A STUDY ON CALIBRATION OF DIGITAL CAMERA

Ryuji Matsuoka[a,*], Kiyonari Fukue[a], Kohei Cho[a], Haruhisa Shimoda[a], Yoshiaki Matsumae[a], Kenji Hongo[b], Seiju Fujiwara[b]

[a] Tokai University Research & Information Center
2-28-4 Tomigaya, Shibuya-ku, Tokyo 151-0063, JAPAN
ryuji@yoyogi.ycc.u-tokai.ac.jp, fku@keyaki.cc.u-tokai.ac.jp, kcho@keyaki.cc.u-tokai.ac.jp, smd@keyaki.cc.u-tokai.ac.jp, jjm@keyaki.cc.u-tokai.ac.jp
[b] Kokusai Kogyo Co., Ltd., 2 Rokuban-cho, Chiyoda-ku, Tokyo 102-0085, JAPAN
kenji_hongo@kkc.co.jp, seiju_fujiwara@kkc.co.jp

Commission III, WG III/5

KEY WORDS: Digital, Calibration, Orientation, Simulation, Camera, Distortion, Non-Metric, Method

ABSTRACT:

Recent increase in number of pixels of images acquired by a non-metric digital camera encourages an amateur to utilize it for 3D measurement. Most of current camera calibration methods are inconvenient and expensive for an amateur to calibrate his digital camera. Therefore we have developed a method for an amateur to calibrate a non-metric digital camera easily.
Our proposed method needs a lot of objects (calibration points) recognizable in an image instead of targets. Eight convergent images are acquired from eight different directions with four different camera frame rotation angles of 0°, +90°, +180° and -90°. Measurement of image coordinates of calibration points are in principle executed by template matching. A set of camera parameters is determined by the bundle adjustment.
A field experiment and a numerical simulation were conducted to investigate performance of our proposed method. The results of the field experiment and the numerical simulation indicate that the proposed method using a set of calibration points distributed on the 2D plane can provide a reliable set of camera parameters. Error of an image distortion model estimated by the proposed method is expected to be up to approximately ±3 pixels or ±12 µm on the image.
Since our proposed method needs neither special equipment nor ground survey of control points, we believe that the proposed method is useful for an amateur to calibrate his digital camera.

1. INTRODUCTION

As performance of a digital camera becomes better and its price becomes lower in recent years, digital camera images are becoming more popular in diverse fields. Increase in number of pixels of images acquired by a digital camera seems to go on forever without stopping. Some of current popular digital cameras, whose prices are less than US$ 1000, can acquire an image of more than 5 million pixels. The increase in number of pixels of images encourages an amateur to utilize a non-metric digital camera for 3D measurement. However the increase in number of pixels causes two problems: One is radiometric degradation of image quality due to reduction in area of an imaging element (Ohmori, 2001), and the other is a disclosure of geometric distortion of an image because of smaller interval between imaging elements. In this paper we focus on calibration of geometric distortion of digital camera images. We propose a new calibration method of a non-metric digital camera for an amateur, and indicate effectiveness of the method by a field experiment and a numerical simulation.

2. A PROPOSED CALIBRATION METHOD

There are several calibration methods of close range cameras (Fryer, 1996; Fraser, 2001). Optical calibration by using a multi-collimator or a goniometer is popular for metric cameras, but is rarely conducted for a non-metric camera owing to its higher cost. Field calibration methods including self-calibration are usually adopted for a non-metric camera. Since most of field calibration methods need a ground survey for determining precise positions of controls points or to place an array of 3D distributed targets, these methods are inconvenient and expensive for an amateur to calibrate his digital camera. Therefore we have developed a method for an amateur to calibrate a non-metric digital camera with no special equipment, no ground survey or no special targets.

Figure 1 shows the procedure of our proposed calibration method.

