Parameterised structured light imaging for depth edge detection

J.-K. Na, J.-Y. Park, J.-H. Yi and M. Turk

This reported research features parameterised structured light imaging that is practically useful for detecting depth edges. Given input parameters such as the range of distances of an object from the camera/projector and minimum detectable depth difference, the presented method is capable of computing an optimal pattern width and the number of structured light images that are needed to detect all depth edges in the specified range of distances that have at least the given detectable depth difference. Application of this parameter control to the detection of silhouette edges for visual hull reconstruction shows the effectiveness of the method.

Introduction: Recently in [1], we presented parameterised structured light imaging for detecting depth edges where structured light with a pattern comprising black and white stripes of equal width is employed. The parameters involved are 'detectable range of depth edges, $[a_{\min}, a_{\max}]$, from the projector/camera', 'width of horizontal stripes, w', and 'minimum detectable depth difference, $r_{\min}$'. As can be seen in Fig. 1*a*, $a_{\max}$ and $r_{\min}$ are given as the input parameters, then the width w and $a_{\min}$ are determined. Depth edges having depth difference of at least $r_{\min}$ in the range of $[a_{\min}, a_{\max}]$ are guaranteed to be detected. However, awkwardly enough, $a_{\min}$ is found at a later step from other parameters. Thus, setting the target range $[a_{\min}, a_{\max}]$ at the beginning is not within one's control. This makes it hard to apply the method in a real scenario, especially in a dynamic environment. In addition, when the foreground object point is located within the range $[a_{\max} - r_{\min}, a_{\max}]$, detection of depth edges of which depth difference is no less than $r_{\min}$ is not simply feasible because depth difference between the object point and $a_{\max}$ is less than $r_{\min}$.

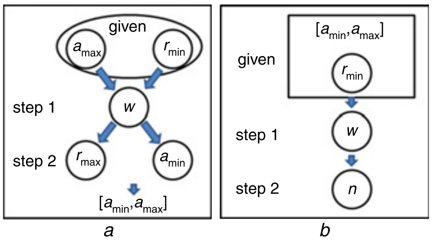

Fig. 1 *Previous against new control of key parameters*

a Method in [1]
b New method

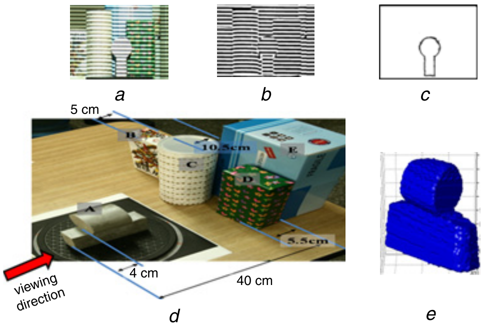

Fig. 2 *Silhouette edge detection of foreground object A from viewing direction indicated by arrow and 3D reconstruction from its visual hull*

a Structured light image
b Pattern image
c Silhouette edge map of foreground object A
d Experimental setup
e 3D reconstruction using visual hull
For experimental setup shown in Fig. 2*d*, silhouette edges detected for foreground object A are displayed in Fig. 2*c*. Note, depth edges having depth difference of 4 cm are not found. In this experiment, minimum detectable depth $r_{\min}$ is set to 15 cm, and only depth edges having depth difference $r \geq r_{\min}$ are extracted. Using silhouettes extracted from multiple viewing directions, 3D reconstruction in Fig. 2*e* is computed. In this case, 12 views used

In this Letter, we present a new parameter control method that is practically useful, and show its usefulness by applying it to the detection of silhouette information for visual hull reconstruction [2, 3]. While others have used a known fixed background such as a chroma-key background for silhouette extraction, our method can be employed for a scene with complex background textures (refer to Fig. 2). In the new parameter control method, as can be seen in Fig. 1*b*, $[a_{\min}, a_{\max}]$ and $r_{\min}$ are given as the input parameters, then it provides the width of stripes, w, and the number of structured light images, n, to guarantee the detection of depth edges having depth difference $r \geq r_{\min}$ in the range $[a_{\min}, a_{\max}]$.

