RANGE IMAGING BASED ON MOVING PATTERN LIGHT AND SPATIO-TEMPORAL MATCHED FILTER

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ABSTARCT

In this paper, a new structured light projection method for measuring 3D and range objects is proposed. The method projects a moving structured light pattern modulated by time-compression signal, then the objects are captured as a dynamic and spatio-temporal image by a camera. By applying a matched filter to the spatio-temporal image, the ideal slit light is realized even using an actual light projector. According to the extracted slit light and triangulation principle, 3D geometric information of the objects scene more accurately.

By using separable signals which have no correlation each other, the method is able to project multiple light patterns at different positions simultaneously. It solves occlusion problem due to single projector. Some experimental results show its advantages.

1. INTRODUCTION

In most cases of optical measurement of 3D and range objects, some active mechanism is utilized for obtaining reliable 3D measurement. Although stereo range finding is regarded as passive way, many researchers tried to capture image sequences by actively moving camera in order to acquire reliable range data [1-3]. The captured image sequences is analyzed to find characteristic lines in image processing of its spatio-temporal image.

On the other hand, the most of active range finding utilizes structured light, especially for industrial uses. Slit light projection method is realized by projecting slit light on objects, and by observing the bent light stripe image along the outline of the objects [4]. Triangulation calculating 3D position is done based on known positions of a projector and a camera. Although this kind of method takes many images when sweeping the structured light, the conventional methods do not pay strong concern on changes of the images in time domain.

Some modified structured light projection method uses time-sequential patterns modulated by Gray code instead of single light stripe [5]. Although the method reduces the measurement time considerably, the accuracy of the measurement is same as the conventional way. Because the accuracy of these methods process not the image sequence, but each frame of the sequence. In other words, they loose important cues on range data contained in the time-varying data.

To improve the accuracy without any additional instruments, this paper proposes a new type of structured light employing a moving modulated pattern light and spatio-temporal image processing of the observed image sequence [6].

It projects a moving structured light pattern

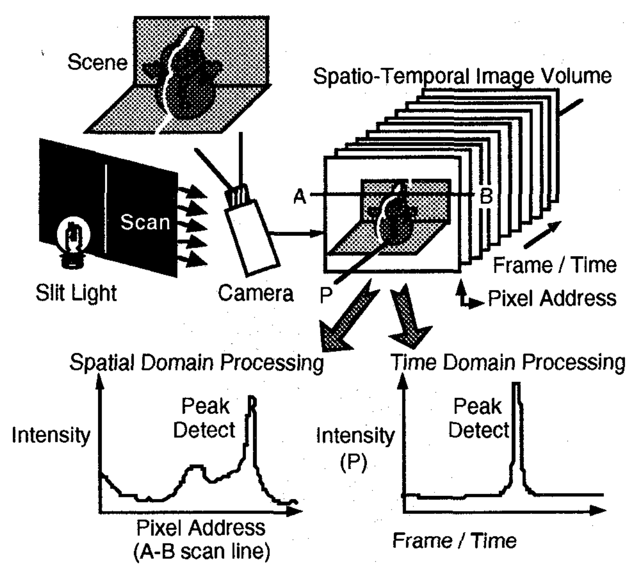

Fig. 1 Image processing in spatial domain versus one in time domain

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modulated by time-compression signal [7], then the objects are captured as a dynamic and spatio-temporal image by a camera. A matched filter produces the phase-shift of the modurated signal in each pixel of the spatio-temporal image pixel-by-pixel. The phase-shift determines the orientation of the ideal slit light.

Because the proposed method is based on signal processing, the method is able to project multiple light patterns at different positions simultaneously, while separable signals which have no correlation each other are applied. It may solve occlusion problem due to single projector.

