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Accuracy of ray pinning compared to model-based image matching for forensic investigations

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ABSTRACT

Forensic investigations often require accurate placement of objects or persons in an incident scene in order to establish the most likely scenario of how events transpired. This can be accomplished through ray pinning, a technique in which control points on a model of an object of interest and a 2D image of the incident scene are correlated to optimally match the location of the object in 3D space to its location in the 2D image. Alternatively, a technique referred to as model-based image matching (MBIM) relies on the acuity of an operator's vision to manually manipulate the location of the model until the operator judges that the model of the object is overlaid as accurately as possible on the 2D image of the object, as represented in the 3D space. The purpose of this study is to compare the accuracy of ray pinning to MBIM in positioning an object using 2D images from video frames. A simulated scene, in which a Blueguns rifle had been placed on the ground, was captured in videos taken by three stationary cameras placed in different locations. The position and orientation errors for the rifle placement was calculated for ray pinning and MBIM. Both techniques employed a 3D scan of the scene used to calibrate the cameras. The results of statistical analysis showed that MBIM was significantly more accurate in positioning the rifle than ray pinning, although the two techniques were equally accurate in orienting the rifle.

1. Introduction

In forensic investigations, it is often necessary to determine the location of objects in a scene based on video or photographic records. These images are often the most objective evidence available for assessing the likelihood of various scenarios which may have transpired during the incident under investigation. Therefore, it is critical that the location of an object or individual associated with the incident can be accurately placed at the location it would have been at the time of the incident. For example, surveillance video may capture a shooter aiming and firing a firearm, in which case determining the position and orientation of the shooter and firearm are critical in determining the bullet trajectory. Similarly, a vehicle may be captured at the incident scene by a surveillance camera and moved prior to the forensic investigation. The position and orientation of the vehicle at the time of the incident may be critical for determining the positions of individuals involved in the incident, both inside and outside of the vehicle. Current technology used to reconstruct and analyze an incident scene from 2D video and photographs exploits information in digital representations of photographed objects, employing principles of optical physics, referred to as photogrammetry [1].

Inverse photogrammetry is a process by which the position, orientation, and characteristics of the recording camera are determined from a representation of the 3D space of the incident scene. This can be done using multiple 2D camera images [2] to create the 3D representation or by using a point cloud representation obtained with a laser scanner [3–5]. This involves correlating the location of identical features seen in 2D video frames and the 3D scan of the scene, which allows for correction of image distortion caused by the optical properties of the lens. Once the location and characteristics of the camera are established through inverse photogrammetry, reverse projection can be used to determine the location of an object, employing a technique sometimes referred to as ray pinning. Ray pinning involves projecting rays from the camera through selected points on the 2D video image as it would be seen from the camera's viewpoint in the 3D scan. The location where the rays intersect the 2D view in the 3D scan determines the 3D position of the object. Alternative reverse projection techniques have been proposed that involve adjusting the position of an the outline of the scene projected onto the 2D image of a camera positioned at the incident scene [6–8].

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Another technique which can be used for object placement in a 3D scene is model-based image matching (MBIM). MBIM involves placing a 3D model of the object in the 3D scan such that the model, seen as a 2D image from the camera's viewpoint, visually matches the 2D video image and conforms to physical restrictions, such as not passing through physical barriers. MBIM generally involves the use of a geometric registration function to computationally superimpose the model over the 2D video image of the object [9,10]. Although a registration function for MBIM is essential in computer vision applications, where an algorithm must be executed multiple times during a short interval, it may not be necessary in forensic investigations where the acuity and discrimination of human vision can be exploited.

Both methods involve a degree of subjectivity. In ray pinning, it is necessary for the operator to select matching control points in the 2D images and 3D representation of the incident scene. In MBIM performed without a registration function, the operator must decide, based on their visual judgement, the location of the 2D image of the model that best matches the 2D location of the object in question, as seen in 2D images obtained during the incident. The present study was conducted to compare the accuracy of ray pinning, using commercial photogrammetry software (Photomodeler[1]), with MBIM, using open source 3D creation software (Blender[2]), in placing a 3D model of a M4 A1 blue rifle in the same location and orientation as its known location and orientation in a 3D scan of a simulated forensic incident scene. This would be similar to determining the position and orientation of a shooter's firearm based on an incident scene photo or placing a vehicle at the incident scene. MBIM was performed by two operators and involved digitally moving the model under human visual guidance in the 3D scan of the scene, rendered in Blender. In addition to comparing the placement accuracy of the two techniques, reproducibility was assessed by comparing the placement locations of the two operators.

