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# A comparison of reverse projection and PhotoModeler for suspect height analysis

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ABSTRACT

The purpose of this study was to compare the accuracy and precision between the Reverse Projection and PhotoModeler methods for suspect height analysis. Thirty analysts were assigned to measure the heights of three different suspects, one for each method, with the suspects having been recorded standing at three different distances in a scene. For Reverse Projection, the analysts were provided with height scales to place and video-record at the same positions their suspects stood in at the test scene, so that frames could be extracted from the video and overlaid onto frames of the suspects to measure height. For PhotoModeler, analysts calibrated frames of the suspects using 3D point cloud data obtained from a laser scan of the scene, so that measurements could be made in PhotoModeler software. Errors were calculated for the measurements and compared using the Mann-Whitney U-test and Kruskal-Wallis H-test, which indicated significant differences for errors between the two methods ($p = 0.0025$ and $p = 0.008$). Reverse Projection yielded a greater range of error and tended to have higher standard deviations than PhotoModeler, but the overall accuracy between the two methods was found to be comparable. The majority of absolute measurement errors for both methods were less than 2 cm.

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## 1. Introduction

### 1.1. Background

Forensic video analysis has changed significantly over the past two decades, mainly due to the modernization of hardware and software used for CCTV (closed-circuit television) systems and the growing number of places from which digital video can be sourced. The abundance of mobile phones, in-car cameras, body cameras and the relatively low cost of installing a home security system have all contributed to the ubiquitous nature of these devices. In addition, the quality and resolution of present-day cameras, with intelligent recording algorithms and increased storage capacity, are improving. Cases involving speeding vehicles, officer-involved shootings and instances where suspects are seen on video are now more commonly being caught on cameras. Thus, there is a rising need for the analysis of video and still frames in these cases for substantive purposes.

Reverse projection (RP) is a method for image analysis developed before the digital era that is still used today with the evolution of video into a digital format. RP has been taught by agencies such as the Federal Bureau of Investigation for use in suspect height analysis cases [1]. Early on, RP was also used to relocate evidence at accident scenes by way of placing a transparent photograph at the same location or very near to the same perspective as the film camera which took the image [2]. Literature exists warning about some of the hazards of this method [2] since there is a subjective component to this type of analysis. However, the advent of digital cameras and imaging software has allowed for more robust types of RP to be applied in the field which can limit the amount of subjectivity introduced with the method.

In addition to Reverse Projection, another method that can be employed for image analysis is Photogrammetry. Photogrammetry is defined by the American Society of Photogrammetry and Remote Sensing as "the science or art of obtaining reliable measurements by means of photography" [3], and is based on triangulation. It can be especially useful when analyzing video and photographic evidence in order to acquire measurement information about an object depicted in a still image. Whenever a digital photo is taken, the three-dimensional (3D) information about that object is lost. Photogrammetry can be seen as the process of working backwards from a single image (or multiple images), such that when the

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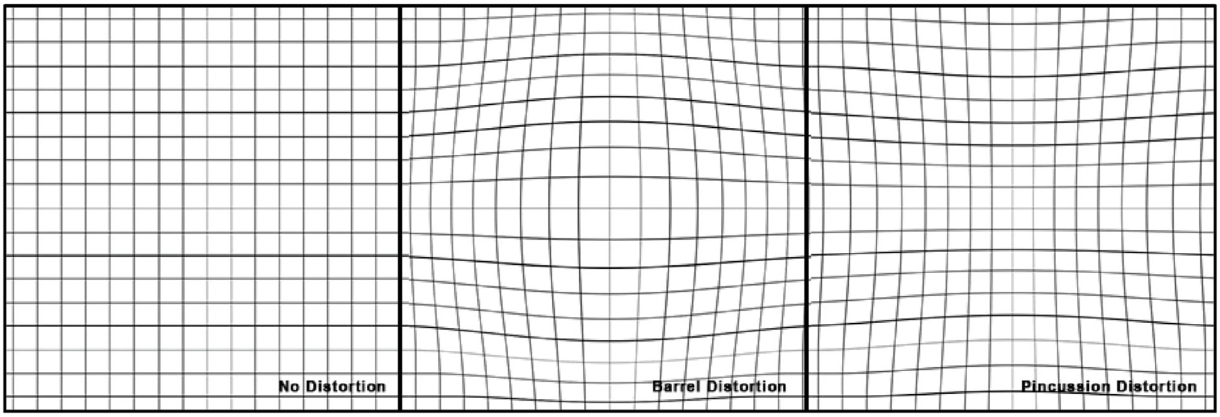


**Fig. 1.** Graphics showing some various kinds of lens distortion.

information in the photo(s) is combined, metric information that was lost can be recovered. Both manual and photogrammetric camera matching methods attempt to find a camera's position and orientation in 3D space, by choosing an individual pixel on a digital sensor and then projecting a light ray through the focal point, out the lens, and then straight back out to the object. However, this simplified process does not come without its real-world challenges.

A basic principle of light is that light rays travel in straight lines [4]. Thus, when taking a photograph and light rays travel from an object through the camera lens, they get focused to a focal point and onward where they eventually hit a two-dimensional (2D) sensor [5]. Whilst moving from a 3D object to a 2D sensor, one dimension is lost and direct, accurate measurements from a photograph are no longer possible (except in special circumstances). The lens acts as a focusing instrument and concentrates all light rays entering the lens to the focal point. Most modern-day cameras have a Charge Coupled Device (CCD) or a Complementary Metal Oxide Semiconductor (CMOS) sensor, which converts light into electrons and into digital values (1's and 0's) that eventually form a digital image [5–7]. In a perfect scenario, cameras would be consistent and the path of light rays would have no deviations. In the real world, the individual characteristics of cameras need to be considered, as the final goal is to estimate or calculate the position and orientation of the camera which took the original photograph/video.

The focal length of a camera is the distance between the imaging plane (i.e. digital sensor on a digital camera) and the point where all the light rays intersect (i.e. focal point) [8]. A large focal length is equivalent to greater zoom and a smaller focal length provides a wider viewing angle so that more of the object appears on the image plane [8]. Focal length is key to solving any photogrammetry problem since any single photo can only be taken with one focal length setting. Once the orientation and focal length is solved for, it is possible to take measurements from a photo.

Two types of distortions that relate to photos and video are perspective distortion and optical distortion. Perspective distortion refers to the disproportionality of objects relative to each other depending on their proximity to the camera (i.e. objects located closer to the camera appear larger and take more image space than objects located further from the camera), and changes depending on the focal length [9]. Optical distortion is mainly caused by the design of the lens in the camera and can be described as an abnormality that distorts physically straight lines and makes them appear bent [7]. In photogrammetry it is always an undesirable anomaly that requires correction. Two types of optical distortion are referred to as "barrel" and "pincushion" distortions (see Fig. 1). Barrel distortion is most commonly found with security camera systems and is associated with a wide angle or a "fisheye" lens where straight lines are curved outwards just like a "wine barrel" (see Fig. 2). Pincushion distortion has an opposite effect, where straight lines are more distorted away from the center, and is often associated with telephoto lenses.

