A New Approach to Obtain Height Measurements from Video

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ABSTRACT

Over the last few years computer based signal processing has become more prominent in forensic image analysis. Using the processing power of computers and the advances in mathematical algorithms it is now possible to generate a wealth of information from an image once it has been digitized.

It has already been recognised that the image quality from many CCTV systems is generally too poor for facial recognition. However, there are other human characteristics which allow us to recognise individuals from a distance long before other aspects of their person become distinguishable. One of these parameters is a human's height.

In this paper a new measurement algorithm is presented which generates height measurements and their associated errors from a single known physical measurement in an image. The method draws on results from projective geometry and computer vision. A height measurement is obtained from each frame of the video. A "stereo like" correspondence between images is not required. Nor is any explicit camera calibration. The accuracy of the algorithm is demonstrated by a number of examples where ground truth is known. Finally, the height measurements and their variation are described for a person in motion. We draw attention to the uncertainty in heights associated with humans in motion, and the limitations of using this description for identification.

Keywords: Video metrology, forensic science, projective geometry

1. INTRODUCTION

The use of video camera surveillance systems is on the increase both in private premises and public areas. This has lead to an increasing number of crimes and incidents being caught on video. There are several papers and guidelines[2,3,19] advising on how to set up a CCTV system for a specific task e.g. monitoring and control, detection, recognition and identification. These guidelines are there to help operators install operating systems for specific purposes.

When an incident has been captured on video, typically the footage is replayed to gain an understanding of the event(s) or to identify a particular individual. In many instances the video quality and content is sufficient for evidential and or intelligence purposes. However, there are occasions when straightforward replay and enhancement is inadequate. For instance, the quality of the footage is insufficient to enable the recognition of an individual. This could be because the individual is too far from the camera or the individual is disguised. Other factors can compound these problems such as blur, poor quality recording due to over use of tape and poor lighting. In such instances the forensic examiner must rely upon other ways of uniquely identifying individual. This may involve techniques that include the comparison of clothing recovered from an individual with those seen on a video.

One important parameter for identification is a person's height, and several techniques[10,11] have been developed for obtaining height information from video. However, these methods require revisiting the scene and obtaining footage with a calibrated object following the path of the suspect or undertaking an extensive measuring program of the layout of the scene. This requires assurance that the camera set up and scene has not altered and it is also time consuming. The aim of this paper is to present a new measurement algorithm which generates height measurements and their associated errors from a single known physical measurement in an image. It also scrutinises the effects of taking such measurements.

a b

Figure 1. An example of measuring heights from a single image. (a) The four columns have the same height in world, although their images clearly are not of the same length due to perspective effects. (b) As shown, however, all columns are correctly measured to have the same height.

In section 2 we describe a method of single view video metrology where distances of points from planes, such as a person's height from a ground plane, can be measured directly from a single image on providing only minimal geometric information. In particular the method does not require the camera to be calibrated, e.g. the focal length need not be known, or the camera's position relative to the scene. As illustrated in figure 1 perspective effects are correctly modelled. The algorithm is applied to various examples in section 3. The uncertainty of the heights computed by the algorithm is also modelled and estimated. This is of particular importance since measurements are meaningless if the related uncertainty is unknown.

Section 4 investigates the effects of height variation arising from walking, and section 5 draws attention to the limitation of using this height description for identification.

2. METROLOGY FROM ONE VIEW

In this section we describe the algorithm used to compute distances of points from a reference plane. The method is applicable to a reference plane of any orientation, and the direction along which distances are measured does not necessarily have to be orthogonal to this plane. However, in all the applications given here the reference plane is the horizontal ground plane, and the direction is vertical, so in the sequel only this case will be referred to. Then the vertical distance of a point to the ground plane is the height of the point.

The mathematical theory employed is based on results of projective geometry.[7,13] Unlike classical photogrammetry,[17] calibration information such as the location (pose) of the camera, its orientation and its internal camera parameters (e.g. focal length) are *not* required. In general, these type of parameter are difficult to obtain in retrospect due to possible changing in the CCTV camera setting and scene layout. Instead only the minimal geometric information provided by vanishing points, lines and reference heights is required. The method given here generalizes earlier work by Proesmans *et al.*[16]

We will show the following result:

> Given the vanishing line of the ground plane, the vertical vanishing point, and at least one reference height in the scene; then the height of any point from the ground plane may be computed by specifying the image of the point and the image of the vertical intersection with the ground plane at that point.

Figure 2 illustrates the geometry and perspective imaging.

