University of Baghdad
College of Engineering
JOURNAL OF ENGINEERING

Journal of Engineering

journal homepage: www.jcoeng.edu.iq
Number 9 Volume 24 September 2018

Water Resources and Surveying Engineering

Accuracy Assessment of Various Resolutions Digital Cameras For Close Range Photogrammetry Applications

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ABSTRACT

Due to the great evolution in digital commercial cameras, several studies have addressed the using of such cameras in different civil and close-range applications such as 3D models generation. However, previous studies have not discussed a precise relationship between a camera resolution and the accuracy of the models generated based on images of this camera. Therefore the current study aims to evaluate the accuracy of the derived 3D buildings models captured by different resolution cameras. The digital photogrammetric methods were devoted to derive 3D models using the data of various resolution cameras and analyze their accuracies. This investigation involves selecting three different resolution cameras (low, medium and high) and evaluating their calibration accuracies. Assessing the accuracy of the three selected cameras in capturing indoor and outdoor objects; and analyzing the accuracy and the quality of the produced models. The study revealed that:1) It is recommended to use the photos of a high-resolution camera for producing precise 3D models of objects in the outdoor environment especially when the camera/object distance is more than 40 m because the accuracy of the produced models can be precise (RMSE ±10.36mm) with excellent quality; 2) The Low-resolution camera can be utilised to produce adequate 3D models of object in the indoor environment (RMSE ±6.32mm) especially when the camera/object distance is less than 40 m.

Key Words: digital photogrammetry, accuracy assessment, camera resolution, 3D model.

تقييم دقة الكاميرات الرقمية ذات الدقة التمييزية المختلفة المستخدمة في تطبيقات المسح التصويري القريب

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الخلاصة

نتيجة التطور الكبير الذي شهدته الكاميرات الرقمية في السنين القليلة الماضية برزت العديد من الدراسات تتطرق الى استخدام تلك الكاميرات في العديد من تطبيقات الهندسة المدنية والمسح التصويري القريب كعمل النماذج الثلاثية الابعاد لمختلف

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Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2018.09.06

Article accepted: 18/12/2017

الاجسام مثل الابنية والعمارات. غير ان الدراسات السابقة لم تناقش لغاية الان العلاقة التي تربط بين الدقة التمييزية للكاميرا ودقة النماذج الثلاثية الابعاد المستخرجة بالاعتماد على صور تلك الكاميرات. يهدف البحث الحالي الى تقييم دقة النماذج ثلاثية الابعاد المنتجة للابنية المرصودة بواسطة الكاميرات الرقمية ذات الدقة التمييزية المختلفة. في هذه الدراسة تم استخدام تقنيات المسح التصويري الرقمي القريب في استخراج وتحليل النتائج. تضمن البحث مايلي :1) اختيار ثلاثة انواع من الكاميرات مختلفة الدقة التمييزية (واطئة ومتوسطة وعالية الدقة) وتمت معايرتها وتقييم دقتها جميعا، 2) تقييم دقة الكاميرات الثلاثة المختارة في رصد الاجسام والابنية الموجودة في الفضاءات الداخلية والخارجية، 3) تحليل دقة ونوعية النماذج الثلاثية الابعاد المنتجة بالاعتماد على الصور المجسمة الملتقطة للاجسام الموجودة في الفضاءات الداخلية والخارجية بواسطة الكاميرات الثلاثة المختارة.

وخلصت الدراسة لمايلي:1) ينصح باستخدام الصور المجسمة الملتقطة بكاميرات عالية الدقة في انتاج النماذج المجسمة للاجسام الموجودة في الفضاءات الخارجية في الاعمال التي تحتاج دقة عالية ونوعية متميزة وبالاخص اذا كانت المسافة التي تفصل الكاميرا عن العارض اكثر من 40 متر، حيث يقدّر مقدار الخطا حوالي (RMSE ±10.36mm). 2) الكاميرات واطئة الدقة من الممكن استخدامها في انتاج نماذج ثلاثية الابعاد بدقة مقبولة (RMSE ±6.32mm) للاجسام الموجودة في الفضاءات الداخلية على ان لا تتجاوز المسافة التي تفصل الكاميرا عن العارض الـ20 متر.

1. INTRODUCTION

The 3D building models are considered very important for studying, analysing and rehabilitating buildings and architectural designing of the building structures. At present time, 3D building models are represented using CAD software based on ground surveying data **Pop, 2008, and Gadei, Loan, 2012**, **and Luhmann, and Fraser, 2016**. For example **Pop, 2008, and Gadei, and Loan, 2012** created 3D building models using AutoCad software and conventional surveying observations. The researchers indicated that the generated 3D building models were very accurate. In spite of the precision of the 3D model created using the current method, it needs many professional staff and it consumes a lot of time **Borkowski, and Jozkow,2012**.Thus, a number of researchers developed a new digital photogrammetric procedure for 3D building modelling **Yilmaz, et al., 2008, Khalfa, et al., 2013, and Shashi, and Jain, 2007.**

Generally, the digital photogrammetric method involves generating 3D surface models of objects from digital stereo photos that are normally captured by a digital camera. The merit of the photogrammetric procedures is that the captured photos are fast, precise and adequate for taking all the efficient measurements **Schenk, 2005, and Luhmann, and Fraser, 2016**. Also, the economic aspects of the photogrammetric procedure have motivated many researchers to utilize it for 3D models producing **Schenk, 2005**. For instance, **Yilmaz, et al., 2008, and Khalfa, et al., 2013** proposed a digital photogrammetric approach to generate a 3D surface model of irregular objects. **Yilmaz, et al., 2008** photographed an artificial object from different positions utilizing 8 MP (Mega Pixel) Sony cameras. The 3D model of the object was generated based on the stereo photos with accuracy about 1.0 mm. Whereas, **Khalfa, et al., 2013** established a 3D model of clay face statue utilizing 16 MP Nikon cameras. The researchers created the 3D models with accuracy about 1.00 mm.

