# A 100Hz Real-time Sensing System of Textured Range Images

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***Abstract*—This paper describes a small high-speed range image sensor which can acquire a range image mapped with a color texture captured by another camera. The constructed sensor consists of only commercially available products: a monochrome CCD camera, a color CCD camera, a laser projector, and two optical filters. The resolution of the range image is 19×19 for a total of 361 points, and the measurement speed is 100Hz. A three-dimensional (3D) mapping method using the constructed sensor is introduced. The measurement precision of the sensor and the accuracy of the constructed 3D map are evaluated with some experiments. In addition, measurement examples of the sensor are shown. Experiments verify that the constructed sensing system can acquire 100Hz real-time textured range images and that it can be applied to 3D mapping by using range and color information.**

## I. INTRODUCTION

There has been an increasing requirement for range images over a wide range of application fields. Many methods to acquire range images have been studied in the field of computer vision, robot vision, and optics [1], and several range image sensors are commercially available at present. High-speed sensing systems have had significant impact on several applications, such as visual tracking by a robot [2], [3]. In the same way, a high-speed three-dimensional (3D) measurement system will have a great impact over a wide range of application fields, such as control tasks in robotics (e.g., a bin-picking task of a manipulator, the observation of a moving/deforming object, and a newly human-machine interface system).

Umeda [4] constructed a compact range image sensor using a multi-spot laser projector suitable for robots in several aspects, including size, cost, and, especially, measurement time. This sensor's measurement speed was 30Hz. Watanabe et al. [5] achieved a 955Hz shape measurement using a newly constructed high-speed vision system, but this system needs special devices. Tateishi et al. [6] achieved the construction of a 200Hz small range image sensor using only commercially available products. Measurement precision and speed were evaluated.

To apply such kind of sensors to a task like 3D mapping, the sparseness of the data sometimes become an issue. Popescu et al. [7] showed that even a range image with only 16 points is effective for modeling using a color texture mapped to sparse range images. A color texture is important information for sparse range images [7], [8].

In this paper, we improve the Tateishi's sensor[6] and construct a small high-speed range image sensor which can acquire a range image mapped with a color texture. And additionally, we apply the constructed sensor to the 3D mapping task. The structure for range imaging is the same as Tateishi's sensor except that the sensor realizes outdoor range image measurement in the sun with the help of newly attached optical filters.

This paper is organized as follows. Firstly, construction of the sensor is described. Next, a method of 3D mapping with the sensor is introduced. Then experimental results are described, and finally the paper is concluded.

## II. CONSTRUCTION OF THE SENSOR

Fig.1 shows the structure of the constructed sensing system's range image measurement part. Multiple spots are projected from the laser projector as a dot matrix pattern, as shown in Fig.1. These spots are observed using a monochrome CCD camera. According to the configuration of the projector and the CCD camera, these spots move horizontally on the camera image corresponding to its distance (see Fig.1). The distance of each laser spot from the lens center is calculated by triangulation.

### A. Measurement Principle

Fig.2 illustrates the measurement principle and related sensor parameters. The distance $Z$ is calculated by

$$Z = \frac{\alpha}{d}, \qquad \alpha = \frac{b \cdot f}{p}. \tag{1}$$

where

$p$ [mm/pixel]: width of each pixel of the image

$d$ [pixel]: length between $k_\infty$ and $k$ (see Fig.2)

$b, f$ and $p$ are collectively thought as one constant $\alpha$ [mm·pixel] because they are constants of hardware.

### B. Sensor Calibration

Distance $Z$ of a range image is calculated by detecting the spot position on the camera image. To do this, it is necessary to obtain the constants $k_\infty$ and $\alpha$ in advance. $k_\infty$ and $\alpha$ can be obtained from $k$ corresponding to given $Z$. To improve the

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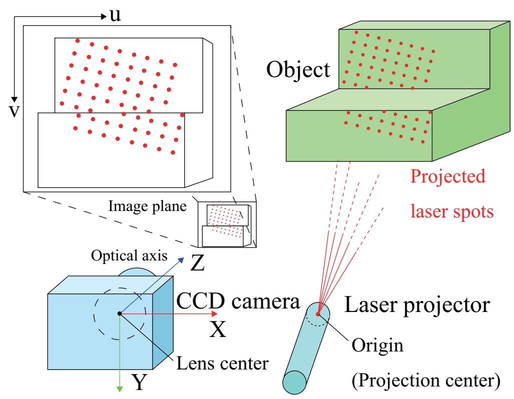



