Pixel Binning Effects of Smartphone Camera on Three-Dimensional (3D) Model Reconstructed Crime Scene

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ABSTRACT

Pixel binning, a feature of high-megapixel smartphone cameras, exhibits performance comparable to traditional cameras. The field of photogrammetry has explored and adopted most kinds of technology, hence, pixel binning too should be adopted into forensic photogrammetry. This study evaluates the application of pixel binning technology in forensic photogrammetry, specifically in 3D reconstruction at crime scenes. A simulated crime scene conducted at the UTM-PDRM lab was captured using smartphone cameras of 12MP and 50MP, and a 20MP DSLR camera. First, the cameras were calibrated to ensure their stability. Following the image capture, the data were processed to generate 3D point cloud models of the simulated crime scene. The geometric parameters resulting from the camera calibration were discussed. The 3D point cloud model by DSLR camera exhibited better visual quality than the smartphone cameras. This finding was supported by an analysis of overlapping images by each camera and a side-by-side comparison of the models. Measurements from the smartphones 1, 2 and the DSLR camera were compared to conventional Vernier calipers used in crime scene documentation. The resulting Root Mean Square Error (RMSE) differences were approximately ±5.62mm, ±5.59mm, and ±5.40mm, respectively. In conclusion, the pixel binning of smartphone cameras was able to produce reliable accuracy but requires stability in technology for 3D reconstruction.

Keywords-pixel binning; smartphone camera; close-range photogrammetry; 3D model; crime scene reconstruction

I. INTRODUCTION

Recent advancements in powerful three-dimensional (3D) imaging technologies are increasingly used in crime scene investigations emphasizing the vital role of image resolution and accuracy and the applicability of those techniques in a wide range of situations [1, 2]. 3D data acquisition techniques, such as point cloud generation from laser scanners and photogrammetry, serve various purposes including documentation, preservation, management, analysis, and decision-making [3]. These innovative technologies offer unprecedented capabilities for capturing detailed spatial information crucial for forensic analysis, providing forensic experts with accurately reconstructed crime scenes, helping them make informed decisions [4]. With the advent of 3D surface scanning technology, capturing current crime scenes has become more efficient and detailed [5]. Technologies like Unmanned Aerial Vehicles (UAVs), particularly micro UAVs, are being explored for their use in forensics as parts of evidence capture [6]. However, even with modern technologies, it is necessary to take into consideration the technical constraints, user-friendliness, cost, and time duration of data acquisition [7]. That is why smartphone cameras have emerged as valuable tools for 3D data acquisition, leveraging techniques like pixel binning to enhance image quality while reducing noise, particularly in low-light conditions [8]. By adhering to Close-Range Photogrammetry (CRP) standards, smartphone cameras can efficiently capture detailed imagery for forensic reconstructions, e.g. analyzing footwear evidence and conducting measurements in forensic anthropology [9-11]. CRP involves capturing a series of overlapping images of an object or scene from various angles, which are then processed into raw data known as point cloud, and are later generated as highly detailed and accurate 3D models, making it an ideal technique for forensic applications [12-14]. There are also cases of a combination technique between laser scanning and CRP, creating a comprehensive crime scene model [15]. This data fusion process merges point clouds from different sensors, producing a hybrid point cloud with as-built visualization and geometry for smooth 3D modeling assessment [16]. The future of forensic crime scenes seems brighter with each advancing technology introduced. Pixel binning, a technique commonly employed in modern smartphone cameras, involves combining adjacent pixels to form larger superpixels [17]. Typically, when a smartphone camera employs pixel binning, its Image Signal Processor (ISP) creates superpixels by combining groupings of four neighboring pixels of the same color or nine for nona-binning, to create image data. The introduction of this technology shows potential advancements in 3D reconstruction for forensic investigations. The use of this technology may have limitations in the level of detail and precision that can be achieved. Therefore, the ability of smartphone cameras to capture images accurately in a controlled and consistent manner must be considered.

This study examines how pixel binning in smartphone cameras affects 3D crime scene models. It highlights their potential to simplify forensic documentation due to their mobility, widespread use, and advanced imaging, despite acknowledging their resolution and precision limitations compared to DSLR cameras [18].

II. METHODOLOGY

This section discusses the research methodology, presenting a systematic approach to fulfilling the purposes. Figure 1 illustrates the flowchart outlining the employed methodology.