The measurement is achieved in two stages:

1. *Minimal calibration*: the required vanishing line and vanishing point are determined from the image, together with the image of the reference line segment. The vertical reference height is measured in the scene.
2. *Height measurement*: the height is computed from the imaged top point, $\mathbf{t}$, and base point, $\mathbf{b}$.

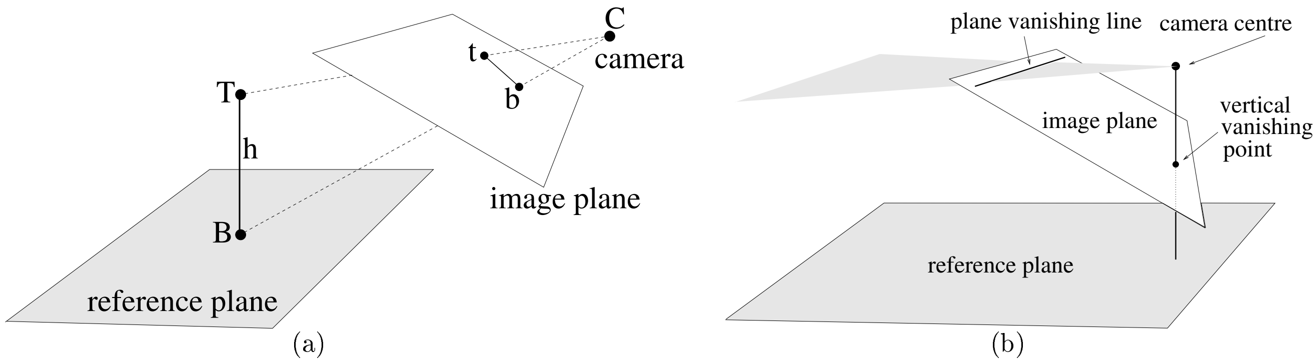

Figure 2. Perspective imaging: (a) A line in space, orthogonal to the reference plane and identified by its top point **T** and base point **B** is projected onto the image plane as the line segment **tb**. Note, the image plane is conventionally placed in front of the camera centre in schematic figures of this type. (b) The vanishing line of the reference plane appears at the intersection of the image with a plane parallel to the reference plane and containing the camera centre. The vertical vanishing point is the point of intersection of the image plane with the vertical line through the camera centre.

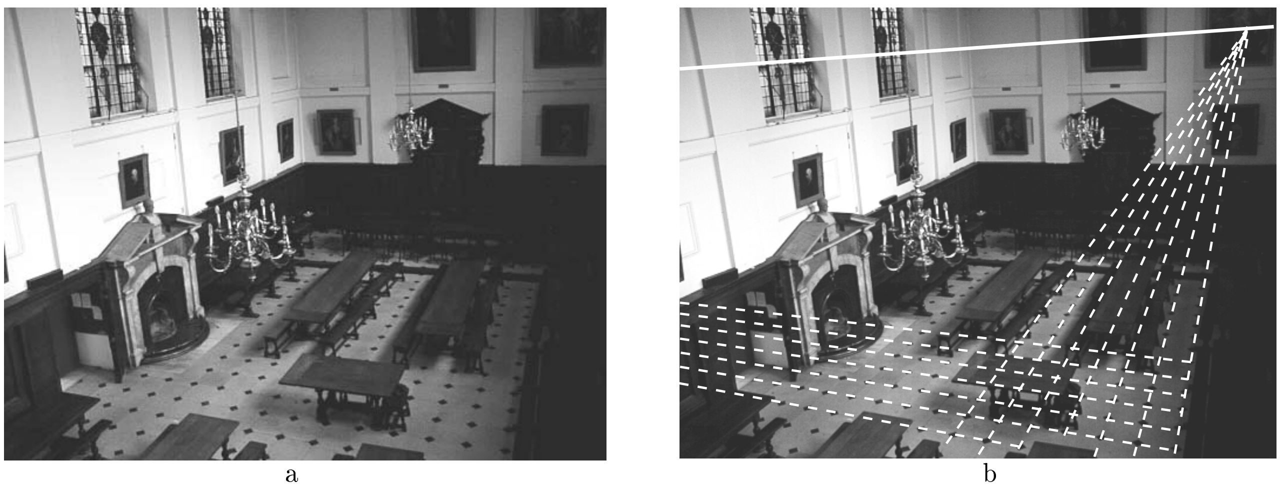

Figure 3. The dining hall of Queen's College, Oxford. (a) Original image. (b) The vanishing line of the floor is shown in solid white; sets of parallel lines on the floor (dashed) intersect in points on the vanishing line.

It is only necessary to carry out stage 1 once, of course, and then heights can be measured at any point on the reference plane.

