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CAMERA CALIBRATION TECHNIQUES USING MULTIPLE CAMERAS OF DIFFERENT RESOLUTIONS AND BUNDLE OF DISTANCES

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ABSTRACT:

A convenient 3D measurement using a consumer grade digital camera is enormously expected in various fields with the appearance of low cost and high resolution consumer grade digital cameras. In these circumstances, the authors have been concentrating on developing a convenient 3D measurement system which is called as IBIM (Image Based Integrated Measurement) system. The device of IBIM system consists of a consumer grade digital camera and laser distance meter. The most remarkable point of the system was its ability to calculate exterior orientation parameters and interior orientation parameters and the pseudo GCPs (Ground Control Points) without using a scale bar or the GCPs in object field. However, there were still some issues which need to be resolved before this system may become operational. These problems include, improvement of labor and time consuming in distance measurement and the deterioration of image quality.
In order to resolve these problems, the IBIM system is improved using triplet images of multiple cameras of different resolutions and bundle of distances. This paper describes camera calibration techniques and its evaluations using images of multiple cameras of different resolutions and bundle of distances.

1. INTRODUCTION

Convenient 3D measurement using consumer grade digital camera is enormously expected in various fields with the appearance of low cost and high resolution consumer grade digital cameras. In these circumstances, calibration methods to perform convenient 3D measurement using consumer grade digital cameras were proposed (Chikatsu & Kunii, 2002; Habib & Morgan, 2003) and much software for digital photogrammetry was also designed (Chikatsu & Kunii, 2002; Chikatsu & Ohdake, 2006; Fraser & Hanley, 2004; Fraser et al., 2008). However, these almost software requires GCPs which have exact 3D coordinates for camera calibration or scale bar for absolute orientation or interior orientation parameters which should be acquired beforehand. These restrictions should be removed for an ideal convenient photogrammetry using consumer grade digital cameras.
With this objective, the authors have been concentrating on developing a convenient 3D measurement system. One of photogrammetric systems is Image Based Integrated Measurement system called as IBIM system. The device of IBIM system consists of a consumer grade digital camera and laser distance meter (Ohdake & Chikatsu, 2007). The most notable point of the system was its ability to calculate exterior orientation parameters and interior orientation parameters and pseudo GCPs without scale bar or GCPs in object field.
There were still issues, however, as further work. These issues are improvement of labor and time consuming in distance measurement and the deterioration of image quality. Identification for the same points and the detection of occlusion area in measuring procedures at different camera positions are performed with labor and time consuming as manual task. In particular, the deterioration of image quality is caused by a half mirror, and the images in IBIM system are taken through the half mirror. Therefore, the deterioration of image quality was unavoidable problem.
In order to resolve these problems, IBIM system is improved using triplet images of multiple cameras of different resolutions and bundle of distances. This paper describes camera calibration techniques and its evaluations using images of multiple cameras of different resolutions and bundle of distances.

2. IBIM SYSTEM

2.1 The device of IBIM System

The device of IBIM system consists of a consumer grade digital camera (OLYMPUS C-770 Ultra Zoom, 4.0 mega pixels), a laser distance meter (Leica DISTO Lite [4], accuracy is ±3mm) and full/half-mirrors, and it is able to rotate in vertically and horizontally so that precise distance from the centre of digital camera to feature points on object field can be measured.
Furthermore, the camera and laser axis can be precisely adjusted using 4 adjusting screw on the eaves.
Figure 1 shows the appearance of the device of IBIM system, and Figure 2 shows the configurations of the device of IBIM system. Table 1 shows configurations of laser distance meter from user manuals (Leica, 2009).