A digital photogrammetry has been exploited for 3D buildings modeling and 3D city and archaeological sites reconstruction **Castagnetti, et al., 2017**. For example, **Shashi, and Jain, 2007** developed a digital image-based modeling procedure for 3D geometric building reconstruction and visualization. The researchers claimed that the accuracy (RME in XYZ coordinates) of the generated 3D models were 1.5 pixels. This accuracy is considered efficient for 3D models reconstruction work compared with the current CAD method.

On the other hand, some researchers utilized terrestrial laser scanner for 3D objects modeling due to the advantages that concede with laser scanning procedure **Guarnieri, et al., 2006 and Yang, et al., 2017.** Laser scanning is an accurate and a fast acquisition procedure. In addition, the laser scanner can capture a big amount of 3D data can be captured in a short time. **Guarnieri, et al., 2006** introduced a new procedure applied for 3D building and heritage modeling. The image-based technique used to capture the surfaces of the main structures using the 7MP digital camera while TOP laser scanner used to model fine and complex features. The researchers concluded that the new technique can generate high-quality 3D models. Although the laser scanning technique has many advantages, it has a number of drawbacks such as 1) the scanner is expensive; 2) it is hard to handle the massive amount of data that taken by laser scanner; and 3) it is difficult to manage the quality of the measurements **Guarnieri, et al., 2006 and Yang, et al., 2017**.

Form the literature survey; it is clear that digital photogrammetric technique is an appropriate for 3D building and architectural structures modelling. However, the previous studies have not addressed a precise connection between a camera resolution and the precision of the generated 3D models which are produced based on stereo photographs captured by this camera. Consequently, this study aims to assess the accuracy of the derived 3D buildings models captured by different resolution immature cameras which are available in markets.

2. RESEARCH METHODOLOGY

2.1 Equipment and Software

As mentioned above, the main purpose of this research is assessing the accuracy of 3D models of buildings captured by different cameras that have different resolutions. Thus, the equipment and the software utilized have to be corresponding with work accuracy. For instance, the equipment includes a precise Total Station Topcon (GTS-750, reflectorless) with an angular accuracy of 5', three various resolutions digital cameras fixed on an improved camera tripod. In addition, PhotoModeler scanner (PMS) software (ver. 2013) was chosen for data processing and 3D buildings models creation. MATLAB (R. 2015 a) language was also employed to build up a program to check the accuracy of the generated 3D models.

2.1.1 Establishing test field targets

In photogrammetry test field targets are usually established to provide object-space control points for referencing, orienting and relating photos to the ground **Wolf, and Dewitt, 2000**. These points are used for assessing the accuracy of the photogrammetric project. Therefore, the test field targets have to be sharp and well identified. Techniques and instruments utilized to establish test field targets are many and varied. In this study, trilateration method and total station Topcon (GTS-750) for determining the 3D coordinates (X, Y, Z) of 55 target points. These points were fixed on a wall as a grid net (5 row × 11 columns) as shown in **Fig.1**. The distance between the two adjacent target points is about 40 cm. The dimensions of the wall are (2m ×4.20 m). Each target has a high contrast ring cod around black dot. This code can provide the ability of automatically recognizing, marking and referencing by the used software (PhotoModeler Scanner) as shown in **Fig.1**.

2.1.2 Digital camera

A camera is a vital device in photogrammetry. It captures photos of objects that a photogrammetric project relies on **Wolf, and Dewitt, 2000**. Normally, a camera in terrestrial photogrammetry can be categorized to the metric and nonmetric camera. The metric cameras have fiducial marks fixed on their focal plane. These marks are exploited for finding the position of a principal point. A metric camera is firmly manufactured and completely calibrated before usage. Thus, a metric camera can be employed for a long time before the need to re-calibrate it all over again. On the other hand, digital cameras are classified as a non-metric camera because they do not have fiducial marks and do not manufacture for photogrammetric aims **Schenk, 2005**.

Today, a digital camera (non-metric) has been involved in various photogrammetric applications which were dominated previously by metric cameras. This is mainly because of the better performances, comfortable features and low prices of a digital camera compared with a metric camera. **Shortis, and Beyer, 1996** categorizes a digital camera to low resolution (No. of pixels < 500,000), medium resolution (No. of pixels between 500,000 & 1.5 million) and high resolution (No. of pixels >1.5 million) digital camera. In recent time many types with different quality of digital camera are commercially available. However, with using a digital camera, it hard to expect the accuracy of a photogrammetric project because of the quality and the resolution of the used camera has to meet the standard of the photographic project. Thus, this study aims to link the quality of a digital camera with the required accuracy of the photogrammetric project and the measurements. Three different digital cameras (Kodak, Samsung, and Olympus is shown in **Fig.2** utilize for photography. The characteristics of these cameras are illustrated in **Table.1**.

2.1.3 Software

PhotoModeler Scanner software generally utilizes to create high quality, precise 3D models, and measurements from stereo photos based on close-range photogrammetric algorithms. These algorithms are derived from the collinearity equations (1&2) **Schenk, 2005**. It is required to capture images of objects by a camera from differing viewpoint to generate the 3D model of the selected objects. PhotoModeler software was adopted for camera self-camera calibration and for the calculation the precise retro-target coordinates. The software has also the ability to create DSM (Dense Surface Model) and 3D mesh surface **PhotoModeler User Manual, 2012**.

$$\acute{x} = \acute{x}_o + \acute{z}\,\frac{R_{11}(X-X_o)+R_{21}(Y-Y_o)+R_{31}(Z-Z_o)}{R_{13}(X-X_o)+R_{23}(Y-Y_o)+R_{33}(Z-Z_o)} + \Delta\acute{x} \quad (1)$$

$$\acute{y} = \acute{y}_o + \acute{z}\,\frac{R_{12}(X-X_o)+R_{22}(Y-Y_o)+R_{32}(Z-Z_o)}{R_{13}(X-X_o)+m_{23}(Y-Y_o)+R_{33}(Z-Z_o)} + \Delta\acute{y} \quad (2)$$

x'_i, y'_i: Image coordinates of points,

x'_o, y'_o: Image coordinates of the perspective center,

$\Delta\acute{x}, \Delta\acute{y}$: Small corrections for image coordinate

X, Y, Z : Object coordinates,
X_o, Y_o, Z_o: Exposure station coordinates,
$R's$: Rotation matrix,

To assess the accuracy of measurements and created 3D models, (ASSESSMENT.m) program was built using MATLAB (R. 2015 a) to achieve all assessment processes in this study. The program has also the ability to represent the assessment results in a table.