2.1. Minimal calibration

The following three elements are required:

1. The *plane vanishing line* defines the orientation of the reference plane relative to the image plane; see figures 2b and 3.
2. The *vertical vanishing point* defines the vertical direction relative to the image plane; see figures 2b and 4.
3. The imaged line segment corresponding to the scene *reference height* defines the metric calibration for vertical lines; see figure 5.

The plane vanishing line and vertical vanishing point can be computed directly from the image, as described below, and *no* explicit knowledge of the relative geometry between the camera and viewed scene is required. Often, the computed vanishing line and vanishing point will lie outside the physical image.

a b

Figure 4. The tower of Magdalen College, Oxford. (a) Original image. (b) All vertical lines intersect in the image plane at the vertical vanishing point, which is marked in white.

Figure 5. A reference height: (a) The known height of the phonebox (h_r) is used as a reference to measure the height (h) of the person standing nearby. $\mathbf{t}$ and $\mathbf{t}_r$ are top points respectively of the unknown height and of the reference height; $\mathbf{b}$ and $\mathbf{b}_r$ are the corresponding base points on the ground plane. (b) The height of the person in the picture is measured at $h = 185.3cm$. The ground truth height is $187cm$. The discrepancy between measured height and ground truth is caused by the person leaning down slightly on his right leg (see section 5).

Computing the vanishing line. An example is shown in figure 3 of computing the vanishing line of the floor. Note that parallel scene lines on the floor intersect in the image on the vanishing line; two sets of parallel lines on the reference plane, with different directions, are sufficient to compute the plane vanishing line. If more than two orientations are available then a maximum likelihood estimate of the line may be computed.

Computing the vertical vanishing point. An example is shown in figure 4 of computing the vertical vanishing point. All vertical world lines intersect in this vanishing point on the image plane. Two lines are sufficient to compute the point. However, if more are available then a maximum likelihood estimate of the point may be computed.[12]

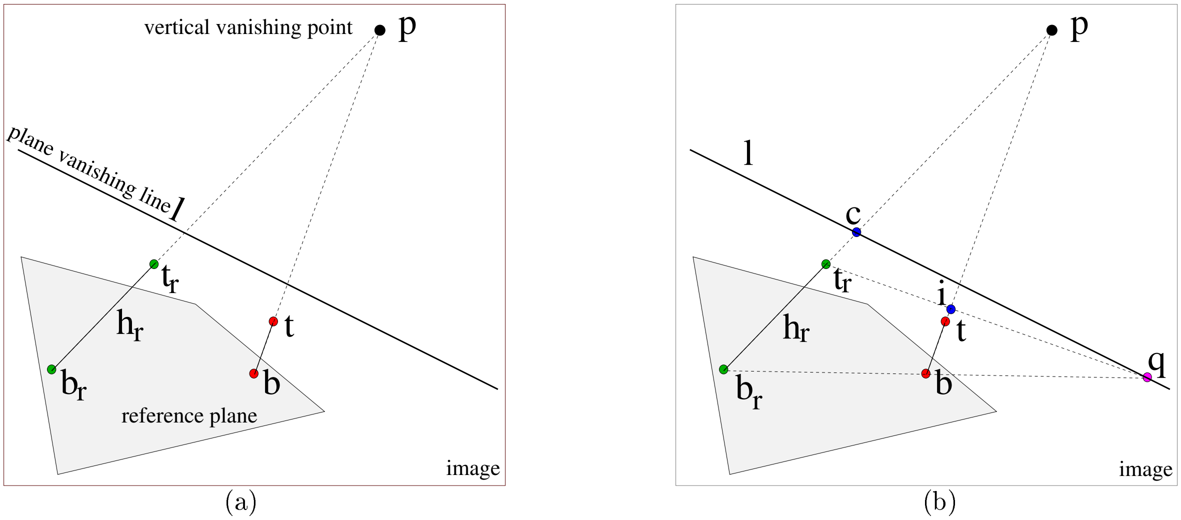

Figure 6. Basic geometry viewed in the image: (a) Plane vanishing line ($\mathbf{l}$), vertical vanishing point ($\mathbf{p}$), reference height (top point $\mathbf{t}_r$ and base point $\mathbf{b}_r$) and height to be computed (top point $\mathbf{t}$ and base point $\mathbf{b}$). See also figure 5 for these points on an image. (b) Geometric construction to compute heights of points from the reference plane, see text.

The reference height. A reference height requires both the top and base points of a length in the vertical direction. Any object in the scene can provide the required reference length. Figure 5 shows a picture of a person standing next to a phonebox. The known height of the phonebox is used as reference to compute the unknown height of the person.

