Multiple Fisheye Camera Calibration and Stereo Measurement Methods for Uniform Distance Errors throughout Imaging Ranges Supplementary materials

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1 Experimental video results

We demonstrate stereo measurement using our method and a quad-fisheye mounted on a car in the attached video. The quad-fisheye camera obtained the depth map in an outdoor parking lot. The video shows that our quad-fisheye camera obtains sufficient depth throughout imaging ranges. Further, we are able to recognize walking persons from the depth map.

2 Calibration object

We describe the calibration object with checker patterns to obtain the ground truth of the world coordinates and image coordinates. Our calibration object consisted of two calibration boxes and two chains of panels. The two boxes covered the whole fields of views in our quad-fisheye camera in Fig. 1 (a) and (b). The chains of panels covered only the horizontal fields of view and parts of the vertical fields of view due to space limitations in Fig. 1 (c) and (d). We selected 1898 calibration points commonly captured in quad-fisheye images.

A 3D laser scanner (FARO Focus^{3D} X 130) measured the calibration points, and the origin of the world coordinate was the same as the origin of the laser scanner. The 3D points measured by the laser scanner were precise enough for our experimental evaluation.

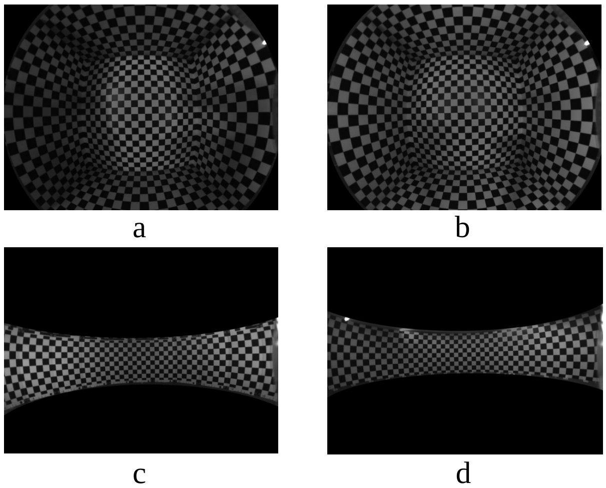

Figure 1: Calibration targets captured by the lower-left lens of quad-fisheye camera. Parts of the image without any calibration target are trimmed for visualization. (a) Calibration box sized $1000 \times 1000 \times 500$ mm with a 50-mm square checker patterns. (b) Calibration box sized $2000 \times 2000 \times 1000$ mm with a 100-mm square checker patterns. (c) Chain of panels sized 1800×900 mm with a 180-mm square checker patterns located about 3000 mm away from the camera. (d) Chain of panels sized 2700×900 mm with a 300-mm square checker patterns located about 5000 mm away from the camera.

3 Reprojection errors

Tables 1, 2, and 3 show comparison of the root-mean-square (RMS) reprojection errors using four cameras, three cameras and two cameras, respectively. The reprojection error is the total sum of distances between points projected on an image based on the world coordinates using camera parameters and the corresponding points on the image.

Tsai's method [1] individually calibrates each camera. In contrast, our baseline weighting simultaneously calibrates all cameras using our objective function. The comparison of reprojection errors shows that the errors in our method were 0.17–0.25 pixels whereas those in Tsai's method [1] were 0.30–0.94 pixels. These results demonstrate that our calibration method precisely calibrates cameras owing to its baseline weighting in the cases of two or more cameras.

References

[1] R. Y. Tsai. A versatile camera calibration technique for high-accuracy 3D machine vision metrology using off-the-shelf TV cameras and lenses. *IEEE Journal of Robotics and Automation*, 3(4):323–344, 1987.

Table 1: Comparison of RMS reprojection errors using four cameras (pixels).

Calibration methods	LL[1]	LR[2]	UL[3]	UR[4]	Mean[5]
Tsai's method [1]	0.94	0.33	0.85	0.30	0.60
our baseline weighting	0.22	0.19	0.17	0.18	0.19

[1] Lower-left camera in our quad-fisheye camera
[2] Lower-right camera in our quad-fisheye camera
[3] Upper-left camera in our quad-fisheye camera
[4] Upper-right camera in our quad-fisheye camera
[5] Mean among LL, LR, UL, and UR

Table 2: Comparison of RMS reprojection errors using three cameras (pixels).

Calibration methods	LL[1]	UL[2]	UR[3]	Mean[4]
Tsai's method [1]	0.94	0.85	0.30	0.70
our baseline weighting	0.24	0.25	0.21	0.23

[1] Lower-left camera in our quad-fisheye camera
[2] Upper-left camera in our quad-fisheye camera
[3] Upper-right camera in our quad-fisheye camera
[4] Mean among LL, UL, and UR

Table 3: Comparison of RMS reprojection errors using two cameras (pixels).

Calibration methods	UL[1]	UR[2]	Mean[3]
Tsai's method [1]	0.85	0.30	0.57
our baseline weighting	0.17	0.20	0.18

[1] Upper-left camera in our quad-fisheye camera
[2] Upper-right camera in our quad-fisheye camera
[3] Mean between UL and UR