2.2 Camera Calibration

Camera calibration is the process of calculating the precise value for interior orientation elements of the camera (principal point (xo, yo), focal length (f), and lens distortion parameters (K1, K2, K3) **Wolf, and Dewitt, 2000**. The calibration procedure is a vital stage in every photogrammetric data assembly and processing. Determining the precise values for orientation parameters is essential to calculate an accurate data from photographs. In this research, camera calibration process was achieved using PhotoModeller software. The single-sheet calibration procedure was selected because it is more suitable for the small photogrammetric project. Every camera from the three selected cameras (Kodak, Samsung, and Olympus) was calibrated separately.

Single calibration sheet contains 4 coded targets and 96 grid dots arranged in a grid form **Fig.3**. Twelve photos by every chosen camera were captured to the calibration sheet **Fig.4** from different positions with various angles. Usually, three photographs from four sides of the calibration sheet. After uploading the captured photos to the calibration sheet, PhotoModeler software will perform the calibration process. The output results will be the interior orientation elements and their residuals.

2.3 Data Acquisition

The data acquisition procedure was performed under two stages, indoor and outdoor data acquisition. The indoor data acquisition was accomplished through photographing the 55 test field targets points that were fixed on the wall of the room in the indoor environment, **Fig.1**. The three selected cameras were mounted separately on a developed camera tripod, **Fig.5** away 20m from the wall of the test field targets. According to **Yi, et al., 2012**, a camera tripod is very necessary to hold a camera and keep it steady during photographing because camera wobbling and shaking might cause blurry images and could diminish the resolution of the photos by up to 75 %. Each camera (Kodak, Samsung, and Olympus) was employed to capture stereo photos to the test field targets (with overlap about 60% to 80%). The captured stereo photographs of each camera were imported to PhotoModeler scanner software to determine the 3D ground coordinates (X, Y, Z) of the targets points based on the stereo photographs.

In the outdoor data acquisition procedure, a stereo pair photos for buildings of the Technical Engineering College of Baghdad (TCB) were captured as shown in **Fig.6**. Each camera (Kodak, Samsung, and Olympus) was used to photograph the same selected outdoor buildings. Then, the captured stereo photos (with overlap about 60% to 80%) of each camera were imported to PhotoModeler scanner software to create 3D models of the selected building based on the captured stereo photographs.

2.4 3D models generation

The captured stereo photographs of each selected camera were uploaded and processed in the PhotoModeler Scanner (PMS) software (R 2013) using the DSM (Dense Surface Model) options. The **base/height** ratio of these stereo pairs has to be less than one to produce a precise 3D model of captured building **PhotoModeler User Manual, 2012**. The 3D surface modeling using PMS software includes importing stereo photographs, marking points either with feature targets or with coded targets for high accuracy and then processing the oriented photos. The uploaded photos were relatively and absolutely orientated using PMS software. The natural features targets (e.g. corners of windows or doors, Electric Lantern …etc.) were utilized primarily to expedite the orientation process as exhibited in **Fig.7**. It is important to ensure the produced 3D models using PM software are high quality and have low residuals. Once the total residual of the generated 3D models was less than ±1.5 pixels the orientation results were assumed acceptable **PhotoModeler User Manual, 2012.**

2.5 Accuracy Assessment

Three accuracy evaluation procedures were adopted in this research to assess the validity and the precision of the proposed photogrammetric approach. The first evaluation was performed through the camera calibration procedure. The calibration procedure included capturing 12 shots to the camera calibration sheet. After calibration process, PMS software calculated the overall residuals for the inner orientation parameters of selected cameras.

The second assessment procedure involved checking the accuracy of the selected three cameras (various resolution cameras) in capturing and identifying the spatial locations of the 55 test field targets in the indoor environments. The 3D coordinates of the 55 test field targets were determined three different times using PMS software based on the stereo photos of each selected camera. The effects of the camera resolution on finding the spatial locations of points were assessed. The assessment is achieved through comparing the precise distances between the test field targets with the same distances measured on stereo photos. The precise distances were determined from the coordinates of the test points which were observed by the total station (see section 2.1.1). While measured distances were determined from stereo photos of each selected camera separately.

The third accuracy assessment process includes determining the suitability of various resolutions cameras for photographing natural features of buildings in outdoor environments. Thus, six check distances were selected on a building at the outdoor environment for accuracy evaluation process. These distances were determined precisely by the total station. PMS software was utilized to measure the same six check distances from stereo photos captured by three selected cameras (Kodak, Samsung, and Olympus). The assessment process was achieved through comparing the precise check distances with measured distances from stereo photos.

3. RESULTS ANALYSIS

3.1 Camera Calibration Results

Each camera was calibrated individually. Twelve photographs were captured by each camera to the single-calibration sheet. The captured photographs were uploaded and processed in PMS software (as clarified in section (2.2)). The calibration results of the three cameras are demonstrated in **Table.2**. The results show that there are slight discrepancies in the Overall residual (RMSE) in the three cameras (Kodak = ±0.385 pixel, Samsung = ±0.342 pixel, and Olympus = ±0.270 pixel) and all the residuals were under 1/2 pixel.

3.2 3D Test Field Targets

As emphasized in section (2.1.1), the 3D spatial position of 55 test field targets points was measured precisely using a total station Topcon (GTS-750). **Table 3** clarifies the 3D coordinates and the standard deviations (SD) of the test field targets. The root mean square errors ($RMSE_{XYZ}$) in the 3D spatial position of the target points are ± 5.54 mm. Note, the $RMSE_{XYZ}$ represents the standard deviation (SD) of the residuals (V_{XYZ}).