2. Methods

2.1. Simulated incident scene

Three video cameras were positioned to record a simulated forensic incident scene, consisting of a Blueguns Colt M4 Commando LE6933 rifle placed on an outdoor patio floor (Fig. 1). The cameras were placed at the heights and locations, listed in Table 1, in order to view the rifle from different angles. The cameras were placed approximately in line with one another, with Camera 3 to the left of the rifle, Camera 1 to the right of the rifle and Camera 2 in the center, as shown in Fig. 2. The camera specifications are listed in Table 2. The setup was selected to represent an incident scene where the location of a firearm was captured by surveillance cameras and later photographed or scanned by forensic investigators. The camera locations were dictated by the space available at the simulated incident location and the requirement that the rifle occupy a sufficient number of pixels in the image so that accurate error calculations could be performed.

2.2. 3D scanning and camera calibration

The scene was 3D scanned using a Dot3D DPI-10-SG scanner with an Intel RealSense D415 sensor attachment. A maximum scan range of 1.5 m to the surface being scanned was was used as it has been shown that the D415 has a depth error of approximately ±3.9 mm within a scanning range of 0.5 – 1.5 m. The scan was processed with CloudCompare[3] to remove artifacts and extraneous data points to improve accuracy, as well as subsampling the scan for computational efficiency. The scan was used for camera calibration and to establish the 3D reference position of the blue rifle. Prior to placement of the cameras for recording the incident scene, each camera was calibrated by photographing an array of nine April tags (calibration sheets), arranged in a 3 × 3 grid, using views from each of its four sides. In addition, images were recorded after each camera had been rotated 90° clockwise and 90° counterclockwise, resulting in 12 calibration images. After being uploaded to PhotoModeler, the lens parameters necessary to remove distortion of the grid's geometry was determined using PhotoModeler's built-in calibration function.

2.3. Creation of rifle model

A 3D mesh model of an M4 A1 rifle similar to the Blueguns Colt M4 Commando LE6933 rifle was downloaded from the Turbosquid[4] website. The 3D mesh of the M4 A1 rifle model was modified based on measurements of the dimensions of the Blueguns rifle. The 3D model and the 3D scan of the Blueguns rifle were then imported into Blender and the mesh model was overlaid on the 3D scan. The dimensions of the mesh model were modified in Blender until the overlay of the mesh model visually matched the 3D scan based on the investigator's judgement. The M4 A1 rifle mesh model is shown overlaid on a scan of the Blueguns rifle in Fig. 3. The red and green patches indicate areas of mismatch. The modified mesh model was imported into CloudCompare to convert it into a point cloud represented by 100,042 points for computational efficiency. The point cloud representation of the model was imported into PhotoModeler and its placement in the 3D scan was determined by minimizing the distance between the points representing the mesh model and the points representing the 3D scan of the blue rifle, i.e. placing it at closely as possible to the location of the rifle in the 3D scan. The reason for doing this was to have a rifle image in the 3D scan with an identical surface representation as the 3D mesh model used for MBIM.

2.4. Ray pinning

Selected frames from the 2D videos recorded by each camera were uploaded to PhotoModeler where they were corrected for lens distortion and the camera locations were determined using inverse photogrammetry. The 3D rifle model, at its object position in the incident scene, was imported to PhotoModeler where the ray pinning analysis was carried out. Control points were selected at 3D object points on the model that could also be clearly identified as image points in 2D image of the Blueguns rifle in each selected video frame. The number of control points varied from 8 to 13, depending on the camera view, i.e. depending on the number of image points that could be clearly identified in the 2D camera view. Ray pinning involved aligning the selected 2D image points with the corresponding 3D object points on the rifle model by projecting rays from the 2D image points through the camera lens and through the 3D object points on the rifle model in the incident scene. The ray-pinned location of the rifle was determined by the position where the rays from the selected 2D image points intersected the corresponding 3D object points on the rifle model. The 100,042 coordinates of the point cloud representing the 3D rifle model at its ray-pinned location were saved in a text file for later comparison with the true rifle position and orientation. The selection of control points and ray pinning was repeated for five different video frames for each camera in order to perform statistical comparison tests.

