

Photogrammetric System using Visible Light Communication

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Abstract—We propose an automated photogrammetric system using visible light communication. Our system can be applied to the measurement of a variety of distances using a light as a reference point. In addition, the matching of same lights in different viewpoints can be automatically done by using unique blinking patterns. A light area is extracted based on a rule of the lighting patterns without a pre-known threshold. Experimental results show that our system can provide enough accuracy for photogrammetry.

I. INTRODUCTION

Photogrammetry is one of remote sensing technologies, in which geometric shapes are computed from photographic images [1]. Since photogrammetry is non-contact measurement, it is applied to a monitoring system for landslides and distortion of a building, a bridge and a tunnel [2], [3]. Besides, 3D mapping from an aerial photograph is also done by photogrammetric technologies [4]. These days, digital photogrammetry is widespread thanks to a digital camera [5].

In photogrammetry, reference points such as planar markers are set as an initial setting and the coordinate system consisting of these points is manually measured [6]. The coordinate system is the reference system and estimation of a camera position and orientation is done on the system [7], [8], [9], [10]. Other planar markers are set on the positions which will be measured by photogrammetry. Next, all these markers are captured from more than two viewpoints due to triangulation. A camera position and orientation of each viewpoint is computed from reference points. The positions measured by photogrammetry are computed by triangulation using the camera position and orientation of each calibrated viewpoint.

One of problems for developing automated photogrammetry is to match same markers in images captured from different viewpoints. In the case that the matching is manually done, the accuracy of photogrammetry depends on the accuracy of input by a human. For achieving the automated matching, each marker should have a unique pattern [6]. However, it is difficult to design the markers for the stable detection from arbitrary viewpoints and distances.

In this paper, we propose an automated photogrammetric system using a light as a marker and the method for extraction of a light and its ID based on wireless communication

technologies. These are main topics of this paper.

The concept of our system is based on visible light communication. Visible light communication is one of communication technologies and uses wavelength of a light for wireless communication [11]. Another technology close to visible light communication is proposed [12], [13], [14], in which lighting on and light off mean a binary and a blinking pattern is detected by image processing. In our system, the automated matching of same markers is achieved by extending the latter technology. For detecting a blinking pattern in the technology, multiple images should be captured at a fixed viewpoint. In photogrammetry, a fixed camera can be utilized and multiple images can be captured at a viewpoint. In fact, photogrammetry is one of best applications for using the technology.

In the related works, a photo diode and a high-speed camera were utilized for detecting a blinking pattern [12], [13]. In addition, a system for estimation of a car position using a traffic light was proposed [14]. In these related works, they used a simple thresholding method and the method for stable detection of a lighting pattern and accurate extraction of a light was not discussed. For achieving them, we propose a method based on wireless communication technologies.

II. SYSTEM OVERVIEW

Our system is composed of a digital single-lens reflex camera, LED lights and a computer. The camera we are currently using is Nikon D300 (Fig.1(a)) and can consecutively capture 100 images, which resolution is 4288×2848 . A LED light (Fig.1(b)) works with a battery and we can arbitrarily change its interval of blinking. The blinking pattern of the light means its ID as a transmitted data.

Before using our system, the interval of capturing images should be measured accurately since the interval of capturing images and blinking should be synchronized. On the other hand, the starting times of blinkings don't have to be synchronized.

At the beginning, the positions of some lights are measured by a laser system such as a Total Station. These lights are reference points and an ID and coordinates of each light are input into our system. The world coordinate system consists of these measured lights. Next, 100 images are captured and

stored into memory of the camera at each fixed viewpoint. As for Nikon D300, it takes about 16 seconds to capture 100 image. While capturing images, the camera is completely fixed to capture the light at the same position.

After capturing images from more than two viewpoints, a user transfers images into a computer and operates a graphical user interface (Fig.1(c)), which is implemented in Visual Studio 2005 by Microsoft and includes OpenCV by Intel as an image processing library. When a user load each time-series images into our system, our system automatically extracts lights and their IDs from a blinking pattern and classifies a reference point or the points which will be measured by photogrammetry. The result of the classification is displayed on the GUI (Fig.1(c)). Next, The camera position and orientation of each viewpoint are estimated from the reference points. After more than two viewpoints are calibrated, 3D coordinate of each points which will be measured from photogrammetry are computed and the result is output as a text file.