Depth edge detection: The basic idea in [1] to detect depth edges is to exploit distortion of patterns along depth discontinuities. To detect depth discontinuities, we consecutively project a white light and a structured light onto the scene and extract a binary pattern image by differencing the white light and structured light images. This differencing effectively removes texture edges. The application of a Gabor filter to the pattern image provides depth edge locations because the amplitude response of the Gabor filter is very low where pattern offset occurs. From the modelled imaging geometry of a camera, projector and object, we obtain the exact amount of pattern offset, Δ_{exact}, as

$$\Delta_{exact} = fd\left(\frac{1}{a} - \frac{1}{b}\right) = \frac{fdr}{a(a+r)} \tag{1}$$

which is the key equation to parameterised structured light imaging [1]. Here, a, b, d and f are the distances of object locations A and B, projector and virtual image plane from the camera, respectively. r denotes the depth difference between object locations A and B. Since they use simple black and white stripes with equal width, Δ_{exact} may not be measurable, depending on the object location from the camera. The observable amount of pattern offset is periodic as the distance of object location from the camera is increased or decreased. Thus, what is actually measurable is different from Δ_{exact}. Let us denote the measurable amount of pattern offset by $\Delta_{visible}$. To reliably detect pattern offset with a Gabor filter, $\Delta_{visible}$ must be larger than a certain amount. A threshold value of $2w/3$ is used.

With r and d fixed, the relation between Δ_{exact} and a from (1) shows that there are ranges of distances where detection of depth edges is difficult due to the lack of offset, depending on the distance of a depth edge from the camera or projector. To extend the detectable range, additional structured lights with width of stripe $2w$, $4w$, etc., are employed to fill the gap of $\Delta_{visible}$, and the corresponding range, a, of object locations is extended.

Novel method of parameter control: First, to guarantee the detection of all depth edges having depth difference of $r \geq r_{\min}$ even in the range $[a_{\max} - r_{\min}, a_{\max}]$, we exploit the range $[a_{\min}, a_{\max} + r_{\min}]$ in actual computation while the target range $[a_{\min}, a_{\max}]$ is specified as the input by a user. This makes it possible to detect depth edges having depth difference of $r \geq r_{\min}$ even if an object point lies at the distance of $a_{\max}$.

We start with (1) and, in subsequent derivations, we replace $a_{\max}$ by $a_{\max} + r_{\min}$. We want the value of Δ_{exact} corresponding to $a_{\max}$ to be $2w/3$. Thus, in (1), by equating Δ_{exact} with $2w/3$ and substituting a by $a_{\max} + r_{\min}$ instead of $a_{\max}$, we get the following expression for w:

$$w = \frac{3fdr_{\min}}{2(a_{\max} + r_{\min})(a_{\max} + 2r_{\min})} \tag{2}$$

We can see that the maximum achievable value of $\Delta_{visible}$ is $4w/3$ when a single structured light is employed. If we use two structured lights, then their stripe widths are w and $2w$, respectively, and the maximum achievable value of $\Delta_{visible}$ is $10w/3$. When n number of structure light is used, it can easily be shown that the maximum achievable value of $\Delta_{visible}$ becomes $(2^n - 2/3)w$. Then, we solve the following inequality for n:

$$(2^n - 2/3)w \geq \frac{fdr_{\max}}{a_{\min}(a_{\min} + r_{\max})} \tag{3}$$

Since n is a natural number, we finally get

$$n = \left\lceil \log_2\left(\frac{dfr_{\max}}{w(a_{\min} + r_{\max})} + \frac{r}{3}\right) \right\rceil \tag{4}$$

Experimental result: As illustrated in Fig. 2, given the experimental setup where the scene has a complex background with objects B, C, D, E, we only extract the silhouette edges of the foreground object A even though it has depth edges inside the object that have depth difference of 4 cm. Using the proposed parameter control, we can reliably detect the silhouette edges of object A by properly setting $a_{\min}$ and $r_{\min}$. Inner depth edges of an object have smaller depth difference than silhouette edges assuming that the silhouette edges are not adjacent to edges from other objects. Silhouettes extracted in this way from multiple viewpoints are fed into visual hull reconstruction. We have used a rotating turntable as shown in Fig. 2 to get multiple views of the foreground object. We exploit camera calibration information that is computed for visual hull reconstruction so that the value of $a_{\min}$ is set to the distance of the foreground object from the camera/projector. Then using an arbitrary large value of $r_{\min}$, for example, a value a little smaller than the difference, $a_{\max} - a_{\min}$, can guarantee reliable extraction of silhouette edges. For capturing structured light images, we have used an HP xb31 DLP projector and a Cannon EOS 350D digital camera. All computations are carried out on a Pentium 4 3.0 GHz personal computer.

Conclusions: We view background segmentation as the problem of silhouette extraction of foreground objects. We are investigating further how to apply our method of parameter control to object detection and background segmentation.

Acknowledgment: This work was supported by the Korea Research Foundation Grant funded by the Korean Government (2009-0073365).

5 October 2009
doi: 10.1049/el.2010.2791
One or more of the Figures in this Letter are available in colour online.

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