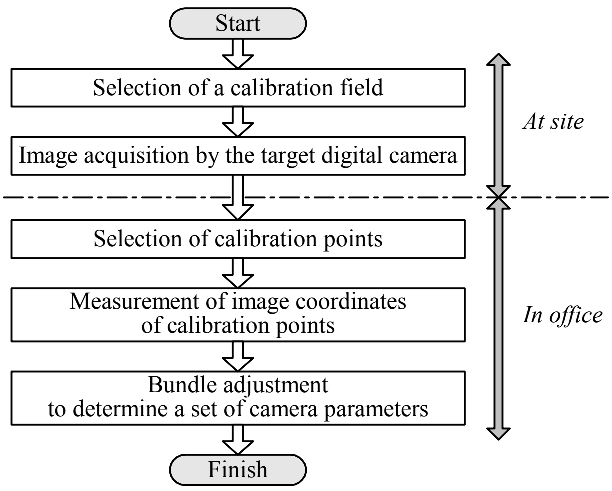


Figure 1. Procedure of the proposed calibration method

(1) Selection of a calibration field
Our method needs a lot of objects recognizable in an acquired image instead of targets. These objects are called calibration points from now on. It is requested that calibration points are impartially distributed in a calibration field. Calibration points are not necessary to be placed spatially. A plane with calibration points placed at regular intervals, for instance a tiled pavement or a brick wall of a building, is suitable for a calibration field. Figure 2 shows a suitable calibration field.

Figure 2. A suitable calibration field

(2) Image acquisition by the target digital camera
Eight convergent images are acquired from eight different directions with four different camera frame rotation angles of 0°, +90°, +180° and -90° around the optical axis of the camera as shown in Figure 3. An appropriate inclination angle α depends on the field of view of the target camera.

(3) Selection of calibration points
More than hundred calibration points are selected on a PC display, and a template image of each calibration point is automatically created by rectification of the image used in the selection to the calibration field plane.

(4) Measurement of image coordinates of calibration points
Measurement of image coordinates of calibration points are in principle executed by template matching on the calibration field plane. If template matching of a point fails, the position of the point is manually measured on a PC display.

(5) Bundle adjustment to determine a set of camera parameters
A set of camera parameters is determined by the bundle adjustment. In the proposed method image distortion (Δx, Δy) of a point (x, y) is represented as

$$\begin{cases} \Delta x = x_p + \overline{x}\left(k_0 + k_1 r^2 + k_2 r^4 + k_3 r^6\right) \\ \quad + p_1\left(r^2 + 2\overline{x}^2\right) + 2p_2\overline{xy} \\ \Delta y = y_p + \overline{y}\left(k_0 + k_1 r^2 + k_2 r^4 + k_3 r^6\right) \\ \quad + 2p_1\overline{xy} + p_2\left(r^2 + 2\overline{y}^2\right) \end{cases} \tag{1}$$

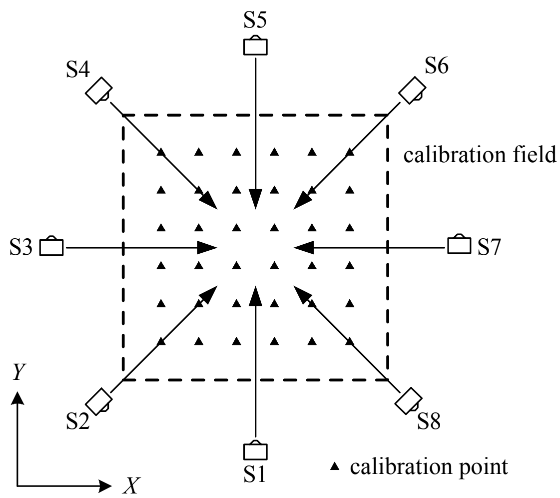
$$\begin{cases} r^2 = \overline{x}^2 + \overline{y}^2 \\ \overline{x} = x - x_p \\ \overline{y} = y - y_p \end{cases} \tag{2}$$