### 1.2. Suspect height analysis

Suspect height analysis is an area of forensic science that is concerned with the estimation of height of an individual based on a security camera video or a photographic image [10]. This can be achieved by applying the fundamental principles of photogrammetry as well as by using various instruments and software packages [11]. Common methods to perform suspect analysis include reverse projection and camera matching, as well as projective geometry and 3D modelling of scenes and suspects [12]. Suspect height analysis is not intended to identify a suspect, but rather to obtain a class characteristic that may include or exclude an individual as a suspect. Thus, the importance of understanding

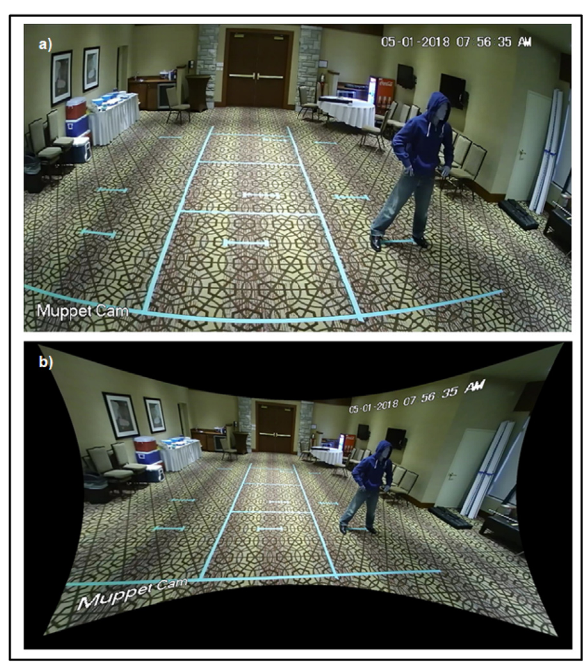


**Fig. 2.** a) A security camera image with barrel distortion. Straight lines are curved outwards.
b) A corrected security camera image without barrel distortion. Straight lines appear straight.

errors in this process is vital in determining the strength of this evidence since a wide range of error can include a large population of people. Also, it is important to note that when measuring a person's height from a single video frame or photograph, the analyst is measuring how tall that person was at the moment when the image was captured [12,13]. This measurement may not be a true representation of the person's height under different circumstances due to several variables which can be summarized in four categories: Camera Factors, Individual Factors, Environmental Factors, and Analyst Factors. Each of these factors can have an impact on the accuracy and precision of measurements.

Camera Factors refer to the variables concerned with the camera's position, image quality (e.g. in or out of focus), resolution, angle, mounted height, movement (e.g. motion blurring), lighting contrast, the distance of the camera from the source object or person being measured, and lens distortion [12,13].

Individual Factors deal with the issues that can alter a suspect's stature on camera. Human height is known to be variable throughout the day as the spine compresses under the weight of the body or through physical activity [14]. The variation of hairstyles, headwear, and footwear (e.g. high heels versus flat shoes) is a contributing factor that may cause an overestimation or underestimation of height [12,13]. Posture can make a person appear taller or shorter, especially when in motion [15].

Environmental Factors refer to the area and environmental effects which might cause inaccuracies during suspect height analysis, such as the lighting conditions, physical traits and colors of the scene, obstructions, uneven ground, the change in ground elevation between the camera and the suspect, or a lack of reference features which are needed for camera matching (e.g. a field or snow-covered landscape) [11,16]. It may also include items which affect visibility such as fog, rain or snow.

Analyst Factors comes into play during the processing and analysis phase of the suspect height measurement. It is up to the analyst to determine the best location for reference points and the points which specify the vertex of the head and the ground point for feet location [12,13]. These positions are often difficult to discern and can be subjective. In any suspect height analysis project, it is best when the analyst has no knowledge of the suspect's height in advance.

### *1.3. Reverse projection and camera matching methods*

Reverse Projection and Camera Matching are two common methods that allow users to obtain measurements from a single frame of video or a photograph. These methods vary in their robustness, flexibility and ease of execution and can all be proven useful when applied correctly. The variations in these methods are mainly dependent on several factors such as:

1. The availability of the camera;
2. Scene preservation;
3. Quality of the overall image (i.e. how clearly the items can be discerned);
4. The change in camera position or movement (Panning cameras, mobile phones, body worn cameras and in-car cameras are all considered moving cameras and are rarely fixed and stationary), and;
5. The presence of a sufficient number of common features between the captured video and the scene in its current state [17].

The items above define the overall quality of the available video/photographic evidence and when considered in their totality, should provide the analyst with a set of standards by which they can determine the method most likely to provide a successful solution. In some cases where the quality of evidence is poor, the analyst must simply accept that a solution is not attainable, or the accuracy of results may not be sufficient. However, when the quality of evidence is good, a method that employs a true mathematically sound photogrammetric solution should be at the top of the hierarchy. As the quality of evidence diminishes, the need for a more flexible solution must be employed at the expense of introduction of subjectivity. However, this does not diminish the effectiveness of the technique or method, but instead tells the analyst that they must consider how and which possible errors could affect their analysis.

The basic premise of reverse projection is that the original camera perspective can be matched by overlaying an original "suspect" image on top of a new or additional frame of video [17]. Both are aligned such that objects in the images like walls, door frames, road lines, etc. match up. By overlaying the two sets of camera images and knowing the position of other objects at the scene, measurements of objects which are no longer present (like a suspect or car) can be estimated [17]. One limitation of reverse projection is that the original camera's position should remain the same as it was at the time when the picture was taken, including the field of view [17]. Cameras which have changed their position or focal length require an additional step to solve for the orientation and focal length of the camera at the time when the "suspect video" was taken. Thus, there are three common scenarios for a reverse projection project:

1. Return to the location where an unchanged CCTV system exists to locate the evidence from a suspect video;
2. Return to the location where the camera is no longer in the same position but can be repositioned such that an overlay of the "suspect" image and current image can be made (this method can also be used when the original camera is no longer accessible, but an exemplar camera is available).
3. In some cases, a completely different camera may be substituted such that the images are made to align closely. In this case, measurements are possible, but care must be taken to validate and deduce the errors of using this method.