2.2. Measuring heights from a minimally calibrated image

Once the image has been calibrated the height of any point from the reference plane can be computed using a quite simple geometric construction.

Figure 6a shows the basic geometry involved as it appears in the image. The line $\mathbf{l}$ is the plane vanishing line, and $\mathbf{p}$ the vertical vanishing point. One imaged reference height (segment $\mathbf{t}_r\mathbf{b}_r$) and the imaged line to be measured (segment $\mathbf{tb}$) are also shown. The intersection of the line through the two base points $\mathbf{b}$ and $\mathbf{b}_r$ with the vanishing line $\mathbf{l}$ is the point $\mathbf{q}$ (see figure 6b); and the intersection of the line through $\mathbf{t}_r$ and $\mathbf{q}$ with the line through $\mathbf{p}$ and $\mathbf{b}$ defines the point $\mathbf{i}$. The point $\mathbf{i}$ is the image of a point in the world at distance h_r from the reference plane where h_r is the reference height (this follows because the lines $\mathbf{t}_r\mathbf{q}$ and $\mathbf{b}_r\mathbf{q}$ are parallel in the scene).

We have constructed, in the image, four collinear points $\mathbf{p}, \mathbf{i}, \mathbf{t}, \mathbf{b}$ and thus there is a cross-ratio (a 1D projective invariant) available.[13] We also know that $\mathbf{p}$ is image of the point at infinite distance from the reference plane in the vertical direction, and the distance in the world between $\mathbf{i}$ and $\mathbf{b}$. We now have sufficient information to solve for the distance between $\mathbf{b}$ and $\mathbf{t}$ in the world — this is the sought height h. This computation can be carried out using either cross-ratios or 2×2 line-to-line-homographies. In the following we use a line-to-line homography method since it avoids degeneracies which arise in using cross-ratios.

The line to line homography may be written as

$$\begin{pmatrix} x_w \\ 1 \end{pmatrix} = \mathtt{H} \begin{pmatrix} x_i \\ 1 \end{pmatrix}$$

where x_i is the image position, x_w the world position, $\mathtt{H}$ is the 2×2 homography matrix, and "=" is equality up to scale. This homography is determined from the three point correspondences: $\infty \to \mathbf{p}$, $h_r \to \mathbf{i}$, and $0 \to \mathbf{b}$ as

$$\mathtt{H} = \begin{pmatrix} h_r\,(d(\mathbf{p},\mathbf{b}) - d(\mathbf{i},\mathbf{b})) & 0 \\ -d(\mathbf{i},\mathbf{b}) & d(\mathbf{p},\mathbf{b})d(\mathbf{i},\mathbf{b}) \end{pmatrix} \tag{1}$$

where $d(\mathbf{p}_1, \mathbf{p}_2)$ is the image distance between two points $\mathbf{p}_1$ and $\mathbf{p}_2$.

The height of $\mathbf{t}$ may then be determined as

$$h = \frac{s_1}{s_2} \tag{2}$$

where s_1 and s_2 are components of the 2-vector $\mathbf{s}$ defined by

$$\mathbf{s} = \mathtt{H} \begin{pmatrix} d(\mathbf{t}, \mathbf{b}) \\ 1 \end{pmatrix} \tag{3}$$

If image points and lines are represented as homogeneous 3-vectors, then the intersection point $\mathbf{i}$ can be directly computed by using the cross product operator as: $\mathbf{i} = (\mathbf{p} \times \mathbf{b}) \times (\mathbf{t}_r \times (\mathbf{l} \times (\mathbf{b}_r \times \mathbf{b})))$. In this manner the height of any object in the scene can be computed.

An algebraic parametrization of the algorithm has also been developed in Criminisi *et al.*[4] which has many advantages over the simple geometric method described above, although the underlying geometry is the same. The parametrization allows multiple reference heights to be used in a statistically optimal fashion, and an error propagation analysis to be developed. This analysis allows an uncertainty range to be given for each height measurement. This is very important in forensic applications.

The height of the camera from the plane can also be recovered. In fact, in figure 6b the point $\mathbf{c}$, the intersection of the line through $\mathbf{b}$ and $\mathbf{p}$ with the vanishing line $\mathbf{l}$, is the image of a point at the camera's height, h_c, from the reference plane. Therefore, one of the ways to compute the height of the camera is to apply the same equations as before (2,3,1) where h has been replaced by the height of the camera h_c, the top point $\mathbf{t}$ has been replaced by the point $\mathbf{c}$, the base point $\mathbf{b}$ by $\mathbf{b}_r$ and the point $\mathbf{i}$ by $\mathbf{t}_r$ as shown in the following table:

height of any object	h	$\mathbf{t}$	$\mathbf{b}$	$\mathbf{i}$
height of camera	h_c	$\mathbf{c}$	$\mathbf{b}_r$	$\mathbf{t}_r$

Using homogeneous 3-vectors the point $\mathbf{c}$ can be computed as: $\mathbf{c} = (\mathbf{p} \times \mathbf{b}_r) \times \mathbf{l}$.