Figure 1. Appearance of IBIM system

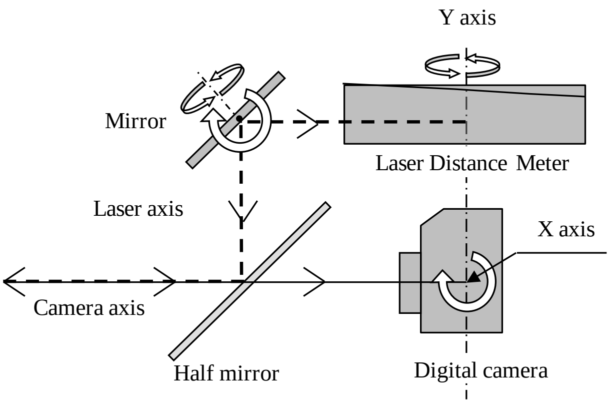

Figure 2. Configuration of the system

Model	Leica DISTO lite[4]
Measuring accuracy	±3mm
Smallest unit	1mm
Range	0.3m to 100m
Laserspot (at distance)	6/30/60mm (10/50/100m)
Laser	Visible; 635nm
Dimensions	154×69×44mm
Weight	360g

Table 1. Specification of laser distance meter

2.2 IBIM System

Ohdake and Chikatsu(2007) developed IBIM system which have-ability to calculate both of exterior orientation parameters and interior orientation parameters without scale distance or GCPs in object field using stereo images. Figure 3 shows the concept of IBIM system using 2 IBIM dataset which consist of stereo images and distances from the different exposure stations. However, there were still some issues. One issue is deterioration of image quality which is caused by the half mirror of the device of IBIM system. This problem is very important problem for the practical IBIM system to perform image based stereo matching and 3D texture model. Other issue is labor and time consuming in distance measurement. In order to remove these issues, IBIM system is redefined as camera calibration system using triplet images and bundle of distances in this paper. The both side images of the IBIM device are taken using the other digital cameras. Figure 4 shows the concept of IBIM system using triplet images. Table 2 shows the specifications of digital cameras.

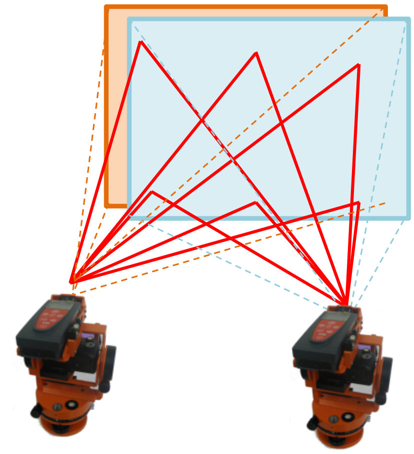

Figure 3. IBIM system using Stereo images

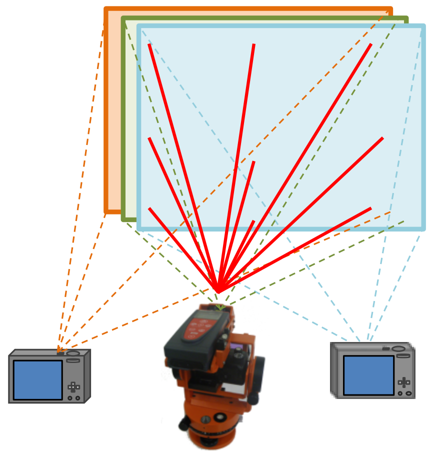

Figure 4. IBIM system using Triplet images

Supplier	Camera model	Pixel [M]	Lens [mm]	Sensor type / size
OLYMPUS	C-770Ultra Zoom	4.0	6.3	1/2.5”
SONY	Cyber-shot DSC-N1	8.1	7.9	1/1.8”
Nikon	COOLPIX S600	10.0	5.0	1/2.33”
PENTAX	Optio W60	10.0	5.0	1/2.3”
Panasonic	DMC-FX100	12.0	6.0	1/1.72”
Nikon	COOLPIX S710	14.5	6.0	1/1.72”
Canon	EOS 20D	8.2	17.0	22.5×15.0 [mm]
Canon	EOS Kiss X3	15.1	17.0	22.3×14.9 [mm]