Fig. 1. Range image measurement of the sensor using a multi-spot laser projector

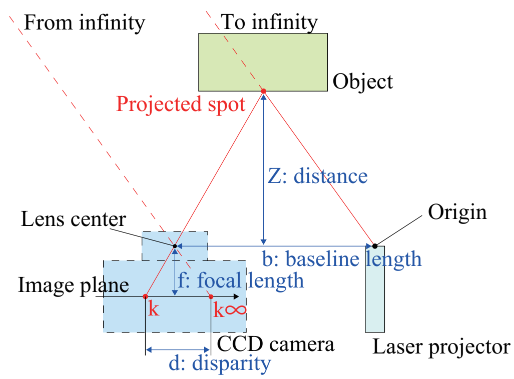



Fig. 2. Measurement principle and sensor parameters

precision of the calibration, $k_\infty$ and $\alpha$ are obtained by the linear least-squares method as

$$\begin{bmatrix} k_\infty \\ \alpha \end{bmatrix} = \frac{1}{D} \begin{bmatrix} n\sum Z_i^2 k_i - \sum Z_i \sum Z_i^2 k_i \\ \sum Z_i^2 \sum Z_i k_i - \sum Z_i \sum Z_i^2 k_i \end{bmatrix}, \tag{2}$$

$$D = n \sum Z_i^2 - (\sum Z_i)^2 \tag{3}$$

where $n$ is the number of measurement for calibration.

### C. Texture Mapping

Fig.3 shows the configuration of the constructed sensing system's texture mapping part. It shows the relation between the 3D coordinates of spots obtained by the range image sensor and the projection point of spots on a color CCD camera image.

The texture coordinates for texture mapping to range images can be obtained using a perspective projection matrix. A perspective projection matrix is a 3×4 matrix which describes the relation between the 3D coordinate and the projection point. It is given as

$$\boldsymbol{P} = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \end{bmatrix}. \tag{4}$$

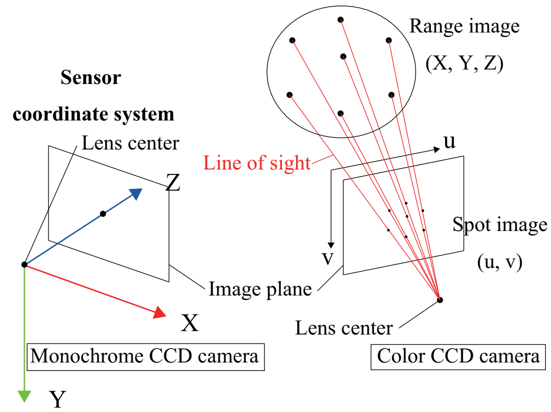



Fig. 3. Perspective projection for texture mapping

The relation between the 3D coordinate $\boldsymbol{X_w}$ and the texture coordinate $\boldsymbol{m}$ can be given as follows.

$$\boldsymbol{m} = \boldsymbol{P}\,\boldsymbol{X_w} \tag{5}$$

From $\boldsymbol{m} = (u, v, 1)$ and $\boldsymbol{X_w} = (X_w, Y_w, Z_w, 1)$, simultaneous equations can be set up, and $\boldsymbol{P}$ is calculated as a solution of these equations. To reduce the influence of the measurement errors, many known $\boldsymbol{X_w}$ and $\boldsymbol{m}$ are used for setting up simultaneous equations. The matrix $\boldsymbol{P}$ can be given as a linear least-squares solution by

$$\boldsymbol{p} = (\boldsymbol{A}^T \boldsymbol{A})^{-1} \boldsymbol{A}^T \boldsymbol{q} \tag{6}$$