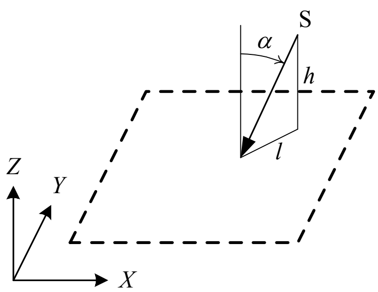
where x_p, y_p is the offsets from the principal point to the center of the image frame, k_0, k_1, k_2, k_3 are the coefficients of balanced radial distortion, and p_1, p_2 are the coefficients of decentering distortion.
The first order coefficient k_0 of balanced radial distortion is also expressed as

$$k_0 = \frac{\Delta c}{c_0} \tag{3}$$

using the correction Δc to the assumed principal distance c_0. Both balanced radial distortion Δr and the profile of decentering distortion Δd referred in the next chapter are functions of a radial distance r from the principal point. They are expressed as

$$\begin{cases} \Delta r = k_0 r + k_1 r^3 + k_2 r^5 + k_3 r^7 \\ \Delta d = \left(p_1^2 + p_2^2\right)^{1/2} r^2 \end{cases} \tag{4}$$





Camera frame rotation angle around the optical axis of the camera at each exposure station as follows:
[T] S1 and S4: 0° (no rotation)
[L] S3 and S6: +90° (left sideways)
[B] S5 and S8: +180° (upside down)
[R] S7 and S2: -90° (right sideways)

Figure 3. Convergent image acquisition from eight different directions

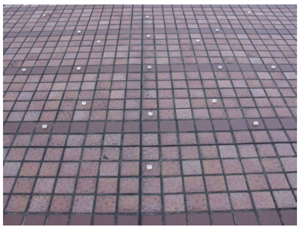
3. EXPERIMETNS

A field experiment and a numerical simulation were conducted to investigate performance of the proposed method.

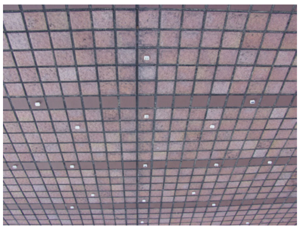
3.1 Field experiment

The field experiment was aimed at investigating stability of estimation results of the proposed method and assessing influence of camera frame rotation on camera calibration.

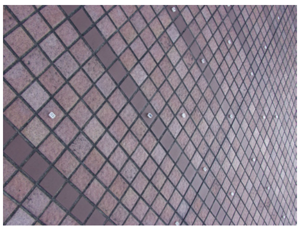
3.1.1 Outline of the field experiment: The field experiment was conducted at an open space paved with square tiles. The dimensions of each tile are 0.1 m by 0.1 m. The digital camera used in the field experiment is Olympus CAMEDIA E-10. Its image pickup element is 2/3-inch primary-color interlaced CCD (4 million pixels total; 3.9 million pixels effective), and its lens is 9 - 36 mm (equivalent to 35 - 140 mm zoom in 35 mm film format), F2 - F2.4 Olympus lens. Each image was acquired with 9 mm of the focal length (at the widest view) and recorded as a 2240 pixels by 1680 pixels image. Hence, the radial distance from the center to each corner of the image frame is 1400 pixels, and the interval between pixels is approximately 3.9 μm.



