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SINGLE IMAGE PHOTOGRAMMETRY

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ANALYSIS:

SINGLE IMAGE PHOTOGRAMMETRY

1 INTRODUCTION TO SINGLE IMAGE PHOTOGRAMMETRY

Combining modern scene analysis with traditional geometry enables valuable information on sizes and distances to be obtained from video images. These techniques replace potentially misleading subjective interpretation with objective analysis. With practice and correct application, these techniques can be a powerful tool to assist police video technicians to extract the maximum amount of information from video evidence.

Applying the principles of perspective geometry to an image to obtain dimensional information is termed **photogrammetry**. These principles have been known about for centuries and were first successfully applied by 15th Century Renaissance artists, such as Leonardo De Vinci, to ensure objects were realistically represented in their paintings. Photogrammetry became regarded as a respected scientific discipline a few centuries later with the analysis of aerial photographs first captured by Wilbur Wright.

Diagram 4.1 Hogarth's 'Satire on False Perspective' demonstrates the incorrect application of perspective geometry

Aerial surveillance, film special effects and accident reconstruction rely heavily on photogrammetry. The rather recent emergence of robust and affordable 3D modelling software has meant that crime scene analysis now regularly employs photogrammetry. Although the principles of geometry remain the same whether applied to a painting, a photograph or computer generated images in a film, extra issues need to be considered when applying these ideas to video evidence such as CCTV. This chapter concentrates on using images from CCTV systems since these are the most likely sources of imagery in police investigations, although it is a simple process to apply them to other situations. Also it should be noted that this chapter only deals with photogrammetry techniques using images from a single view, as this is by far the most common occurrence in forensic applications. Different techniques may be used if simultaneous multiple views of a scene are available.

This chapter aims to provide police video technicians with sufficient information to allow them to apply photogrammetric techniques accurately to video evidence. It is structured as follows:

- CCTV and Other Video Evidence – the issues regarding typical video evidence that cause difficulty when applying photogrammetry techniques
- Basic Concepts of Photogrammetry – the essential ideas that are used in photogrammetric techniques
- Initial Steps – details of the necessary preparation work required to obtain accurate measurements using photogrammetry
- Photogrammetric Techniques – the main part of the chapter describes the most useful photogrammetry methods and how to apply them
- Estimation of Errors – how to obtain a numerical estimate of the uncertainty involved with a photogrammetric measurement
- Bibliography – list of relevant books and articles
- Computer Software – list of software packages that are useful for performing photogrammetry

2 CCTV AND OTHER VIDEO EVIDENCE

The techniques of photogrammetry remain the same whether applied to an architect's drawing, a digital still image, a painting or a frame from a video clip. However, the images that are typically used as video evidence, particularly from CCTV systems, tend to have certain traits that present unique problems when applying photogrammetry. (See EQUIPMENT 2 EVIDENTIAL VIDEO). Primarily, these traits make it hard to accurately define those points within the image necessary to abstract dimensional information. (See Diagram 4.2).

2.1 Poor Quality Images

If the imagery is not of sufficient quality, the accuracy of photogrammetric techniques may be severely affected. Usually, image quality is by far the most detrimental factor in the process and manifests itself as low resolution, low contrast, poor colour rendition and/or artefacts that arise due to excessive file compression. These may make it difficult to accurately determine points and edges within the image.

2.2 Camera Effects

Low quality optics are a feature of many CCTV systems and can cause distortion, object blur and poor colour rendition in the imagery. Software is available that can repair, to some degree, the effects of lens distortion particularly curvilinear barrel distortion. (See 4.1.2 CORRECTING IMAGE DISTORTION).

2.3 Aspect Ratio Distortion

The aspect ratio, the ratio of height to width of an image, can be easily distorted so that objects look squashed or stretched. This can occur either at capture or at replay, especially with proprietary digital CCTV replay software. (See EQUIPMENT 17.2.4 PROPRIETARY DIGITAL DEMULTIPLEXER and DIGITAL CCTV RETRIEVAL 6.1 REPLAY SOFTWARE).

2.4 Elevated Camera Viewpoint

Positioned to monitor a wide field of view and be beyond the reach of vandals, CCTV cameras tend to look down upon a scene. Therefore any person or object within the image is likely to be at an angle to the camera plane. If the angle is too extreme then it will be difficult or impossible to accurately determine the top and bottom of the target object.

Diagram 4.2 Typical CCTV image showing the effects of an elevated viewpoint, low resolution, poor colour rendition and aspect ratio distortion

2.5 Timelapse Recording

As CCTV systems usually do not record at full frame rate, there may only be a few images available for analysis in which the target object appears, especially if the object is moving fast or erratically. (See EQUIPMENT 2.1.1 TIMELAPSE). This issue can be further exacerbated if frames are dropped on replay, which can easily occur with poor digital CCTV replay software. (See EQUIPMENT 17.2.4 PROPRIETARY DIGITAL DEMULTIPLEXER and DIGITAL CCTV RETRIEVAL 6.1 REPLAY SOFTWARE).

2.6 Pan-Tilt-Zoom Cameras

Though rarely detrimental to most types of photogrammetry these cameras can cause problems when it is necessary to know their position and zoom setting at the time the video sequence was recorded. Such circumstances arise when correcting for aspect ratio distortion or when recreating the scene using a stand-in recorded through the original CCTV system. (See 4.2.2 RESTORING THE CCTV SYSTEM and 5.1 REVERSE PROJECTION).

3 BASIC CONCEPTS OF PHOTOGRAMMETRY

Although the techniques of photogrammetry may seem rather complicated, they are based on a number of simple ideas. This section covers the basic ideas that will be used in the more in depth discussions of practical applications of photogrammetry. (See 5 PHOTOGRAMMETRIC TECHNIQUES).

3.1 Perspective

Many definitions can be applied to this term, but in the context of photogrammetry it means 'the relative size of objects within an image as captured by the camera system'. In simple terms this means the further away from the camera an object is, the smaller it will appear in the image. It is this relativity of size that allows measurements to be taken from within the image and translated into real world data. The effect of perspective is to provide a sense of distance and solidity to what is seen in a two-dimensional image. (See Diagram 4.3).

Diagram 4.3 In the two-dimensional world of an image the gap between the rails gets narrower as they head into the distance although this is obviously not the case in the real world

3.2 Vanishing Points and Lines

Parallel edges or lines found in the three-dimensional real world will, when captured on a two-dimensional image, meet at a definable point termed a **vanishing point.** For example the rails of a railway track appear to converge or meet as they head into the distance. (See Diagram 4.3). Additionally the edge of a platform parallel with the track would, if extended, also meet at the same vanishing point. The lines used to determine the location of vanishing points are called **perspective lines**.

Determining the position of vanishing points most accurately can be best achieved with a thorough scene survey and a suitable software package. (See 4.3.3 ACCURATELY DETERMINING VANISHING POINTS). Whilst it is possible to calculate these points manually, this can be a lengthy process. It should be noted that locating vanishing points may require lines in the image to be extended, and that they often lie beyond the borders of an image. (See Diagram 4.4).

Diagram 4.4 Typical scene where the edges of parallel objects are used to locate vanishing points.

The vanishing points associated with a given plane all lie on the same line, termed a **vanishing line**. (See Diagram 4.5). This is in effect the horizon for the plane in question. Some photogrammetric techniques require the vanishing line associated with the ground plane to be identified, usually through the location of two vanishing points. (See 5.3 SINGLE VIEW METROLOGY (SVM)).

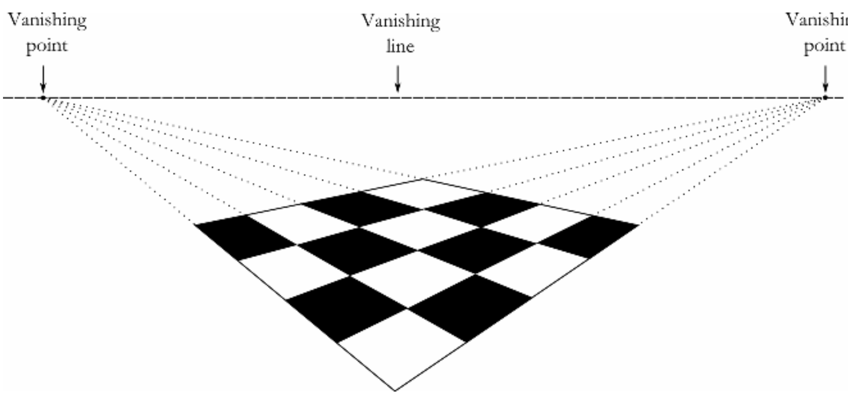


Diagram 4.5 Vanishing points and lines

Selecting the most suitable perspective lines to locate vanishing points and lines is essential to maintaining the accuracy of results. This is achieved by visiting the actual scene and checking which edges are parallel and lie in the desired direction, e.g. are certain lines truly vertical. (See 4.3.3 ACCURATELY DETERMINING THE VANISHING POINTS).

3.3 Pinhole Camera Model

The pinhole camera, the basic model for all cameras, is a closed box with a hole or aperture on one side that allows light to enter and then land on the image plane. (See VIDEO IMAGING 5 CAPTURE OF VIDEO IMAGES). At this image plane, a physical process measures the intensity of the light, e.g. photographic film, CCD array. (See VIDEO IMAGING 5.3 CHARGE COUPLED DEVICE (CCD)).

A simplified mathematical version of the pinhole camera assumes that the aperture is infinitely small, i.e. a single point, and is referred to as the pinhole camera model. (See Diagram 4.6). Consequently a ray of light emanating from a particular point *A* in the scene will fall onto the image plane at a single point *a*.