3.3 Accuracy Assessment

As clarified in section (2.5), the accuracy assessment procedures were achieved through three stages. The results of the first one are shown in **Fig.8** and **Table 2**. **Fig.8** reveals the residuals in calibration grid point's locations of the three cameras. It must be noted that these residuals were exaggerated 200 times for demonstration purposes. It is clearly from the **Fig.8** that: 1) the maximum residuals in the dot points on the calibrated sheet where increase in the edges; and 2) the photo of the calibrated sheet captured by Kodak camera (**Fig.8a**) has higher residuals (RMS =± 0.385 pixels) than the photo captured by Samsung (RMS =± 0.342 pixels), and Olympus cameras (RMS =± 0.270 pixels) as illustrated in **Table 2** and shown in **Fig.8 b, c**.

The second accuracy assessment procedure was conducted in the lab room (indoor environment). The assessment procedure involved comparing the computed and the precise 3D distances between the test points which were fixed on the lab wall. Six distances were selected for assessment as shown in **Fig.9**. As explained in section (2.1.1), the total station was utilized to determine the precise 3D distances (distances in 3D space) between test points. The RMSE is obtained via comparing the precise 3D distances (AB, BC, CD, DA, AC, and BD) with the same 3D distances determined from the stereo photos which were captured by Kodak, Samsung, and Olympus cameras. As illustrated in **Table 4**, the RMSE in the distances is determined from the stereo photos of Kodak, Samsung, and Olympus cameras were ± 6.32 mm, ± 4.98mm and ± 4.67 mm respectively.

The third accuracy assessment process involves examining the suitability of various resolutions cameras for photographing natural features of buildings in the outdoor environments. As mentioned in section (2.5), six check distances were selected on an outdoor building as shown in **Fig.10**. These distances were determined precisely by the total station. PMS software was utilized to measure the same six check distances from stereo photos captured by three selected cameras (Kodak, Samsung, and Olympus). The assessment process was achieved through comparing the precise checked distances with the measured distances from stereo photos as summarized in **Table 5**. The table reveals the RMSE in the distances determined from the stereo photos of Kodak, Samsung, and Olympus cameras were ± 22.67mm, ±11.62mm and ±10.36mm respectively.

3.4 Evaluating the quality of 3D models

As explained in section (2.4), PMS software was employed to reconstruct 3D models of the three buildings in the Technical Engineering College-Baghdad (TCB). The models created based on stereo photos taken by each selected camera. For instance, **Fig.11** exhibits samples of 3D models created from stereo photos captured by Olympus camera. The average distance between the cameras stations and the buildings was 30 meter and the base height ratio was about around 0.30. According to PMS software manual, the base/height ratio should be within (0.2 to1.0) in order to get a better quality of a 3D model.

The quality of the 3D models produced from the stereo photos of all three cameras was evaluated by inspecting the exact 3D model's shape and the quality of the texture of extracted models. In addition, quality assessment process was taken into account whether a 3D model was extracted for a structure in indoor or outdoor environments. A small architectural model building located inside a lab room, **Fig.12a** was captured by three selected camera. Three different 3D models of the architectural model were remonstrated using captured photos of each selected camera. An empirical quality assessment, **Fig.12a** of the 3D models was achieved to the produced 3D models via checking dimension of the model with the real one, see **Fig.12. a,b**. The empirical evaluation showed that all three reconstructed models in the indoor environment were high quality and precise (RMSE around ±7.32 mm). Or it can be said that, the models produced from the stereo photos of Kodak camera (low-resolution camera) an excellent quality as models produced from the medium (Samsung camera) and high-resolution photos (Olympus camera). The main reasons behind that are the distance between the camera and the object is too short (about 1m), and the light inside the lab room was appropriate so that the captured photos of the architectural model by all three cameras were very clear.

In addition, the quality of 3D models of the building located in the outdoor environments was analyzed in this study. A 3D model to the library building in the college was reconstructed three different times as shown in **Fig.13**. The 3D models of the building were created based on stereo photos captured by three selected cameras (Kodak, **Fig.13a**), Samsung **Fig.13b**, and Olympus **Fig.13c**. The distance between a camera and the building (**camera/object** distance) was kept around 40 m. The empirical and visual evaluation reveals that:

a) The model produced based on Kodak (low-resolution camera) photos **Fig.13a** was inaccurate ($RMSE_{XYZ}$ = ± 97.32 mm), and having a poor quality of the texture (distorted texture) with many holes and gaps on it.
b) The model produced based on Samsung (good resolution camera) photos **Fig.13b** was having a proper accuracy ($RMSE_{XYZ}$ = ± 42.69 mm), and having a good quality of texture with a few gaps in the edges of the model.
c) The model produced based on Olympus (high-resolution camera) photos **Fig.13c** was having a high accuracy ($RMSE_{XYZ}$ = ± 25.69 mm), and having an excellent quality of texture with a slightly dark area on it.

4. DISCUSSION AND CONCLUSIONS

The using of a digital camera can be involved in many civil engineering and close range photogrammetric applications. However, a specific relationship between a camera resolution and photogrammetric work accuracy (e.g. 3D models generation) has not been addressed clearly by previous literature. Thus, this study has evaluated the accuracy of the derived 3D buildings models captured by different resolution cameras. The investigation included: 1) Selecting three different resolution cameras (Kodak (low resolution), Samsung (medium resolution), Olympus (high resolution) and evaluating the accuracy of camera calibration of the three selected camera; 2) Assessing the accuracy of the three selected cameras (various resolution cameras) in capturing indoor and outdoor objects; 3) analyzing the quality of the produced models.

The accuracy assessment results showed that:

1. The camera calibration results showed that there are slight discrepancies in the overall calibration residuals (RMSE) in the three cameras (Kodak = ± 3.85 pixels, Samsung = ± 0.342 pixels, and Olympus = ± 0.270 pixels) and all the residuals were small (under 1/2 pixel).
2. The second accuracy assessment procedure was involved comparing the computed and the precise 3D distances between the test points which were fixed on the lab wall. Six distances were selected for assessment procedure as explained in section (2.1.1). The RMSE was obtained via comparing the precise 3D distances (AB, BC, CD, DA, AC, and BD) with the same 3D distances determined from the stereo photos captured by selected

cameras (Kodak, Samsung, and Olympus). The results showed that the RMSE in the distances determined from the stereo photos of Kodak, Samsung, and Olympus cameras were ± 6.32 mm, ± 4.98mm and ± 4.67 mm respectively. The results (in the indoor environments) reveal that: a) the RMSE is not significantly affected by the camera resolution; and b) All digital cameras (with different resolutions) can give acceptable results (RMSE less than ±1 cm) especially when the **camera /object** distance is less than 20 m.

