 3D reconstruction [1][2], self-calibration [3][4], ubiquitous display system and AR (augmented reality) [5][6] etc. The crucial problem of the projector related applications is that the focusing range (depth-of-field) of the projector is too short. In that case, focal blur [7] (or out-of-focus blur) of the projector's pattern on the objects in the scene occurs when these objects are placed outside depth-of-field of the projector. Even though several camera auto-focusing techniques are proposed [8][9], relatively few methods about projector auto-focusing are introduced. In the case of a commercially available auto-focusing projector, it utilises the infra-red sensor to measure the distance between the scene and the projector. This method assumes that the scene is relatively flat and perpendicular to the projector like a wall. The limitation of this method is that it can only focus on some specific area the infra-red sensor measures and it assumes that the distance between the scene and the projector is almost constant. However, in many applications where projector-camera systems are used, the scene is not flat and/or not perpendicular to the projector. Consequently, it requires additional equipments such as a camera to focus the projector on the specific area since a projector cannot *see* the scene.

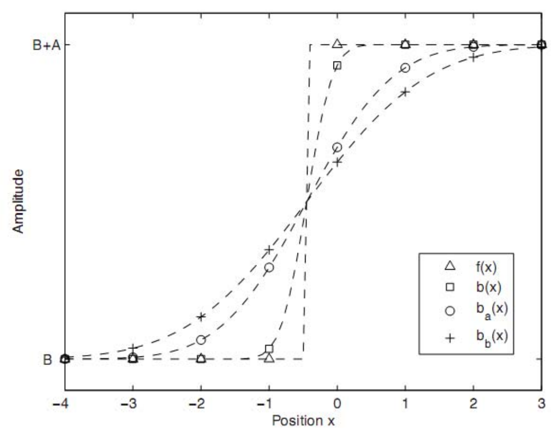

Figure 1. The ideal step edge *f(x)*, the blurred edge *b(x)* and its two re-blurred versions $b_a(x)$, $b_b(x)$.

In this paper, we present a projector auto-focusing technique with low complexity in computation aiming at real-time implementation. The proposed method adopts a simple blur estimation algorithm, as proposed in Hu's work [10]. The blur estimator uses a Gaussian isotropic PSF model and the difference between digitally re-blurred versions of a captured image is used to estimate the blur radius without edge detection.

The major contributions of the paper are:

- We have proposed and implemented a control algorithm for projector's lens.
- We have then implemented the auto select region of interest[1] (ROI), and finally
- We implement focusing the pattern of projector on the ROI.

The remainder of the paper is organised as follows: In Section II, we review the blur estimation algorithm [10]. Our auto-focusing algorithm is described in Section III. A simple projector's lens control algorithm is proposed in Section IV. In Section V we show the setup of projector-camera system. Experimental results are provided in Section VI and, finally, Section VII concludes the paper.

II. LOCAL BLUR ESTIMATION

We analyse the edge in one dimension (1D). The edge *f(x)* is modelled as a step function with amplitude *A* and offset *B* as

[1]Here, the region of interest is the object that we want to focus on.

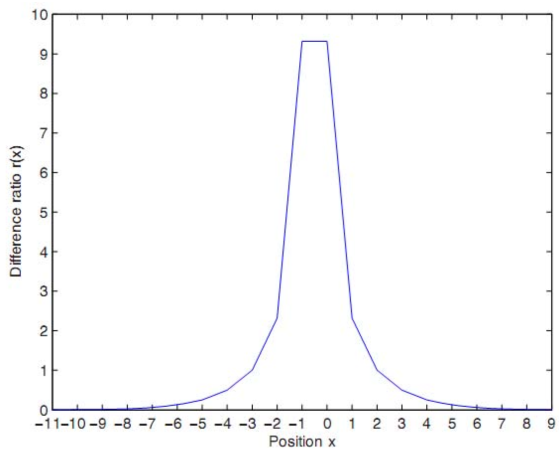

Figure 2. Difference ratio among the edge.

shown in Figure 1,

$$f(x)=\begin{cases}A+B, x\geq 0\\ B, \quad x<0\end{cases}, \qquad x\in\mathbb{Z} \tag{1}$$