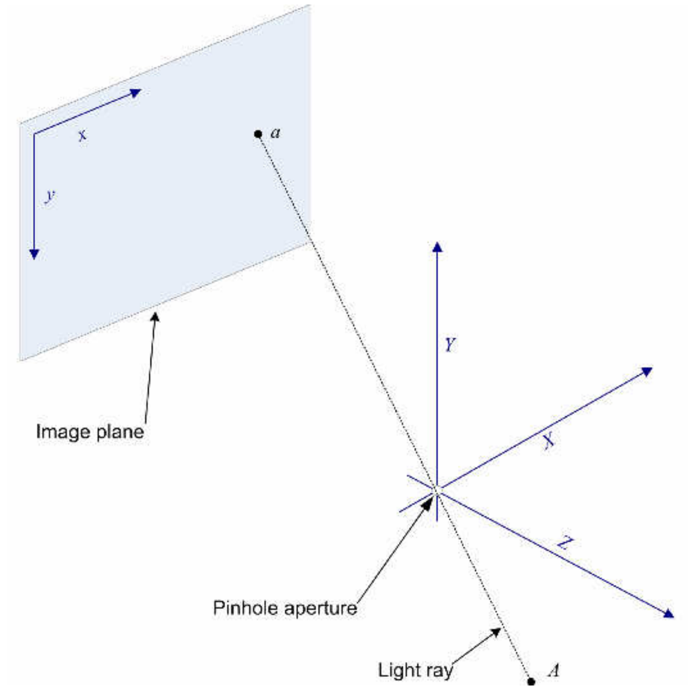


Diagram 4.6 Pinhole camera model

This model allows imaging to be viewed as a mapping of the three-dimensional world to a two-dimensional image and is easily expressed mathematically in terms of a camera matrix. Note that any point on the light ray from *A* will be imaged at the same point *a*, demonstrating that the process of imaging does lose some dimensional information.

3.4 Control Points

Essential elements in applying some photogrammetry techniques, these points allow the estimation of the imaging map from the three-dimensional world to the two-dimensional image. (See 3.3 PINHOLE CAMERA MODEL). Once this is done, it is possible to reverse the process and calculate the three-dimensional position of a point given its location within the image up to the uncertainty of how far along a light ray it lies. This uncertainty can often be removed by making reasonable assumptions, e.g. the person is standing on the floor.

A control point has a known position in the real world and in the image. Its real world position is written as a three-dimensional coordinate from a defined origin. (See Diagram 4.7). In other words the coordinate of a control point is defined by how far above, to the right and in front of the origin it is. If a point is below, to the left or behind the origin, the related coordinate entry will have a negative value. Similarly, the position in the image is given as a two-dimensional co-ordinate from a defined origin.

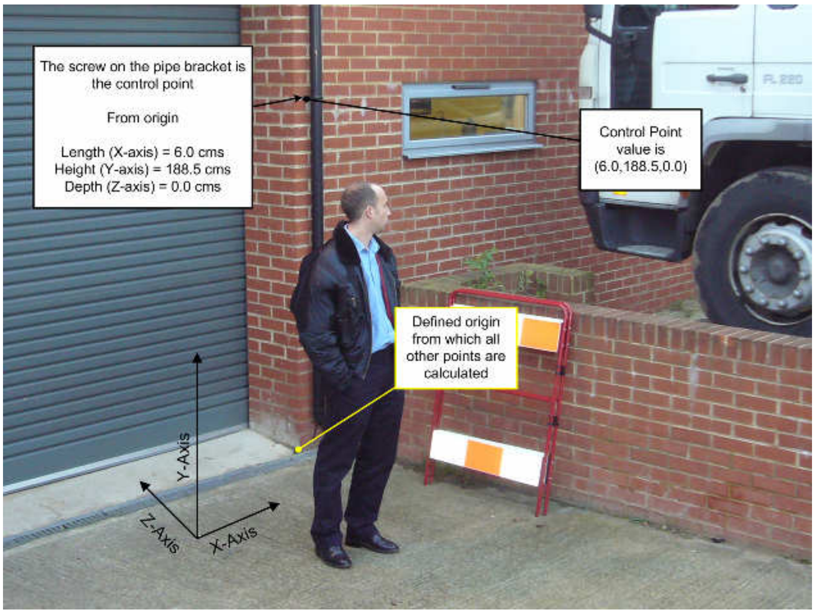


Diagram 4.7 Description of how a control point is determined through measurements taken at the scene.

3.5 Projecting Points to Other Objects

This entails the virtual projection of an object of unknown size to one of a known size using vanishing points and other geometric ideas. (See 3.2 VANISHING POINTS AND LINES). For example, a person's height can be determined by locating the point on a nearby wall that is at the same height above the ground as the person. (See Diagram 4.8).

Diagram 4.8 The height of the suspect can be projected onto the wall

This technique often relies on the knowledge or assumption that the target object and the known object on which it is to be 'projected' both sit on the same plane.

4 INITIAL STEPS

Although the theory and science behind photogrammetric techniques are sound, their implementation can give scope for inaccuracies as human judgements are often called upon. Especially with poor quality images, these decisions can be subjective and therefore prone to errors. However as experience is gained through the application of these techniques margins of error are reduced and accuracy optimised. This section describes various methods for improving accuracy when applying photogrammetry. The three areas this includes are issues regarding the images, how to conduct a site visit and how to place perspective lines and control points accurately.

4.1 General Image Considerations

4.1.1 SELECTING THE BEST IMAGE(S)

Although restricted by the low frame rates associated with CCTV systems, it is possible that the target may appear in more than one frame giving a choice of images to use for analysis. (See 2.5 TIMELAPSE RECORDING). Generally the best images for photogrammetry should have the all of the target visible and filling as much of the image frame as possible, while still showing the location of reference items. (See 4.3.1 ACCURATELY DEFINING THE TARGET OBJECT). If the target is human, the image with the target standing as still and upright as possible should be used. If the target moves throughout the sequence, the image in which the target is in mid stride will often prove to be the best to use.

4.1.2 CORRECTING IMAGE DISTORTION

Curvilinear distortion, which images straight lines in the real world as being curved, is usually very apparent when viewing an image and arises from the optics used to capture the scene. (See 2.2 CAMERA EFFECTS). It is most commonly encountered in the form of **barrel distortion**. (See Diagram 4.9). This distortion has a greater impact on objects close to the periphery of the image.

Diagram 4.9 Image showing the effects of barrel distortion

Lens corrector software is available either as a stand-alone application or as a plug-in or integral part of image editing software. Such software allows the distortion to be corrected either manually or automatically. (See Diagram 4.10). However, the user should be aware that performing this correction may have the side effect of reducing other image quality factors such as resolution.

Diagram 4.10 Image corrected for barrel distortion

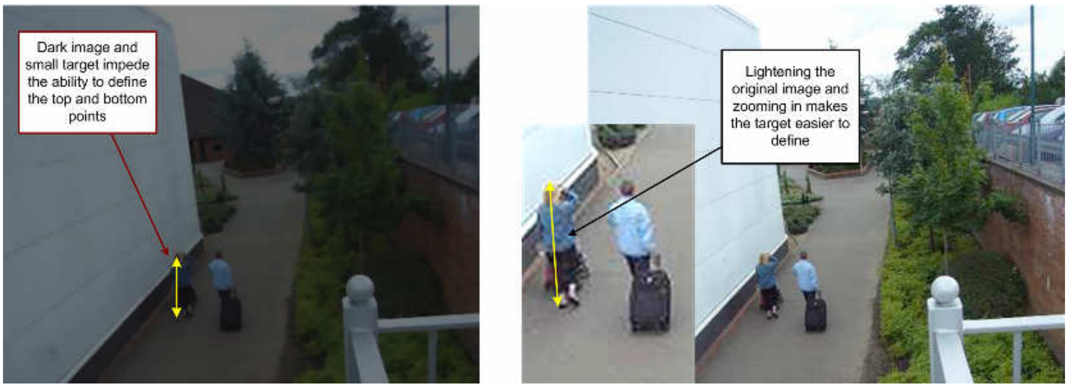
Aspect ratio distortion is a common problem and can be corrected using standard image editing software. (See 2.3 ASPECT RATIO DISTORTION and Diagram 4.11). In some circumstances it may be possible to apply corrections by just looking at the image and the objects within it. However, it is recommended that a more suitable method is to visit the scene with a calibrated test target. (See 4.2.3 MEASURING ASPECT RATIO DISTORTION).

Diagram 4.11 Scene showing the effects of aspect ratio distortion

Should the image suffer from both barrel and aspect ratio distortion then it is best to correct for the former first.

4.1.3 ENHANCING THE IMAGE

A number of image-based factors including low resolution, poor contrast and over exposure can hamper the accurate determination of the target points. (See 2.1 POOR QUALITY IMAGES). These can be counteracted, to some degree, using image-enhancing software. (See Diagram 4.12). Simply zooming in and adjusting the brightness and contrast of the target area can allow points to be identified more accurately. It is worth noting that applying too many filters tends to have a detrimental effect on the overall image quality so they should be used with a degree of caution.



(i) ***(ii)***

Diagram 4.12 Original image and improvement through enhancement

4.2 Visiting the Scene

Conducting a scene survey is an essential part of the photogrammetry process. It is required to obtain further necessary information and to help with error minimisation and estimation. To assist in this process, it is advised to take a tool kit containing the following:

- Measuring stick – such as used by surveyors
- Large circular object (e.g. Lastolite reflector)
- Laptop with original video and/or still images
- Tape measure
- Spirit level
- Digital camera
- Tripod
- Torch
- A pad and pen

4.2.1 OBTAINING REFERENCE MEASUREMENTS

A number of measurements will need to be taken for use in the photogrammetric calculation. Which actual measurements will be required will depend upon the scene and the photogrammetric techniques used. (See 5 PHOTOGRAMMETRIC TECHNIQUES). It is recommended that as many appropriate measurements as possible are taken to minimise the need to return later. This will also be the opportunity to decide which techniques will be appropriate to use and to verify whether what appears to be true in an image is really the case, e.g. whether various lines are truly parallel.