3. FORENSIC APPLICATIONS AND EXAMPLES

In this section we show various examples of height measurements on real images. The height of the camera from the reference plane is also computed in each case. This provides another mean of assessing the accuracy of the system.

Height of people in outdoor scenes. See figure 7. Note that two reference heights (one more than the required minimal configuration) is used in this example. The camera height is computed to be $1.63m$ from the base of the porch.

Height of people in indoor scenes. See figures 8 and 9. The images are acquired using a wide angle lens camera and have significant radial distortion — for instance the edge of the filing cabinet on the left side of the image appears curved. A preprocessing of the image is required in order to correct this distortion. This is achieved using an algorithm developed by Devernay and Faugeras[6] which determines the radial distortion from the images of straight lines in the scene. The effect of the correction is quite noticeable by comparing the corrected image (figure 8b) to the original one (figure 8a). In the corrected image straight lines in the world are imaged as straight lines. More details of this correction are given in.[5]

Since no parallel lines can be detected on the floor the vanishing line is computed, as in the previous example, by intersecting two sets of horizontal lines in space not necessarily lying on the floor. In particular, the edges of the tables, edges of the filing cabinet, and of the shelves are used. The vertical vanishing point is obtained by intersecting vertical edges from the filing cabinet on the left and the photocopier machine on the right. The vertical vanishing point lies outside the physical image.

Figure 9 shows images of the same scene with the same people, but acquired from a different point of view. The calibration proceeds in the same manner. Notice that the difference between the measurements in this figure and the corresponding ones in figure 8 are less than half a centimeter. This demonstrates the accuracy of the measurements and their invariance to camera location. Note, it is not necessary to have a second view of the same scene — this is included only for a comparison with the previous result.