Amped FIVE (Amped SRL, Trieste, Italy) and iNPUT-ACE (iNPUT-ACE, Spokane, WA) are two software programs that can be used to make reverse projection overlays for estimating suspect height on camera frames [18,19]. Reverse Projection is used to align a past and recent image from a camera over top of one another so that items that are no longer present in the "past" image can be measured. With respect to suspect height analysis, this can be accomplished by using a height scale in the present image and placing it vertically where the suspect was originally standing [17]. The video images of the height scale are exported and brought into an image editing program with layering capabilities, such as Adobe Photoshop (Adobe Inc., San Jose, CA) or GIMP (GIMP Team, Berkeley, CA) [17,20,21]. By changing the opacity of the height scale overlaid on top of the suspect video image, it is possible to take a direct reading of height from the height scale as shown in Fig. 3. This method works best when the camera position and focal length has not changed so that there is perfect agreement with all common, stationary objects in the scene.

There are two main camera matching methods which exist in variant forms, but both may be used depending on the quality of evidence present. The first is an automatic calculated method referred to as 'Camera Resection', while the other is a manual method of moving a virtual camera in a 3D software program, such as Autodesk 3 ds Max (Autodesk Inc., San Rafael, CA), and adjusting its parameters until the analyst decides that the virtual camera appears to be a close match the original frame of an image [10,22]. In each case, some type of measurement information about the

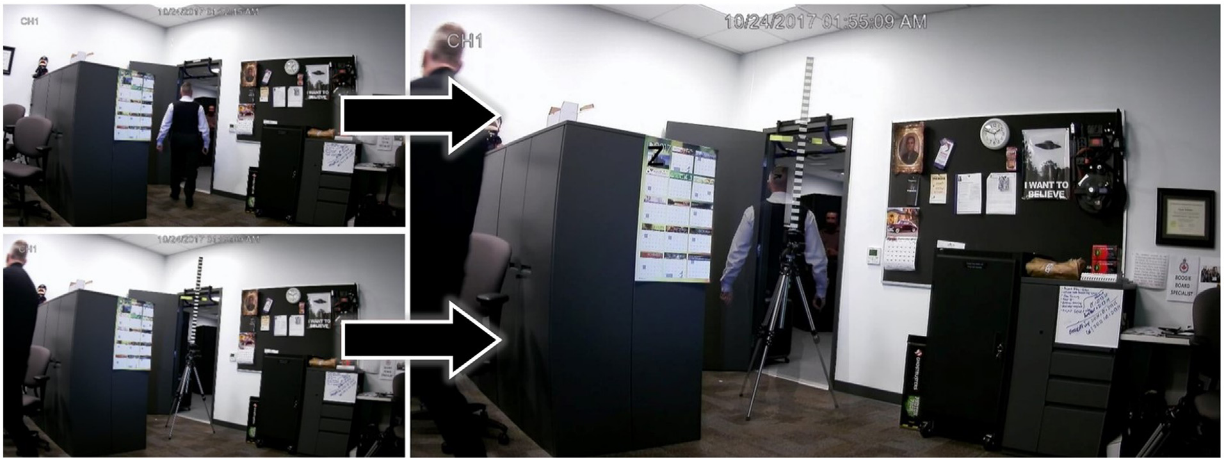


**Fig. 3.** An example showing how Reverse Projection is performed using the height scale in an image overlay. Top left, "suspect image", Top right, height scale placed in approximate same location as suspect. Bottom, combined overlay so that direct measurements can be made.

scene must be obtained and there must be existing reference points between the original image and the existing scene. The Camera Resection method is more objective, as it uses a software package to project the control points chosen by the analyst to the 2D pixel information on the image and mathematically 'solve' for the camera's orientation and field of view to provide the best estimate of camera parameters. Autodesk 3 ds Max has a camera match utility that can be used to reproduce the position, orientation, and field-of-view of an original scene camera using a photo [22]. Another software that similarly allows for Camera Resection analysis is PhotoModeler (Eos Systems Inc., Vancouver, BC, Canada) [23]. The method for analyzing single camera images with PhotoModeler is described in detail in *Extracting Accurate Measurements from Single Surveillance Camera Images* (by E. Liscio, 2017) [24].

PhotoModeler is a comprehensive photogrammetry package that allows the user to work with digital images as well as exported video frames to calculate measurements in 3D [25–27]. One feature of PhotoModeler is that it can use a single image from a security camera or any digital photograph to calculate a camera's position [26]. It is also possible to obtain measurements by combining multiple photographs while marking and referencing common objects [10,25]. It also includes a field calibration option which allows users to correct for the camera's distortion using control data [26,27]. Part of the process includes the identification of features that can be used to reference the still image(s) to the collected 3D data. Such features include unchanged, stationary, distinct points on the image such as corners of door frames, road cracks, etc. (Fig. 4). If the scene lacks features, the analyst can place high contrast targets in the scene and use them for reference together with a newly acquired footage from the day of documentation (Fig. 5). PhotoModeler requires a minimum number of seven reference points to be selected for image distortion corrections, but using more than at least 12 reference points, or as many as possible, results in more robust solutions. Features in images that are chosen as reference points should be distributed over as wide as the image's surface area as possible to ensure proper camera parameter identification later on while using PhotoModeler (Fig. 6). PhotoModeler also requires 3D measurement information, which can be acquired by measuring the distance between reference points with a measuring tape, surveying them with a total station, or documenting them with a laser scanner [11,28].

The purpose of this study was to examine and compare the accuracy and precision of Reverse Projection and the camera resection method using PhotoModeler.

## 2. Materials and methods

### 2.1. Setup and data collection

The data collection and analysis were performed at the Ontario Forensic Video Analyst Association (OFVAA) Conference in 2018 at Niagara Falls, ON. A rig of cameras as seen in Fig. 7 was created with the intent of testing multiple cameras, but due to limited time, only one camera was used to test for the differences when measuring suspect height using two different analytical methods between various analysts. The camera used was a Honeywell HD72HD4

[a]



**Fig. 4.** Security camera videos showing [a] a feature-full parking lot with variety of corners and high-contrast points well spread-out throughout the image, and [b] a less feature-full location where more than 50% of the image has no identifiable features on the ground. Note that vegetation, snow and dirt are often subject to change quite rapidly and thus, features in existence at the time a suspect was present may be gone after a very short time. Both images were captured by the authors.