4.2.2 RESTORING THE CCTV SYSTEM

It is often the case that some more video will need to be captured through the CCTV system in question, e.g. when using stand-ins to estimate errors, measuring aspect ratio distortion and doing reverse projection. It is important that when doing so the CCTV system is as close as possible to its state when the original sequence was recorded. If the relevant camera's position or settings have not altered since the original material was recorded this is a relatively painless process.

In some cases the settings of the camera including its position will have been altered and in the case of PTZ cameras one should assume that they have. (See 2.6 PAN-TILT-ZOOM CAMERAS). To restore the camera to its original position it is necessary to compare the image from its live feed to the image selected from the original recorded sequence using a vision mixer or appropriate software. First the original pan and tilt settings should be restored, which is best achieved by using the object most central in the original image as a marker. Once this has been done the zoom setting can be determined. Note that some additional tweaking of the pan and tilt may be required especially if zooming into the scene is necessary.

4.2.3 MEASURING ASPECT RATIO DISTORTION

CCTV systems can often introduce aspect ratio distortion. (See 4.1.2 CORRECTING IMAGE DISTORTION). This can be corrected by first determining the degree of distortion by capturing an image of a large symmetrical object onto the CCTV system and then seeing how much it has been distorted. An example of a suitable target is a circular Lastolite reflector with a square drawn on it.

This object should be placed parallel to the camera's image plane and filling as much of the field of view as possible. Using the same system settings as for the original sequence, a short sequence should be recorded. Though not essential, performing this act in similar light conditions could be beneficial in order to use a similar iris setting. When this sequence is viewed, the distortion can be corrected using image-editing software so that the object appears symmetrical again. The same settings used to correct the distortion in this image can then be applied to the original sequence.

4.2.4 USING A STAND-IN

Whenever possible it is beneficial to recreate the scene using stand-in targets of varying heights. This is especially helpful for indicating how much the target's gait or posture has affected photogrammetric measurements. As well as using stand-ins of different heights it is worth replicating the target's clothing as best as possible to ensure accurate compensation is applied for any issues that would arise from this. The use of stand-ins allows the degree of confidence in a measurement to be quantified. (See 6 ESTIMATION OF ERRORS). Naturally, test video of the recreated scene is best taken through the actual CCTV or video system using the same settings as was used with the original recording. (See 4.2.2 RESTORING THE CCTV SYSTEM).

4.3 Placing Points and Lines

It is recommended that as many appropriate photogrammetric techniques are used as possible. (See 5 PHOTOGRAMMETRIC TECHNIQUES). The following are general areas of advice regarding applying these methods.

4.3.1 ACCURATELY DEFINING THE TARGET OBJECT

Often the aim is to locate the top and bottom points of the target object's axis. With fixed rigid objects, this is usually not a problem. However, if the target is a person then a number of factors need to be considered when selecting points to define the top and bottom:

- Clothing – hats, high-heeled shoes and other items of dress can obscure vital areas of the target thus making it difficult to determine the target points. To combat this, select the image that has been least affected and provides the best view of the relevant points on the target.

- Stance and gait – people rarely stand still and bolt upright but instead tend to lean against an object such as a wall or relax their body into a slouch. It is necessary therefore to consider this posture when conducting photogrammetry. Targets in motion can also present difficulties since a person who is walking, jogging or running have a constantly changing gait making the determination of target points more difficult. (See 4.1.1 SELECTING THE BEST IMAGE(S)).
- Camera angle – the high camera angle typically found with CCTV systems makes it difficult to accurately decide where the top and bottom of a person lies. (See 2.4 ELEVATED CAMERA VIEWPOINT). The placing of points in such cases thus becomes rather subjective and prone to inaccuracy. However, accuracy can be improved with practice and a bit of experimentation.

4.3.2 ACCURATELY DEFINING THE REFERENCE OBJECT

Many photogrammetric techniques require a reference height or position to be taken. Most scenes contain several potential reference objects, but some will be more suitable than others. (See Diagram 4.13). The following should be considered in order to maintain the best accuracy:

- Reference points that define the top and bottom of the object should be clear and unambiguous.
- Reference objects must be in the same plane as the target object for Single View Metrology. (See 5.3 SINGLE VIEW METROLOGY (SVM)).
- Vertical reference objects are most common, but do check at the scene that they are indeed vertical.
- Objects near the centre of the image will have been less affected by distortion.
- Select a reference object of similar size to the target object.
- Avoid using an object that is made up by a small number of pixels.
- Use a static object and not one that could have been moved.
- Select an inanimate object as this will not change shape.

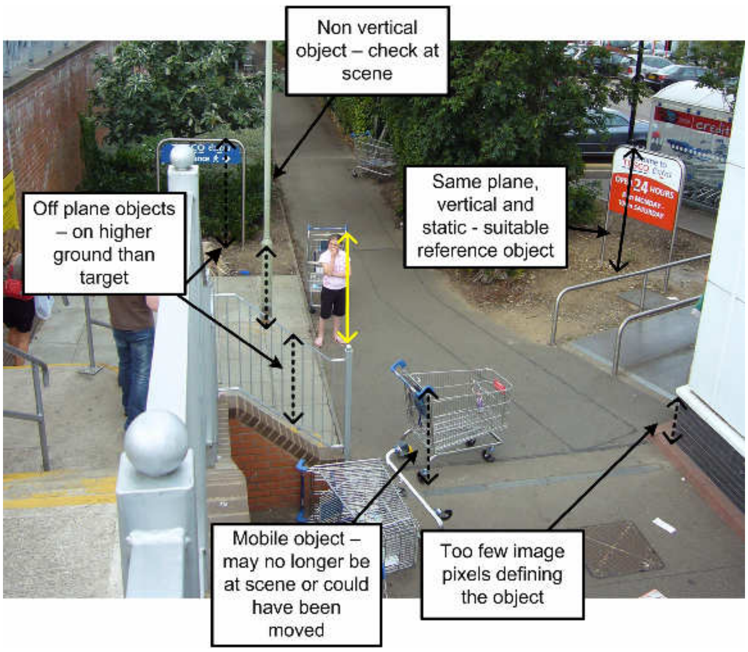


Diagram 4.13 Annotated scene showing how to select the best reference object

4.3.3 ACCURATELY DETERMINING VANISHING POINTS

The locating of vanishing points is an essential step in some photogrammetric techniques. (See 3.2 VANISHING POINTS AND LINES). For example, Single View Metrology requires the location of three vanishing points; one vertical and two in the horizontal ground plane. (See 5.3 SINGLE VIEW METROLOGY (SVM)). The appropriate selection of parallel edges used as perspective lines is essential if the vanishing points are to be determined accurately. (See Diagram 4.14).

The vertical vanishing point is found using the edges of objects that are vertical, i.e. perpendicular to the ground plane. Similarly, horizontal vanishing points are located using edges of objects that are parallel with the ground plane. It is often the case that one set of these horizontal perspective lines will tend to the left of an image and the other to the right, e.g. the green and blue lines in Diagram 4.14.

Consider the following when selecting edges to locate a vanishing point:

- Select perspective lines that are as wide apart and as long as possible.
- Ensure perspective lines are as straight and distinct as possible in the image.
- Beware of any kinks or ambiguities along an edge.
- It is not essential for the parallel edges to be from the same object, just parallel.
- Use as many suitable perspective lines as possible to locate a vanishing point.
- Avoid edges close to the image's periphery as they may be more affected by distortion.
- The vanishing line for the ground plane, usually constructed by joining two horizontal vanishing points, should be parallel with the ground.
- Vertical vanishing points will tend to be much further beyond the image than the horizontal ones.
- Avoid edge-enhancing filters as these generally work in a non-linear manner.

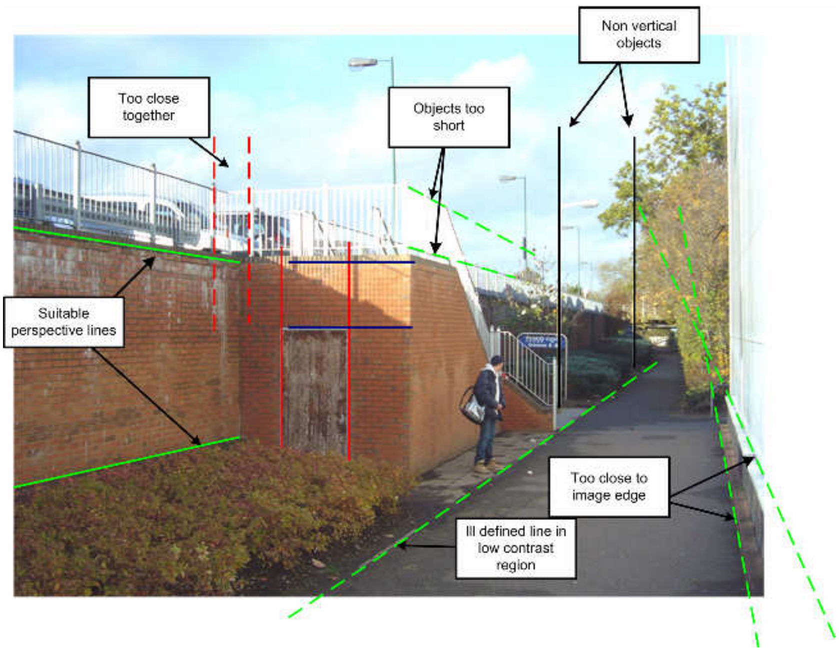


Diagram 4.14 Annotated scene showing issues to consider when selecting perspective lines

5 PHOTOGRAMMETRIC TECHNIQUES

This section details the photogrammetric techniques most likely to be of use to police video technicians. The techniques are described in as much detail as required to allow a technician to replicate them using appropriate software. Any technical details are contained within blue boxes at the end of the relevant section and can be safely omitted by those not wishing to deal with the underlying mathematics. The bibliography of this chapter is a good starting point for those wishing to learn more technical information about the techniques described here. (See 7 BIBLIOGRAPHY).