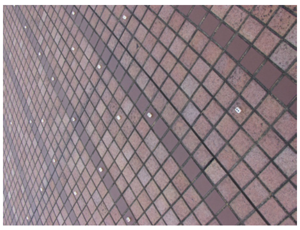
(a) Image at S1 [T]



(b) Image at S5 [B]

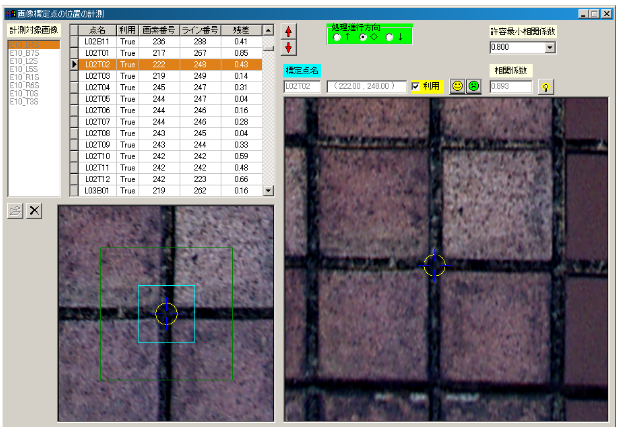


(c) Image at S6 [L]



(d) Image at S2 [R]

Figure 4. Images acquired in the field experiment



Left: template image for matching
Right: target image

Figure 5. Measurement of image coordinates of a calibration points

The inclination angle α at image acquisition is approximately 45° ($h \approx 1.5$ m, $l \approx 1.5$ m). Figure 4 shows some images acquired in the field experiment and Figure 5 shows a screen for measuring image coordinates of calibration points.

Six sets of images are investigated. Set-1 and Set-2 are sets of eight convergent images acquired according to our proposed method. Set-T is a set of eight images from eight different directions with no camera frame rotation. Set-L, Set-R and Set-B are sets of eight images from eight different directions with the fixed camera frame rotation angles of +90°, -90° and +180° respectively.

3.1.2 Results and discussion: Root mean square errors (RMSEs) of image coordinates of calibration points are shown in Table 1.

Table 1 shows sets of the calibrated principal distance c and the offsets x_p, y_p from the calibrated principal point to the center of image frame obtained in the field experiment. The offsets x_p, y_p are also illustrated in Figure 6. Figure 7 shows graphs of the balanced radial distortions Δr and the profiles of decentering distortions Δd obtained in the field experiment.

Set	RMSE (pixels)	c (mm)	x_p (pixels)	y_p (pixels)
Set-1	0.55	9.239	-19.5	-22.1
Set-2	0.55	9.243	-18.3	-18.7
Set-T	0.63	9.143	-20.5	1.3
Set-B	0.76	9.148	-19.6	-41.5
Set-L	0.50	9.329	11.4	-22.9
Set-R	0.54	9.301	-43.5	-22.2

Table 1. Camera parameters obtained in the field experiment

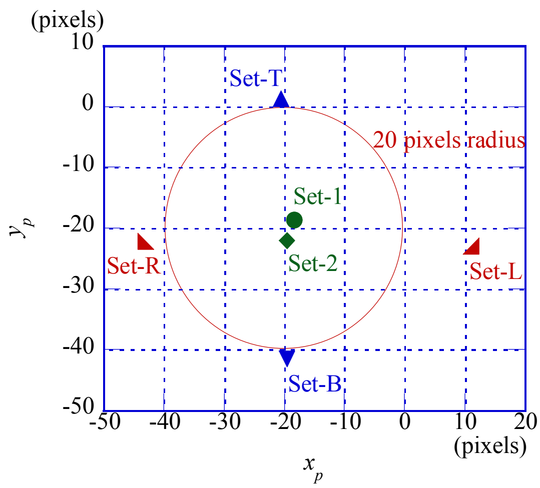
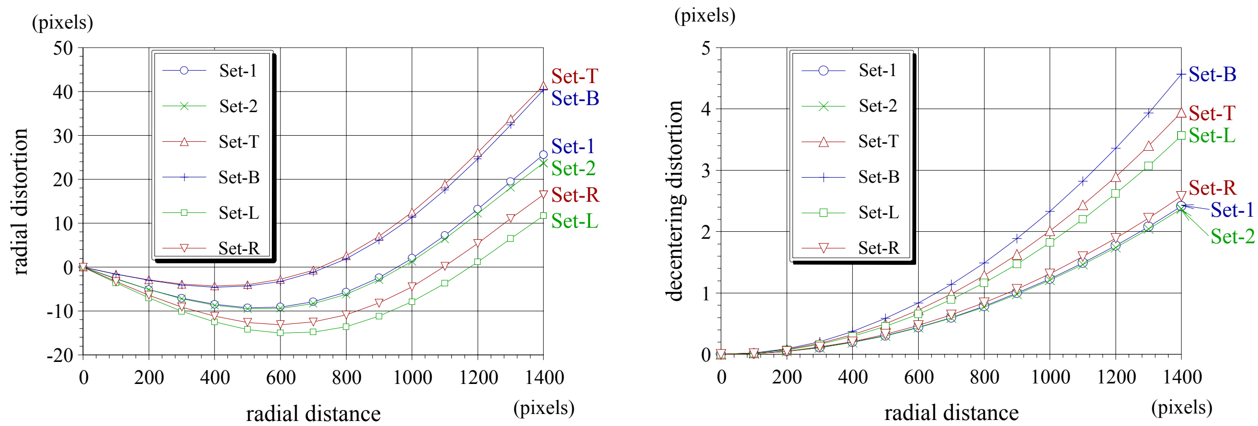