3. The third accuracy assessment process involves examining the suitability of various resolutions cameras for photographing natural features of buildings in the outdoor environments. Six check distances on an outdoor building were determined precisely by the total station. The assessment process was achieved through comparing the precise chick distances with measured distances from stereo photos of the three cameras. The RMSE in the distances resulted from the stereo photos of Kodak, Samsung, and Olympus cameras were ± 22.67mm, ±11.62mm and ±10.36mm respectively. The RMSE results show that: a) there are a significant discrepancies between the accuracy of measurements of Kodak (low resolution) camera and Olympus (high resolution) camera in the outdoor measurements; b) The RMSE of the low resolution camera increases noticeably with increase a **camera/object** distance (40 m in this study); and c) there a slight differences between the results and the accuracy of Samsung (medium resolution) camera and Olympus (high resolution) camera.

The quality of the 3D models produced from the stereo photos of all three cameras was also evaluated in this study. The evaluation included inspecting the exact 3D model's shape and the quality of the texture of extracted models. The empirical evaluation showed that all three reconstructed models of a small architectural model building in the indoor environment were high quality and precise (RMSE around ±7.32 mm). In the other hand, the quality assessment of 3D models of building located in outdoor environments reveals that: 1) the models produced based on low-resolution camera were poor quality and low accurate ($RMSE_{XYZ}$ = ± 97.32 mm) and 2) the models produced based on high-resolution camera were an excellent quality and precise ($RMSE_{XYZ}$ = ± 25.69 mm).

Briefly, it is highly recommended to use the stereo photos of a high-resolution camera for producing 3D models of objects in the outdoor environment and if the camera/object distance being more than (40 m). Low-resolution camera can be utilized to produce adequate 3D models of an object in the indoor environment and if the camera/object distance being less than (20 m).

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Table 1. The specifications of the selected three cameras**, Camera User Manuals.**

Properties	**Kodak CX7300**	**Samsung ST50**	**Olympus SZ-10**
Sensor	3.2 MB	12 MB	18 MB
Optical zoom	Fixed focus	3.0 x	18x
Maximum image resolution	2080 x 1368	4000 x 3000	4288 x 3216
Resolution	230 dpi	96 dpi	72 dpi
Focal length	6 mm	6 mm	5 mm
Dimensions (WxHxD) Weight	104 x 65 x 40 mm Weight: 147g	56x94x17mm Weight: 121g	105.9x67.3x37.9 mm Weight: 215g
Output format	JPGE	JPGE	JPGE

Table 2. Camera calibration properties of the three mobile cameras (Kodak, Samsung, and Olympus).

Camera Calibration Properties	Kodak CX7300	Samsung ST50	Olympus SZ-10
Calibrated Focal Length mm	6.2639	6.8185	5.4074
Principal Point co. (x,y) mm	(2.7893, 2.0081)	(3.1599, 2.4199)	(3.2506, 2.3999)
Lens distortion (K1)	1.483e-003	4.959e-003	3.058e-004
Lens distortion (K2)	6.330e-005	-1.287e-004	-3.588e-006
Overall residual (RMSE) pixel	±0.385	±0.342	±0.270

Table 3. The 3D spatial positions of the 55 test field targets and the residuals (V) in the locations of these points.

No	**Ground Coordinates**			**Residuals**	**No**	**Ground Coordinates**			**Residuals**
	X m	**Y m**	**Z m**	**V_{XYZ} (mm)**		**X m**	**Y m**	**Z m**	**V_{XYZ} (mm)**
1	2.953	0.599	3.648	2.8	**30**	5.861	1.259	4.130	5.3
2	3.434	0.579	3.662	5.7	**31**	6.021	1.158	4.025	4.7
3	3.806	0.457	4.124	3.5	**32**	6.258	1.255	4.132	3.8
4	4.189	0.467	4.076	4.6	**33**	6.650	1.250	4.135	3.1
5	4.819	0.438	4.116	5.7	**34**	6.971	1.257	4.133	5.1
6	5.004	0.449	4.116	4.1	**35**	2.797	1.510	4.123	6.2
7	5.475	0.444	4.124	3.9	**36**	3.059	1.672	4.124	4.1
8	5.839	0.461	4.116	4.7	**37**	3.446	1.673	4.127	4.7
9	6.256	0.473	4.126	5.2	**38**	3.848	1.667	4.128	6.0
10	6.626	0.484	4.127	2.9	**39**	4.237	1.673	4.130	2.8
11	6.980	0.503	4.127	5.7	**40**	4.655	1.669	4.132	5.5

12	2.961	0.891	3.766	5.3	**41**	5.044	1.664	4.131	4.9
13	3.442	0.919	3.780	4.8	**42**	5.468	1.655	4.132	6.6
14	3.827	0.854	4.127	2.8	**43**	5.857	1.661	4.139	2.4
15	4.237	0.866	4.128	5.5	**44**	6.265	1.663	4.138	5.3
16	4.637	0.850	4.126	4.9	**45**	6.651	1.661	4.137	4.6
17	5.034	0.843	4.128	4.1	**46**	6.967	1.652	4.138	5.1
18	5.515	0.853	4.127	3.1	**47**	3.052	2.092	4.115	2.7
19	5.850	0.858	4.127	5.7	**48**	3.427	2.089	4.123	7.2
20	6.266	0.930	4.081	5.4	**49**	3.810	2.090	4.094	4.9
21	6.645	0.929	4.130	4.3	**50**	4.238	2.091	4.130	4.8
22	6.968	0.918	4.090	3.0	**51**	4.639	2.083	4.098	3.2
23	3.015	1.276	4.114	4.4	**52**	5.034	2.085	4.133	4.3
24	3.451	1.265	4.126	4.5	**53**	5.462	2.073	4.096	4.4
25	3.842	1.261	4.121	5.5	**54**	5.865	2.072	4.135	5.8
26	4.246	1.264	4.129	6.2	**55**	6.261	2.081	4.138	1.2
27	4.655	1.253	4.131	4.0					
28	5.049	1.268	4.105	3.7					
29	5.499	1.275	4.119	5.1					

Table 4. The distances and the residuals in the six check distances based on the data of the three cameras in the indoor environment.