where

$$\begin{aligned}
\boldsymbol{p} &= \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{21} & \cdots & p_{33} \end{bmatrix}^T, \\
p_{34} &= 1, \\
\boldsymbol{A} &= \left( \boldsymbol{B} \mid \boldsymbol{C} \mid \boldsymbol{D} \right), \\
\boldsymbol{B} &= \begin{bmatrix} X_{w1} & Y_{w1} & Z_{w1} & 1 \\ 0 & 0 & 0 & 0 \\ X_{w2} & Y_{w2} & Z_{w2} & 1 \\ 0 & 0 & 0 & 0 \\ & \vdots & & \end{bmatrix}, \\
\boldsymbol{C} &= \begin{bmatrix} 0 & 0 & 0 & 0 \\ X_{w1} & Y_{w1} & Z_{w1} & 1 \\ 0 & 0 & 0 & 0 \\ X_{w2} & Y_{w2} & Z_{w2} & 1 \\ & \vdots & & \end{bmatrix}, \\
\boldsymbol{D} &= \begin{bmatrix} -u_1 X_{w1} & -u_1 Y_{w1} & -u_1 Z_{w1} \\ -v_1 X_{w1} & -v_1 Y_{w1} & -v_1 Z_{w1} \\ -u_2 X_{w2} & -u_2 Y_{w2} & -u_2 Z_{w2} \\ -v_2 X_{w2} & -v_2 Y_{w2} & -v_2 Z_{w2} \\ & \vdots & \end{bmatrix}, \\
\boldsymbol{q} &= \begin{bmatrix} u_1 & v_1 & u_2 & v_2 & \cdots \end{bmatrix}^T.
\end{aligned}$$

### D. Constructed sensor hardware

Fig.4 shows the constructed sensor. The laser projector is fixed to the monochrome CCD camera with the aluminum

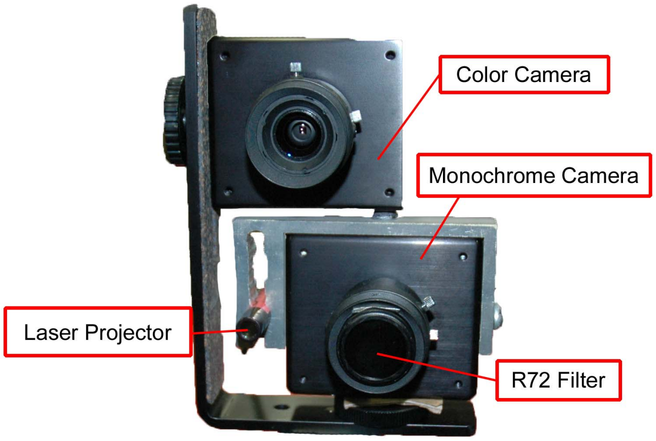



Fig. 4. Constructed sensor

frame. The color CCD camera is installed for a color texture.

The laser projector is StockerYale Mini-519X [9]. Its wavelength is 785nm (infrared), and its power is 35mW. It projects 19×19 for a total of 361 spots using a diffraction grating attached at its tip. The angle between adjacent spots is 0.90°. The monochrome CCD camera and the color CCD camera are Point Grey Research Dragonfly Express [10]. These cameras are attached to a PC (DELL XPS XPS720, Core2 Extreme CPU Q6850 @ 3.00GHz, DRAM 2.00GB) by an IEEE1394b PCI Express Card, and each maximum frame rate is 100Hz. The resolution of the CCD camera is 640×480 (VGA), and the size of the pixel is 7.4×7.4$\mu m^2$. The lens is TAMRON 13FM08IR and its focal length is 8mm. The optical low-pass filter HOYA R72 is attached to the top of the monochrome CCD camera's lens. The optical band-pass 785nm filter produced by Edmund optics Co. is attached behind the lens of the monochrome CCD camera. Disturbance lights are cut by these two filters, and high S/N ratio is realized, which enables the outdoor measurement in the sun.

The baseline length is 47.5mm. The size of the sensor is width 130mm × height 157mm × depth 70mm. The weight of the sensor is 690g including the frame.

## III. 3D MAPPING

In this section, a 3D mapping method with the constructed sensor is proposed. The sensor's ability to obtain texture images and its high speed are used. First, matched point sets between two color textures are estimated. Next, 3D coordinates of the matched points are obtained. Registration of range images is done using the matched points in 3D, and registered range images are integrated to one range image. The integration is iterated between the previously integrated range image and a new range image. Finally, the integrated range image becomes a 3D map of measured scene. The details of each step are shown as follows.