Table 2. Specifications of digital cameras

2.3 Coordinates System

The coordinates system of the IBIM system is local coordinates system which takes into account an absolute orientation. Figure

5 shows the coordinates system of the IBIM system which is defined as follows:

i) The origin is O_c, which is the centre of digital camera on the IBIM device.
ii) 3D coordinate of pseudo GCPs are computed using image coordinates and distances which are obtained by the laser distance meter.
iii) 3D coordinate of the pseudo GCPs are transformed into local coordinate system, which P_1 is origin point.
iv) X axis direction is given using the other pseudo GCP (P_2).
v) Z value for the pseudo GCP (P_3) is given as 0.

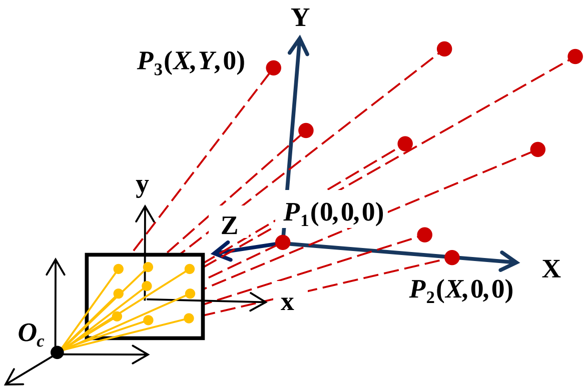

Figure 5. Coordinates system of the IBIM system

2.4 Initial value

The initial value of the pseudo GCPs are computed using relationship with bundle of distances, focal length and image coordinates of the IBIM device. Horizontal angle (α) and vertical angle (β) are computed by the image coordinates and nominal focal length using Equation (1) (Wolf, 1974). 3D coordinates of the pseudo GCP *P* in figure 6 is obtained using the angles and the distance from the centre of digital camera (O_c) in the IBIM device from Equation (2). Figure 6 shows the geometric condition of pseudo GCP.

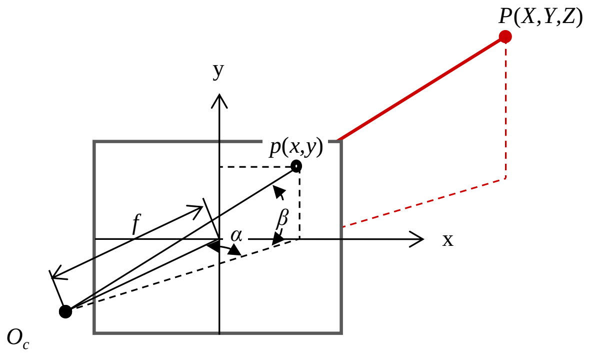

Figure 6. Angles of pseudo GCP on the image

$$\alpha = \tan^{-1}(x/f)$$
$$\beta = \tan^{-1}\left(y/\sqrt{x^2+f^2}\right) \quad (1)$$

where, α, β = angles from X, Y axis

$$X = D\sin\alpha\cos\beta$$
$$Y = D\sin\beta \quad (2)$$
$$Z = D\cos\alpha\cos\beta$$

where, X, Y, Z = initial value of pseudo GCP on ground coordinates

On the other hand, each approximate exterior orientation parameter of triplet images is calculated by single orientation using the pseudo GCPs and the nominal value of the interior orientation parameters.

2.5 Camera Calibration

In order to use the multiple cameras of different resolutions, unknown parameters are exterior parameters (X_0, Y_0, Z_0, ω, φ, κ) and the interior parameters {f (focal length), u_0, v_0 (principal points), a, b (scale factor, shear factor), k_1, k_2 (lens distortion)} for triplet images respectively and pseudo GCPs (X_i, Y_i, Z_i). These unknown parameters are calculated by collinearity condition and constraint of bundle of distances simultaneously under the local coordinate system.