The focal blur kernel is modelled by the normalized Gaussian function:

$$g(n,\sigma)=\frac{1}{\sqrt{2\pi}\sigma}e^{\left(-\frac{n^2}{2\sigma^2}\right)}, \qquad n\in\mathbb{Z} \tag{2}$$

Where σ is the unknown blur radius that we want to estimate, and $g(n,\sigma)$ is normalised function. Then blurred edge is the result of the convolution between step edge and focal blur kernel:

$$\begin{aligned}b(x)&=\sum_{n\in\mathbb{Z}} f(x-n)g(n,\sigma)\\ &=\begin{cases}\frac{A}{2}(1+\sum\limits_{n=-x}^{x} g(n,\sigma))+B, & x\geq 0\\ \frac{A}{2}(1-\sum\limits_{n=x+1}^{-x-1} g(n,\sigma))+B, & x<0\end{cases}, x\in\mathbb{Z}\end{aligned} \tag{3}$$

Re-blurring the blurred edge using Gaussian focal blur kernels with blur radius σ_a and σ_b ($\sigma_a<\sigma_b$) we have two re-blurred versions $b_a(x)$ and $b_b(x)$ as mentioned below:

$$b_a(x)=\begin{cases}\frac{A}{2}(1+\sum\limits_{n=-x}^{x} g(n,\sqrt{\sigma^2+\sigma_a^2}))+B, x\geq 0\\ \frac{A}{2}(1-\sum\limits_{n=x+1}^{-x-1} g(n,\sqrt{\sigma^2+\sigma_a^2}))+B, x<0\end{cases}, \tag{4}$$

$$b_b(x)=\begin{cases}\frac{A}{2}(1+\sum\limits_{n=-x}^{x} g(n,\sqrt{\sigma^2+\sigma_b^2}))+B, x\geq 0\\ \frac{A}{2}(1-\sum\limits_{n=x+1}^{-x-1} g(n,\sqrt{\sigma^2+\sigma_b^2}))+B, x<0\end{cases} \tag{5}$$

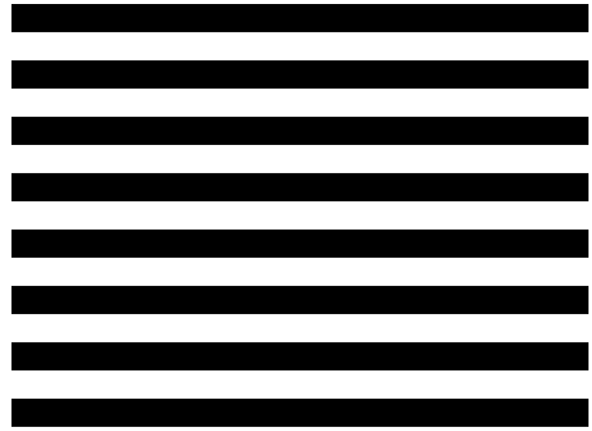

Figure 3. Stripes pattern 1024x768 size.

with $x\in\mathbb{Z}$. Take the ratio *r(x)* of the differences between the original blurred edge and its two re-blurred versions to eliminate the dependence of blur estimation on the offset and amplitude.

$$r(x)=\frac{b(x)-b_a(x)}{b_a(x)-b_b(x)} \tag{6}$$

As indicated in [10], the peaks of ratio are at the edge position $x=-1$ and $x=0$ as shown in Figure 2, and the blur radius can be approximately estimated by the equation following:

$$\sigma\approx\frac{\sigma_a\sigma_b}{(\sigma_b-\sigma_a)r(x)_{\max}+\sigma_b} \tag{7}$$

with $\sigma_b>\sigma_a>>\sigma$.

Equation 7 shows that the estimated blur radius σ is independent of the edge offset *B* and amplitude *A*.

III. Projector Auto-focusing Algorithm

A. Obtaining the ROI

We assume that the focal length of the camera is short enough, so all observed objects are located in depth-of-field of the camera, and the blur of stripes on objects is Gaussian. Projector projects a pattern with horizontal stripes as shown in Figure 3. All the stripes have the same width which is decided experimentally. In our experiments, the width equals 50 pixels. Since the depth-of-field of the projector is too short, and the objects that locate in front of projector with different distances, the stripes on them will be blurred with different blur radii. By estimating the blur radii of stripes on all objects using the method described in Section II, we obtain the blur-map of the scene.