2. SPATIO-TEMPORAL IMAGE ILLUMINATED BY MOVING LIGHT

2. 1 Spatial domain vs. time domain

So far, conventional range finding based on light projection is performed by extracting the light from observed images with image processing in spatial domain. Range finding using spot light scanning or slit light scanning are given as its examples. Fig. 1 shows an outline of the technique using slit light scanning. In this figure, while the projector scans the slit light in direction of $q(t)$ at the time t along a target object, and a spatio-temporal image is obtained. In this situation, the position and attitude of the projector and camera, and $q(t)$ are able to established voluntarily. Therefore, to obtain 3D topographic information of the object by triangulation, the last unknown parameter should be determined from the spatio-temporal image.

When we cut the spatio-temporal volumetric image to apply spatial domain image processing, each spatial image showing reflected slit light on an target object appears. In the image, we can see the

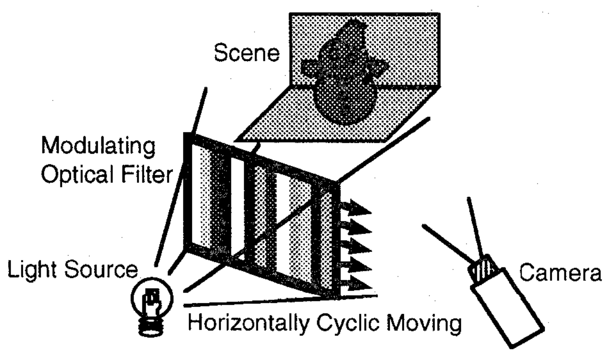


Fig. 2 Projection of moving modulated light patterns.

usual scene of the object. The coordinates $x(t_1)$,... , $x(t_n)$ at the time $t_1,\ldots,t_n$ from the corresponding frame of the images are the last parameter to calculate the triangulation. The coordinates usually determined by image processing in spatial domain; peak detection or center of gravity operation.

On the other hand, we can cut the spatio-temporal volumetric image along the time axis to apply time domain image processing. On this axis, the variation of light intensity $I(t)$ on each physical position are observed as shown in right side of Fig. 1. With slit light scanning, the $I(t)$ make a peak of intensity at a time t_I The time t_I determined by image processing in time domain is another kind of the last parameter to calculate the triangulation. In this case, it is necessary to find the time $t_I(x,y)$ at each pixel from the spatio-temporal volumetric image.

From the view point of image memory, time domain processing consumes considerably larger storage. However, the recent computer is able to handle it easily.

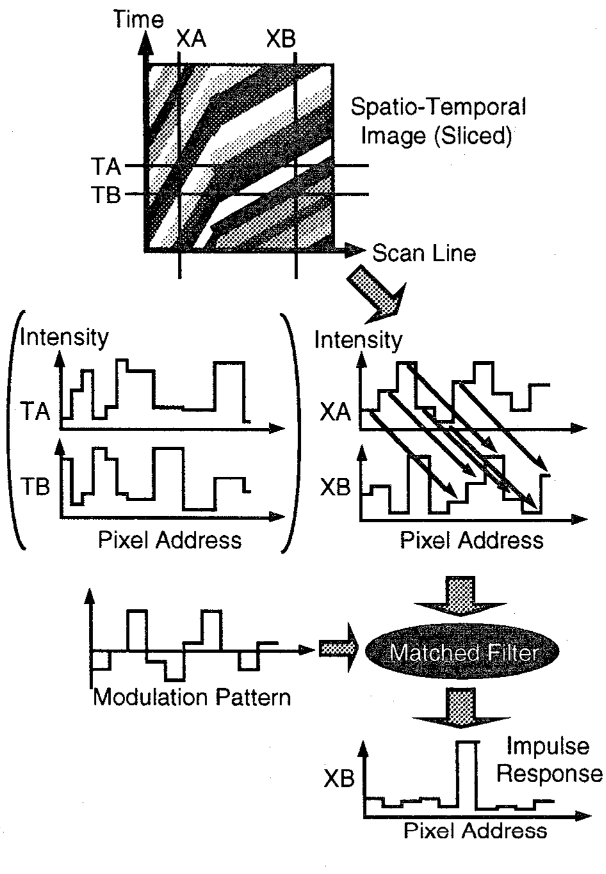
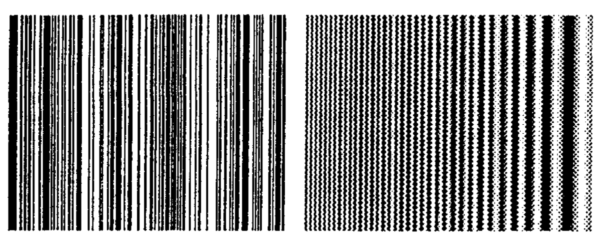