5.1 Reverse Projection

Although not strictly a photogrammetric technique, this is a very simple but effective method. It involves a subjective recreation of the scene but using an adjustable marker to act in the place of the target object, and recording this on the CCTV system in question. By superimposing the images from this recreation onto the original image scene, the size of the target object can be estimated.

This method is suitable in almost all situations as long as the original imaging equipment is in place and can be restored to its settings used for the original recording. (See 4.2.2 RESTORING THE CCTV SYSTEM). Problems may arise if the scene has changed dramatically as it will prove difficult to align original image with the recreation. The same issues may occur if a non-static camera has been used. (See 2.6 PAN-TILT-ZOOM CAMERAS).

5.1.1 BASIC IMAGE REQUIREMENTS

A suitable scene would contain a number of static objects that will allow accurate alignment of the original and recreated images. If the height of a person is being estimated, both the head and the feet need to be visible. In addition the image should be of a high enough quality to easily resolve edge detail.

5.1.2 REVERSE PROJECTION EXAMPLE

The image displayed in Diagram 4.15 has few geometric features within the scene and so is it would be difficult to apply other photogrammetric techniques. However it is possible to approximately determine where the target is standing using objects in the scene.

Diagram 4.15 A typical image suitable for use with the reverse projection technique

In this example, the camera was in the same position when the recreation was staged as it was for the original image of Diagram 4.15. If this were not the case, the camera's position and/or zoom would need to be adjusted so that it matched that when the original image was taken. (See 4.2.2 RESTORING THE CCTV SYSTEM).

With the camera in the same position as for the original imagery, the recreation is performed using a surveyor's measuring stick in place of the target. The base of the measuring stick needs to be placed at the estimated position of feet of the target and ensured to be vertical by use of a spirit level. (See Diagram 4.16). Attaching the stick to a tripod will help to keep it in the correct position when recreating the image.

Diagram 4.16 A recreation of Diagram 4.15 using a measuring stick in place of the target

Next it is necessary to superimpose the two images. This can be again be done using a vision mixer or computer software. For example, standard image editing software can import the two images as different layers, which are then linked and aligned before setting their opacity to 50%. (See Diagram 4.17).

Diagram 4.17 Superimposition of Diagrams 4.16 and 4.17

To improve the accuracy when estimating the target's height it is necessary to zoom into the image. (See Diagram 4.18). Note that if the resolution is low then the markers on the staff may need to be altered to be more visible.

Diagram 4.18 The enlarged image allows a more accurate reading of the marker

In this example the target was measured as being 1.72m compared to the actual height of 1.77m. Having a number of people to position the stick will help reduce any human errors.

5.2 Camera Matrix Photogrammetry

Most commonly encountered in 3D modelling software and forensic photogrammetry software, this technique requires the measurement of at least six control points within the scene. Each point is measured at the scene in terms of its height, length and depth from a defined origin to create a three-dimensional world coordinate. (See 3.4 CONTROL POINTS). With the corresponding two-dimensional image co-ordinate, this allows the mapping between the real world and the image to be calculated. This in turn allows the determination of the real world location of other points in the image, up to an uncertainty concerning how far along the relevant light ray they lay.

This method can be applied where it is possible to locate sufficient control points around the object of interest. To extract measurements using this method, some basic information has to be used or assumptions need to be made; usually that the target is standing on the ground and is exactly upright.

5.2.1 BASIC IMAGE REQUIREMENTS

Control points should be located where they are easily measurable both within the image and at the scene. (See Diagram 4.19). These points should be clustered (three dimensionally) around the target object and number at least six. Relying on points relatively far from the target object will lead to a drop in accuracy. It is recommended that more than six control points be used to improve accuracy.

At a site visit, the following should be determined:

- Origin is best placed
- Control points are on fixed objects

Measurements of the position of at least six points are required.

Diagram 4.19 Annotated image showing how to select control points

5.2.2 CAMERA MATRIX EXAMPLE

In Diagram 4.20, the real world coordinates of eight control points around the target person have been measured at the scene from a chosen origin. (See 3.4 CONTROL POINTS). Generally the more control points used, the more chance the final result will be accurate. By employing either 3D modelling or specialist forensic software it is possible to use this information to extract the height of the subject. While each software package applies slightly different functionality and terminology to perform photogrammetry, they work in the same general manner. The image is imported into the software and the user selects the points in the image to use as control points. The real world coordinates of these points are then entered manually.

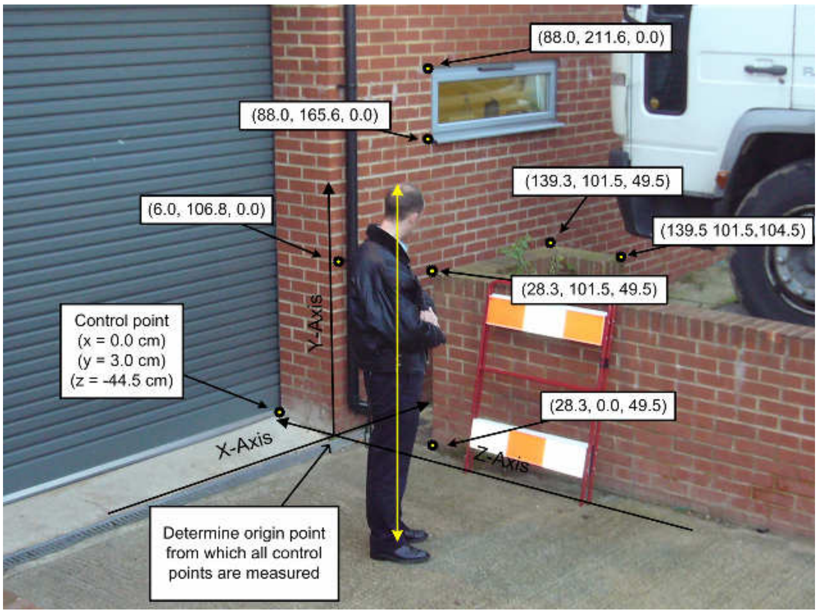


Diagram 4.20 Annotated image showing the selected control points and their real-world coordinates as measured from the chosen origin

These control points should supply sufficient information to allow the software to calculate how points in the real world are mapped into an image by the camera by estimating the **camera matrix**. (See 3.3 PINHOLE CAMERA MODEL and 5.2.3 CAMERA

MATRIX THEORY). Some software will reject control point information if it considers it too inaccurate whereas others tend to have a greater degree of tolerance. The software usually re-projects where it calculates the control points should appear in the picture. These re-projected points give a good determination of the potential accuracy of the result, as they should match the selected control points in the image. If for example, one re-projected point seems very inaccurate, this generally suggests an error when its co-ordinate has been measured or entered, so values should be checked or other control points used.

When the re-projections are sufficiently accurate, the height of the target person can be calculated in the following manner. A point in the image at the target's feet is selected. By assuming the person is standing on the ground, the software can calculate what the three-dimensional coordinates to which this point corresponds. The user has to impose this assumption on the software, usually by entering the real word height coordinate of this point to match that of the ground, i.e. to 0 in this example. This will enable the software to calculate the other two coordinates of the three-dimensional real world coordinate. A point in the image at the person's head is then selected. Assuming the person is standing upright, in the real world this point should be directly above the point at the feet. Thus, by taking one of the calculated coordinates of the foot point and using this as the equivalent coordinate of the head point, the software has enough information to extract the height of the point.

5.2.3 CAMERA MATRIX THEORY

The pinhole camera mode is an accurate model of how real cameras work (See 3.3 PINHOLE CAMERA MODEL). It allows the process of capturing an image to be viewed in mathematical terms as a mapping from the three-dimensional world to the two-dimensional world of an image. This mapping is called a camera matrix or a homography. In theory, the camera matrix contains all the information that can be known about a pinhole camera. By determining this matrix it is possible to make measurements in the image and relate to the real world.

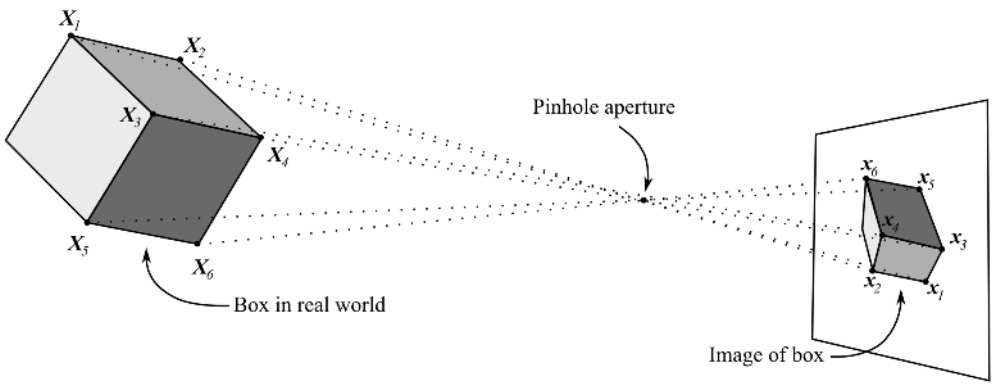


Diagram 4.21 How real world points are mapped to an image

Diagram 4.21 shows how an object such as a box in the real world transforms or maps into the image world. In mathematical terms this would be expressed as:

$$\mathbf{x}_i = H\mathbf{X}_i$$

where $i = 1...6$ and H represents a 3×4 matrix. As one component of H corresponds to an overall scale factor, there are 11 components to be determined. In order to estimate the mapping matrix it is therefore necessary to have at least six control points and know their positions in the real world and in the image. (See 3.4 CONTROL POINTS). Increasing the number of control points above six will lead to a more accurate estimate of the matrix. There are a number of different mathematical algorithms that can be used to produce this estimation. Which one will be used will be dependent on the software used.