We assume the distance between objects is long enough, so that the estimated blur radii of stripes on this objects are different from on other objects. The histogram of the blur-map depicts the order of objects that sorted by estimated blur radius, there are *n* maxima corresponding to *n* objects. To obtain the ROI, we first segment the blur-map by thresholding technique [11] using thresholds which are computed by searching algorithm described in Figure 4, then applying morphological operations: dilation and erosion [12] to remove noise elements. After getting the area of each object by segmentation, we compute the mean value of blur on each object, denoted as $\sigma(obj_i)$. And finally, set the object has minimum σ as ROI.

To find the threshold between two maxima, we employ a searching algorithm as follows:

1. Smoothing and dilating by morphology dilation the histogram to eliminate local peaks. Local maxima should not change.

2. Start from the leftmost maximum, traverse the histogram computing the slope in a window of a given size, until the slope becomes larger than a certain threshold *P* of positive slope.

3. When the slope becomes higher than the threshold *P*, the final threshold *T* is the mean position of the window at that instant.

Figure 4. Threshold searching algorithm.

B. Projector Auto-focusing Algorithm

The proposed algorithm is stated as follows:

1. Projector projects a stripes pattern.
2. Capture the image *I*, compute the blur-map of image *I*.
3. Decide the ROI as described in Section A above. Let $\sigma_0(ROI)$ is the mean value of blur on ROI, and choose an arbitrary direction for projector's lens rotation.
4. Control the motor to rotate the projector's lens for one step.
5. Capture the image *I*, compute $\sigma_k(ROI)$ (*k* be an integer representing the *k*-th iteration, *k*>*0*) in *I*.
6. If $\sigma_1(ROI) > \sigma_0(ROI)$, reverse the direction of rotation and go to step 4.
7. If $\sigma_k(ROI) > \sigma_{k-1}(ROI)$, with $k > 2$, (that means the estimated blur radius passed the minimum)

   Rotate projector's lens one step back.

   Else

   Go to step 4.
8. Remove this object from the blur-map. Go to step 3 until all objects are focused in turn.

Figure 5. Projector auto-focusing algorithm.

IV. Projector's Lens Control Algorithm

The movement of projector's lens is controlled by a DC motor. For each step, the lens rotates 1.4 degree. The control circuit controls the speed of DC motor by pulse-width modulation (PWM) method [13]. Moreover, the accuracy of the system almost depends on the accuracy of lens movement. The lens rotating must be synchcronised with the algorithm on the computer. The flowchart of simple control algorithm is illustrated in Figure 6.

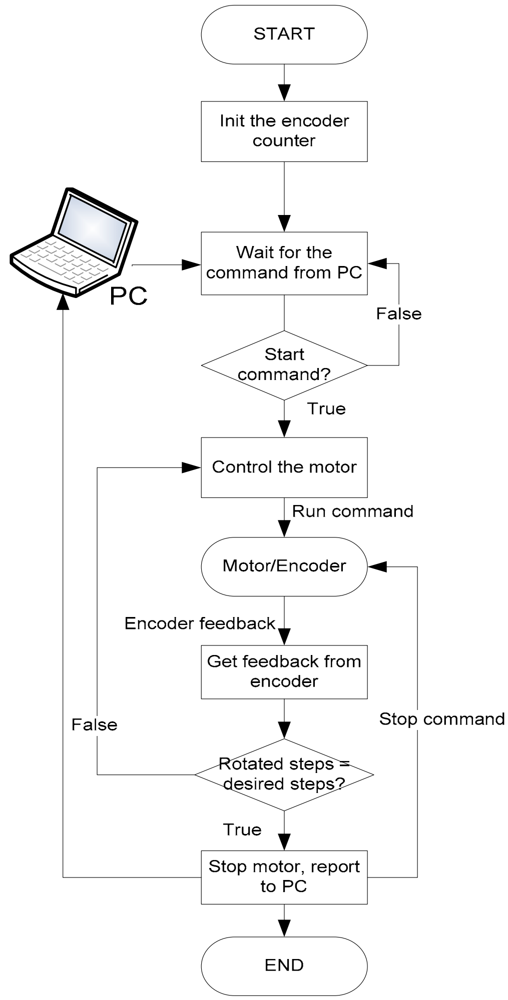

Figure 6. Projector's lens control algorithm.