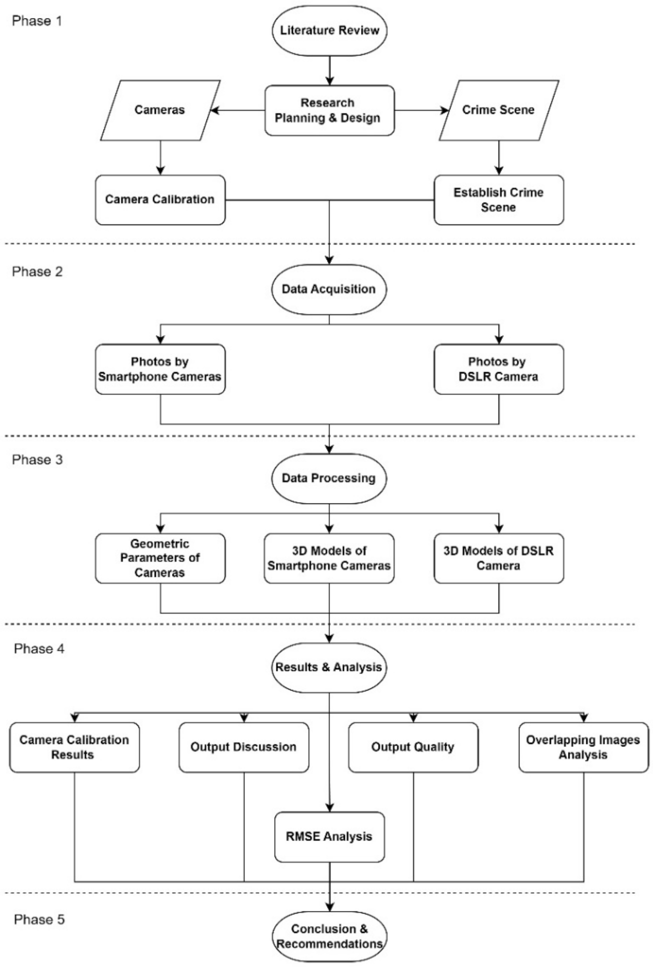


Fig. 1. Methodology flowchart of this study.

A. *Research Planning*

Three cameras were selected for this study, which are: Smartphone 1 (12 MP), Smartphone 2 (50 MP), and DSLR (20 MP). Smartphones with resolutions higher than 12 MP make use of pixel binning [19]. The DSLR camera was included to serve as the benchmark of this research. Camera calibration, a process that uses intrinsic characteristics to stabilize camera sensor interior orientation, was conducted using a structure consisting of rods, retro targets, and precise camera placements [20]. The crime scene was established at the UTM-PDRM Geospatial Forensic Satellite Laboratory on Level 2 of Block C05. The purpose was to simulate a controlled crime scene, utilizing a closed room with consistent "white light" illumination. A standardized method of capturing 10 photos per camera was employed to avoid biases during data processing, ensuring fair and accurate comparisons while minimizing the risk of unexpected errors.

B. Data Collection

The crime scene, as shown in Figure 2, was captured by all cameras from multiple perspectives. The procedure involves systematically encircling the crime scene at consistent intervals and overlapping angles while following the rules of CRP. Prior to 3D data processing, two physical scale bars were positioned as geospatial elements, enabling precise measurements of the crime scene. The scale bars served as rulers, offering established and unchanging reference points for accurate measurements.

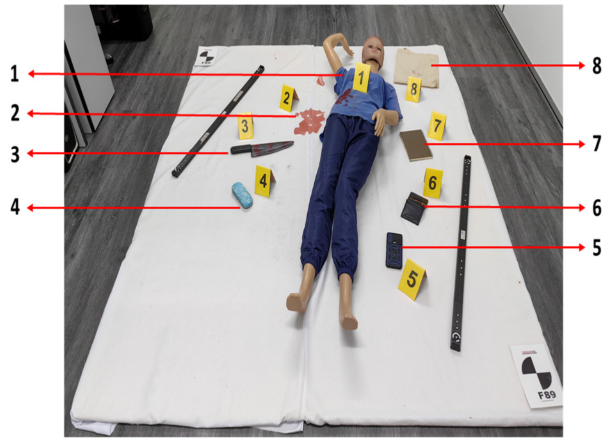


Fig. 2. Simulated crime scene with items: (1) Body, (2) blood splatter, (3) knife, (4) case, (5) smartphone, (6) wallet, (7) notebook, and (8) bag.