Name	**Precise Distances (m)**	**Measurements on KODAK photos**		**Measurements on SAMSUNG photos**		**Measurements on OLYMPUS photos**	
		Distances(DK) (m)	**V_{DK}= true-measured (mm)**	**Distances (DS) (m)**	**V_{DS}= true-measured (mm)**	**Distances (DO) (m)**	**V_{DO}= true-measured**
AB	3.587	3.594	-6.62	3.582	5.09	3.590	-2.66
BC	1.601	1.604	-2.95	1.603	-1.64	1.603	-1.97
CD	4.057	4.051	5.86	4.050	6.53	4.050	6.15
DA	1.568	1.565	2.83	1.569	-1.79	1.564	3.32
AC	4.237	4.229	8.32	4.231	6.55	4.243	-5.77
BD	3.993	3.999	-5.97	3.990	2.62	3.997	-3.98
RMSE*			±6.32		±4.98		±4.67

*$RMSE = \sqrt{\frac{\sum V^2}{n-1}}$

Table 5. The distances and the residuals in the six check distances based on the data of the three cameras on an outdoor building.

Name	Precise Distances (m)	Measurements on KODAK photos		Measurements on SAMSUNG photos		Measurements on OLYMPUS photos	
		Distances(DK) (m)	V_{DK}= true-measured (mm)	Distances (DS) (m)	V_{DS}= true-measured (mm)	Distances (DO) (m)	V_{DO}= true-measured
D_1	1.538	1.519	19.54	1.528	10.65	1.545	-6.90
D_2	1.246	1.228	18.44	1.254	-7.57	1.255	-8.88
D_3	2.199	2.223	-26.77	2.187	11.76	2.186	12.86
D_4	1.016	1.026	-12.68	1.025	-8.98	1.024	-7.67
D_5	3.287	3.259	28.34	3.271	15.90	3.275	11.73
D_6	1.035	1.048	-12.89	1.030	5.69	1.042	-6.94
RMS*			± 22.67		±11.62		±10.36

Figure 1. Establishing test field targets.

Figure 2. The three selected cameras**.**

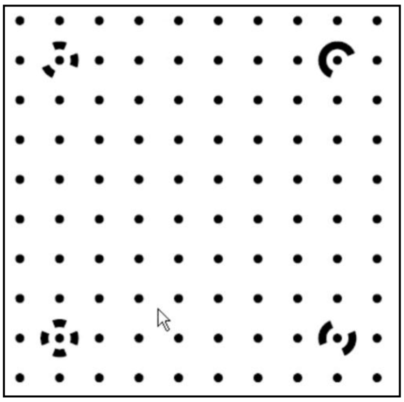

Figure 3. Single-sheet for camera calibration **PhotoModeler User Manual, 2012.**

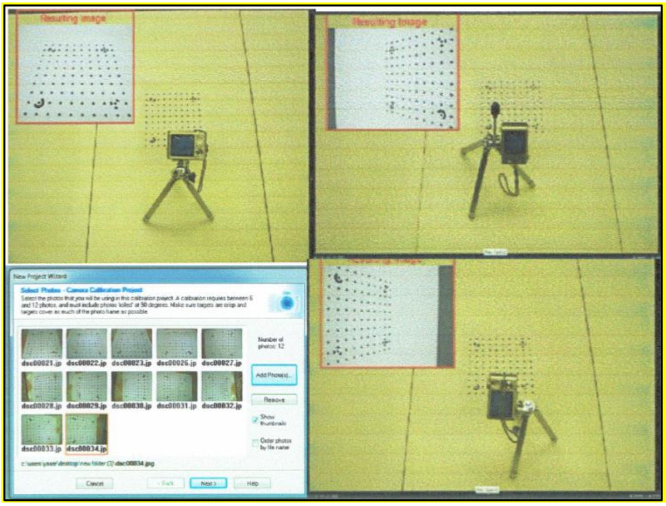

Figure 4. Twelve photos by every chosen camera were captured to the calibration sheet, **PhotoModeler User Manual, 2012**.

Figure 5. The developed camera tripod.

Figure 6. The three buildings of the Technical Engineering College of Baghdad (TCB) in the outdoor environment captured by the three cameras.

Figure 7. The selected natural features on a building in an outdoor environment.

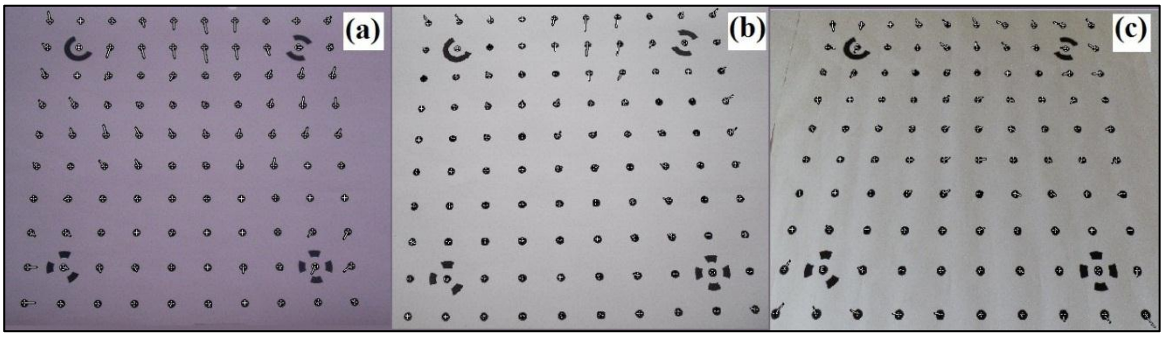

Figure 8. The residuals in calibration grid points photos captured by the three digital cameras; (a) Kodak; (b) Samsung; and (c) Olympus.