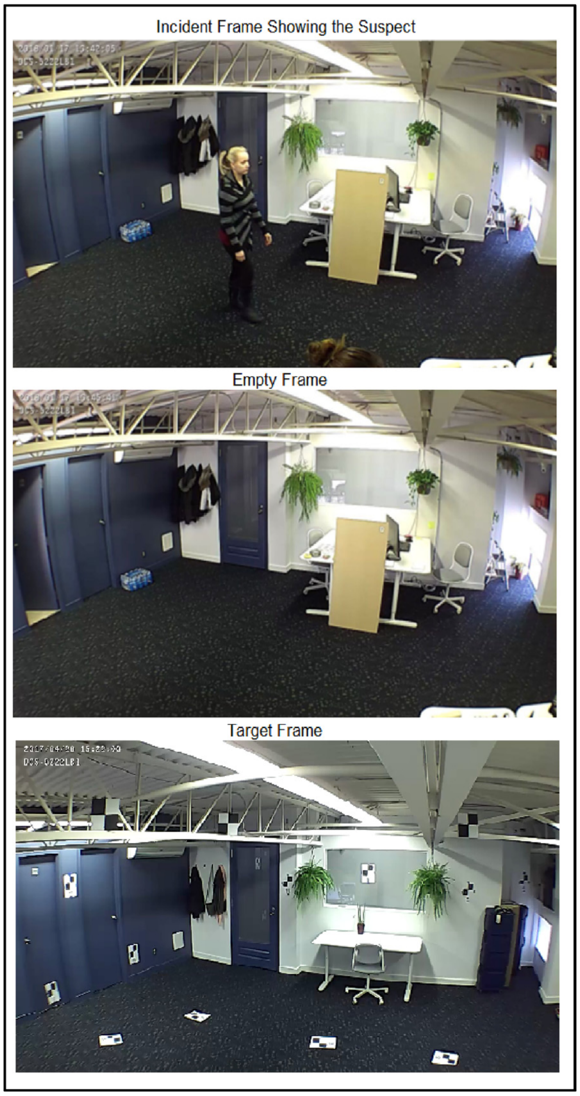


**Fig. 5.** Frames from a security camera showing various types of frames used when conducting PhotoModeler analysis. Target frames are useful if more than 30% of the frame area has no distinctly identifiable features.

4 MP IR Mini Dome model (Honeywell International Inc., Charlotte, NC), joined together with a WatchNET EVI-040-1 T DVR system (WatchNET Inc., Markham, ON, Canada). The chosen camera had a resolution of 2560 × 1440 pixels (i.e. 1440p or QHD). The camera was mounted on a rig in a conference room at height of roughly 8 feet from the ground. A lane/pathway was created on the floor of a conference room, using painter's tape, going down the middle of the room, and a line was marked at three different distance positions in each lane to specify the specific position of each suspect (see Fig. 8). The three distance positions were marked at approximately 3.2 m, 4.4 m and 7.2 m away from the camera rig.

Three individuals were asked to pose as suspects and their heights were measured using a height scale and tape measure. Their height was not reported to any of the participants prior to the analysis to avoid bias. The 'suspects' were then asked to enter the room one by one, stand across the indicated tape in the center lane/pathway (see Fig. 8), and remain in a stationary relaxed position whilst keeping their feet together for several seconds before switching to the next position. After the video was downloaded from the DVR, individual frames were extracted that depicted the three positions of each suspect located at 3.2 m, 4.4 m and 7.2 m away from the camera for a total of nine suspect images (three suspects each standing at all three positions) and one empty-frame reference image. Still frames of the suspects were extracted from the camera footage based on their clarity and the suspects' stillness in position, to ensure that any confounding factors like movement/gait or blurriness were controlled for. Once this was completed, the room where the camera and suspects were located was scanned using a FARO Focus S350 laser scanner (FARO, Lake Mary, FL) using 1/5 resolution and 3x quality settings, and processed using the FARO Scene 7.1 software package to produce a point cloud of a room as seen in Fig. 9.

Once the data was processed and exported as an. e57 file, the point cloud was imported into 3 ds Max software. Autodesk 3 ds Max software is an extensive 3D modelling package with the function to import and work with 3D point cloud data in an optimized format using the Clouds2Max plugin (Autodesk Recap Files can also be used to open point clouds in 3 ds Max) [29]. This step was performed in order to accurately pick and extract the points of interest which were later referenced to the points on the photographs by the analysts participating the study. After the points and guides were marked, they were exported from 3 ds

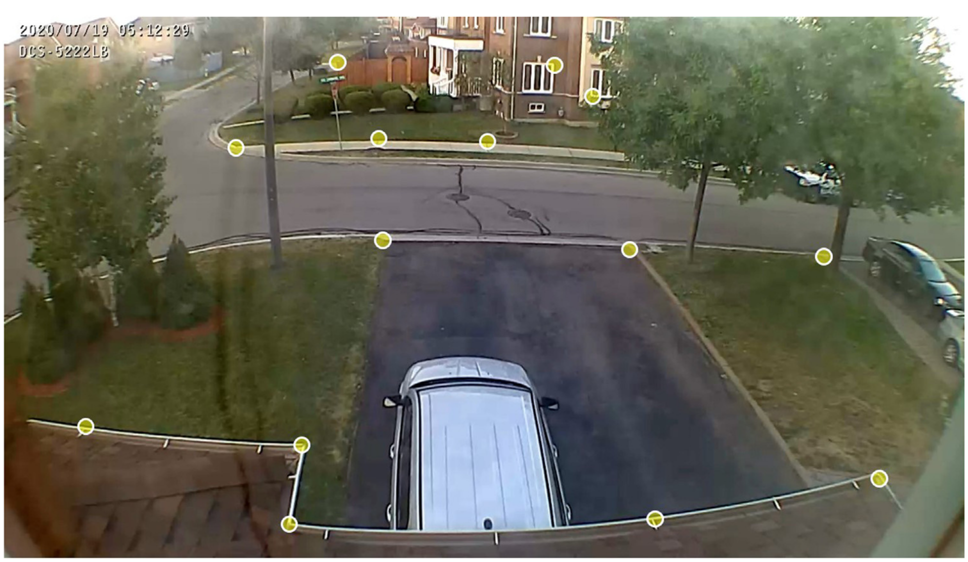


**Fig. 6.** Good example of reference coverage (white circles) - features chosen are stationary, in sufficient quantity and well spread out across the image.

**Fig. 7.** Camera rig with cameras mounted for testing. Only the Honeywell 4MP Mini Dome camera (circled) was used due to time constraints.