C. Data Processing

The collected data were sent for processing, and 3D models by each camera were created utilizing the Structure from Motion (SfM) technique in Agisoft Metashape software. After the processing was completed, all models were resized to their real dimensions, with the use of one physical scale bar, while the second scale bar was used for checking.

III. RESULTS AND DISCUSSION

This study evaluated and compared camera calibration outcomes of smartphone and DSLR cameras. Visual analysis of the outcomes and overlapping image evaluation were performed. RMSE values were compared to assess measurement error accuracy among the three techniques, revealing differences.

A. Camera Calibration Results

According to the results in Table I, the DSLR camera shows more distortion, distinguished by elevated values of both *c* and K_1, especially with wide-angle or fisheye lenses. While smartphones, with relatively lower radial distortion coefficients, try to minimize distortion for more accurate pictures. The point where the camera focuses (*xp* and *yp*) also differs: DSLRs intentionally shift away from the center for creative effects, while smartphones exhibit more confined principal point offsets, keeping it practical for everyday photos. Overall, DSLRs consistently stand out with more distortion, showing a unique pattern compared to smartphones. This interplay of design, lens choice, and purpose is crucial for precision applications like scientific imaging.

TABLE I. INTRINSIC LENS PARAMETERS

Parameter	Smartphone 1	Smartphone 2	DSLR camera
c (mm)	4.215146	4.669569	16.13247
xp (mm)	2.580808	2.308866	11.87281
yp (mm)	1.933854	2.323559	8.04859
K_1 coefficient	-1.25E-02	-2.21E-04	-2.12E-05

B. Point Cloud Models

The point cloud model by Smartphone 1 in Figure 3(a) equipped with a 12 MP sensor, captures the crime scene while striking a balance between image quality and storage considerations, avoiding the use of pixel binning. The 3D point cloud model generated from this data, consisting of 7,699,724 points, exhibits a rough appearance due to the limited number of data points, leading to incomplete representations of the scene. Similarly, the point cloud model of the Smartphone 2 in Figure 3(b) armed with a 50 MP sensor and employing pixel binning technology, also captures the crime scene with imperfections. The resulting 3D point cloud model, comprising 999,193 points, shares a similar rough processing quality, indicating challenges associated with insufficient data points and resulting in gaps within the model. On the other hand, the point cloud model of the DSLR camera in Figure 3(c), featuring a 20 MP sensor and not utilizing pixel binning, excels in producing a visually superior crime scene representation with minimal defects. The larger physical sensor size in DSLR cameras, compared to smartphone cameras, contributes to improved capabilities. The 3D point cloud model derived from the DSLR data, encompassing 39,791,106 points, stands out for its detailed and comprehensive depiction of the entire crime scene.

Fig. 3. Point cloud models from left to right: Smartphone 1, Smartphone 2, and DSLR camera.

C. Output Quality

Table II provides a qualitative analysis of the results between all sensors used based on the visuals and information produced post-processing. The term "presentation" refers to the overall look of pictures and models in each technique. The DSLR camera's model is the best, while both Smartphone 1 and Smartphone 2 models are considered as "Medium" due to similar flaws despite the difference in megapixels. In terms of completeness, the DSLR camera excels in fully reconstructing the crime scene, surpassing the capabilities of Smartphone 1 and Smartphone 2. Regarding color density, the DSLR camera delivers intense colors compared to smartphone cameras, thanks to its larger sensor capturing more light. Point cloud density is crucial for visual quality and data integrity. The model of Smartphone 1, with 7,699,724 data points, offers an acceptable representation with imperfections. model of Smartphone 2, with 999,193 points, appears less dense, possibly due to the pixel binning effects. The DSLR's model, with 39,791,106 points, showcases the advantages of specialized equipment, boasting a larger sensor and consistently detailed 3D models.