Often once a camera matrix has been calculated, the software will re-project the control points. This means the software uses the calculated camera matrix and uses this to project the real world points into the image. Ideally, these will coincide with the originally selected control points in the image. However, the errors inherent in the process mean that this generally does not happen. The difference between the original points and the re-projections are often quoted as a guide to the accuracy of the estimated camera matrix.

It is the inverse of the camera matrix that is used to calculate the positions of the points in the real world from those that lie within the image. However, this matrix will only indicate upon which light ray a point lies and not its precise position along that ray. This information generally takes the form of supplying a known coordinate from the object in question, for example by assuming the bottom of the object is on the ground and the top of the object is directly above.

5.3 Single View Metrology (SVM)

This technique is particularly useful for measuring the heights of people or objects in a man-made environment. The image scene must contain enough parallel edges to allow two horizontal vanishing points and one vertical vanishing point to be located. (See 3.2 VANISHING POINTS AND LINES). These edges can be from walls, lampposts, road markings as well as from office or street furniture. Furthermore it is necessary for the top and bottom of the target to be in plain view.

Although primarily used to measure human dimensions such as height, SVM can be used to determine the distance between two objects, a witness's field of view and whether an image has been altered. However it is the first application that is demonstrated here.

5.3.1 BASIC IMAGE REQUIREMENTS

For the SVM method to be applied, the following features must be present within the image:

- Target object in full view and located on the ground plane;
- A reference target of known height in full view and located on the ground plane;
- Vertical edges representing parallel edges in the real world;
- Two sets of horizontal edges, in opposing planes, representing parallel edges in the real world

An example of an image that would not be suitable is shown in Diagram 4.22.

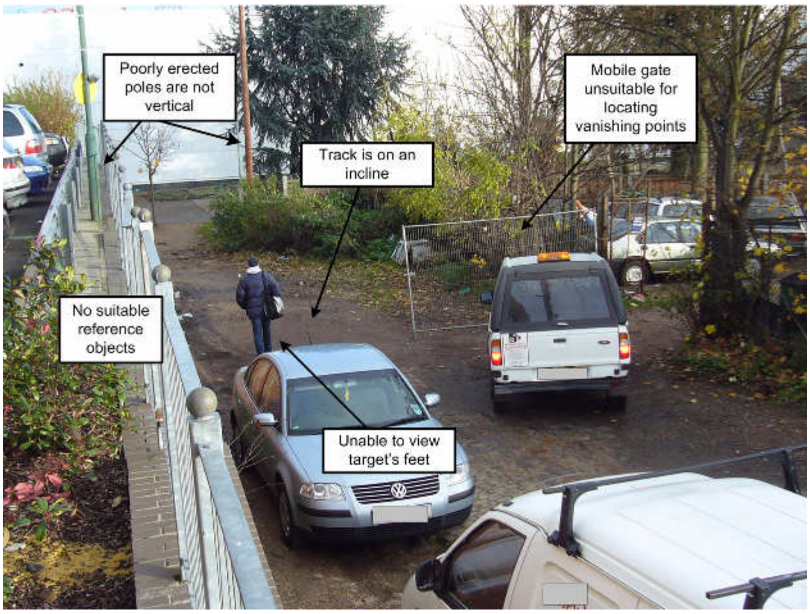


Diagram 4.22 An image for which SVM is not suitable

At a site visit the following should be determined:

- Lines in the scene are straight, parallel and fixed
- Ground plane is truly flat
- Reference object is vertical, positioned on the ground plane and fixed

The height of a number of potential reference objects should be measured.

5.3.2 SVM EXAMPLE 1

The scenario shown in Diagram 4.23 is typical of one encountered during a criminal investigation. However for the purposes of demonstration, the quality of image is better than would normally be expected.

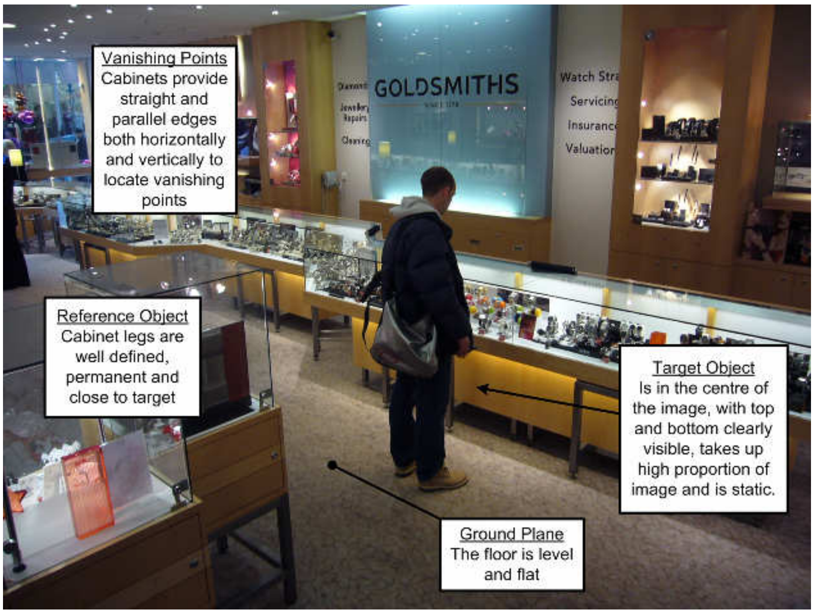


Diagram 4.23 An example of a scene suitable for use with the SVM technique

<u>Image selection</u>

Video retrieved from the jewellery shop showed the target entering from the left and browsing the expensive watches before exiting. From the many images available this one was chosen for photogrammetric analysis using SVM because:

- Target object is largest and is as central as possible
- Top and bottom of target is highly visible and easy to define
- Well defined edges for the locating vanishing points surround the target
- Suitable reference objects are visible
- Target is not in motion

However no image will be completely ideal and in this case problems could arise from the target looking down and having poor back posture as well as wearing heeled boots and standing at an angle to the camera.

<u>Conduct scene survey</u>

Objects viewed in the image can be markedly different when seen in the real world; this is particularly true of those generated from CCTV video. A thorough survey of the scene is essential to maintain accuracy and avoid having to return because something was missed. (See 4.2 VISITING THE SCENE).

- Check that edges chosen to locate the vanishing points are parallel
- Ensure that the ground plane is level
- Measure a few potential reference objects that are vertical and stand on the ground plane
- Recreate the scene using a few stand-in targets of different height for error estimation (See 4.2.4 USING A STAND-IN and 6 ESTIMATION OF ERRORS).

Analyse the selected image

Once the best image has been selected apply any required image enhancement and distortion correction. (See 4.1.2 CORRECTING IMAGE DISTORTION and 4.1.3 ENHANCING THE IMAGE). It is possible to follow the details in the section on the theory behind SVM and implement the technique manually. (See 5.3.4 THEORY OF SVM). The explanation here uses the *Single View Metrology* program developed by HOSDB, which applies SVM to measure the height of an object or person in an image. However, the same considerations will need to be taken if manual analysis is performed.

Since the image needs to be the orientated the correct way (i.e. with the target's feet at the bottom of the image and the head at the top) it may need to be rotated in some image editing software before use with the *Single View Metrology* program.

Starting a project will allow an image to be imported and displayed by the program, which will automatically overlay eight lines (See Diagram 4.24). The red (vertical), blue (horizontal) and green (horizontal) lines can be dragged to lie along suitable edges in the image to be used as perspective lines for the relevant vanishing points. The magenta and cyan lines can be dragged to indicate the reference and target heights respectively. Enlarging parts of the image by using the zoom function will enable the lines to be placed over relevant edges with greater accuracy.

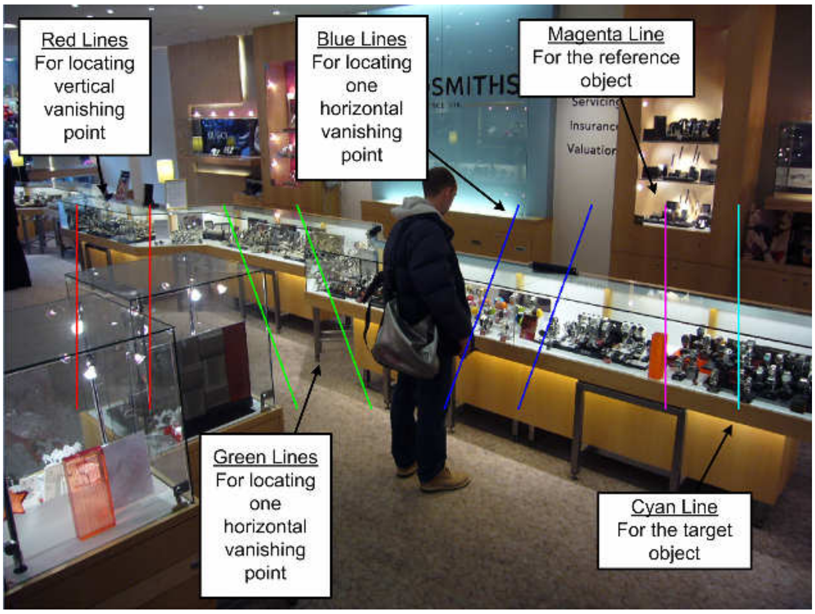


Diagram 4.24 The imported image is automatically overlaid with coloured lines that should be used to define perspective lines and relevant heights

More red, green and blue lines can be added to the image and dragged into suitable positions. It is strongly recommended that additional lines be used as this can increase the accuracy of locating vanishing points. Diagram 4.25 shows an example of the perspective and height-indicating lines in appropriate positions.

Once the lines are in position, the reference height (in metres) can be entered and the SVM calculation performed. The program will calculate and display the target object's height to the nearest centimetre. The program also displays where the vanishing points and the ground's vanishing line (shown in yellow) are located. (See Diagram 4.26).