Max as a. DXF file format for further importation into PhotoModeler by the analysts. A video of chosen points in 3D was created to guide the analysts in the exact location of the points seen in Fig. 10 for their analysis. The analysis package provided for the participants included an empty video frame, a DXF point file exported from 3 ds Max and two sets of three frames for each of the suspects as seen in Table 1 (i.e. three frames for the first suspect they measured with one method, three frames for the second suspect with the other method). Three groups of participants included 30 professionals in the field of forensic video analysis with 9–12 people per group. These groups were asked to measure the heights of two of the three suspects (i.e. switching for the next method) at the three different positions using two different analytical methods as per Table 1. Before performing the analysis, participants were instructed and guided through two sample projects involving Reverse Projection and PhotoModeler techniques to become more familiar with the software and its functions. The majority of the analysts were not highly familiar with using PhotoModeler or Reverse Projection


**Fig. 8.** Example of ‘suspect’ standing in scene as directed.

**Fig. 9.** Point cloud of the scene collected using Faro Focus S350 laser scanner with ceiling removed.

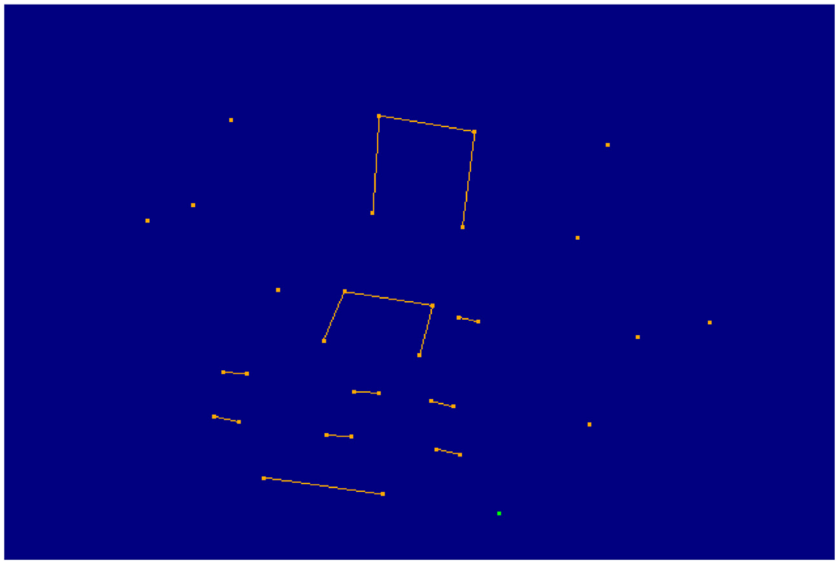

**Fig. 10.** A screenshot of the DXF file provided for the analysts with the marked lines and points that were used to reference the 3D data to the images.

**Table 1**
Description of the assigned suspects to groups.

| Group | Reverse Projection | | PhotoModeler | |
|---|---|---|---|---|
| A n = 9 | Suspect 1 | Position 1 | Suspect 3 | Position 1 |
| | | Position 2 | | Position 2 |
| | | Position 3 | | Position 3 |
| B n = 9 | Suspect 2 | Position 1 | Suspect 1 | Position 1 |
| | | Position 2 | | Position 2 |
| | | Position 3 | | Position 3 |
| C n = 12 | Suspect 3 | Position 1 | Suspect 2 | Position 1 |
| | | Position 2 | | Position 2 |
| | | Position 3 | | Position 3 |

prior to this study; they knew of the techniques but few of them had used either of them regularly in their work. After the training was completed, an analysis package as described earlier was provided to each participant.

## 2.2. Reverse projection

The participating analysts were asked to perform reverse projection on the provided frames for their first suspect. They were provided with a height scale and full access to the original room where the video was recorded with the security camera system still in place. They were required to position their height scales at the position of their suspect's location and to export the frames from the video that was recorded of them holding the height scale, as seen in Fig. 11. A photograph of the DVR screen showing analysts placing their height scales Fig. 11. They were instructed to use Adobe Photoshop, GIMP, or any other image overlay/editing software of their choice to measure the height of their respective suspects for each of the three provided positions.

## 2.3. PhotoModeler

The analysts were asked to use the PhotoModeler software to import the provided frames for their second suspect. They were then instructed to reference the provided points to appropriately chosen pixels on the empty frame of their scene, process the project and remove any high residual error points which might have resulted from faulty marking. Their target residual error was 1.00 or less, with an error of 3.00 being the accepted maximum. After processing, the participants were instructed to create a frame sequence using the suspect frames to allow the analysts to scroll through any images of interest. The participants were then asked to create a flat surface in PhotoModeler near the area of suspect location by marking the appropriate floor points for each frame and marking the position of the suspect's feet where they deemed necessary on all three frames. The marked point was then vertically offset to match the tip of the suspect's head and the resulting height value was recorded for each participant.

## 2.4. Statistics

The Kolmogorov-Smirnov test for normality was used to determine whether the errors for Reverse Projection and PhotoModeler methods were normally distributed, with a criterion of $p < 0.001$ [30]. A one-sided Mann-Whitney U-test and the Kruskal-Wallis H-test were used to compare the errors between the two methods to determine whether the differences were significant, as well as to determine which method displayed greater errors, using a criterion of $p < 0.05$ [31,32]. Statistical tests were performed using Minitab (Minitab, LLC; State College, PA) and Microsoft Excel (Microsoft, Redmond, WA) [33].

# 3. Results

As mentioned previously, the heights of 3 suspects were measured using both Reverse Projection and PhotoModeler methodologies by 30 participants. A total of n = 177 height estimates (i.e. data entries) were taken (and therefore n = 177 calculated errors), across both methods, all three suspects and all three distance positions. The summary of results as well as the general spread of height measurements for both techniques can be seen in Fig. 12. The measurements for Suspect 1 showed greater variation when PhotoModeler was used, while the measurements for Suspect 2 showed greater variation with the use of Reverse Projection. The measurement results for Suspect 3 were similar


**Fig. 11.** A photograph of the DVR screen showing analysts placing their height scales.

between the two methods. Based on the visual assessment of the results, there was not a constant increase/decrease in error at closer/further distances.

The results have been broken down to visually represent how technique affected the measurements between the three suspects and three distance positions, in Fig. 13 for Reverse Projection and Fig. 14 for PhotoModeler.

The average measurements and standard deviations for both techniques as well as the actual heights of the suspects together with the total error are summarized in Table 2. It can be observed that the standard deviations were greater for Reverse Projection than for PhotoModeler for Suspects 2 and 3. PhotoModeler had the greater standard deviation between the two methods for Suspect 1.

The accuracy of both methods was analyzed by looking at the individual errors between the measured results and the actual height values of the suspects. The error frequency results for both methods (i.e. how frequently particular errors occurred/were recorded) are shown in Fig. 15.

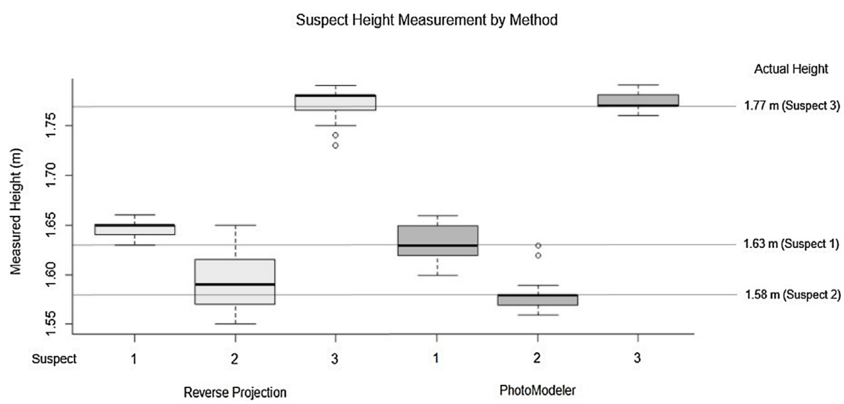


**Fig. 12.** Boxplot showing the height measurements of the three suspects taken using Reverse Projection and PhotoModeler methods.