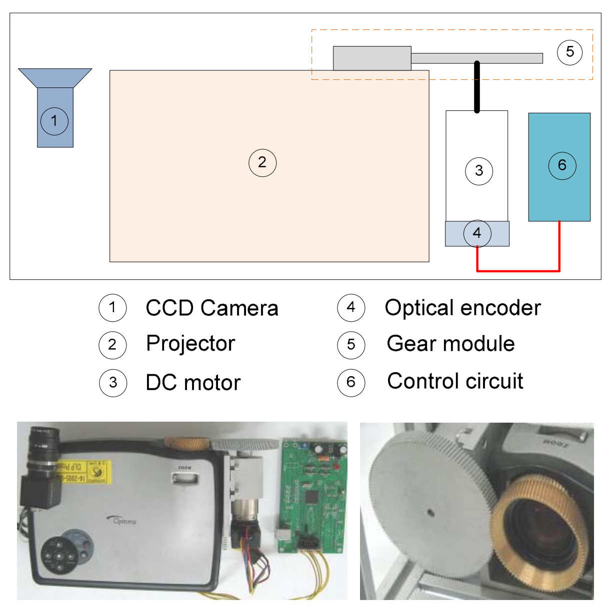

Figure 7. Diagram of projector-camera system (top), implemented system (bottom left) and gear module (bottom right).

V. SETUP OF THE PROJECTOR-CAMERA SYSTEM

The projector-camera system performs the light projection, projector's lens rotation and image acquisition. It consists of three main parts: a camera, a projector and a control part. Figure 7 shows the schematics of projector-camera system and the actual implemented prototype.

A Flea CCD camera with 1024x768 resolution and Optima EP 729 model projector are used in our research, we set projector resolution at 1024x768. A 90-teeth-gear is mounted on the projector's lens in order to transfer the rotation of DC motor to the movement of the lens. The DC motor has a 134-teeth-cogwheel on the head and an optical encoder with 256 optical slots. The cogwheel is connected with the gear on the projector's lens and the gear ratio is 1:1.489. Control circuit controls the speed of motor by PWM method, gets the feedback signal from encoder and communicates with computer by USB interface.

VI. EXPERIMENTAL RESULTS

In this section we discuss the experimental results of our algorithm. We have performed the experiment with two different objects: a statue and a board with different distances from the projector. In the blur estimation procedure, the blur radii for the re-blurring kernels are decided experimentally, and in our experiment, $\sigma_a = 7$ and $\sigma_b = 27$. The estimated blur radius is computed by using Equation 7.

Figure 8 shows the image with initial position of projector's lens. After applying the blur estimation algorithm, we obtain a blur-map as shown in Figure 9, where the lighter area indicates a larger blur radius, while the darker area indicates a smaller blur radius. The histogram of the blur-map is illustrated in Figure 10, the threshold for thresholding the blur-map is decided by applying the searching algorithm which is described in Figure 4, as shown in Figure 11. After thresholding the blur-map based on histogram, the statue is decided as a ROI, which is illustrated in Figure 12. The auto-focusing algorithm first focuses the stripes patterns on the statue, as shown in Figure 13. And then, when the board is decided as a ROI, Figure 14, the algorithm will change to focus on the board, Figure 15. Figure 16 illustrates the evaluation of the estimated blur radius while the algorithm is running. When the estimated blur radius reaches the minimum that means the stripes pattern is well focused on the current object.

VII. CONCLUSION

In this paper, we have presented a projector auto-focusing algorithm for projector-camera system which is widely applied in 3D vision and many other such applications. The proposed algorithm is based on a robust blur estimator and histogram process. All the objects in the scene are focused in turn. However, when the stripes are highly blurred, due to the limitation of local blur estimator, the system cannot work correctly. This drawback opens a new issue for our research in near future.

ACKNOWLEDGMENT

This research was performed for the Intelligent Robotics Development Program, one of the 21st Century Frontier R&D Programs funded by the Ministry of Commerce, Industry and Energy of Korea. This work was supported by the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korea government (MOST) (No. R01-2006-000-11297-0). The work was also supported by the Science and Technology Program of Gyeonggi province as well as in part by the Sungkyunkwan University.