The features of our system is as follows:

- Equipment is widespread and is not expensive.
- Matching of a same light is automatically done.
- Measurement during a night is possible.

The third feature is very effective for construction of a bridge. During a daytime, the shape of a bridge always changes because of the sun and its heat. During a night, the shape is stable because the temperature is stable and it is easy to measure the shape.

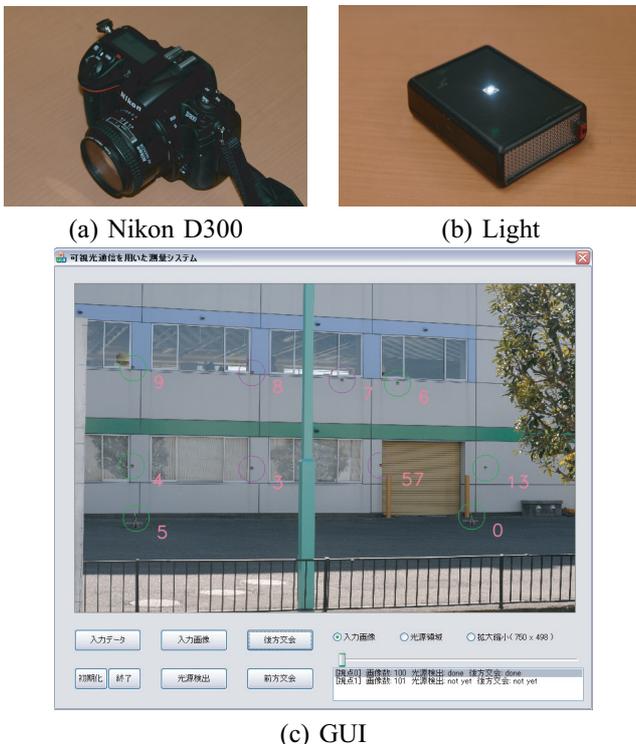


Fig. 1. System overview

III. EXTRACTION OF A LIGHT

A. Format of a Transmitted Data

The number of transmitted bits depends on the number of images captured consecutively. In our system, Nikon D300 captured 100 images consecutively. "Image" is called "sample" henceforth because "image" is replaced by "sample" in the research of signal communication.

Since the starting time of capturing time and blinking are not synchronized, the number of usable samples per a packet is 50. For error detection and correction, 1 bit is represented by 4 samples and the number of bits per a packet is 12.5, basically 12 bits. In our system, the case that the light is on means 1 and the case that the light is off means 0. A bit is represented as follows:

4 samples → 1 bit
 0011 → 0
 1100 → 1

When 4 samples are extracted, the distances of each bit as mentioned above are computed and nearest pattern is selected. In fact, 1 sample error is corrected if there is the error in 4 samples.

The format of a transmitted data is defined as follows:

Header	Data	CRC
3bit	6bit	3bit

Fig. 2. Format of transmit data

Since the starting time of capturing and blinking are not synchronized, a header system is applied and defined as follows:

Header → 111111000000

Since a data is 6 bits, 64 IDs can be generated for lights. For another error detection, 3 bits are assigned for cyclic redundancy checking (CRC) [15]. In CRC, an input data is divided by a CRC polynomial and the remainder is calculated at a sending side. Next, the input data is added to the remainder and the data become dividable number by the CRC polynomial. At a receiving side, a received data is divided by the same CRC polynomial as a sending side's. If the data is dividable, the data is correct, and vice versa. In our system, a CRC polynomial is

$$x^3 + x + 1 \tag{1}$$

For example, Table.I represents the case that ID:10 is transmitted.

B. Computation of a Threshold

For extracting a light area and computing an ID of a light from the blinking pattern, it is necessary to convert a value of a pixel into a binary for recognizing lighting on and off at first. In the related works, a pre-known threshold is prepared and a light area is defined if the value changes more than the

TABLE I
EXAMPLE OF A TRANSMITTED DATA

ID	10
ID bit	001010
CRC bit	011
TD	11111100000001100111100 001111000011001111001100

threshold [12], [13]. However, it is not desirable to set a pre-known threshold and use the same threshold for all pixels in an image because a value of a pixel changes depending on an intensity of a light and a distance between a camera and a light. In our system, a threshold of each pixel in an image is computed from time-series images.