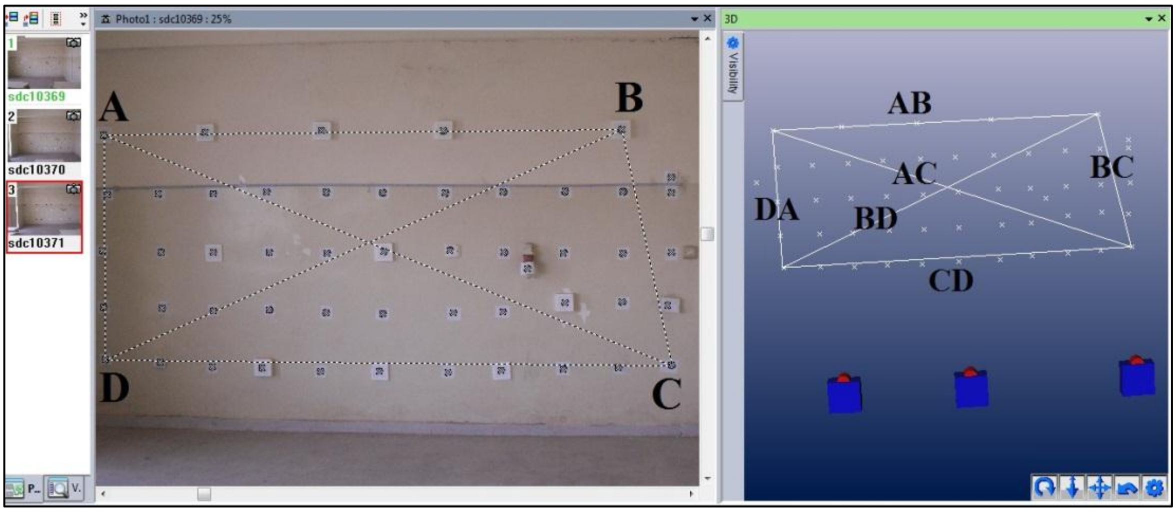

Figure 9. The photos and the 3D view of the six check distances at an indoor environment.

Figure 10. The photos and the 3D view of the six check distances at the outdoor environment.

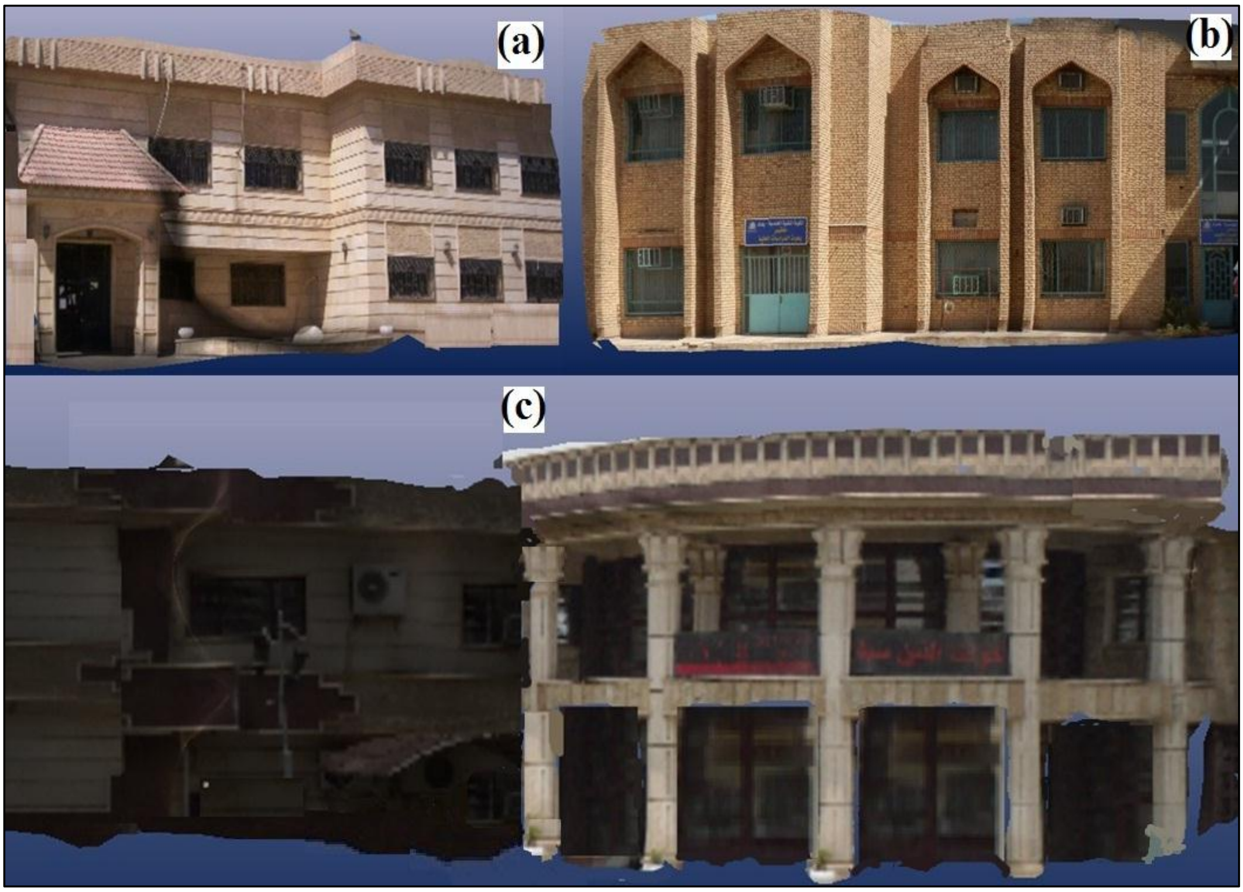

Figure 11. A sample of 3D models of the three buildings of the Technical College-Baghdad (TCB) in the outdoor environment: *Note stereo photos taken by Olympus camera.*