2.5. Model-based image matching

The selected frames from the 2D videos recorded by each camera were uploaded to PhotoModeler where they were corrected for lens distortion and the camera locations were determined using inverse

[1] https://www.photomodeler.com/
[2] https://www.blender.org/
[3] http://cloudcompare.org/index.html
[4] https://www.turbosquid.com/

Fig. 1. Frames from camera views of simulated forensic incident scene as recorded on the left and the same frames after lens correction for distortion in Photomodeler on the right.

Table 1
Camera placement.

Camera	Height (m)	Rifle Distance (m)	Rifle Image Length (pixels)
1	1.23	6.86	59
2	1.70	5.31	446
3	1.42	4.90	247

photogrammetry. The lens corrected video frames and the 3D rifle model were imported to Blender where the MBIM was performed. Blender provided a 2D virtual camera view of the rifle model, based on the position and lens parameters determined by PhotoModeler, as well as showing the selected 2D video frame. The rifle model was translated and rotated by the operator, who viewed it as a 2D image from the perspective of the virtual camera. A semi-transparent virtual camera view of the rifle model was projected onto the 2D video frame The operator moved the projected 2D rifle model over the 2D video frame until the rifle model was aligned with its image in the 2D video frame to the 's operator's satisfaction. The 100,042 coordinates of the point cloud representing the rifle model at its superimposed location were saved in a text file for later comparison with the true rifle position and orientation. The procedure was repeated for each camera view for the same five video frames used for ray-pinning. MBIM was performed by two independent operators using the same video frames in order to verify the reproducibility of the results.

To test whether the accuracy of MBIM could be improved by employing two camera views, frames from Cameras 2 and 3 were both imported to Blender, allowing the operator to view the semi-transparent 2D projection of the rifle model model on both video frames simultaneously. The operator moved the 2D rifle model until satisfied that the best compromise had been achieved in aligning the 2D model with the 2D image of the rifle in the video frames from both camera views. The procedure was repeated for the same five video frames used for ray

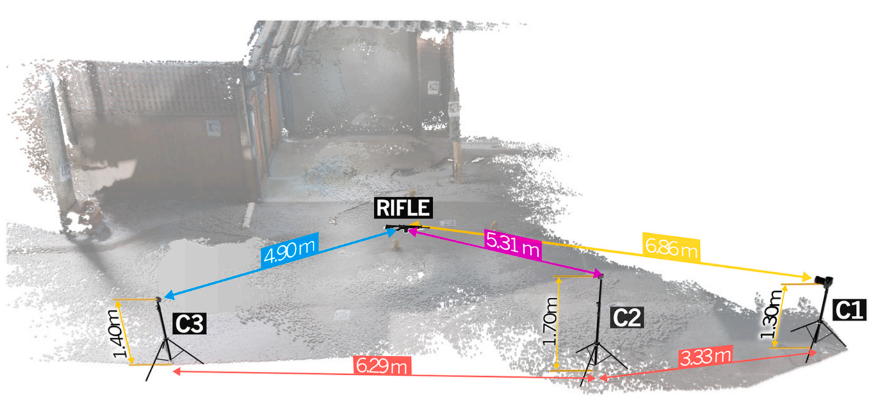

Fig. 2. Camera locations shown schematically with respect to the Blueguns rifle.

Table 2
Video camera specifications.