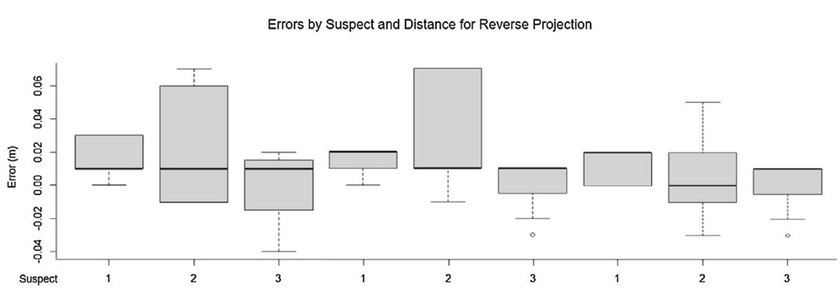


**Fig. 13.** Errors by suspect and distance for the Reverse Projection method.

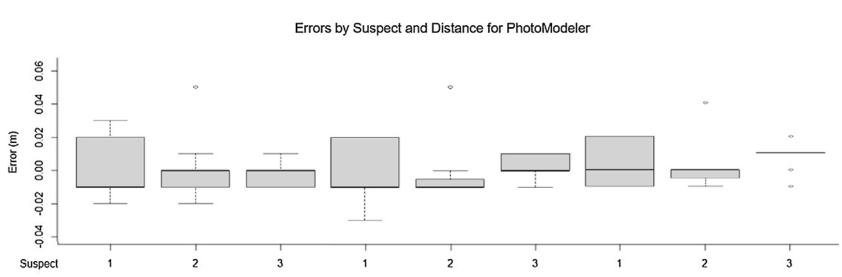


**Fig. 14.** Errors by suspect and distance for the PhotoModeler method.

**Table 2**
Average measurement of suspect height by method.

| | Suspect 1 | | Suspect 2 | | Suspect 3 | |
|---|---|---|---|---|---|---|
| | Reverse Projection | Photo Modeler | Reverse Projection | Photo Modeler | Reverse Projection | Photo Modeler |
| Actual Height (cm) | **163** | | **158** | | **177** | |
| Average Measured Height (cm) | 164.41 | 163.33 | 159.74 | 157.94 | 177.08 | 1 77.30 |
| Standard Deviation for Error (cm) | 0.97 | 1.77 | 3.13 | 1.64 | 1.73 | 0.91 |
| Average Error (cm) | 1.41 | 0.26 | 1.74 | −0.06 | 0.08 | 0.30 |
| Average Absolute Error (cm) | 1.41 | 1.59 | 2.48 | 0.97 | 1.42 | 0.74 |

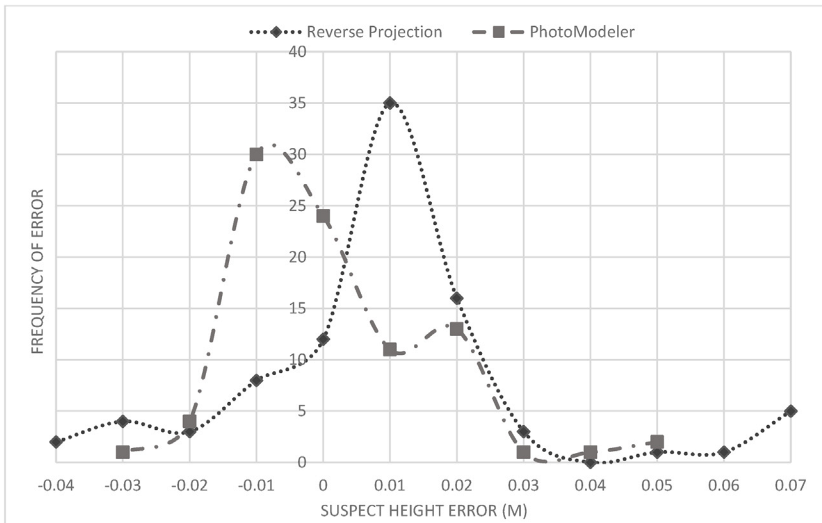


**Fig. 15.** Graph showing the frequency and magnitude of errors relating to Reverse Projection and PhotoModeler methods.

The range of errors for Reverse Projection Methodology was between 7 cm overestimation and 4 cm underestimation (-4 cm to +7 cm). The range of errors for the PhotoModeler methodology was between 5 cm overestimation and 3 cm underestimation (-3 cm to +5 cm). When looking at the general errors for both techniques, it was observed that Reverse Projection tended to overestimate a suspect's height whereas PhotoModeler tended to underestimate a suspect's height. The Kolmogorov-Smirnov test for normality was performed for each of the tested methods and revealed that the data was not normally distributed at $p < 0.001$ for the PhotoModeler and Reverse Projection methods. As such, a nonparametric statistical test was subsequently employed. The Mann-Whitney U-test showed that there was a significant difference between the two methods with Reverse Projection displaying a larger error (α=95%, $p = 0.0025$).

The absolute errors between the two methods were then compared. 75% of the error data for both methods were below the 2 cm error mark. The Mann-Whitney U-Test was employed a second time to assess the absolute errors between the two methods; it showed that there was a significant difference between the methods at $p = 0.0025$ at 95.0% CI with Reverse Projection method having a larger error. The absolute error frequency results for both methods (i.e. how frequently particular absolute errors occurred/were recorded) are shown in Fig. 16.

The maximum error for the Reverse Projection method was at 7 cm with 75% of the data being below the 2 cm mark. The maximum error for the PhotoModeler method was at 5 cm with 75% of data also being below the 2 cm mark. When looking at the absolute errors of the suspect height measurement for both groups, the distributions were very similar as seen in Fig. 16. Statistically speaking, the Kruskal-Wallis H-Test (n = 177, H = 6.93, DF = 1, p = 0.008) showed that the two groups are significantly different from each other with Reverse Projection having a higher overall error.