Figure 6. Offsets (x_p, y_p) of the principal point obtained in the field experiment

RMSEs of all six sets are less than 0.8 pixels as shown in Table 1. This means that image coordinates of calibration points were measured precisely.

The estimated principal points of six sets are distributed widely as Figure 6 shows. The principal points estimated by Set-1 and Set-2 are located nearly in the center of the distribution of six estimated principal points. Moreover the distance between these two principal points is 3.6 pixels, which does not seem so long. On the other hand, the principal points estimated by the



(a) Balanced radial distortion Δr (b) Profile of decentering distortion Δd

Figure 7. Balanced radial and decentering distortion graphs obtained in the field experiment

other Set-T, Set-B, Set-L and Set-R are located far from the center of the distribution, and the dispersion of these four principal points from the center exceeds 20 pixels, which cannot be allowed.

The results on the estimated balanced radial distortion give the same indications as the results on the estimated principal point give. The balanced radial distortion curves estimated by all six sets are distributed widely as shown in Figure 7 (a). Two curves of Set-1 and Set-2 are located nearly in the center of the distribution of all six curves. The maximum difference between the balanced radial distortions estimated by Set-1 and Set-2 is 1.9 pixels. On the other hand, the curves of the other Set-T, Set-B, Set-L and Set-R are far from the curves of Set-1 and Set-2, and the dispersion of these four curves amounts to approximately 15 pixels at the corners of the image frame where radial distance r is 1400 pixels.

The estimated decentering distortions of all six sets are considerably smaller than the estimated radial distortions as Figure 7 (b) shows. The difference between the profiles of Set-1 and Set-2 is small, while the dispersion of the profiles of the other Set-T, Set-B, Set-L and Set-R from those of Set-1 and Set-2 is rather large.

From the field experiment results shown in Table 1, Figure 6 and Figure 7, it can be concluded that a set of different camera frame rotations has a great influence on camera calibration. And furthermore, sets of images acquired with the same camera frame rotation cannot provide a reliable set of camera parameters. Though reliability of our proposed method will be investigated in the numerical simulation mentioned in the next section, deviation of image distortions estimated from different sets of images may be up to ±3 pixels (±12 μm) on the image.

3.2 Numerical simulation

The numerical simulation was aimed at investigating reliability of estimation results of the proposed method, assessing influence of an inclination angle at image acquisition on camera calibration, and verifying effectiveness of a set of calibration points distributed on the plane.

3.2.1 Outline of the numerical simulation: Conditions of image acquisition in the numerical simulation were almost equal to those of the field experiment mentioned in the previous section. Setup values of the principal distance c_0 and the offsets x_p, y_p from the principal point to the center of the image frame were 9.270 mm, -20.0 pixels, and -20.0 pixels respectively.