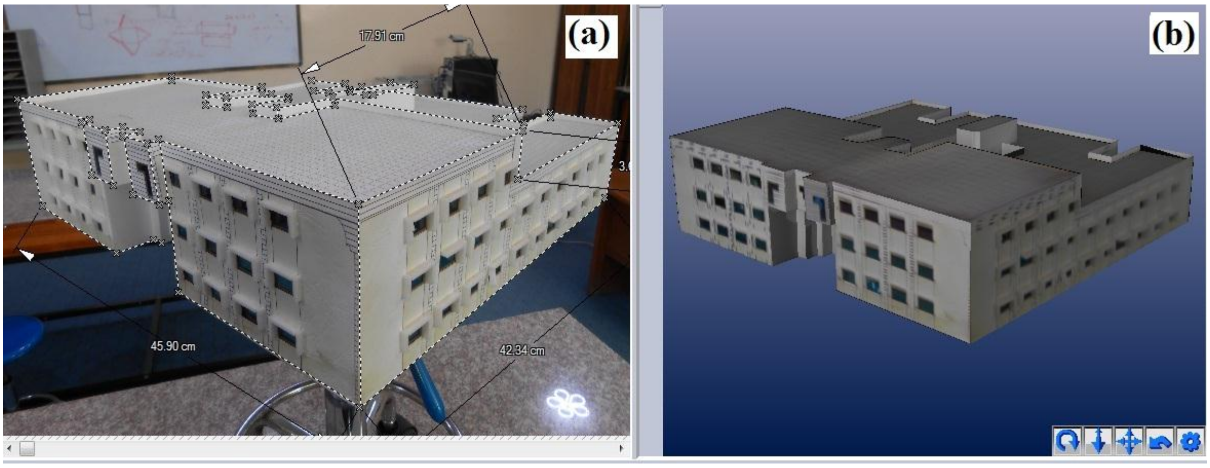

Figure 12. (a), Photo of a small architectural model building; (b) A 3D model of a small architectural model building. *Note stereo photos taken by Kodak camera.*

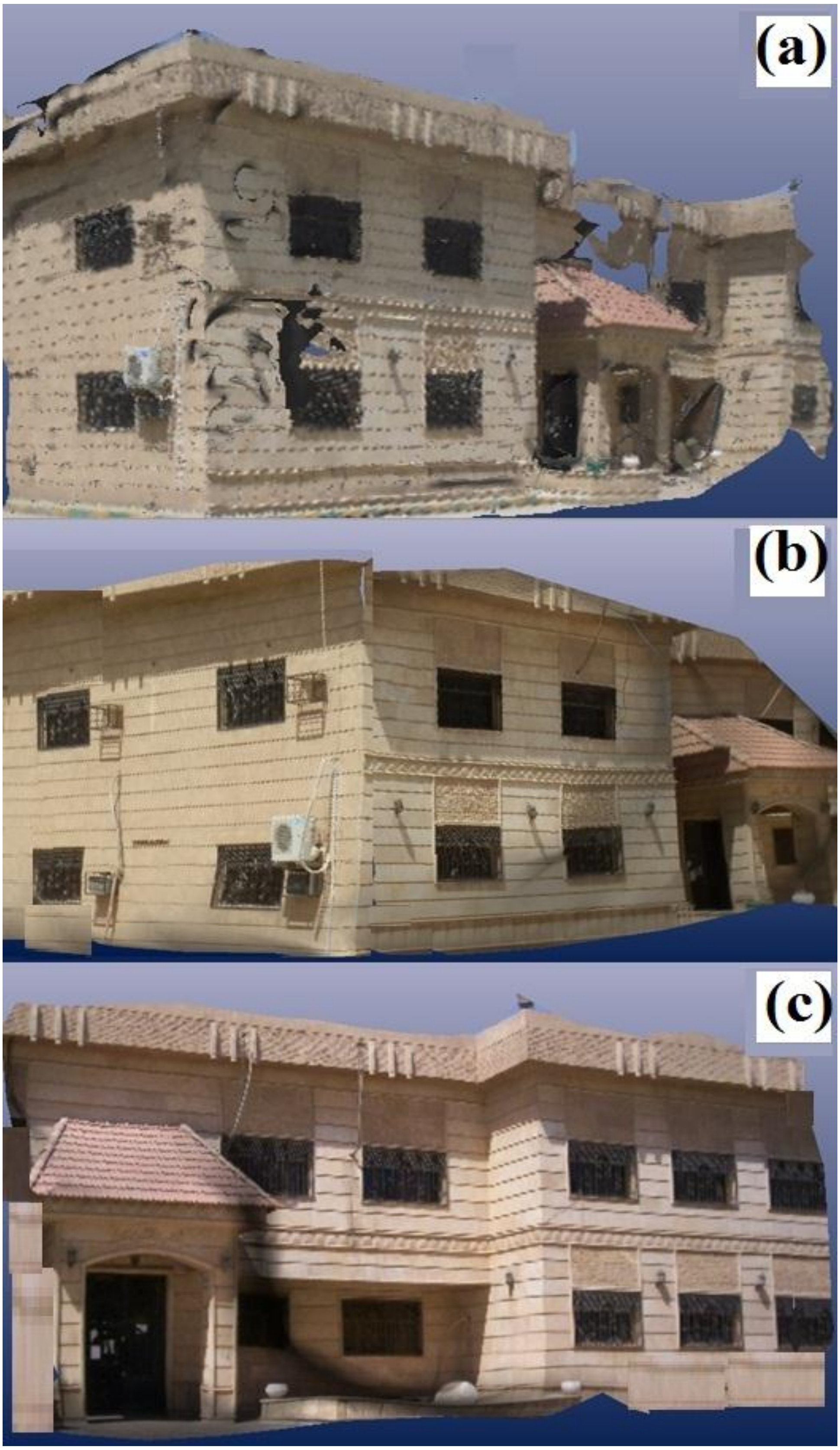

Figure 13. 3D models of the three buildings of the Technical College of Baghdad in the outdoor environment which were captured by the three cameras: (a) Kodak; (b) Samsung; (c) Olympus.