Fig. 3 Appearance of projected light in epipolar plane of spatio-temporal image and peak-shift detection by spatio-temporal matched filter

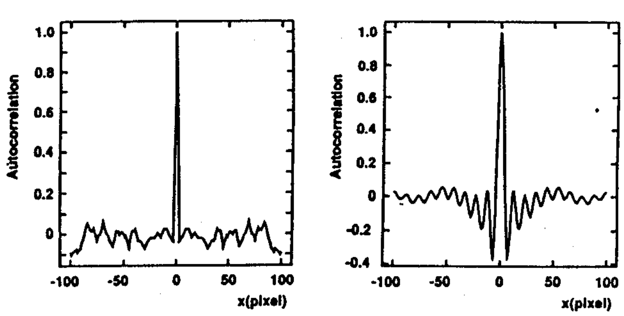
2.2 Time-compression for light striping

When projecting slit light, both above processing realizes the same accuracy. Because utilized image processing is the same peak detection of 2D intensity image. Now, considering not slit light but light with some spatially spread 2D pattern as shown in Fig. 2, this argument is invalid. Fig. 3 shows $\boldsymbol{x}\text{-}\boldsymbol{t}$ cross-sectional image of the spatio-temporal image. In spatial domain, the observed patterns are disturbed in various ways according to the topography of the objects. It is difficult to determine the exact position of the pattern.

However in time domain, the observed patterns keep the original modulated pattern's feature. If the projected pattern has one conspicuous peak in auto-correlation, it is able to determine the exact time when the edge of the original pattern passes each objective pixel by calculating cross-correlation between the original modulated pattern and the observed time-series signal from the intensity change. Based on this remarkable feature in time domain, several kind of signal processing techniques to increase accuracy might be utilized in time domain. Time-compression technology in radar [7] and spectrum-spread modulation technology gives good suggestions to light patterns to be projected, such as chirp signal or pseudo noise signal.



(a) M-sequence code pattern (b) chirp code pattern



(c) auto-correlation of (a) (d) auto-correlation of (b)

Fig. 4 Projected patterns having impulse auto-correlation

3. RANGE FINDING BY MOVING PATTERN LIGHT PROJECTION

To take advantages of the time domain processing, the pattern to be projected should have a conspicuous peak in auto-correlation. As examples of such signal, there are Maximum-sequence (M) code and chirp code. In the configuration shown in Fig. 2, while the pattern is scanned horizontally, a 2D projected pattern shows a set of vertical stripes as shown in Fig. 4. These patterns are constructed with particular signal e.g. M-sequence and chirp signal. These signals have the unique peak at the moment of zero in auto-correlation.

In range finding, cross-correlation between the original projected signal and observed intensity signal in time domain is calculated and its peak is extracted. The cross-correlation is calculated as,

$$C(shift) = \sum_{frame=0}^{FRAME-1} O(frame) * P((frame + shift)\%FRAME) \quad (1)$$

Here, *frame, FRAME, shift, O, P and C* are the frame number of image sequence, the total number of image sequence, intensity along frame, modulation pattern and correlation, respectively.

Because the peak of cross-correlation shows sharper impulse than that of slit light, the precision of range finding using modulated patterns realizes better than conventional slit light projection. Finally, triangulation is calculated with a value of the phase-shift. The value determines a sight line along the projector.

4. SIGNAL SEPARATION FOR MULTIPLE PROJECTION

In the proposed method, there is another kind of advantage that it is able to project plural modulated patterns from different positions simultaneously as shown in Fig. 5. In condition of using modulated patterns which have no correlation each other, each projected pattern is separable from measured mixed signal by matched filter as shown in Fig. 6. In the field of radio communication, this kind of approach is called spectrum-spread modulation, which multiple channels is able to share a same radio band.