Four values of the inclination angle α at image acquisition in Table 2 were set up. Two sets of calibration points were set up: One was a set of calibration points distributed on the 2D plane $Z = 0$ m, and the other was a set of calibration points distributed in the 3D space $-(h \times 20\%) \le Z \le +(h \times 20\%)$, that is -0.3 m $\le Z \le +0.3$ m. Accordingly, eight cases 2D-C, 2D-N, 2D-M, 2D-F, 3D-C, 3D-N, 3D-M and 3D-F, which were combinations of two calibration points sets (2D and 3D) and four inclination angles (C, N, M and F), were investigated. Random Gaussian errors with 0.5 pixels of standard deviation were added each image coordinate of calibration points.

Case	2D-C 3D-C	2D-N 3D-N	2D-M 3D-M	2D-F 3D-F
h	1.5 m	1.5 m	1.5 m	1.5 m
l	0.5 m	1.0 m	1.5 m	2.0 m
α	18°	34°	45°	53°

Table 2. Inclination angle α in the simulation

3.2.2 Results and discussion: Table 3 shows sets of the calibrated principal distance c and the offsets x_p, y_p from the calibrated principal point to the center of the image frame obtained in the numerical simulation. The offsets x_p, y_p are also illustrated in Figure 8. Figure 9 shows graphs of the balanced radial distortion Δr obtained in the numerical simulation.

Case	c (mm)	x_p (pixels)	y_p (pixels)
Setup	9.270	-20.0	-20.0
2D-C	9.270	-21.5	-17.5
2D-N	9.274	-19.8	-19.0
2D-M	9.274	-21.3	-21.4
2D-F	9.270	-20.9	-21.0
3D-C	9.267	-17.9	-21.5
3D-N	9.270	-20.4	-19.4
3D-M	9.266	-20.5	-18.4
3D-F	9.270	-21.4	-20.5

Table 3. Camera parameters obtained in the simulation

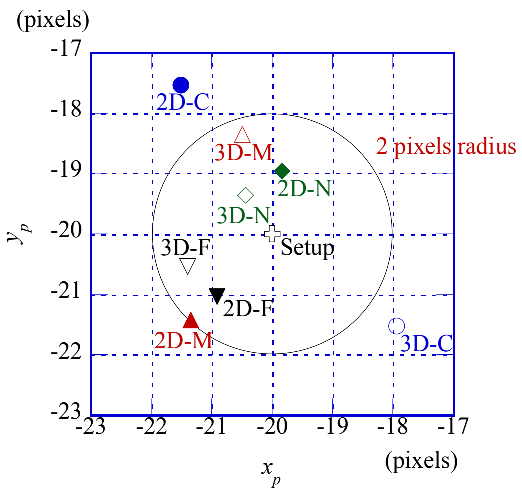


Figure 8. Offsets (x_p, y_p) of the principal point obtained in the simulation

The estimated principal points of all eight cases are distributed within a slightly small area as shown in Figure 8. The estimated principal points of two cases 2D-C and 3D-C whose inclination angle is the smallest one are located without the circle of 2 pixels radius from the setup position. The dispersion of the principal points from the setup position estimated in all cases except 2D-C and 3D-C is less than 2 pixels. This dispersion is nearly equal to that of Set-1 and Set-2 in the field experiment stated in the previous section. An inclination angle at image acquisition seems to have a slight influence on estimation of the position of the principal point. A set of calibration points on the 2D plane may be as effective in estimation of the position of the principal point as a set of calibration points in 3D space.

The balanced radial distortion curves estimated in two cases 2D-C and 3D-C are slightly away from the setup curve as Figure 9 shows. The balanced radial distortion curves of all cases except 2D-C and 3D-C are found close to the setup curve. Deviations of these six curves from the setup curve are less than 1 pixel all over the image. A set of calibration points on the 2D plane may be as effective in estimation of the balanced radial distortion as a set of calibration points in 3D space.