### A. 2D Matching

We use SIFT features [11] for two-dimensional (2D) matching. SIFT features are extracted for each color camera image and matched, and correspondences in 2D are obtained. With the constructed sensor, images are obtained fast, and thus changes between two color images are small. Therefore, many 2D matched pairs can be obtained at this step.

### B. 3D Matching from 2D Matching

3D matching is necessary for registration of range images. As the constructed sensor obtains a textured range image, 3D coordinates corresponding to the matched 2D points can be obtained. The 3D coordinate is obtained as the intersection of the 3D mesh of the range image and the 3D line that is formed by projecting the 2D point in 3D space along the view direction.

### C. Alignment of Matched Point Sets

Let $P = \{\boldsymbol{p_i}\}$ be a previous frame's 3D matched point set, and $X = \{\boldsymbol{x_i}\}$ a new frame's matched point set, where point $\boldsymbol{p_i}$ corresponds to the point $\boldsymbol{x_i}$. The evaluation function to be minimized for the registration is represented as

$$f = \frac{1}{N_p} \sum_{i=1}^{N_p} \|\boldsymbol{x_i} - \boldsymbol{R}\boldsymbol{p_i} - \boldsymbol{t}\|^2 \tag{7}$$

where $N_p$ is the number of the matched pair, $\boldsymbol{R}$ is the 3×3 rotation matrix, and $\boldsymbol{t}$ is the translation vector. To minimize this function and estimate $\boldsymbol{R}$ and $\boldsymbol{t}$, we use the quaternion-based algorithm[12]. Additionally, LMedS estimation [13] is adopted to remove wrong matched pairs, for SIFT feature matching produces wrong pairs to some extent.

### D. Integration using Error Ellipsoid

With the alignment, range images are overlapped. To construct a 3D map, the overlapped images should be integrated. We consider errors of range images for the integration. We use the error ellipsoid of each measurement point of the new frame. Each point of the range image is checked whether it is inside the ellipsoid, and the average of the points inside the ellipsoid is produced as a new point and the original points are deleted. The ellipsoid's radii can be obtained by applying the law of propagation of errors to the measurement model. From (1),

$$\sigma_z = \frac{\sigma_k}{\alpha} Z^2. \tag{8}$$

is obtained. $\sigma_z$ is used for the radius for $Z$.

## IV. EXPERIMENTS

We evaluate the performance of the proposed sensing system and its application to 3D mapping by means of some experiments.

### A. Evaluation of Speed

The speed of the sensor is very important for its advantage. The sensor's processing time was measured with the timer of the computer. The software system we constructed consists of two threads. Each processing time is shown in Fig.5 (range data calculation thread) and Fig.6 (texture mapping and rendering thread). The average time of the thread loop is 10ms, i.e., 100Hz, for both threads.