Here, collinearity condition is shown as Equation (3), and distance condition is shown as Equation (4).

These unknown parameters can be calculated as the values by minimizing following function *H* (Equation (5)) under the least square method.

$$x = -f\frac{m_{11}(X-X_0)+m_{12}(Y-Y_0)+m_{13}(Z-Z_0)}{m_{31}(X-X_0)+m_{32}(Y-Y_0)+m_{33}(Z-Z_0)}$$
$$y = -f\frac{m_{21}(X-X_0)+m_{22}(Y-Y_0)+m_{23}(Z-Z_0)}{m_{31}(X-X_0)+m_{32}(Y-Y_0)+m_{33}(Z-Z_0)} \quad (3)$$

where, x, y = image coordinates
f = focal length
X, Y, Z = object coordinates of pseudo GCP
X_0, Y_0, Z_0 = perspective centre
m_{ij} = elements of rotation matrix

$$D = \sqrt{(X-X_{0C})^2+(Y-Y_{0C})^2+(Z-Z_{0C})^2} \quad (4)$$

where, D = distance from feature point to perspective centre
X, Y, Z = object coordinates of pseudo GCP
X_0, Y_0, Z_0 = perspective centre of centre position

$$H = \sum_{i=1}^{m}\sum_{j=1}^{n}\left\{p_{1i}\left(\Delta x_{ij}^2+\Delta y_{ij}^2\right)+p_2\left(\Delta D_j^2\right)\right\} \Rightarrow \min \quad (5)$$

where, Δx_{ij}, Δy_{ij} = residuals for image coordinates
ΔD_j = residuals for distance
M = numbers of pseudo GCP
N = numbers of image
p_{1i} = weight for image coordinates
p_2 = weight for distance

Furthermore, the radial polynomial 5th degree of Equation (6) was adapted to correct lens distortion in this paper (Fryer J. G. and Brown D.C, 1986).

$$x = x' + \frac{x'}{r}\left(K_1 r^3 + K_2 r^5\right)$$
$$y = y' + \frac{y'}{r}\left(K_1 r^3 + K_2 r^5\right) \qquad (6)$$
$$r = \sqrt{x'^2 + y'^2}$$

Where, x, y = corrected image coordinates
x', y' = image coordinates
K_1, K_2 = coefficients of radial distortion
r = radial distance from principal points

Due to different measurement accuracy of the digital cameras and laser distance meter, it must be determined weights (p_{1i}, p_2) for camera calibration using Equation (7). It can be presumed that pointing accuracy of image coordinates is determination accuracy for laserspot of the laser distance meter on the image. Therefore, it is estimated that pointing accuracy is 1.5 pixels by followings, the diameter of laserspot spreads depending on measurement distance from Table 1 and divergence of laser beam which is computed by distance and diameter is 0.6 mrad.
On the other hand, measurement accuracy of the laser distance meter is 3mm at twice the standard deviation from user manual. It is supposed that the real measurement accuracy is higher than the specification value. Standard deviation of the laser distance meter is 0.5mm, which was obtained by indoor experiment.
For example, weights for the DSC-N1 (8M), the IBIM device (C-770UltraZoom: 4M), the COOLPIX S600 (10M) and distance, p_{11}, p_{12}, p_{13} and p_2 are defined as 5: 2: 6: 3.

$$p_{11} : p_{12} : p_{13} : p_2 = \frac{1}{\sigma_{G1}^2} : \frac{1}{\sigma_{G2}^2} : \frac{1}{\sigma_{G3}^2} : \frac{1}{\sigma_D^2} \qquad (7)$$

where, p_{1i} = weight for image coordinates
p_2 = weight for distance
σ_{Gi} = measurement accuracy in object field
σ_D = standard deviation of distance

3. EXPERIMENT

3.1 Detail of experiment

Indoor experiment was performed using 6 consumer grade digital cameras (4M,8M,10Mx2,12M,14.5M) and 2 single lens reflex digital cameras (8M, 15.1M).