As for Nikon D300, it takes about 16 seconds to capture 100 image and we assume that the lighting condition doesn't change while capturing images. From the number of time-series images described in III-C, maximum value Max_i and minimum value Min_i of each pixel i is obtained and a threshold Th_i is computed as follows:

$$Th_i = \frac{Max_i - Min_i}{2} + Min_i \quad (2)$$

C. Extraction of Light's Candidates

After binarizing a value of a pixel by the threshold, the pixels which change of the binary data follow a rule derived from III-A is extracted as a candidate of a light.

Samples of a transmitted data are composed of a header (111111000000) and a bit (0011 or 1100). If the header and the bit are arbitrarily combined, the number of consecutive 1 and 0 is even. This means that switching points of 1 and 0, which are 01 and 10, happen at even interval. For example, Fig.3 is a part of a transmitted data and the switching points happen at even interval. This is a rule of a transmitted data. In our system, a pixel following the rule is extracted as a candidate of a light.

00:11111111:00000000:1111:0000:11

Fig. 3. A part of a transmitted data

In the method as mentioned above, the number of extracted candidates depends on the number of time-series images utilized for extracting the change of a pixel. Light areas are selected from the extracted candidates by using cyclic redundancy checking described in III-D and the computation cost depends on the number of extracted candidates. For this reason, it is desirable to decrease the number of extracted candidates as much as possible.

Fig.4 represent the relationship between the number of extracted candidates and time-series images. In our system, the image resolution 4288×2848 and the number of extracted candidates are 26649 pixels in the case that the number of time-series images is 16. Since the number of light's pixels is 236, the change of many non-light pixels follow the rule as mentioned above. As Fig.4 shows, the extracted candidates

can be decreased by increasing the time-series images. This is because a longer variation of a non-light pixel doesn't match the rule. Since the number of usable time-series images depends on the image resolution and a size of memory in a computer, our system uses 20 images.

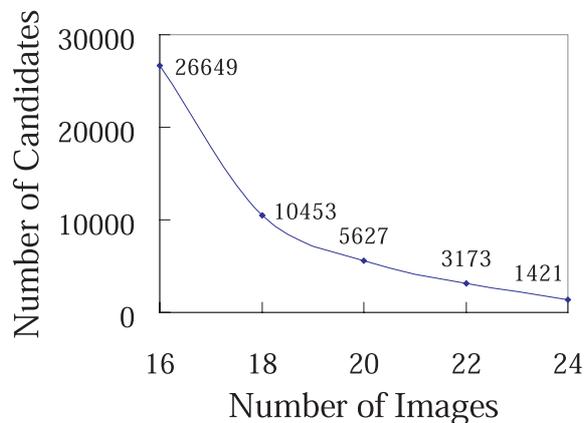


Fig. 4. Relation between number of candidates and time-series images

D. Extraction of a Light Area and Computation of its ID

In III-C, candidates' pixels of lights are extracted. The pixels are converted into areas by combining adjacent pixels. For example, in the case of 20 time-series images in Fig.4, 5627 pixels are converted into 2110 areas. Since the number of the area which size is only 1 pixel is 1466 in the areas, the areas of light candidates can be decreased by using an assumption that the size of a light area is more than 2 pixels.

Next, the transmitted data of each candidate's area are computed from all time-series images (in our system, 100 images). Each pixel of the candidate's area is binarized by using a threshold computed in III-B and the binary of the candidate's area is determined by voting. The transmitted data of a non-light area is removed by using cyclic redundancy checking (CRC). After the CRC, there are only light area and its ID is computed at the same time.

E. Computation of a Light Center

The center of a light area is computed because the center is utilized for photogrammetry.

Fig.5(a) is an example image of a light captured by Nikon D300 in the case that a distance between the camera and a light is 20m. The image resolution is 50×50 . Fig.5(b) is an extracted light area by III-D. For computing the center of the light, weighted average of each pixel in the area is computed. The weight of each pixel is computed by averaging values in the case that the light is on. As you see, the weight of the non-light area and the border area is small (Fig.5(c)). Fig.5(d) shows a light center as a pixel, however the computation is done by sub-pixel analysis.