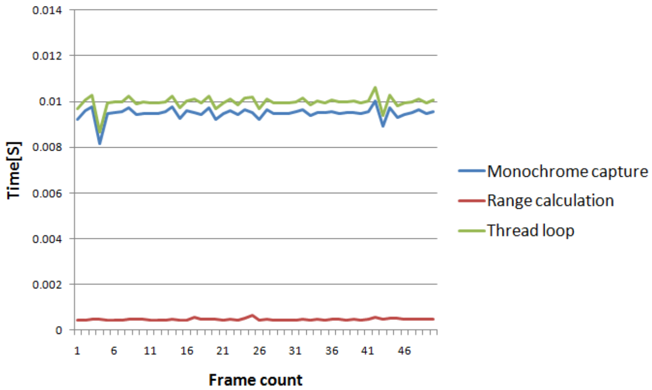



Fig. 5. Processing times of the range calculation thread

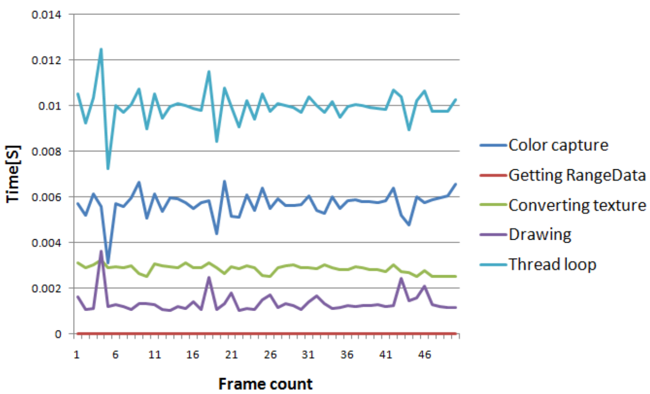



Fig. 6. Processing times of the texture mapping and rendering thread

The speed of the sensor was confirmed by measuring the cycle of an actual pendulum. Fig.7 shows the scene of experiment. A ball with a diameter 90mm is hung with a transparent string of length 300mm. A theoretical cycle of the pendulum becomes 1.18s. Fig.8 shows the distance of the ball's center calculated from the range image data. The number of frames for ten cycles was counted, and it was about 1200 frames. As the theoretical time of 10 cycles is 11.8s, the calculated sampling rate is 101.7Hz, which is close to 100Hz. We can say with the pendulum experiment that the 100Hz sensor speed is realized.

### *B. Evaluation of Texture Mapping*

We evaluated whether the texture can be correctly mapped to the range image. The projection matrix the system uses is calculated by a spot laser image on the color camera image and by its measured 3D position. We measured the range image of the plate attached vertically to the sensor's optical axis. In that time we obtained spot laser images on the color camera image and their measured 3D positions. Measured distances of this experiment were 650mm and 1200mm. We compared the spot laser images on the color camera image and the texture coordinates which ware calculated by the projection matrix we obtained. The subtraction between the spot image coordinate

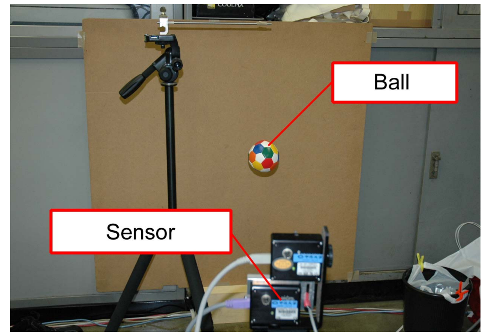



Fig. 7. Experimental scene of measuring the pendulum

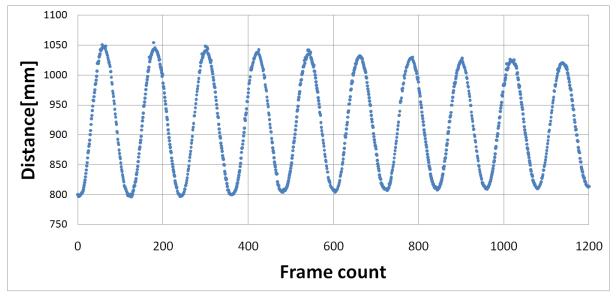



Fig. 8. Distance of the ball's center

and calculated texture coordinate was considered to be an error value, and we obtained the standard deviation. Table I shows the results. In addition, we obtained the distribution of the error value on the color camera image. Fig.9 indicates the distribution of the error on the color image. From the increase of the error value in the area around the image, we think that the lens distortion affects the error distribution. However, we did not consider the lens distortion because the sensor's processing time is important. From these results, we think it is enough precision for the texture mapping.

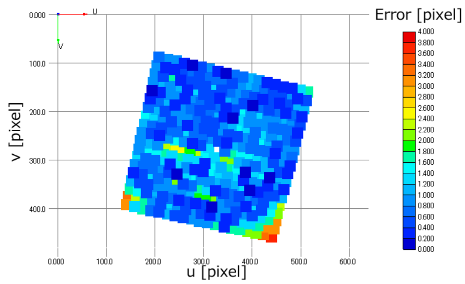
TABLE I
THE PRECISION OF A TEXTURE MAPPING

| Distance (mm) | S. D. (pixel) | Max error (pixel) |
|---|---|---|
| 650 | 1.09 | 3.62 |
| 1200 | 1.01 | 2.79 |

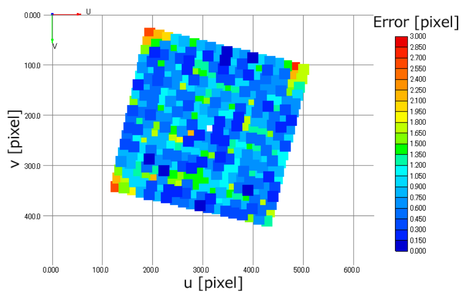
### *C. Evaluation of Measurement Precision*

The measurement precision at each distance was evaluated.