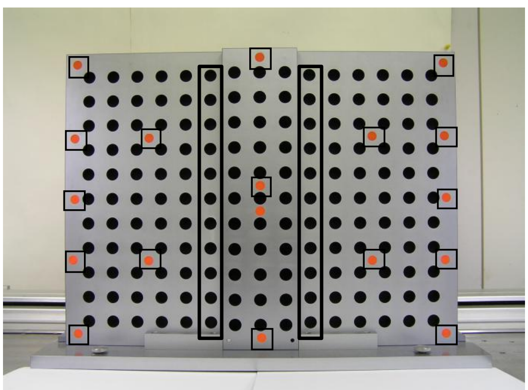

Figure 7. Test target

A test target (H: 640mm, W: 480mm, D: 20mm) with 165 black circular points and 14 red circular points was used in this paper. The red circle points inside of thin line square are control points for camera calibration and 143 black circle points outside of thick line rectangle are check points. Each black circular point was manufactured with ±0.05mm accuracy, and pixel coordinates for these points were obtained as area gravity by image processing procedures. 5 triplet images for every camera were taken with changing altitude between 0.65-0.96m so that uniform image scales be able to keep, and camera calibrations were performed by the simultaneous adjustment using pseudo GCPs and bundle of distances.

3.2 Camera-variant parameters set

There are some combinations of digital cameras in consideration of using multiple cameras. For example, A is digital camera of the IBIM device. B and C are other digital cameras. It is possible to create the combinations of digital cameras such as type 1 (A, A, A), type 2 (B, A, B) and type 3 (B, A, C or C, A, B). These combinations are led to camera calibration with block-invariant (Fraser, 1987), photo-variant (Shortis, et al., 1998), image-variant (Techkenburg, et al, 2001) and camera-variant parameter sets. Camera-variant parameter set is defined as calibration parameters for each camera are unknown values in this paper. In other words, unknown parameters of camera-variant parameter set are principal point (u_0, v_0), focal length (f), scale factor (a, b) and coefficient of lens distortion (K_1, K_2) for each image respectively.
In order to evaluate the efficiency of camera-variant parameters set, camera calibration for 8 cameras were performed using type 1 or type 2. In this section, index of accuracy means the sum of mean error (σ_L) which is computed from Equation (8) using root mean square error for 143 points for 8 cameras respectively.

$$\sigma_L = \sum_{i=1}^{m} \sigma_l \qquad (8)$$
$$\sigma_l = \sqrt{\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2}$$

where, σ_L = sum of the mean error
i = camera model
m = numbers of cameras
σ_l = mean error
σ_X, σ_Y, σ_Z = root mean square error

Figure 8 shows relationship between accuracy and numbers of pseudo GCP for each calibration model respectively. Note that the numbers such as C09 means numbers of pseudo GCP.
From Figure 8, it cannot find significant differences between block-invariant, photo-variant and image-variant parameter set.
On the other hand, camera-variant parameter set are small in comparison with other parameter set with 40%.
It can be found that accuracy of 15 and 17 pseudo GCPs are lower than 13 pseudo GCPs, it is inferred that accuracy was influenced by increasing of pseudo GCPs which are locate at border.
The results of 9 pseudo GCPs show largest sum of ellipsoid error in each parameter set. Therefore, it is estimated that the IBIM system needs more than 11 pseudo GCPs from the point of view of degrees of freedom.
Consequently, it can be said that camera-variant parameter set shows the most stable result.