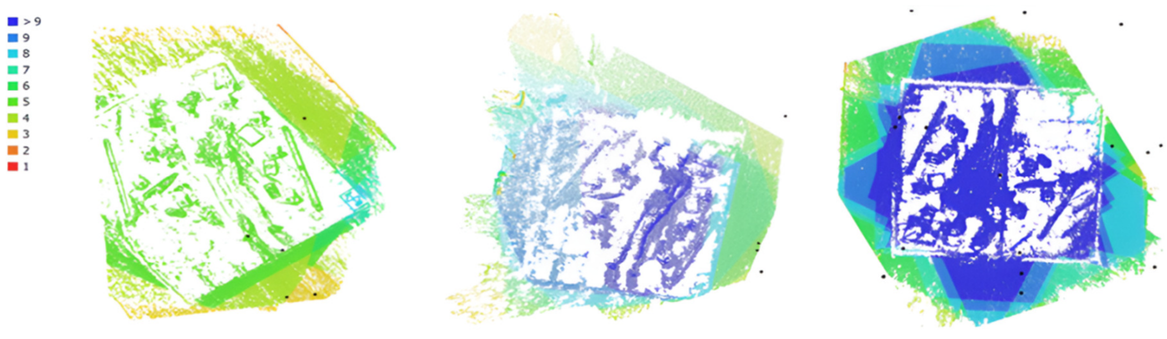
TABLE II. OUTPUT QUALITY

Aspect	Smartphone 1	Smartphone 2	DSLR camera
Presentation	Medium	Medium	Best
Completeness	No	No	Yes
Color density	Light	Light	Intense
Point cloud density	Intense	Light	Intense

D. Overlapping Image Analysis

Successful 3D model point cloud reconstruction requires sufficient overlapping images. Agisoft Metashape Professional generates a report after processing, indicating the image overlap levels. The degree of overlap is color-coded in the report, with deep blue indicating heavy overlap and a gradual color change representing reduced overlap.

On Figure 4(a) - Smartphone 1, the corner of the setup shows the most overlapping images (9), while the rest of the crime scene simulation has up to 7. Figure 4(b) has over 9 (> 9) overlapping images, but only partially covers the crime scene. In contrast, Figure 4(c) has almost the entire crime scene simulation with > 9 overlapping images. This analysis reveals varying reconstruction results due to different numbers of overlapping images for each camera type. Overlapping occurs when the software matches points from one image to another based on shared features. This process, following the CRP concept, happens automatically with well-overlapped input images. However, there are instances where some images or areas lack these points, indicating the software could not find common features. This lack of overlapping images can stem from inconsistent lighting during capture. While image capture was standardized at ten (10) for each camera, lighting remains a significant factor. Smartphone 2 and DSLR camera produce better overlapping photos due to their superior lighting intake. The pixel binning technology enables better lighting intake despite its small sensor, giving it an advantage over Smartphone 1, which captures less light. DSLRs, with larger sensors naturally receiving more light, have the best overlapping photos. Unlike Smartphone 2, Smartphone 1 lacks technology for enhanced light intake, having the least overlapping photo, resulting in less desirable output.



(a) (b) (c)

Fig. 4. Overlapping image analysis: (a) Smartphone 1, (b) Smartphone 2, and (c) DSLR camera.

E. Root Mean Square Error (RMSE) Analysis

A feasible method for a quantitative analysis to compare the models and the measurements is RMSE that follows (1):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \hat{x}_i)^2}{N}} \quad (1)$$

where (x_i) is the observed value from the DSLR Camera and the Smartphone cameras, $\hat{x}_i$ is the true calue from conventional measurement (Conv) with a Vernier caliper, and N is the number of samples.

When precision measurements are a concern in fields like forensics and geomatics, traditional tools such as a Vernier caliper are respected for their millimeter-level precision, serving as benchmarks. Photogrammetry models were measured with software tools, while physical models used Vernier caliper for data collection, ensuring robust method reliability assessment. Table III presents the RMSE analysis, comparing measurement errors between the CRP techniques and the Conv measurements. A lower RMSE value indicates a statistically better model. The RMSE values for Vernier caliper and Smartphone 1 (Conv – Smartphone 1), Vernier caliper and

Smartphone 2 (Conv – Smartphone 2), and Vernier caliper and DSLR camera (Conv – DSLR camera) were 5.62 mm, 5.59 mm, and 5.40 mm, respectively. These findings suggest that the DSLR camera exhibits the lowest RMSE value, indicating that it is the most accurate among the three techniques. Provided that there is no universally global standard for crime scene investigation accuracy, it has been reported in the USA that the acceptable limit is within 0.25 in, which is 0.635cm [21, 22]. Figure 5 illustrates a visual representation of the 12 samples from the dataset, highlighting the RMSE of the integration of DSLR and Smartphone cameras in comparison to the Vernier caliper.