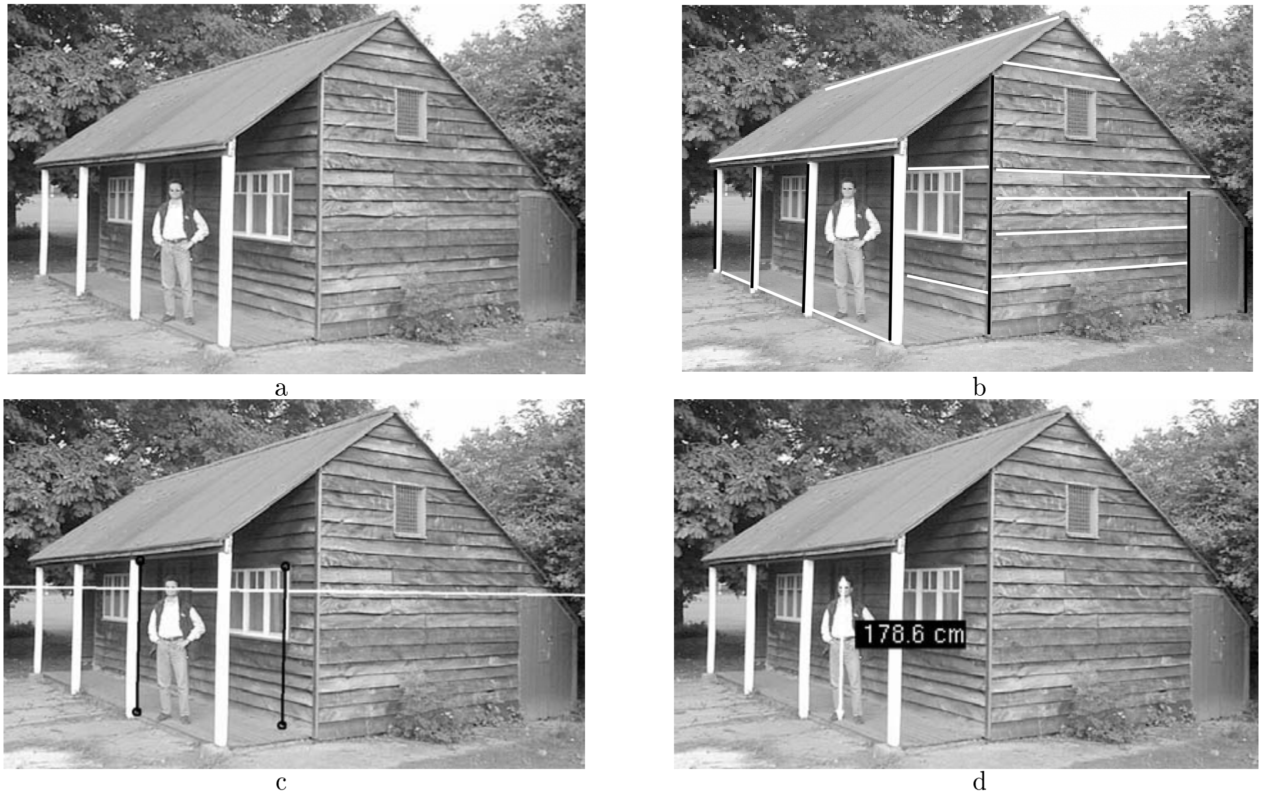

Figure 7. (a) Original image. (b) Lines used to compute the plane vanishing line and the vertical vanishing point: the lines in white correspond to two sets of horizontal lines in the world, they intersect in points on the ground plane vanishing line (the horizon); the black lines (for instance the edges of the columns) are images of vertical lines in the world, they intersect in the image at the vertical vanishing point. (c) The vanishing line (in white) and two reference heights (in black), the column on the left is $201cm$ high and the height of the top frame of the window is $192cm$. (d) The height of the person in the picture is measured at $h = 178.6cm$. The ground truth is $h = 180cm$, the discrepancy between measured height and ground truth is caused by the person leaning down slightly on his right leg (see section 5).

Uncertainty bounds. Figure 10 shows a further example where the heights of furniture are measured. No detectable radial distortion is present in this image and therefore there is no need to perform any correction. In this example the vanishing line has been computed by intersecting lines detected on the wooden floor and the vertical vanishing point by intersecting the vertical edges of the bookshelf.

The results of an error propagation analysis[4] of this example are also shown. The uncertainty in localizing top and base points is represented as a circle of radius $2pixels$. The uncertainty bound is ± 3 standard deviations, which means that there is a likelihood of the 99.7% that the real measurement falls within the associated range. Note, in fact, that all the computed uncertainty intervals always include the ground truth. The height of the camera is computed as $1.71m$.

4. HEIGHT VARIATION OF HUMANS IN MOTION

Any measurement taken from a video image using the method described in this paper, or any other such algorithms,[10,11] to represent a human's true static height must be scrutinised for accuracy. Besides systematic errors associated with the algorithm and operator there are often other factors such as the effect of stance. It is recognised[11] that the main problem in most cases is to decide firstly, if a person is in an upright position and then secondly, the location of the top of the head and its vertical intersection with the ground plane. This is particularly a problem when an individual is walking or running. Therefore, there is a need to understand the variation of an individual's height during such locomotion. This is before other factors such as shoe and head-wear are also considered. The following section deals specifically with an initial study on height variation of humans whilst walking.

Figure 8. (a) Original image. (b) Image after correction for radial distortion. (c) Vanishing line (in white) and reference height (in black), the filing cabinet is 132cm high; (d) Height measurements computed from the image. The ground truth is $h = 1.90m$ for the man and $h = 1.70m$ for the woman. The computed height of the camera is 2.35m.

Figure 9. (a) Original image. (b) Image after correction for radial distortion. (c) The vanishing line (in white) and reference height (in black), the filing cabinet is 132cm high. (d) The height measurements computed from the image. Compare with figure 8. The height of the camera, which is at a different position to that of figure 8, is here computed as 2.24m.

Figure 10. (a) Original image. (b) The vanishing line (white horizontal line) and reference height (white vertical line); the marked shelf is $156cm$ high. (c) Computed height measurements. (d) Computed height measurements and related uncertainties; the uncertainty bound is at $\pm 3 std.dev$. The ground truth is: $h = 150cm$ for the right hand shelf and $h = 97cm$ for the chair. Notice that the three measurements of the same shelf in different points differ by less than half a centimeter.

A controlled scene environment was constructed to complement the capabilities of the algorithm presented earlier (see figure 11). This meant insuring that there were sufficient straight and parallel lines in the fore- and background of the image. These lines where produced by marking out parallel lines on the wall and floor with masking tape. It was also necessary for several known heights (height of inside edge of tape from ground) to be located in the scene so that the image could be calibrated by the metrology algorithm. A standard CCTV camera (JVC TKS-340) was connected to a SVHS video player (JVC BR-S388E) and mounted at 90^o to the planned walkway. A lens (Computar vari focal) was chosen to allow a wide enough field of view to capture approximately 5 walking strides of an individual. Volunteers were then asked to walk up and down the walkway several times at a normal pace. Their static heights (to within +-2mm) were also taken, with a standard 5m tape measure, as a reference.