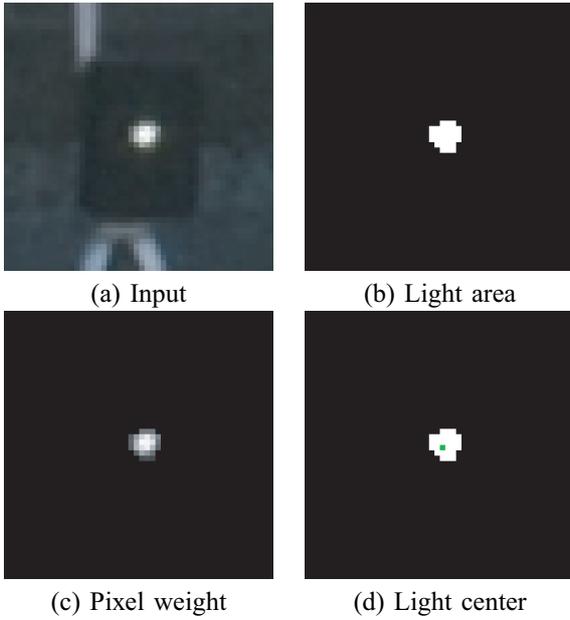


Fig. 5. Computation of light's center

IV. PHOTOGRAMMETRY

A. Coordinate Systems

Fig.6 shows a coordinate system utilized in usual photogrammetry. (X_w, Y_w, Z_w) is world coordinate system, (x_c, y_c, z_c) is camera coordinate system, (x, y) is image coordinate system, f is a focal length of a lens and (X_o, Y_o, Z_o) is a camera position in world coordinate system.

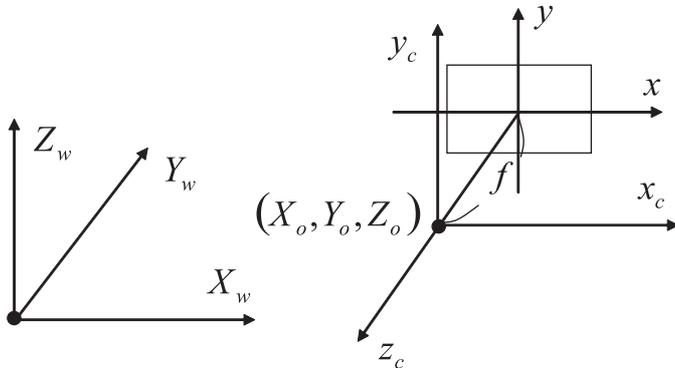


Fig. 6. Coordinate systems

Camera coordinate system is represented from world coordinate system and a camera rotation matrix $\mathbf{R}(\omega, \phi, \kappa)$ derived from a camera orientation (ω, ϕ, κ) as follows:

$$\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \mathbf{R}(\omega, \phi, \kappa) \begin{bmatrix} X_w - X_o \\ Y_w - Y_o \\ Z_w - Z_o \end{bmatrix} \quad (3)$$

Image coordinate system is represented from camera coordinate system and a focal length based on colinearity equation which means that an object, a projected point of the object in

an image and an image center are in a straight line as follows:

$$\begin{aligned} x &= -f \frac{x_c}{z_c} \\ y &= -f \frac{y_c}{z_c} \end{aligned} \quad (4)$$

B. Estimation of a Camera Position and Orientation

For estimating a camera position and orientation, more than 3 points are necessary in the case that a focal length has already been known [7], [8], [9], [10]. In our system, the estimation is achieved based on linearization of the colinearity equation and iterative solution.

For estimating a focal length, the software by Photometrix [16] is applied and the software provides a focal length and distortion parameters of a lens. The order of radial distortion parameters is 3 and the order of decentring distortion parameters is 2. By using these parameters, the computed centers in III-E are revised.

For linearizing the colinearity equation, Eq.4 is transformed as

$$\begin{aligned} F(X_o, Y_o, Z_o, \omega, \phi, \kappa) &= -f \frac{x_c}{z_c} - x = 0 \\ G(X_o, Y_o, Z_o, \omega, \phi, \kappa) &= -f \frac{y_c}{z_c} - y = 0 \end{aligned} \quad (5)$$

Since camera coordinate system (x_c, y_c, z_c) is parameterized by a camera position (X_o, Y_o, Z_o) and camera orientation (ω, ϕ, κ) , Eq.4 is parameterized by these parameters.