Based on the numerical simulation results shown in Table 3, Figure 8 and Figure 9, it may be concluded that our proposed method using a set of calibration points distributed on the 2D plane can provide a reliable set of estimated camera parameters when images are acquired at an appropriate inclination angle α, for instance $\alpha \geq 30°$.

4. CONCLUSION

The results of the field experiment and the numerical simulation indicate that an image distortion model estimated by our method is reliable enough. Error of an image distortion model estimated by the proposed method is expected to be up to approximately ±3 pixels or ±12 μm on the image. The primary component of the estimation error is the estimation error of the position of the principal point, which may be approximately ±2 pixels. The secondary component is the estimation error of the balanced radial distortion, which may be less than ±1 pixel.

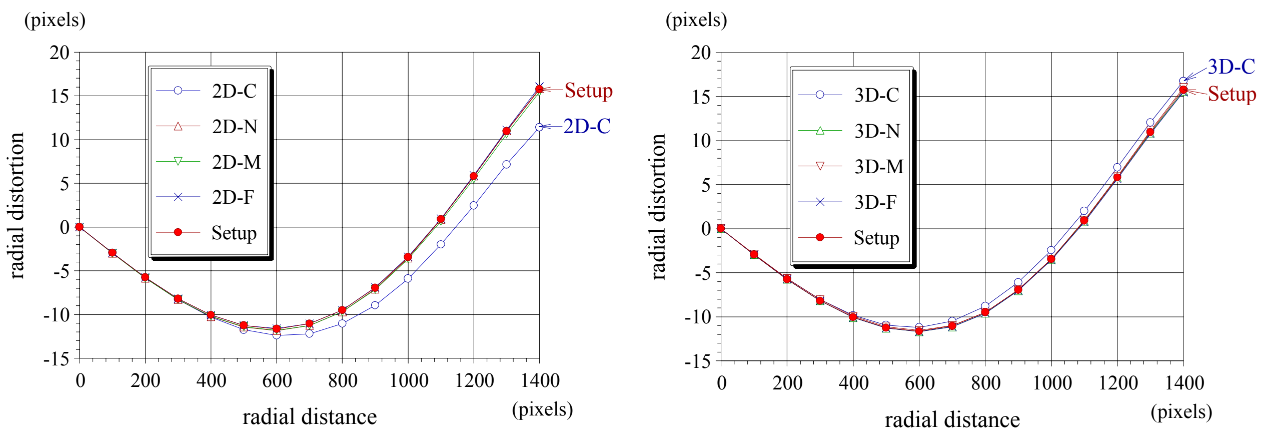
On the other hand, since our proposed calibration method of a non-metric digital camera needs neither special equipment nor ground survey of control points, the proposed method is inexpensive and convenient for an amateur to calibrate his digital camera. Additionally the fact that a set of calibration points distributed on the 2D plane is as effective as a set of calibration points distributed in the 3D space makes our method more convenient. We believe that the calibration method proposed in this paper is useful for some non-professional fields.

REFERENCES

Fraser, C. S., 2001. Photogrammetric Camera Component Calibration in *Calibration and Orientation of Cameras in Computer Vision*, A. Gruen and T. S. Huang Eds., Springer-Verlag, Berlin, pp. 95 - 121.

Fryer, J. G., 1996. Camera Calibration in *Close Range Photogrammetry and Machine Vision*, K.B. Atkinson Ed., Whittler Publishing, Caithness, pp.156 - 179.

Ohmori, T., 2001. Digital Camera of 4 million / 5 million Pixels. *Nikkei Byte*, December 2001, pp. 96 –105. (in Japanese)



(a) 2D distributed calibration points

(b) 3D distributed calibration points

Figure 9. Balanced radial distortion graphs obtained in the simulation