Diagram 4.25 Perspective lines for locating vanishing points, the reference object and the target object have been defined using the coloured lines supplied by the program

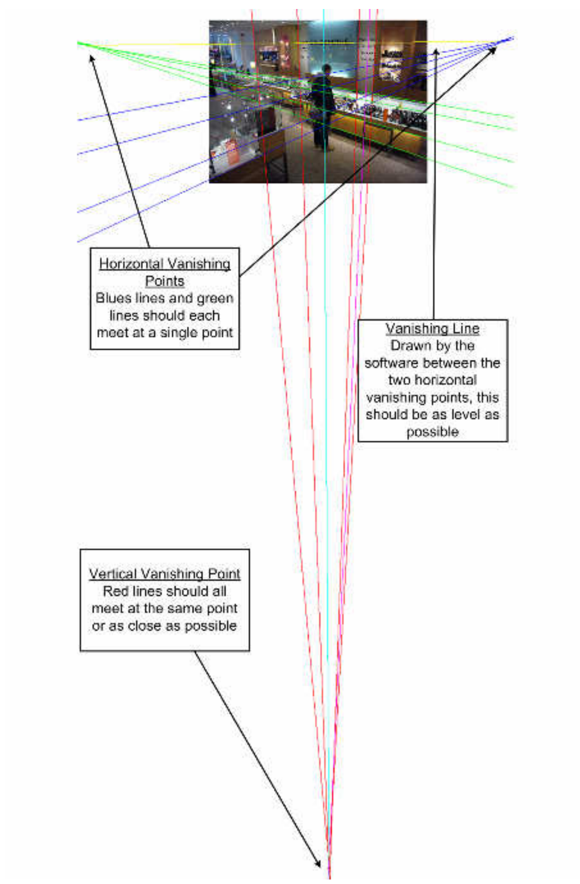


Diagram 4.26 The location of the required vanishing points

Improving accuracy

Diagram 4.26 shows where the perspective lines meet at the vanishing points beyond the boundaries of the original image. If a set of perspective lines does not meet at a clear vanishing point as seen here, then it will be necessary to recheck that the edges used are suitable and that the lines supplied by the program are accurately overlaid. Additionally it may be necessary to check that any image distortion has been corrected appropriately.

Result

By entering the measuring reference height of 0.60m, the software calculated the target height as 1.78m compared to the actual height of 1.77m.

It is good practice for three or so people to examine the image and perform the same procedure, and repeat using different suitable images. From these results the average can be calculated to reduce the effect of human errors. (See 6 ESTIMATION OF ERRORS).

5.3.3 SVM EXAMPLE 2

Diagram 4.27 is a typical example of an outdoor image where the environment is less geometrically regular. Extra care should be taken when assessing the scene to ensure that edges used for locating vanishing points are indeed parallel in the real world. Furthermore those objects used for locating the vertical vanishing point should truly be vertical. The annotations in Diagram 4.27 describe the areas to be considered when assessing the scene.

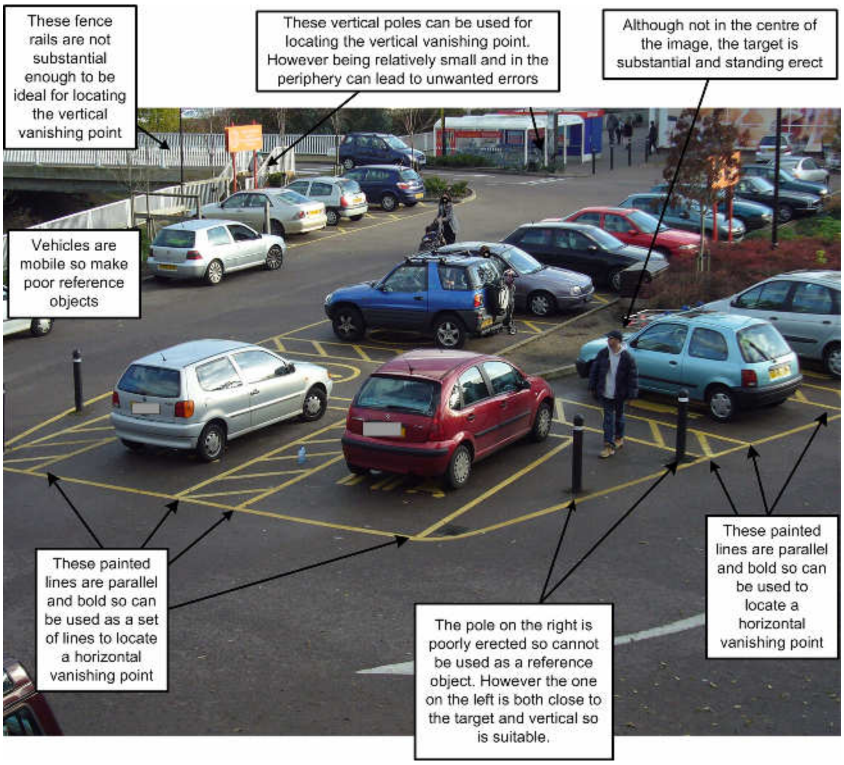


Diagram 4.27 Annotated image showing the decision process in assessing the scene

The lines were placed as shown in Diagram 4.28. Entering the reference height of 0.815m, returned an answer of 1.71m. Compared to the actual height of the target of 1.77m, the result is not as accurate as the previous example. To improve this result the placing of the lines to locate the vanishing lines should be rechecked, having more users perform the exercise to reduce the impact of errors, and making use of a stand-in. (See 6 ESTIMATION OF ERRORS).

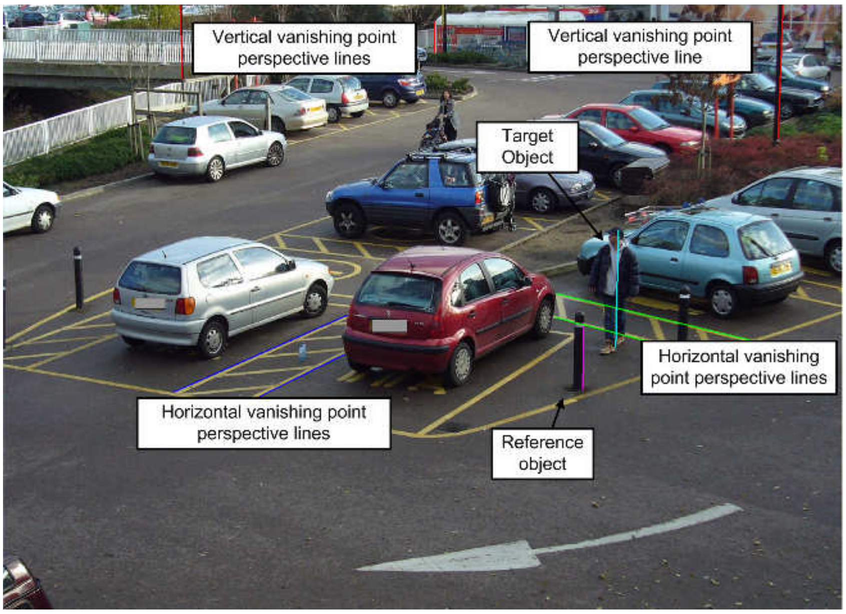


Diagram 4.28 Image showing the selected perspective lines and reference and target objects

5.3.4 SVM THEORY

One of the principal concepts of perspective geometry is the cross ratio and it is around this that Single View Metrology is based. It makes use of the fact that while ratios are not preserved in the imaging process, certain ratios of ratios have the same value in the real world as when they are imaged.

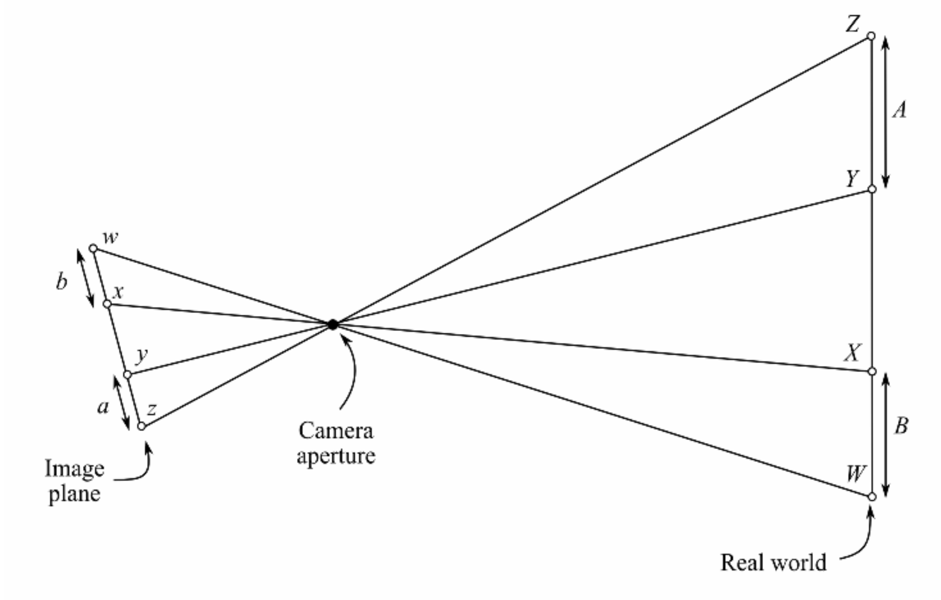


Diagram 4.29 Illustrating the idea of the cross ratio

When two actual objects *a* and *b* in the real world are projected onto an image to form imaged objects *A* and *B*, then the ratios between their real and imaged heights are not equal. (See Diagram 4.29). In other words :

$$\frac{A}{B} \neq \frac{a}{b}$$

However a particular ratio of these ratios, called the cross ratio (CR), does remain invariant:

$$CR = \frac{d(w,y)}{d(w,z)} \times \frac{d(x,z)}{d(x,y)} = \frac{d(W,Y)}{d(W,Z)} \times \frac{d(X,Z)}{d(X,Y)}$$

where *d* represents distance, i.e. *d(w,y)* denotes the distance between the points *w* and *y*.