For iterative solution, first-order approximated equation of Eq.5 is derived from Taylor expansion by giving initial values of (X_o, Y_o, Z_o) and (ω, ϕ, κ) . Next, correction amounts of (X_o, Y_o, Z_o) and (ω, ϕ, κ) is calculated from the approximated equation by least square method and (X_o, Y_o, Z_o) and (ω, ϕ, κ) are updated. These process are iteratively done and convergent values of (X_o, Y_o, Z_o) and (ω, ϕ, κ) are computed.

C. Estimation of a Light Position

After more than two viewpoints are calibrated, the world coordinates of the points which will be measured by photogrammetry can be computed.

Eq.3 and Eq.4 are transformed as

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \sim \mathbf{P} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \quad (6)$$

where \mathbf{P} is called projection matrix in the research of computer vision [17]. \mathbf{P} is a 3×4 matrix and includes a focal length, a camera position and orientation. In our system, triangulation is achieved by using Eq.6. By generating Eq.6 from more than two viewpoints, a light position (X_w, Y_w, Z_w) can be computed.

V. EXPERIMENTAL RESULTS

A. Measurement of a Valid Distance

The usable distance is measured for evaluating that our system can extract a light at a variety of a distance. The shutter speed of the camera is 1/100 sec. and F-number is F/16.

10 lights described in Fig.1(b) are set on 2m, 35m, 50m points from a camera. At each distance, light detection is done

three times. This means that light detection is done for 30 lights at each distance. Fig.7 shows example images at each distance. As for light images included in each example, the image resolution is 150×150 at 2m, 10×10 at 35m and 50m and the light center is displayed as a pixel.

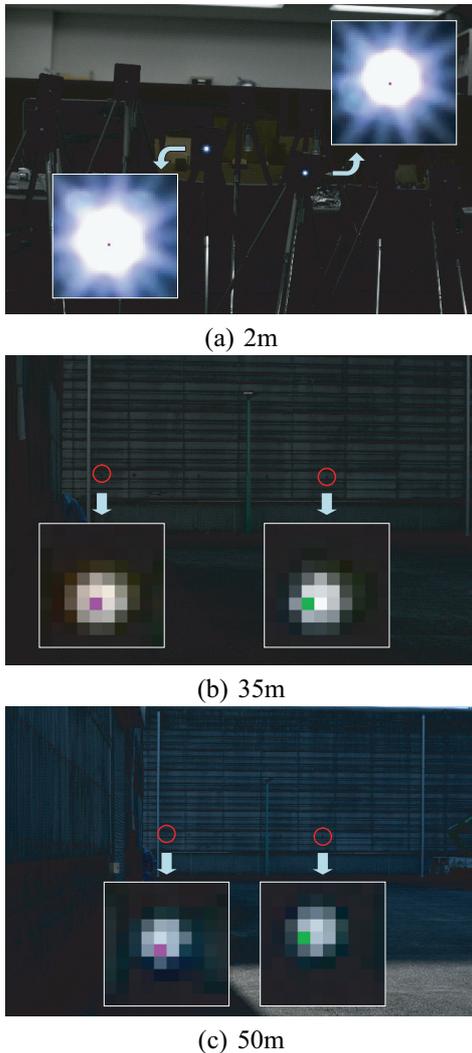


Fig. 7. Examples of each distance

In Table.II, the number of lights which IDs are computed and the average area of the lights are shown. The area of and the brightness of a light depend on the distance between a camera and a light. In the case of 35m and 50m, some lights are not detected because of lack of brightness.

On the other hand, the reason in the case of 2m is different. In a rare case, a light is captured at a moment of lighting off in Fig.8(b). Fig.8(a) is the same light as Fig.8(b) and it is the case of lighting on. In this case, additional sample is captured and cannot be corrected by III-A. This is because the interval of capturing images and blinking are not always synchronized. The capturing interval per an image is 0.16 sec. and an error of 0.01 sec. becomes 1 sec. while 100 images are captured. For this reason, the synchronization is important for our system as a preprocessing.