	Model	Pixels	Lens Model	Focal Length	Zoom	FPS
Camera 1	Canon EOS 7D	1280 × 720	EFS 18–200 mm	18 mm	1x	60
Camera 2	GoPro Hero 8	2700 × 1520	Wide Angle View	21.4 mm	1.4x	60
Camera 3	GoPro Hero 11	5312 × 2988	Wide Angle View	22.4 mm	1.4x	60

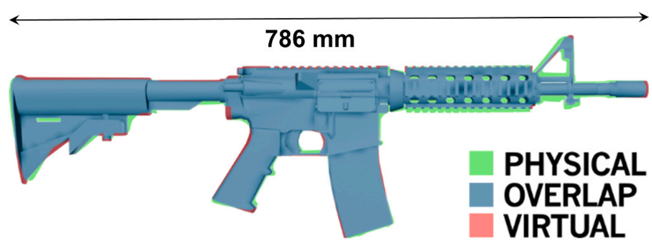

Fig. 3. Modified model of M4 A1 rifle (virtual) overlaid on scan of Blueguns rifle (physical).

pinning in the same order.

2.6. Error calculation

Errors were expressed in terms of the camera coordinate system to reflect the position and orientation of the rifle as seen from the perspective of each camera. In this way errors could be related directly to the focal plane and optical axis of the cameras. The positions of the 3D points representing the true position of the Blueguns rifle and the 3D points representing the position of the rifle model, as determined by ray pinning or MBIM, were transformed to the coordinate system of each camera. The camera position and orientation parameters provided by PhotoModeler were used to translate and rotate the data points such that the origin of the coordinate system was shifted to the center of the camera, with the x-axis representing left-to-right in the camera's focal plane, the y-axis representing bottom-to-top in the camera focal plane and the z-axis representing the optical axis of the camera, using a right-handed convention. Position error between the true position of the blue rifle and the position of the rifle model was determined by calculating the mean difference between all corresponding points of rifle point cloud. The error was expressed as absolute error in the xy plane (r_{xy}) and along the z-axis (r_z). To find the orientation error around each coordinate axis, the positions for corresponding 3D points were projected onto each coordinate plane, i.e, (x,y), (x,z) and (y,z). The signed angle between the position vectors, represented by the coordinated pairs, was then calculated from the cross product on the vectors and the inverse sine function, providing the signed difference in orientation angle around the axis perpendicular to the plane.

$$u \times v = |u||v|\sin\theta$$

$$\theta = \sin^{-1}\frac{u \times v}{|u||v|}$$

For example, in the case of the z-axis (xy plane), vector u would be (x_r,y_r) and vector v would be (x_o,y_o) where the subscript r refers to the true position of the blue rifle and the subscript o refers to the position of the overlaid model determined by ray pinning or MBIM. The absolute value of the mean difference in orientation over all corresponding points in the rifle point cloud was taken as the orientation error

2.7. Statistical analysis

ANOVA was performed to determine whether there was an effect of the method used for rifle positioning. This involved comparing the position and orientation errors obtained with ray pinning and MBIM for the complete data set of five video frames and three cameras. In addition, ANOVA was used to compare the position and orientation errors obtained with MBIM for Cameras 2 and 3 individually and MBIM where the operator simultaneously viewed images from both Cameras 2 and 3. The reproducibility of the MBIM technique was assessed by calculating Fisher's intraclass correlation coefficient (ICC) for the two operators. Fisher's ICC measures the interrater reliability, i.e. the extent to which measurements made by two operators, using the same images, agree. Fisher's ICC was calculated separately comparing the x, y and z coordinates of the rifle model placements by the two operators for each of the video frames analyzed for each single camera view, as well as for the two simultaneous camera views. The mean value of Fisher's ICC across all comparisons was then calculated. Fisher's ICC was not calculated for the ray pinning since ray pinning was performed by only one of the operators.

3. Results

The mean Fisher's ICC for all video frames analyzed (including all camera views) was 0.999 for the x-coordinate, 0.968 for the y-coordinate and 0.981 for the z-coordinate, indicating excellent agreement in performing MBIM between the two operators along all three coordinate axes. This result indicates that MBIM can be reliably performed by a single operator. Therefore, the errors for MBIM are presented as the mean errors for the two operators.

The mean errors and standard deviations for the single camera ray pinning, performing MBIM using single camera images (MBIM 1) and performing MBIM using images from two cameras (MBIM 2) are listed in Table 3.

ANOVA comparing the errors for ray pinning and MBIM1 showed that position error in both the focal plane of the camera (d_{xy}) and along the optical axis of the camera (d_z) were significantly lower for MBIM1 than ray pinning ($p < 0.0001$) whereas the orientation errors were not significantly different ($p = 0.41$ for θ_z, $p = 0.93$ for θ_y and $p = 0.82$ for θ_x).