## 4. Discussion

### 4.1. Technique comparison

The purpose of this research was to compare the Reverse Projection and PhotoModeler techniques for use in suspect height analysis. This was done by comparing the estimated height versus the known height of three suspects that were required to stand in 3 different positions in a room and recorded by a CCTV video camera. The frames were extracted and provided to 30 forensic video analysts which then used the two methods to measure the heights of those suspects. There was a total of 177 data entries, with 90 entries for the Reverse Projection method and 87 for PhotoModeler. One analyst's results were removed prior to statistical testing due to the fact that they measured the same suspect for both methods rather than examining a different suspect for each method as was required. Both the Mann-Whitney and Kruskal-Wallis statistical tests demonstrated that there were significant differences between the error results of the Reverse Projection and PhotoModeler methods, yielding $p$-values of 0.0025 and 0.008, respectively. The distributions of the absolute error data in Fig. 16, by contrast, show little difference between the trends of the two methods, with error frequencies peaking at 1 cm for both and decreasing similarly as errors grew larger (i.e. up to 7 cm measurement error). The standard deviations for both actual and absolute errors (refer to Table 2) tended to be greater for Reverse Projection than for PhotoModeler, suggesting that the PhotoModeler method yielded more precise results in this study.

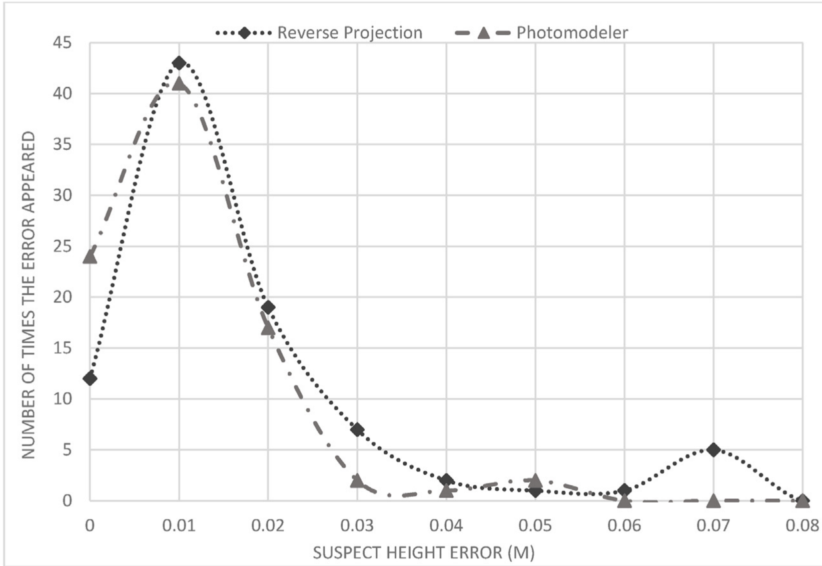


**Fig. 16.** Graph showing the frequency and magnitude of absolute errors relating to Reverse Projection and PhotoModeler methods.

As mentioned in the introduction, there are many issues which pertain to suspect height analysis, and it is imperative to understand how each of those issues contributes to the overall error associated with the measurements using either of the techniques. When looking at the general errors for both techniques, it was observed that Reverse Projection tended to overestimate a suspect's height whereas PhotoModeler tended to underestimate a suspect's height. This might have had to do with the points that were picked at the vertex of the head as well as at the feet. Whenever viewing a subject on camera, it may be difficult to judge the location of the centerline of the body as it is projected to the ground. In the case of Reverse Projection, if the height scale were placed a little closer or farther to the camera in relation to the suspect's actual position, it could have influenced the results and led to an under or overestimation of height. In the case of PhotoModeler, the errors might have been due to a similar issue of inaccurately picking locations on both the head and feet of the individual suspects.

Averaging all of the analysts' height measurements for a given suspect and distance, as shown in Table 3, resulted in a notably smaller range of error for both of the methods. For Reverse Projection, errors for averaged height estimations ranged from -0.1 cm underestimation to 2.6 cm overestimation (-0.1 cm to +2.6 cm). For PhotoModeler, these errors ranged from -0.3 cm underestimation to 0.9 cm overestimation (-0.3 cm to +0.9 cm). The Reverse Projection still had greater errors with a wider range compared to PhotoModeler, but the errors are greatly minimized through averaging measurements than without (i.e. compared with actual maximum errors of 7 cm for Reverse Projection and 5 cm for PhotoModeler).

For the Reverse Projection Method, the most frequently made measurement error was +1 cm (analysts overestimated the height). With PhotoModeler, -1 cm errors (analysts underestimated the height) were most frequently recorded. No errors, or an error result of 0 cm (i.e. 0 cm difference between known and estimated heights) was second-most frequently documented for PhotoModeler, with 24 out of the 87 height measurements taken being correct to the millimeter. As shown in Fig. 14, the use of PhotoModeler was more likely to result in correct height estimations (i.e. no error); with Reverse Projection, just 12 out of the 90 height measurements were correct. Across both methods for all suspects, the analysis of Suspect 3 using PhotoModeler yielded the overall smallest range of error, -1 cm to 2 cm. For Suspect 1, the majority of errors made were overestimations (i.e. positive) across both methods, with all errors for analysts using Reverse Projection on this suspect being positive. Overestimation and underestimation of height varied more across the other two suspects.

### 4.2. Individual errors of each analyst

The largest overestimations of height were associated with Suspect 2, with the highest errors for both methods (i.e. + 7 cm for Reverse Projection, +5 cm for PhotoModeler) being made by the analysts looking at this suspect. Higher standard deviations for both methods, and the highest recorded standard deviations for Reverse Projection, were also associated with Suspect 2. Large errors of +6 to +7 cm for the Reverse Projection method were made by three different analysts who were all in the same assigned team for measuring Suspect 2 and were made for the closest two

**Table 3**
Average results for all analyst data by suspect.

| | **Reverse Projection** | | | | | | | | | **PhotoModeler** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Suspect 1 (9 analysts)** | | | **Suspect 2 (9 analysts)** | | | **Suspect 3 (12 analysts)** | | | **Suspect 1 (9 analysts)** | | | **Suspect 2 (12 analysts)** | | | **Suspect 3 (9 analysts)** | | |
| **Actual Height (cm)** | **163** | | | **158** | | | **177** | | | **163** | | | **158** | | | **177** | | |
| **Distance Position (m)** | **3.2 m** | **4.4 m** | **7.2 m** | **3.2 m** | **4.4 m** | **7.2 m** | **3.2 m** | **4.4 m** | **7.2 m** | **3.2 m** | **4.4 m** | **7.2 m** | **3.2 m** | **4.4 m** | **7.2 m** | **3.2 m** | **4.4 m** | **7.2 m** |
| **Average Height Measurement (cm)** | 164.67 | 164.33 | 164.22 | 160.11 | 160.56 | 158.56 | 176.92 | 177.17 | 177.17 | 163.22 | 163.00 | 163.56 | 158.00 | 157.73 | 158.09 | 176.89 | 177.11 | 177.89 |
| **Average Error (cm)** | 1.67 | 1.33 | 1.22 | 2.11 | 2.56 | 0.56 | −0.08 | 0.17 | 0.17 | 0.22 | 0.00 | 0.56 | 0.00 | −0.27 | 0.09 | −0.11 | 0.11 | 0.89 |

suspect-camera distances. It is quite possible that by working together on the same team, their measurements may have been influenced by one another and thus, been biased. The analyst who made the largest recorded errors for PhotoModeler, +5 cm and +4 cm, was assigned to the same suspect but was in a different team and made such high measurement errors for all suspect-camera distances. These observations could possibly be attributed to individual-specific effects on height analysis, such as a suspect's posture, gait, hairstyle, being relatively close to the camera, etc. [15]. Analyst factors are also believed to have played a significant part in these erroneous measurements, as there was some consistency in the magnitude of errors made across distance positions, indicating that where these analysts were picking points on the suspect affected the accuracy of their measurements.