When the range image of the plate attached vertically to the sensor's optical axis is measured, the distance of each point of the range image from the fitted plane can be considered to be the measurement error. We obtained the standard deviation of the error at each measured distance. Fig.10 shows the results. From (8), the measurement error $\sigma_z$ is proportional to the square of the distance considering that $\sigma_k$ is constant to the distance. $\alpha$ is about 53000 mm$\cdot$pixel from the parameters of the constructed system. Then $\sigma_k$ becomes about 0.11pixels,




(a) 650mm




(b) 1200mm

Fig. 9. Errors between the texture coordinate obtained by the system and spot image on the color camera image

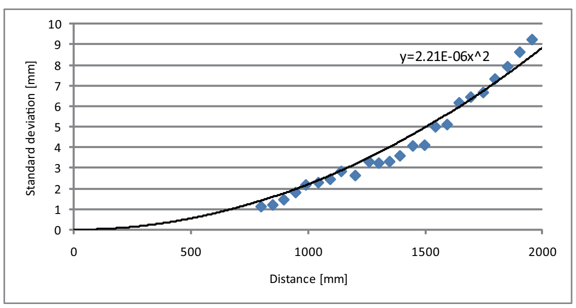



Fig. 10. Standard deviation of the measurement distance

which means that the spot position is measured with high precision.

### D. Example of Measurement

Fig.11 shows the measured objects: from left, a cube with a texture, a tree trunk, and a box of white cardboard. Fig.12 shows the measured results, textured range images rendered by the constructed system.

### E. 3D Mapping

We constructed a 3D map using the proposed 3D mapping method. The measured object is a floor surface which is textured with sheets of newspaper for SIFT features as shown in Fig. 13. In this experiment, the sensor was moved with a free hand such that it makes a raster scan for the newspaper sheets area. Fig.14 shows the 3D mapping result, with the process of the 3D map's development. The measured distance was about 800-900mm, and the area textured by the newspaper sheets was about $1m^2$. We evaluated the 3D map of the floor surface to verify the 3D mapping method with the constructed

Fig. 11. Measured objects with the constructed sensor: from left, a cube with texture, a tree trunk, and a box of white cardboard

sensor. The distance to the plane fitted to the 3D map was considered as the error, and the standard deviation of the distances was obtained. The result is shown in table II. The 3D map constructed with as many as more than 300 range images is very flat, i.e., precise, which shows that the proposed 3D mapping method works well, and that the constructed sensor is applicable for such a mapping task. Notice that 3D mapping of such a flat surface is impossible with range images only, without measuring textures. The 3D mapping cannot be realized at 100Hz; it requires several seconds so far.

TABLE II
THE PRECISION OF THE CONSTRUCTED 3D MAP

| Distance (mm) | S. D. (mm) | Max error (mm) |
|---|---|---|
| 800-900 | 6.28 | 26.8 |

## V. CONCLUSIONS AND FUTURE WORK

In this paper, we have constructed a 100Hz high-speed small range image sensor which can acquire range images mapped with a color texture. The proposed sensor system consists of only commercially available products: a high-speed monochrome CCD camera, a color camera, and a laser projector which can project multiple spots. We evaluated the measurement speed, precision by experiments, and demonstrated the potential of the sensor system by constructing a 3D map. We believe that the high-speed textured range image measurement with the constructed sensor is considered to be effective for several applications.

Future works will include the application of the sensor to other practical problems that require high-speed textured range image measurement. The 3D mapping method does not work in real time, so the speed-up of the method should also be done.