ANOVA comparing the errors for MBIM1 using single camera views and MBIM2 using views from Cameras 2 and 3 simultaneously showed that position error in both the focal plane of the camera (d_{xy}) and along the optical axis of the camera (d_z) were significantly lower when using views from the two cameras simultaneously ($p < 0.0001$) whereas the orientation errors were not significantly different ($p = 0.29$ for θ_z, $p = 0.76$ for θ_y and $p = 0.99$ for θ_x). The large reduction in the error along the optical axis of the camera (up to 8 times) can be expected because the rifle is viewed from two very different virtual camera angles, allowing the operator to see more that small adjustments in position along the optical axis of one virtual camera which may not be detected as changing the alignment from that virtual camera's viewpoint can be detected as relatively large change in alignment from the viewpoint of the other virtual camera.

Table 3
Position and orientation mean errors with standard deviations (brackets).

	d_{xy} (mm)	d_z (mm)	θ_z (deg)	θ_y (deg)	θ_x (deg)
Ray Pinning	69.2 [44.9]	237.2 [187.0]	0.35 [0.36]	0.05 [0.03]	0.09 [0.07]
MBIM1	19.7 [7.2]	42.0 [26.6]	0.29 [0.20]	0.06 [0.04]	0.09 [0.06]
MBIM2	10.5 [2.6]	4.7 [2.4]	0.13 [0.10]	0.07 [0.04]	0.05 [0.03]

4. Discussion

The most important finding of the present study is that the accuracy achieved in positioning the rifle model in the simulated incident scene was markedly better with model-based imaging (MBIM) than ray pinning. Whereas the mean position error with ray pinning was approximately 7 cm in the camera focal plane and 24 cm along the optical axis of the camera, MBIM produced a mean position error of approximately 2 cm in the camera focal plane and 5 cm along the optical axis of the camera when working from a single camera view. Simultaneously employing video frames from two cameras reduced the MBIM position error to approximately 1 cm in the camera focal plane and 0.5 cm along the optical axis of the camera. Given that the blue rifle was placed approximately 5 m from the nearest camera, this represents an error of 0.2 % of the distance from the camera to the object of interest. Mean orientation errors for both ray pinning and MBIM were well below 0.5 deg.

MBIM proved to be highly reproducible, with Fisher's ICC well above 0.95, even though the two operators were using their subjective visual judgement. The finding that human vision is more accurate than ray pinning may seem somewhat surprising given that ray pinning is based on an optimization algorithm and solved computationally. However, in ray pinning, human judgement is initially required to select control points on the 3D model of the object and the actual object as it appears in the 2D video frames. Given that the model and the video image of the object will not be identical, the control points will not have exactly the same geometry on the model and the video image of the object. Furthermore, the precision in placing the control points will be limited by the level of detail of the model and the optical resolution of the video image of the object. In general, the model can be represented with a higher optical resolution that the video image. The lower resolution of the video image of the object, therefore, limits the ability of the operator to precisely place control points at the same locations on the selected features on the video image of the object and the model.

The availability of frames from two cameras with different views of the scene was shown to significantly improve the accuracy of MBIM when the model was moved simultaneously over both frames. The improvement in accuracy with images of the object from two viewpoints is not surprising since it provides the operator with the ability to see errors along more directions than with a single viewpoint. Furthermore, it is not surprising that the error along the optical axis of the camera was reduced more than the error in the camera focal plane since it is much more difficult for the operator to visualize changes in the placement error when moving the model along the optical axis than in the focal plane of the camera when only a single camera view is available. However, it was surprising that the resulting error along the optical axis of the camera was approximately half the error in the focal plane of the camera when two camera views were simultaneously used in moving the model. This may be partially explained by the profile of the rifle, which is long in the focal plane and narrow in cross-section along the optical axis. Thus, small changes in the position of the model in the focal plane of the camera would result in less evident placement error than small changes in its position along the optical axis.