The invariance of the cross ratio lies at the heart of the SVM technique. A scenario for applying SVM is illustrated in Diagram 4.30. The height of object A needs to be determined while object B is of known height. The top of an object is indicated by a '*t*' and the bottom by a '*b*'. Two vanishing points corresponding to the ground plane are used to locate the vanishing line. The vertical vanishing point, *VP*, is also located. The point where a vertical line through an object crosses the vanishing line is identified by a '*c*'.

The cross ratio for object A can be calculated in the image to be:

$$CR_A = \frac{d(t_A, b_A)}{d(t_A, VP)} \times \frac{d(c_A, VP)}{d(c_A, b_A)}$$

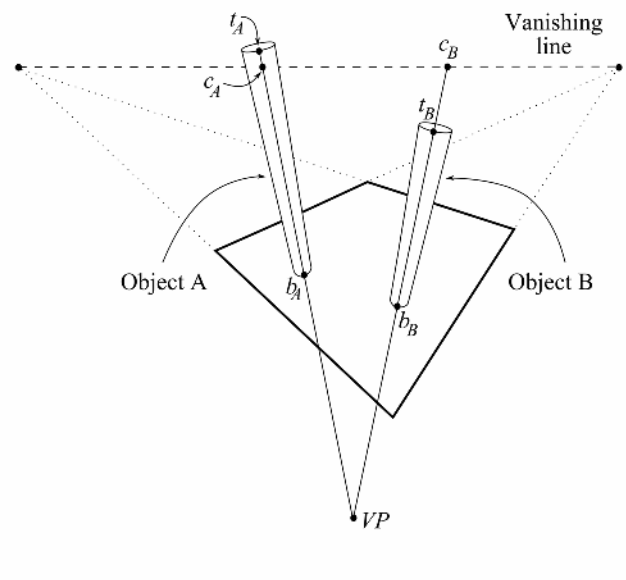


Diagram 4.30 Scenario for applying SVM

Since the cross ratio is invariant, the value calculated from the image is that same value as would be calculated from the points in the real world. As the vanishing point VP lies at ∞ in the real world and the point c_A lies at the same (unknown) height of the camera that took the image, this means that:

$$CR_A = \frac{H_A}{H_C}$$

where H_A is the height of object A and H_C is the camera height. Similarly for object B:

$$CR_B = \frac{d(c_B, b_B)}{d(c_B, VP)} \times \frac{d(t_B, VP)}{d(t_B, b_B)} = \frac{H_C}{H_B}$$

As the height of object B is known, the height of object A is calculated by using the last two equations to remove the unknown camera height, H_C:

$$\begin{aligned} H_A &= CR_A \times H_C \\ &= CR_A \times CR_B \times H_B \end{aligned}$$

In terms of distances within the image, this is:

$$H_A = \frac{d(t_A, b_A)}{d(t_A, VP)} \times \frac{d(c_A, VP)}{d(c_A, b_A)} \times \frac{d(c_B, b_B)}{d(c_B, VP)} \times \frac{d(t_B, VP)}{d(t_B, b_B)} \times H_B.$$

While the exact equation for finding the required height in different scenarios may differ, it can be found by following a similar process.

5.4 Projecting Points

By using features within the scene, it is possible to virtually project the target of unknown size to one of a known or measurable size. (See 3.5 PROJECTING POINTS TO OTHER OBJECTS). This approach is largely graphical in nature and could easily be performed with a suitable Computer Aided Design (CAD) software package.

5.4.1 BASIC IMAGE REQUIREMENTS

As with SVM this technique requires the identification of vanishing points. (See 3.2 VANISHING POINTS AND LINES). Therefore the image requires the presence of straight, parallel lines. In the manner described here, it is required to find vanishing points in the vertical direction and two in the horizontal direction that are orthogonal (i.e. at right angles) to one another in the real world.

At a site survey it would be necessary to confirm which lines are parallel and orthogonal. It would also be necessary to measure the height of the object to which the projection will be done.

5.4.2 PROJECTING POINTS EXAMPLE

Diagram 4.31 shows a scene suitable for estimating the height of a suspect standing near a brick wall. A vanishing point in the vertical direction is located and lies far below the displayed image area. Two vanishing points in the horizontal direction are also found. These correspond to directions that are orthogonal to one another in the real world since they are constructed using the two orthogonal walls.

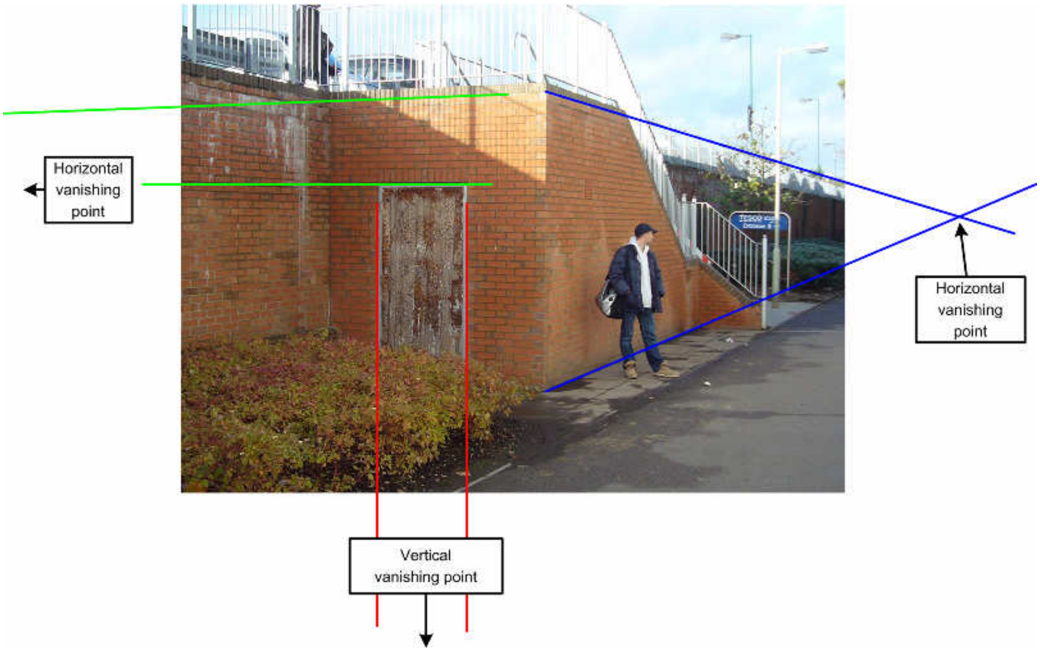


Diagram 4.31 Determining the position of the required vanishing points

Once the position of the required vanishing points have been determined the height of the target can be projected onto the wall and hence estimated. The procedure is as follows with reference to Diagram 4.32.

<u>Blue line</u> – this line is drawn from the target's feet to the left horizontal vanishing point, and intersects the base of the wall at a point.

<u>Orange line</u> – the point where the blue line intersects the wall is joined with the vertical vanishing point by this line.

Red line – this line joins the top of the target's head with the left horizontal vanishing point. This intersects the orange line at one point.

Green line – this line joins the intersection point of the orange and red lines with the right horizontal vanishing point.

Yellow line - the point at which the green line intersects the front edge of the wall lies at the same height above the ground as the height of the suspect. In this example, the height can be estimated by counting the number of bricks up the wall that this point lies, and measuring the corresponding distance at the scene.

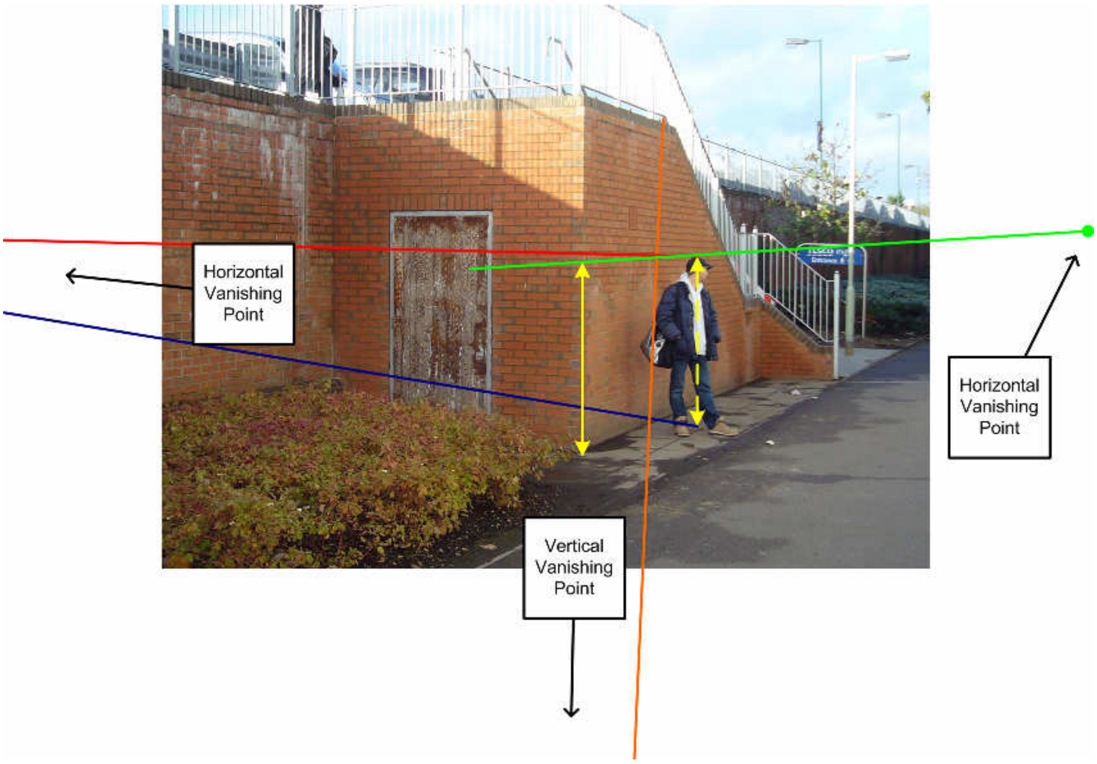


Diagram 4.32 Projecting the suspect's height onto a wall

5.4.3 FURTHER ANALYSIS

The idea of projecting points can be the first step of a more in-depth analysis. With the example in the previous section, the final estimate of the height was performed by counting bricks. In fact, this could be done more accurately by calculating the fraction of the wall height to which the suspect's height corresponds, though perspective distortion prevents this being done simply. However, by using geometric arguments and graphical constructions this can be done. Although this approach is very powerful, it can be complicated to perform and is not commonly implemented in widely available software so it is not discussed further here. Interested readers are referred to *Dimensional Analysis through Perspective: A Reference Manual* by Williamson and Brill for more details. (See 7 BIBLIOGRAPHY).