The video footage was then digitized using a sequence frame grabber (MuTech MV-1000) connected to a PC (Pentium II 300MHz). Using the methods described in section 3 the resultant images were then corrected for lens distortion and calibrated with the ground truth measurement. From the calibrated images, measurements where taken from a point at the top of the head (greatest intensity change) to its vertical intersection with the ground plane. This was made easier by the algorithm only allowing the measurement to follow the imaged vertical direction. This process was repeated 10 times by the same operator to obtain an average result. In figures 12a and 12b the measured height variation of two different male individuals can be seen with respect to their static heights.

5. INTERPRETATION OF HEIGHT MEASUREMENTS

From the initial research into height variation, it was found and can be seen in figures 12a and 12b that there is a significant variation (approximately $6cm$) in an individual height whilst in motion at a steady walking pace. It was

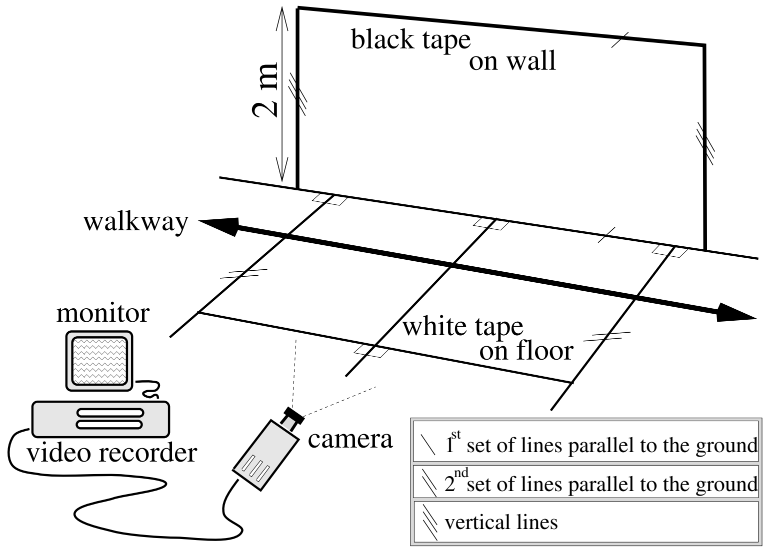

Figure 11. Experimental set up for controlled gait footage: the camera has been placed at 90^o with respect to the walkway; single and double marked lines are parallel to the ground plane in two different directions; triple marked lines are vertical; the edge of the top tape on the wall is $2m$ high from the floor.