Liscio et al. [4] investigated the accuracy of reverse projection and PhotoModeler for measuring the height of suspects in video images, which was similar to the ray pinning technique of the present study. They found mean errors of approximately 1 cm. However, that refers to error in measuring a single dimension of the object rather than the error in placing the object in a 3D space. Furthermore, the suspect occupied a much greater proportion of the image than the blue rifle in our simulated incident scene and the study was conducted indoors under steady room lighting whereas the present study was conducted outdoors where lighting was variable. Therefore, it is likely that the video images and the 3D scan available to the operators in the study of Liscio et al. [4] had a better signal to noise ratio than the video images and 3D scan of the present study, which would allow more accurate measurement. Nevertheless, the present study represents a realistic incident scene where variables such as lighting or object size are less than ideal.

Terpstra et al. [6] used a reverse camera projection technique to estimate distances from a camera to evidence markers at a simulated incident scene. Although not identical to MBIM, reverse camera projection has a number of similarities, which include overlaying an outline of selected features in the scene over the camera image. Whereas, the MBIM employed in the present study involved moving the model in software, the operators in the Terpstra et al. [6] study manually moved a real-time view of the scene displayed on a tablet. They obtained a mean position error of 8.5 cm for three operators, using a single camera view, which is approximately 60 % greater than the position error in the present study. It should also be noted that their study only investigated the error in measuring the position of a single point as opposed to a three-dimensional object. Since a point does not have an orientation, the study could not address the orientation accuracy of the methodology.

In a subsequent study conducted by Terpstra et al. [11], a similar technique was used for image matching, but with a vehicle as the object, rather than a single point. This allowed them to determine both position and orientation errors. The mean position error for placing the vehicle in the incident scene for camera viewing (incidence) angles of of 55 deg or less, was between 6.4 cm and 7.8 cm, whereas for a viewing angle of 80 deg the position error increased to 17.0 cm. The mean orientation error was approximately 0.5 deg for all viewing angles. Thus, both the position and orientation errors were comparable, although still slightly higher, using their camera-based matching technique than those obtained with the MBIM technique of the present study.

A study by Chou et al. [12] analysed rollover crashes by overlaying a 3D mesh model of the vehicle on video frames of the rollover, recorded at 500 fps. They found a mean orientation error in the roll angle of 1.43 deg. Their error calculation was based on a least mean squares fit of the MBIM roll angle to the angle recorded by a roll angle sensor mounted in the vehicle and involved smoothing of the MBIM data because they were investigating the time history of the roll angle. Although their orientation error is somewhat larger that the orientation errors in the present study, it is not directly comparable because their calculated error was not derived from the raw data.

The purpose of this study was to compare the accuracy of ray pinning as implemented in commercially available software (Photomodeler) with MBIM in placing an object at an incident scene. The selected object was a firearm which appears asymmetrical from most viewpoints, allowing it to be accurately oriented. It would be more difficult to use MBIM to accurately orient an object which appears symmetrical from most viewpoints, unless there were distinct markings at different locations on the object. On the other hand, positioning with ray pinning is less likely to be affected by object symmetry since it is more dependent on object size than shape. Any method which uses photogrammetry to determine the location of objects in a scene will be affected by the quality of the images. Highly reflective surfaces often produce noisy 3D scans. Scenes or objects which are homogeneous without distinctive features may limit the number of control points or the accuracy with which they can be located in an image. The accuracy of ray pinning might be expected to improve by selecting control points using images from several cameras with different viewpoints, although this has not been our experience (unpublished observations). Another suggestion to improve the accuracy of ray pinning would be to project a 2D image, obtained from a 3D scan of the incident scene, onto the 2D camera image, which could make the selection of control points less subjective and more accurate.

The present study examined the accuracy of placing an object which is present in a scene. However, in many forensic investigations the object of interest may not be present in images of a scene. For example, it may be important to determine the probability that a person was positioned at a specific location in a scene during an incident under investigation, although there are no images of the scene in which that person appears. MBIM is ideal for such applications since a model of the person of interest can be created and the effect of placing the 3D model in different locations can easily be assessed. Simple 3D models of humans have been previously used for estimating height [13]. However, much more realistic 3D models of humans and objects are available on websites such as Turbosquid and can be imported into applications such as Blender where they can be integrated with 3D scan of scenes. Human models can be scaled to the anthropometric characteristics of an individual and joint angles of body segments can be adapted to any desired posture.