5.4.4 PROJECTING POINTS THEORY

Photogrammetry can be used to 'project' one unknown dimension onto one of a known value. For example the height of a person standing near a doorway can be determined by locating the point on the doorway where the top of their head would reach if standing next to it. This assumes that the person stands on the same ground plane as the base of the doorway.

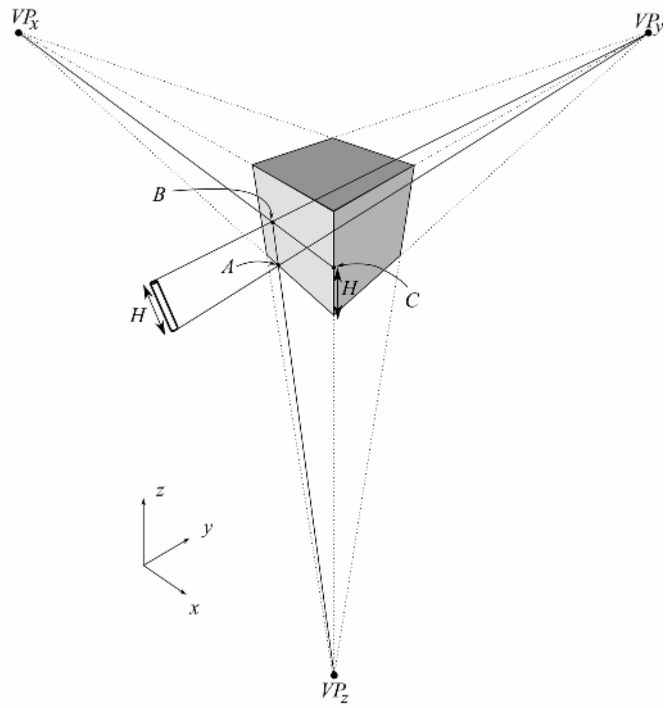


Diagram 4.33 Illustrating projection of points

The theory behind this can be explained by referring to Diagram 4.33. The aim is to determine the height H of the cylinder by calculating the point C on the edge of the cube that is the same distance above the cube's base as the height of the cylinder. This technique requires vanishing points in the x, y and z directions to be first determined.

The procedure is as follows:

Assume that the base of the cylinder lies on the same ground plane as the cube.

Project the base of the cylinder in the y direction towards the cube. This identifies point A as the intersection between the base of the cube with the line linking the base of the cylinder to the vanishing point VP_y.

Project the top of the cylinder in the y direction towards the cube. This identifies point B as the intersection between the line linking point A with the vertical vanishing point VP_Z where it crosses the line linking the top of the cylinder with VP_y. This approach recognizes that all points along the line linking the top of the cylinder with VP_y lie at the same point above the ground plane.

Now it is possible to project the top of the cylinder onto the edge of the cube. This point C is the intersection between the edge of the cube and the line linking point B with the vanishing point VP_x. Point C lies the same distance above the ground plane as the top of the cylinder.

6 ESTIMATION OF ERRORS

Recreating the scene is the best way to estimate the uncertainty in a photogrammetric measurement as it enables the most accurate modelling of the errors. For example, when measuring a person's height, stand-ins should be used who are approximately the same height and then placed at the same position within the scene and recorded through the original CCTV system. (See 4.2.4 USING A STAND-IN). Mimicking the exact pose or gait of the target object is not essential, but a reasonable representation of the target is advised such as walking through the scene or leaning on an object.

Two sorts of errors must be accounted for – systematic and random. The magnitude of both these errors can be estimated from the measurements of the stand-ins.

First an estimate is made of the height of each stand-in using a suitable photogrammetric technique. (See 5 PHOTOGRAMMETRIC TECHNIQUES). The findings are then compared with the actual heights of the stand-ins. The resulting errors are averaged over to estimate the systematic error (X_{SE}). The sample variance of the errors is also obtained:

$$S_N{}^2 = \frac{1}{N-1}\sum_{i=1}^{N}(X_i - X_i^{actual})^2 ,$$

N	number of stand-ins
X_i	estimated height of the i th stand-in
X_i^{actual}	actual height of the i th stand-in

Through statistical theory it is possible to estimate the errors using the Student's *t*-distribution. The final quoted height will use the following equation:

$$(\overline{X} - X_{SE}) \pm t(N-1, CL) \times \frac{S_N}{\sqrt{N}} ,$$

The pre-calculated values for $t(N, CL)$ depend on the number of stand-ins and the required confidence level (also known as the confidence interval). The latter is a measure of how certain the limits of the quoted answer will hold the actual answer, e.g. that there is a 95% chance that the actual answer is between the quoted limits. Since this procedure is only an approximate estimate of the errors, these bounds will not hold precisely. Predetermined values for $t(N, CL)$ are shown in Table 4.1.

N	Two-sided confidence level		
	90%	95%	99%
1	6.314	12.71	63.66
2	2.920	4.303	9.925
3	2.353	3.182	5.841
4	2.132	2.776	4.604
5	2.015	2.571	4.032
6	1.943	2.447	3.707
7	1.895	2.365	3.499
8	1.860	2.306	3.355
9	1.833	2.262	3.250
10	1.812	2.228	3.169

Table 4.1 Values of Student-t distribution (for two-sided confidence levels)

6.1 Example of Error Estimation

Table 4.2 shows the photogrammetric estimates for the height of a suspect in a video sequence and three stand-ins measured in a recreation. The actual heights of stand-ins and the related errors are also included.

	Height of suspect (m)	Height of stand-in one (m)	Height of stand-in two (m)	Height of stand-in three (m)
Actual height	?	1.81	1.83	1.80
Photogrammetric estimate	1.85	1.85	1.89	1.81
Error		0.04	0.06	0.01

Table 4.2 Examples of photogrammetric measurements and errors

The best estimate for the height of the suspect is given by

$$(\overline{X} - X_{SE}) \pm t(N-1, CL) \times \frac{S_N}{\sqrt{N}} \, ,$$

$\overline{X}$ = 1.85m (suspect's estimated height),

X_{SE} = 0.04m (= {0.04+0.06+0.01}m/{3}),

$t(N-1, CL)$ = 2.920 (three stand-ins at 90% Confidence Level),

S_N = 0.025m (Sample Variance),

$$= \sqrt{\frac{1}{3-1}\left\{(0.04-0.04)^2 + (0.06-0.04)^2 + (0.01-0.04)^2\right\}}\,\text{m}$$

This gives an estimate of the height with 90% certainty of

$$(1.85\text{m} - 0.04\text{m}) \pm \left(2.920 \times \frac{0.025}{\sqrt{3}}\right)\text{m} = (1.81 \pm 0.04)\text{m}$$

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8 COMPUTER SOFTWARE

Listed here are a number of software packages that are useful in performing photogrammetry. Inclusion in this list in no way indicates approval for the software. Other software packages are also available.

8.1 Image Editing Software

This software is intended to enhance, edit and process images, and ranges in sophistication from those that come free with digital cameras to more professional products that cost almost £1000.

Adobe Photoshop (<http://www.adobe.com>) - The market leader in image editing software and the current *de facto* standard.

Corel Paint Shop (<http://www.corel.co.uk>) - Another common software program primarily developed for Microsoft operating systems

GIMP (<http://www.gimp.org>) – The GNU Image Manipulation Program is a free software package for use with Windows, Apple and Linux operating systems

8.2 Lens Distortion Corrector Software

A few of the top-end image-editing software packages have lens distortion corrector software built in whilst others require additional plug-ins. These tend to be provided by specialist companies and can be purchased for around £50. Additionally stand-alone software is available.

8.3 3D Modelling Software

Although not primarily designed for police users, these packages apply photogrammetric techniques to areas such as 3D graphics and animation, but can also be used for forensic use.

Photomodeler by EOS Systems (<http://www.photomodeler.com>) - Primarily designed for industrial and commercial applications, but also sold as a tool for crime scene reconstructions.

3DSMax by AutoDesk (<http://www.autodesk.com>) - Initially developed as an animation tool and popular with video game developers, it is increasingly being used as a general modelling software package.

8.4 Forensic Software

These products are designed exclusively for law enforcement and tend to concentrate on crime scene or traffic accident reconstruction.

iWitness by DeChant (<www.iwitnessphoto.com>) - Developed specifically for crime and accident scene reconstruction.

Mapscenes by MicroSurvey (<www.mapscenes.com>) - Primarily designed for surveying purposes, though now being sold as a tool for reconstructing crime and accident scenes.

Cognitech Investigator (<www.cognitech.com>) - A forensic video enhancement and processing software package that also performs photogrammetry.

Single View Metrology - Developed by HOSDB to measure people's heights by implementing the SVM technique. (See 5.3 SINGLE VIEW METROLOGY (SVM)).