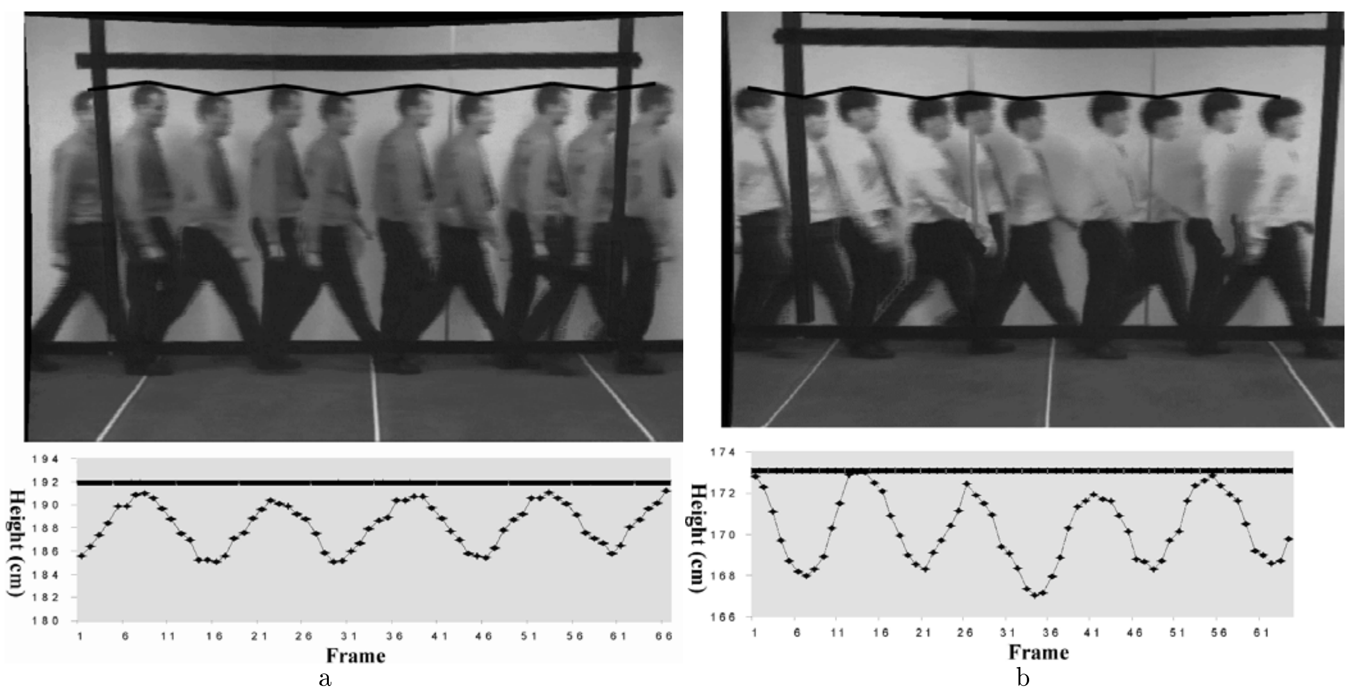

Figure 12. Height variation: (a) Measured height variation of a male person whilst in motion at walking pace. 66 frames have been used. The individual static height is $191.9cm$ and shown by the straight line on the graph; (b) Measured height variation of another male person whilst in motion at walking pace. 64 frames have been used. The individual static height is $173.1cm$ and shown by the straight line on the graph.

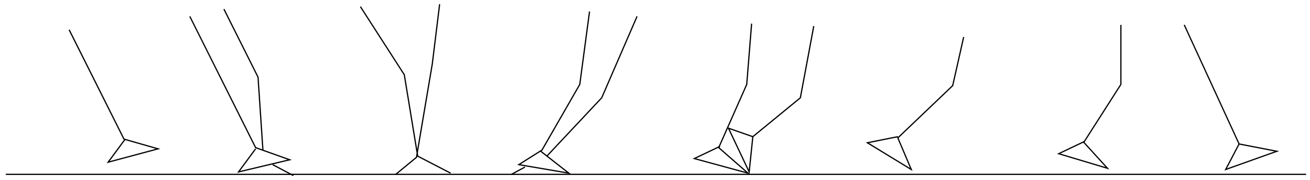

Figure 13. Terminology in gait analysis.

also seen that a person's maximum motion height does not always match their corresponding static height. However, from data analysed to date it was determined that their maximum is the most appropriate measurement to represent the static height of a person. This maximum was found to occur at what is referred to as the Mid Stance in clinical gait analysis,[8,14,18] i.e. when either foot is on the ground and the leg is straight (see figure 13).

These findings show that the accuracy of the measurement algorithm is not the only important factor which must be taken into consideration when trying to identify an individual by height measurements.

The main problem with CCTV is in the amount of information lost from the relevant camera due to the time lapse and multiplexing nature of such systems. This results in a limited number of images of a given suspect in an upright static stance. To reduce this uncertainty of height variation in motion it is recommended that the individual is tracked through the scene whilst taking measurements. This will give an average, maximum and minimum measurement. Ideally, the mid-stance measurements should be averaged if they are available, since this is the most accurate representation of static height.

In order to determine the statistical significance of any height measurement it needs to be considered with respect to the variation of height within the general population. A source of this information is the regular health surveys taken by local government.[1,9,15] Given this background and measured height information standard statistical test determine the significance of the height measurement as evidence. For example the likelihood of measuring a 2.5m height. However, video evidence, which can not give a positive identification, is mainly used for elimination purposes or to aid with a co-operating individual.

Another set of variables, which have not been discussed in this paper, is the effect of shoe and head-wear on the measurement. Ideally, similar shoe and head-wear should be worn when the static measurements are taken.

6. CONCLUSION

We have presented a new algorithm for determining height measurements directly from a video image. The algorithm draws on results from projective geometry and computer vision and only requires minimal geometric information of the viewed scene. This new approach to metrology enables valuable information, about an individual to be obtained, from video footage that is generally too poor for facial recognition.

The metrology algorithm described in this paper was then used to demonstrate the variation in height of a person whilst walking. From the initial interpretation of data to date it was determined that the most representative measurement of an individual's static height is the Mid Stance part of their gait. This is a preliminary study and further work is required to asses the effects of errors on the height variation. However, the findings in this report demonstrate how important it is to scrutinise any measurements obtained from video.

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