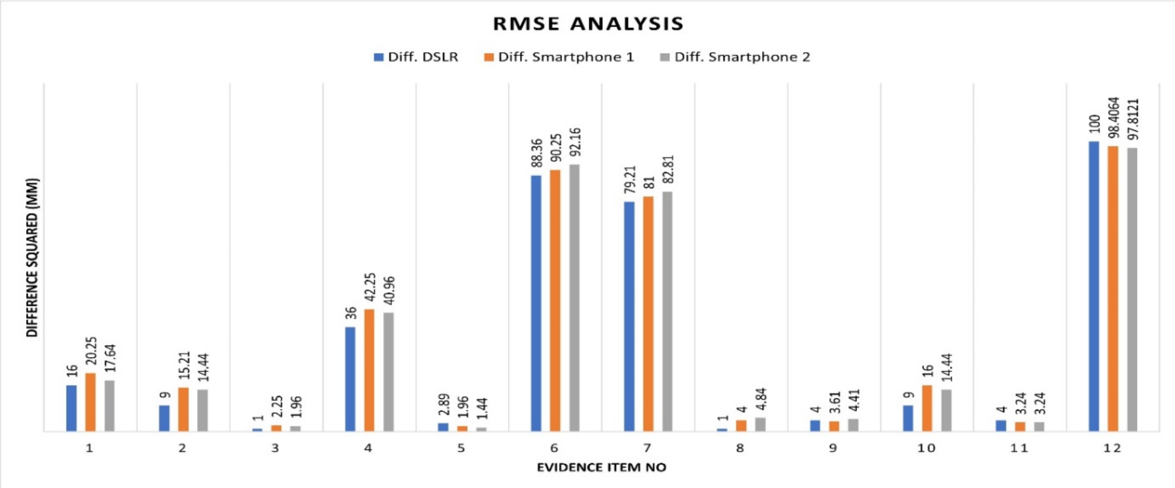


Fig. 5. RMSE analysis.

TABLE III. RMSE ANALYSIS

Item	Measurement Differences (mm)		
	Conv – Smartphone 1	Conv – Smartphone 2	Conv – DSLR camera
Knife	-4.5	-4.2	-4.00
Length Knife Handle	3.90	3.80	3.00
Width Knife Handle	-1.50	-1.40	-1.00
Length Glasses Case	6.5	6.4	-6.00
Width Glasses Case 2	1.40	1.20	1.70
Right Foot	-9.50	-9.60	-9.40
Left Foot	-9.00	-9.10	-8.90
Phone	-2.00	-2.20	-1.00
Wallet	-1.90	-2.10	-2.00
Notebook	-4.00	-3.80	-3.00
Marker 1	-1.80	-1.80	-2.00
Marker 2	-9.92	-9.89	-10.00
RMSE	5.62	5.59	5.40

IV. CONCLUSION

The aim of this research is to explore the applications of smartphone cameras utilizing pixel binning for forensic photogrammetry, addressing the knowledge gap in the effectiveness of high-megapixel smartphone cameras for accurate 3D model reconstruction. The primary objective of this study is to evaluate the stability, quality, and accuracy of 3D models produced by each camera.

To conclude, smartphone cameras with high megapixel values, despite having pixel binning technology, still produce outputs of comparable quality to standard 12 MP smartphone cameras. Furthermore, the outputs of smartphone cameras are found to be inferior to those produced by DSLR cameras. This research coincides with the findings in [23], which highlighted severe image artifacts caused by pixel binning, leading to degradation of image quality and loss of detail, thereby affecting the 3D models. The novelty of this research lies in its detailed comparison of smartphone cameras with different megapixel counts and pixel binning technology, providing insights into their capabilities and limitations in forensic photogrammetry. This study remarkably evaluates the impact of pixel binning on 3D model reconstruction, while DSLR cameras remain the preferred choice for high-quality 3D model reconstruction, the study highlights that pixel binning technology allows smartphone cameras to capture more light, suggesting potential benefits in certain conditions despite some drawbacks.

For future research, it is recommended to incorporate structured structured-light 3D scanners to provide additional input for 3D models, enabling further comparison and analysis. Additionally, Radiometric Performance Analysis, including Modulation Transfer Function (MTF) analysis, noise analysis and linearity test, can offer a more in-depth evaluation of smartphone camera resolution and performance. Pixel matching techniques, typically used in volumetric calculations, should also be recommended to enhance the spatial accuracy of 3D point cloud data in forensic crime scene analysis and various measurement applications. Improved pixel precision can significantly benefit the accuracy of object placement, depth perception, and surface reconstruction.

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