Figure 8. Initial position of projector's lens.

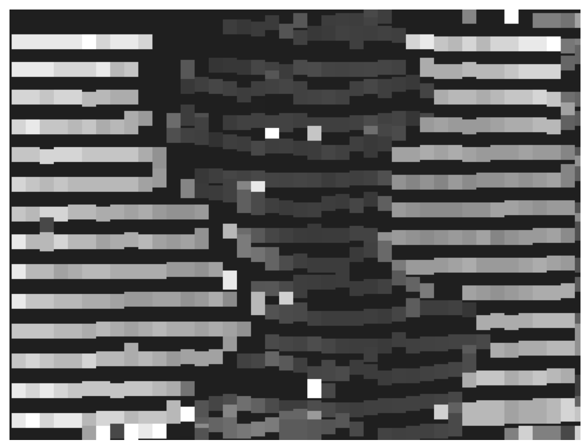

Figure 9. Blur-map of the scene.

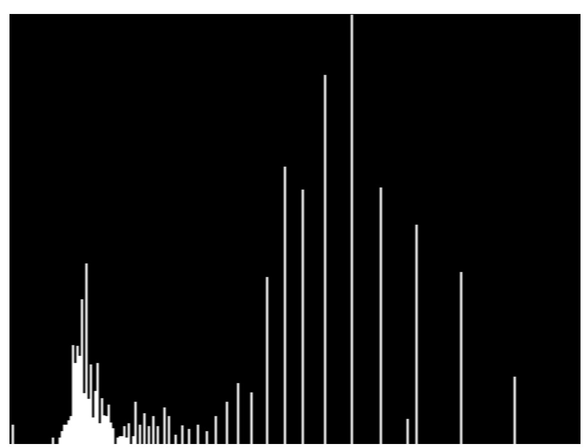

Figure 10. Histogram of blur-map (with zero value removal - which is noise).

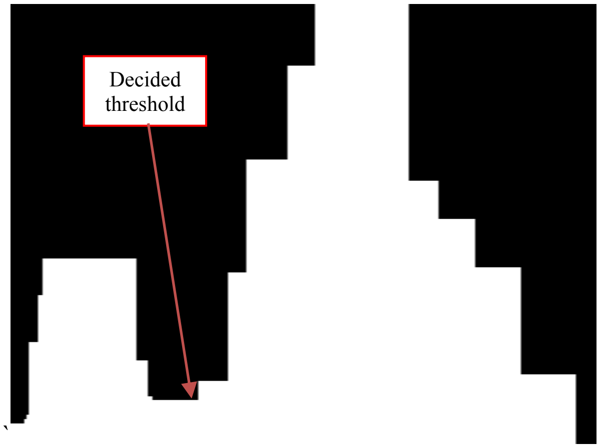

Figure 11. Smoothed and dilated histogram, and decided threshold.

Figure 12. Segmented blur-map, the statue's area is obtained (white colour is 1, black colour is 0).

Figure 13. The stripes are focused on the statue.

Figure 14. Segmented blur-map, the board's area is obtained (white colour is 1, black colour is 0).

Figure 15. The stripes are focused on the board.

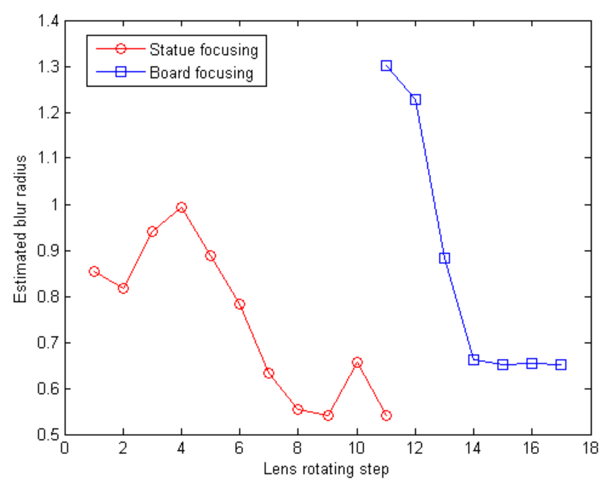

Figure 16. Evaluation of estimated blur radius in focusing process.

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