5. Conclusions

Positioning an object model in an incident scene by model-based imaging (MBIM) was found to be more accurate than by standard ray pinning such that positioning errors were reduced by a factor of 3–5 when applied to single camera images and by a factor of 6–50 when two camera images were used for MBIM. Furthermore, simultaneously employing video frames from more than one camera in MBIM significantly reduced the position error, particularly along the optical axes of the cameras. Furthermore, the accuracy of MBIM was not dependent on the operator, ensuring that it is not biased by subjectivity. Object orientation errors, using either methodology, were relatively small, indicating that either ray pinning or MBIM can be used to reliably orient an object at an incident scene. Although the present study was applied to the positioning of a firearm, MBIM can be used effectively for positioning vehicles or individuals captured in camera images of an incident but no longer present by the time an investigation is undertaken. The principal caveat is that an accurate 3D model of the object of interest can be created. This might involve obtaining a 3D scan of the object, a 3D finite element model or mesh or morphing a similar model to match known dimensions of the object of interest. Blender software is particularly useful, in this respect, for the placement of individuals involved in the incident.

CRediT authorship contribution statement

Theodore E. Milner: Writing – original draft, Formal analysis, Conceptualization. **Marc-André Nolette:** Visualization, Data curation. **Szymon Claridad:** Visualization, Data curation. **Geoffrey T. Desmoulin:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors have no conflict of interest as a result of being involved in this study and the entire study was funded internally by GTD Scientific Inc.

References

[1] B. Hoogeboom, I. Alberink, D. Vrijdag, Photogrammetry in digital forensics, in: A. T.S. Ho, S. Li (Eds.), Handbook of Digital Forensics of Multimedia Data and Devices, John Wiley and Sons, 2015, pp. 185–218.

[2] D. Imoto, M. Honma, M. Asano, W. Sakurai, K. Kurosawa, Method for estimating real-scale 3D human body shape from an image based on 3D camera calibration and computer graphics-based reverse projection photogrammetry. J Forensic Sci. doi: ⟨10.1111/1556-4029.70130⟩.

[3] G.T. Desmoulin, M. Kalkat, T.E. Milner, Forensic application of inverse and reverse projection photogrammetry to determine subject location and orientation when both camera and subject move relative to the scene, For. Sci. Int. 331 (2022) 111145.

[4] E. Liscio, H. Guryn, Q. Le, A. Olver, A comparison of reverse projection and PhotoModeler for suspect height analysis, For. Sci. Int. 320 (2021) 110690.

[5] K.A. Maline, W.E. Breuhs, A comparison of reverse projection and laser scanning photogrammetry, J. Forensic Identif. 68 (2018) 281–292.

[6] T. Terpstra, S. Beier, W. Neale, The application of augmented reality to reverse camera projection, SAE Tech. Pap. (2019), 2019-01-0424.

[7] Epstein, B.G. Westlake, Determination of vehicle speed from recorded video using reverse projection photogrammetry and file metadata, J. Forensic Sci. 64 (2019) 1523–1529.

[8] W.E. Bruehs, D. Stout, Determination of average vehicle speed utilizing reverse projection, J. Forensic Sci. 6t7 (2022) 188–199.

[9] H.S. Baird, Model-Based Image Matching Using Location, MIT Press, 1985.

[10] P.J. Besl, Geometric modeling and computer vision, Proc. IEEE 76 (1988) 936. -358.

[11] T. Terpstra, A. Hashemian, R. Gillihan, E. King, S. Miller, W. Neale, Accuracies in single image camera matching photogrammetry, SAE Tech. Pap. (2021), 2021-01-0888.

[12] C.C. Chou, R.W. McCoy, J.J. Le, S. Fenton, W. Neale, N. Rose, Image analysis of rollover crash tests using photogrammetry, SAE Tech. Pap. (2006), 2006-01-0723.

[13] G. Edelman, I. Alberink, Comparison of body height estimation using bipeds or cylinders, Forensic Sci. Int. 188 (2009) 64–67.