TABLE II
MEASUREMENT OF VALID DISTANCE

Distance	Number	Area
2	29	2963.6
35	27	7.4
50	25	6.5

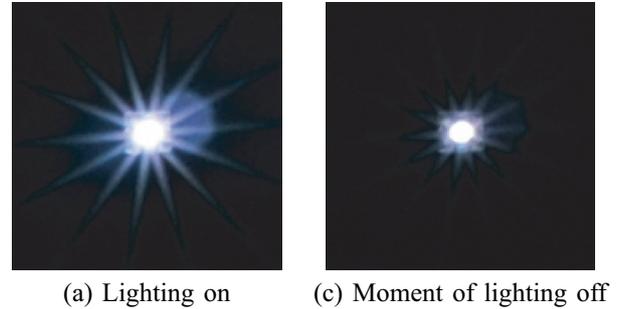


Fig. 8. Example of failure

B. Accuracy of Photogrammetry

As for a distribution of lights that we assume construction of a bridge, the accuracy of photogrammetry is evaluated.

Fig.9(a) represents the distribution and the positions of lights which number are from No.0 to No.5 are measured by Total Station. This means that reference points are set on the bottom parts of a bridge. From each viewpoint of Fig.9(b) and (c), 100 images are captured and the positions of lights which number are from No.6 to No.9 are computed by photogrammetry. This means that the upper parts of a bridge are monitored to detect the distortion. For evaluating the accuracy, the positions of lights which number are from No.6 to No.9 are also measured by Total Station and compared with the result by photogrammetry. The positions by Total Station are utilized for the ground truth. In Table.III, the unit of world coordinate system is m and an average error is 6.5mm. The accuracy is achieved because of a high resolution image and sub-pixel analysis.

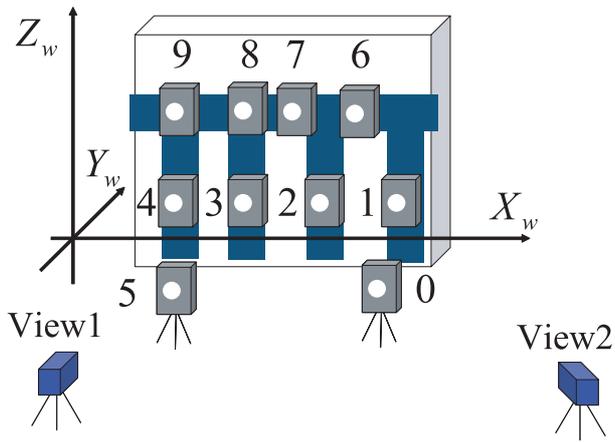
C. Computation Time

Since we assume that our system can be applied at an outside scene, these experiments are done by using a laptop. The laptop we use is X61 by Lenovo, which has 3GB memory and its CPU is Intel Core 2 Duo (2.2GHz).

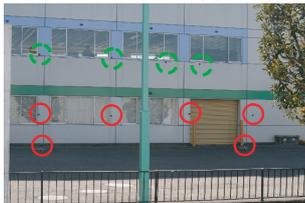
The time of capturing 100 images by Nikon D300 is 16 sec. per a viewpoint. The part which takes most time is extraction of a light from 100 images. In the current environment, it takes around 4 minutes. The process of the extraction can run parallel if there is a laptop for each viewpoint. Engineers of Construction Company said that trained people for our system were not necessary and the computation time was enough for a practical use.

VI. CONCLUSIONS AND FUTURE WORKS

In this paper, we proposed a photogrammetric system based on the concept of visible light communication and the method



(a) Distribution of light



(b) View1



(c) View2

Fig. 9. Experiment for estimating distortion of bridge

for extraction of a light and its ID. We presented that a light was a useful marker for photogrammetry and was extracted at a variety of a distance. In the extraction of a light, a pre-known threshold for detecting a blinking is not necessary and the rule of a blinking is utilized. The matching of same lights in different viewpoints is achieved by using unique blinking patterns.

Currently a light set on 50m away from a camera can be detected. However, the distance should be longer for construction of a large bridge. This is why new light source should be designed. In addition, we should evaluate the influence of the weather and the camera sensor characteristics such as sensitivity, response time or intrinsic noise. As for a preprocessing, the interval of capturing images and blinking should be synchronized. The problem should be solved by a signal processing approach.

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TABLE III
ACCURACY OF PHOTOGRAMMETRY

ID	Total Station			Photogrammetry			Error
	x	y	z	x	y	z	
6	59.227	50.000	25.020	59.225	50.004	25.018	0.005
7	57.164	49.998	25.064	57.164	50.003	25.060	0.007
8	53.998	50.002	25.207	53.998	50.006	25.208	0.004
9	49.991	49.996	25.234	49.992	50.005	25.230	0.010