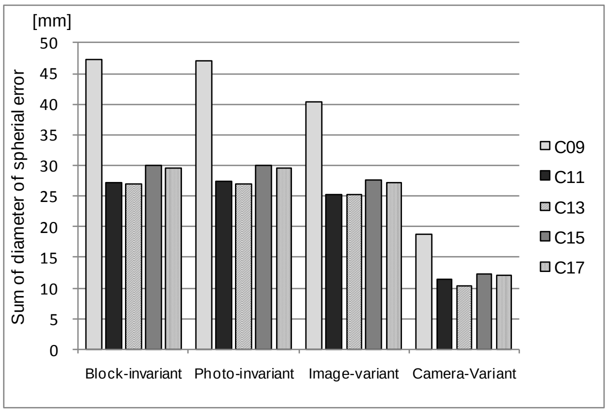

Figure 8. Influence of interior parameter set

4. EVALUATIONS

The evaluation of the IBIM system using camera-variant parameters was performed using 6 combinations with 8 digital cameras. Table 3 shows combinations of digital cameras.

Camera		Combinations name	Resolutions
Left	Right		
Cyber-shot DSC-N1	COOLPIX S600	N1-S600	8.1M-4.0M-10.0M
COOLPIX S600	Optio W60	S600-W60	10.0M-4.0M-10.0M
Optio W60	DMC-FX100	W60-FX100	10.0M-4.0M-12.0M
DMC-FX100	COOLPIX S710	FX100-S710	12.0M-4.0M-14.5M
COOLPIX S710	EOS 20D	S710-20D	14.5M-4.0M-8.2M
EOS 20D	EOS Kiss X3	20D-X3	8.2M-4.0M-15.1M

Table 3. Combinations of digital cameras

4.1 Accuracy

In order to evaluate accuracy, normalized accuracy for 143 check points were drawn in Figure 7. It should be noted that normalized accuracy means the ratio of RMS error in each type to standard error. Normalized accuracy is calculated by Equation (9). Therefore, the ratio larger than 1 means higher accuracy than standard error which is computed from Equation (10) (Abdel-aziz, 1982), and it is estimated that exceeded accuracy rather than standard error is inferred that pointing of image coordinates were performed more than 1 pixel.

$$\frac{1}{\sqrt{\sigma_X^2+\sigma_Y^2+\sigma_Z^2}\Big/\sqrt{\sigma_{X0}^2+\sigma_{Y0}^2+\sigma_{Z0}^2}} \quad (9)$$

$$\sigma_X=\sqrt{\frac{\sum\sigma_{Xi}^2}{n_X}},\quad \sigma_Y=\sqrt{\frac{\sum\sigma_{Yi}^2}{n_Y}},\quad \sigma_Z=\sqrt{\frac{\sum\sigma_{Zi}^2}{n_Z}}$$

where, σ_X, σ_Y, σ_Z = RSM error of X, Y, Z
σ_{Xi}, σ_{Yi}, σ_{Zi} = differences in X, Y, Z coordinates
n_X, n_Y, n_Z = numbers of check points
σ_{X0}, σ_{Y0}, σ_{Z0} = standard error

$$\sigma_{X0}=\sigma_{Y0}=\frac{H}{f}\sigma_p$$
$$\sigma_{Z0}=\sqrt{2}\frac{H}{f}\frac{H}{B}\sigma_p \quad (10)$$

where, σ_{X0}, σ_{Y0}, σ_{Z0} = standard error
H = altitude
f = focal length
B = base line
σ_P = pointing accuracy

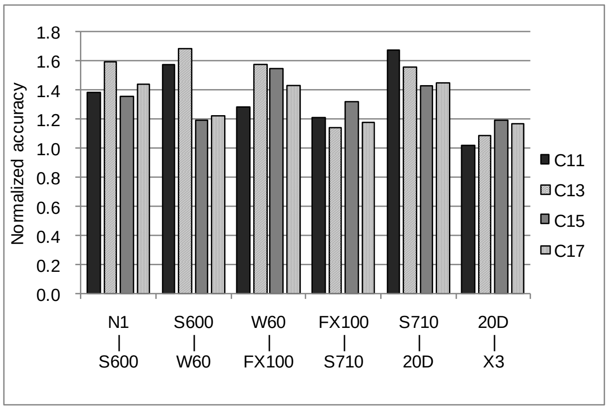

Figure 9. Normalized accuracy

The followings are found from Figure 9.

i) The IBIM system using multiple cameras of different resolutions has ability to obtain the equivalent accuracy with standard error.
ii) The numbers of pseudo GCPs does not have significantly influence on accuracy.
iii) The IBIM system has ability to obtain the stable result without resolution of the digital cameras.