In range measurement this advantage means that the proposed method is able to reduce occlusion problem without increasing measuring time. Another advantage is that we can obtain plural time data correspond to each projected pattern. So it is able to decrease the error by integrating these data.

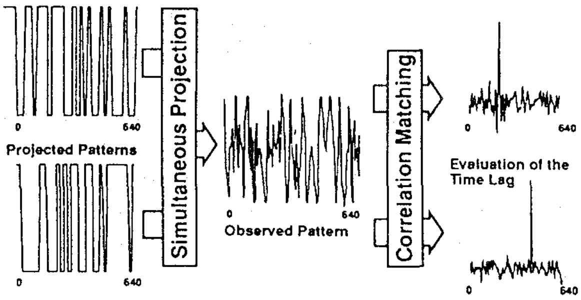


Fig. 5 Separation of mixed signal from intensity data

Table 1 Comparison of obtained accuracy in simulation and experiment
(standard deviation of error)

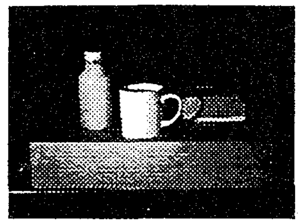
Projected pattern	simulation	experiment
slit light	0.110 pixel	0.091 pixel
M-sequence code	0.010 frame	0.071 frame
chirp code	0.008 frame	0.024 frame

5. EXPERIMENT

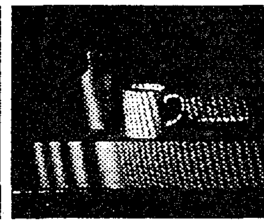
An LCD projector scanned the modulated pattern onto the scene which generates arbitrary patterns including M-sequence code pattern and chirp code pattern shown in Fig. 4. These patterns have width of 640 pixels, and have conspicuous peak enough to evaluate the time lag. A CCD camera takes the sequence of images showing the movement of the bent stripes' pattern as 640 image frames of 640*486 pixels wide. A WS holds a spatio-temporal volumetric data, 640*640*486 pixels wide, and evaluates the time lag of each pixel by calculating cross-correlation. And then, the 3D topographic information is obtained by triangulation.

To evaluate the performance of the proposed method, the accuracy of peak detection in cross-correlation, generated signal and measured signal are experimented with various patterns. Table 1 shows its result. It shows that the proposed method have higher performance than the conventional slit light projection.

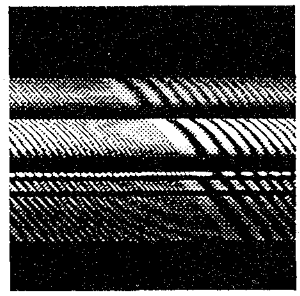
The experimental measurement with a white cup, blue eraser, etc. is shown in Fig. 6. Fig. 6(b) is one of the spatial images. One of the x-t sliced image is shown in Fig. 6(c). It is confirmed that the shape of the original projected pattern is preserved as time series signal anywhere. Fig. 6(d) shows a finally obtained range image.



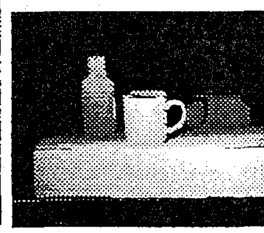
(a) scene



(b) input image



(c) time-epipolar plane



(d) range image

Fig. 6 Result images in experimental measurement

6. CONCLUSIONS

This paper has proposed the new range finding method based on spatio-temporal image processing with projecting moving modulated pattern light. The patterns to be projected is well-designed according to signal compression theory, so that the projected patterns are able to be discriminated accurately by the spatio-temporal matched filters.

The notable features of the method are shown as follows. A) it is able to realize higher accuracy of 3D range measurement than usual light projecting method, B) it is able to project plural projection patterns simultaneously, and to decrease occlusion problem without increasing measurement time.

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