For Reverse Projection, the highest errors were found at distances of 3.2 m and 4.4 m for Suspect 2, with a frequency of two times for the 3.2 m distance and three time for the 4.4 m distance. The highest errors for PhotoModeler were also found at distances of 3.2 m and 4.4 m for Suspect 2, but at a frequency of only once each. While interesting to note, the otherwise lack of trends concerning distance and the overall low frequency of these large errors do not suggest that the greater the suspect-camera distance, the greater the measurement errors made in this study. Overall, analyst-introduced factors always have the potential to affect the process and resulting measurements of suspect height analysis. As such, it is vital that investigators are well-informed about and experienced with the techniques and tools they are using to reduce errors wherever it is possible they may occur.

### *4.3. Additional considerations*

While steps were taken in this study to eliminate or minimize variables that have the potential to affect height analysis, some individual factors cannot be controlled for; one such factor is the natural standing posture of the 'suspects' [15]. The factor of an individual's gait, however, was controlled for by having the analysts estimate height from images of the 'suspects' standing still [15]. Spinal compression can also affect the accuracy of height measurements as changes in stature throughout the day may result in a difference between a suspect's actual height at point of measurement and their height when captured on camera [11]. For this reason, the study suspects were captured on camera shortly after their known height measurements were recorded. Camera-to-head angle could potentially affect measurement accuracy depending on the distance of a suspect to the camera (i.e. making one appear taller or shorter in images), but this variable would require additional research to quantify its effects. All of these factors should be taking into consideration when taking and reporting suspect height measurements, and can influence height estimation regardless of the technique that is employed. Another variable that was controlled for in this study was distance, by marking the positions for suspects to stand on the floor so that analysts were taking height measurements at the same, rather than randomized distances. Suspects were also captured on camera without wearing any hats or head coverings, and all three suspects utilized had short hair. The study suspects were also only captured and measured standing with their backs to the camera and their full bodies in view, while in a real case a suspect may likely be recorded moving about a scene with their body captured at different angles. This scenario does not realistically represent what an analyst would encounter in the field – suspects may be captured far from the camera or towards the edge of the frame, and/or their full body may not be visible – but such additional factors that can affect the reliability of height measurements which were not the focus of the research, so a more standardized approach was taken during data collection.

Since both the Reverse Projection and PhotoModeler methodologies rely on point picking, it is also important to examine the centimeter-to-pixel ratio when measuring suspects and how it can affect the measurements at different distances. A centimeter-to-pixel ratio refers to the amount of uncertainty or error which will result from being 1 pixel off during the marking process. As the distance between the suspect and the camera increases, the centimeter-to-pixel ratio increases as objects or people further from the camera are made up of fewer pixels in the image, leading to a larger potential error which might arise from inaccurately picking a point on the head or feet. In this study, the suspects were positioned in front of the cameras at the approximate distances of 3.2 m, 4.4 m and 7.2 m. Based on this, the relative centimeter-to-pixel ratios for these distances were 0.22 cm/px, 0.29 cm/px and 0.45 cm/px, respectively.

Overall this study's results between the use of Reverse Projection and PhotoModeler were not largely different, making it evident that either of the two techniques are effective for estimating suspect height accurately. It is ultimately up to analysts to employ whichever technique they find most reliable, or themselves most satisfied with, in the field. In contrast with Reverse Projection, using PhotoModeler requires additional work, including using a laser scanner or total station to collect 3D measurement data of a scene, or using PhotoModeler itself to construct a 3D model of the scene. One must also have knowledge of how the software works, which in turn requires time and training. An analyst's discretion when completing and adjusting their project (e.g. whether they fix or remove high residual points, how they assess image correctness) is a factor to consider regarding the accuracy of a PhotoModeler image sequence. However, the high accuracy of laser scanners and features of PhotoModeler such as its distortion correction tool, lend to PhotoModeler's usefulness. Using PhotoModeler also does not require the replication of a scene camera's original parameters as they can be digitally solved for, unlike with Reverse Projection. This information is something for analysts to consider when choosing amongst methods and programs for suspect height analysis, as well as the fact that situational variables can affect the execution and quality of analysis regardless of the method chosen.

## 5. Conclusion

Both Reverse Projection and PhotoModeler methodologies are valid for performing suspect height analysis on CCTV video footage as they had relatively comparable accuracy in this study. The maximum error for the Reverse Projection method was at 7 cm with 75% of the data being below the 2 cm absolute error mark. The maximum error for the PhotoModeler method was at 5 cm with 75% of data being below the 2 cm absolute error mark. The errors associated with Reverse Projection tended to have greater standard deviations than those associated with PhotoModeler, suggesting higher precision with the latter method. Statistical comparison revealed that the PhotoModeler method had a better accuracy for estimating suspect height in this study. In addition to this, the Reverse Projection method demonstrated a larger range of measurement error than did PhotoModeler; the use of Photo-Modeler also yielded a higher number of correct height estimates from the analysts. Distance did not have any significant effect on measuring suspect height, but nevertheless distance does affect distance/pixel ratio and the potential for erroneous marking is possible. When height measurements taken for a given suspect and distance were averaged and errors were subsequently calculated, the results were reduced errors/error ranges. From this finding, it is recommended that analysts could measure suspect height using multiple frames (if possible/available) and compute the average of the height estimations; this can minimize errors and result in a more accurate conclusion as to a suspect's height. The CCTV footage used for analysis in this study was collected under optimal conditions where many of the variables that may be encountered in actual cases were controlled for. Future research could examine how the two methods examined here fare in terms of accuracy when used to measure height at greater suspect-camera distances.


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## CRediT authorship contribution statement

**Eugene Liscio:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Writing - review & editing. **Helen Guryn:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Writing - original draft. **Quan Le:** Formal analysis, Investigation, Methodology, Writing - review & editing. **Angela Olver:** Visualization, Writing - review & editing.

## Declaration of Competing Interest

The authors report no declarations of interest.


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