4.2 Precision

In general, precision is standard deviation which is computed by equation using weighted coefficient matrix derived by variance-covariance information, and precision is evaluated by an equation using the sum of deviation for each check point in this paper (Beyer, 1992).
Figure 10 shows normalized precision which is computed using standard error in the same procedure as accuracy. Precision shows the same tendency as accuracy, and the value of precision shows high value in comparison with accuracy.

$$\hat{\sigma}_{Xi}=\hat{\sigma}_0\sqrt{q_{X_iX_i}},\quad \hat{\sigma}_{Yi}=\hat{\sigma}_0\sqrt{q_{Y_iY_i}},\quad \hat{\sigma}_{Zi}=\hat{\sigma}_0\sqrt{q_{Z_iZ_i}}$$
$$\hat{\sigma}_X=\sqrt{\frac{\sum\hat{\sigma}_{Xi}^2}{n_X}},\quad \hat{\sigma}_Y=\sqrt{\frac{\sum\hat{\sigma}_{Yi}^2}{n_Y}},\quad \hat{\sigma}_Z=\sqrt{\frac{\sum\hat{\sigma}_{Zi}^2}{n_Z}} \quad (11)$$

where, $\hat{\sigma}_{Xi},\hat{\sigma}_{Yi},\hat{\sigma}_{Zi}$ = standard deviation for check points
$\hat{\sigma}_0$ = standard deviation of unit weight
$q_{X_iX_i},q_{Y_iY_i},q_{Z_iZ_i}$ = diagonal element of the inverse of the normal equation matrix at the position of the corresponding unknown
n_X, n_Y, n_Z = numbers of check points

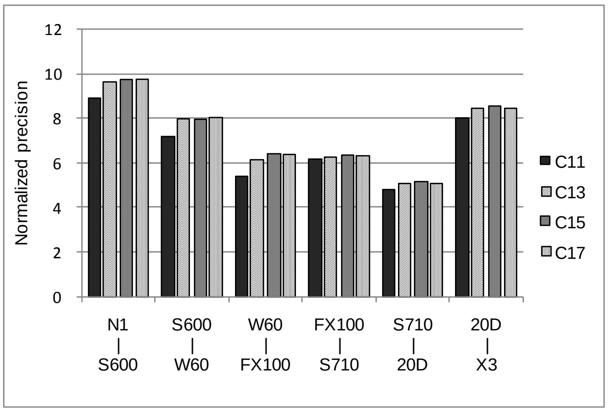

Figure 10. Normalized precision

5. CONCLUSIONS

The IBIM (Image Based Integrated Measurement) System using multiple digital cameras of different resolutions was developed by the authors for a convenient digital photogrammetry, and camera calibration techniques and performance evaluation for the IBIM system were investigated in this paper.
Though, the deterioration of image quality was unavoidable problem for the IBIM device since the deterioration of image quality is caused by half-mirror. It is verified, however, the deterioration of image quality is resolved by using the left and right side camera. In particular, it can be said that the camera-variant parameters have practicability in combination of the multiple cameras.
Similarly, it is verified that it can't find significant differences between the accuracy of the IBIM system and standard error.
Consequently, it is concluded that a convenient 3D measurement is accomplished by the IBIM system which have ability to combine multiple cameras of different resolutions, and the IBIM system is expected to become a useful measurement system for the various close range application fields from view point of non-contact measurement.

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