## ACKNOWLEDGMENT

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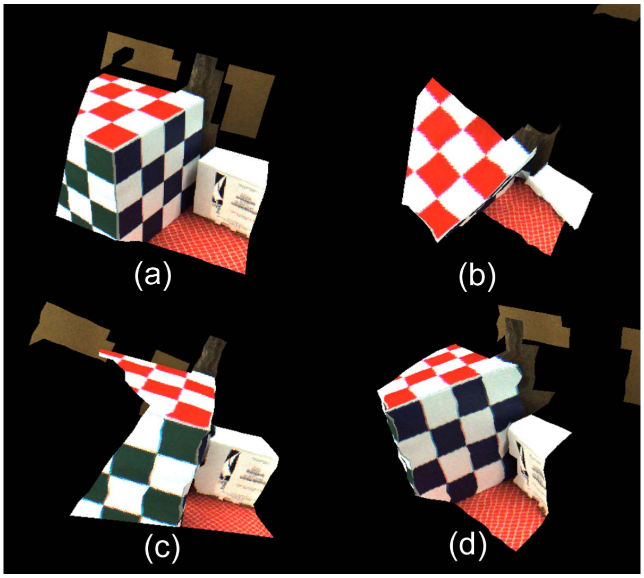


Fig. 12. Textured range images: (a) front view, (b) top view, (c) left-side view, (d) right-side view

Fig. 13. measured object for the 3D mapping: the floor surface textured by a newspaper

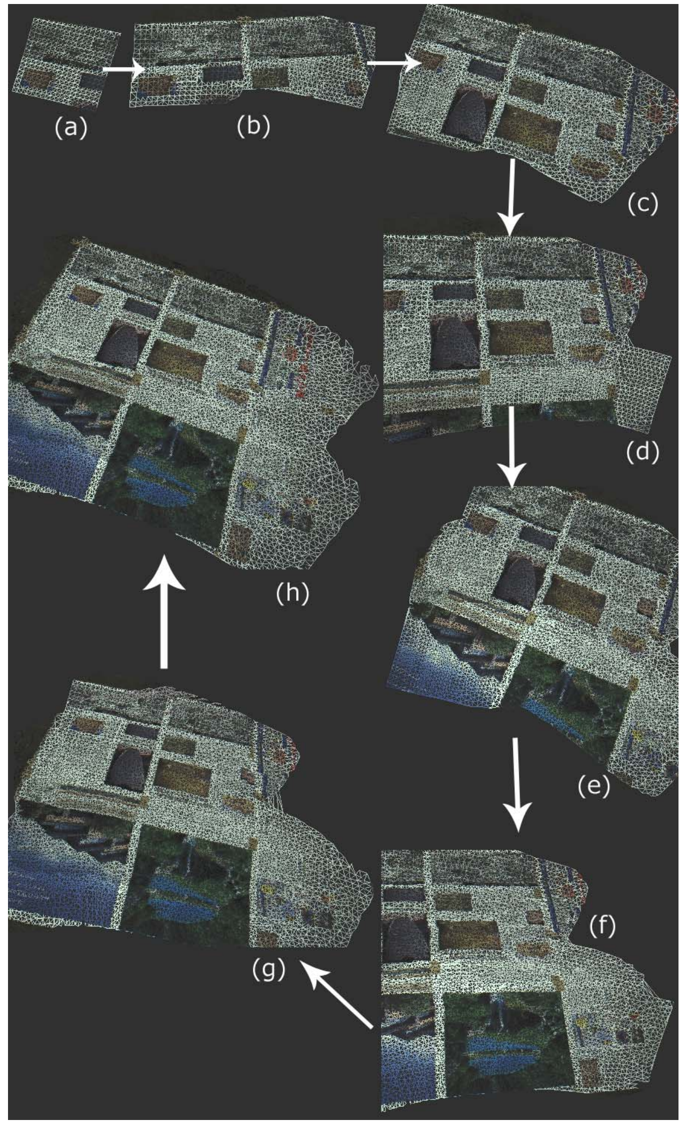


Fig. 14. 3D mapping results: (a) 1st frame, (b) 26th frame, (c) 63rd frame, (d) 105th frame, (e) 154th frame, (f) 207th frame, (g) 267th frame, (h) 340th frame

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