iWitness **Technical Note 4-1**

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Three-Dimensional Measurement with *iWitness*

1. The Basic Process

The *iWitness* software system enables a user to convert two-dimensional (2D) coordinate (x,y) information of feature points on an object recorded in two or more images of a photographed scene into three-dimensional (3D) coordinates (X,Y,Z). The measurement process is illustrated in basic form in Figure 1. Imagine that three images of an object are recorded from three different viewing directions, with a consumer grade digital camera, such that feature points P_1 to P_5 appear in all images. Intuitively, it is clear that if the positions of the camera stations S_1, S_2 and S_3 are known in a 3D reference system, with the X, Y and Z axes as illustrated, and the directions of the three imaging rays to a feature point are also known, then the position, say P_1, will lie at the point of intersection of the three rays at coordinates (X_1, Y_1, Z_1). This part is straightforward. Unfortunately, the matter is complicated because we generally do not know the precise locations of the camera stations and we do not directly measure the spatial directions of the imaging rays.

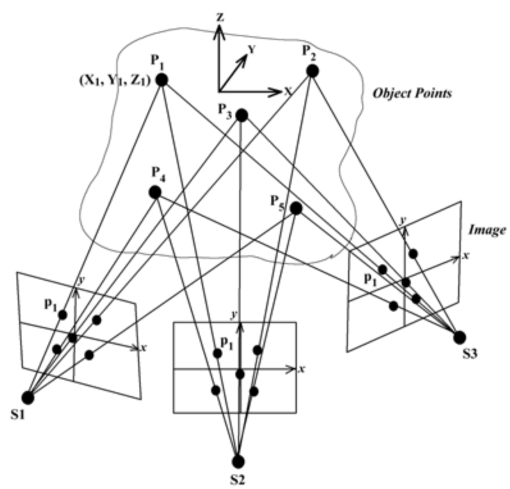

Figure 1. Photogrammetric triangulation; object XYZ coordinates are determined from intersecting rays.

This is where the science of photogrammetry comes in. If you imagine Figure 1 as illustrating the mutual intersection of three bundles of imaging rays, then this assemblage of camera stations and object points forms a 3D shape. The bundles will only fit together in one way if the corresponding rays for each point are going to intersect perfectly. To achieve this mutual intersection of all matching rays, it is necessary to recover the same ‘Relative Orientation’ between the images that they possessed at the time of photography. This reconstruction of the spatial orientation of images, with the 3D reconstruction of the true shape represented by the object points, is termed photogrammetric orientation. The situation described is no different in principle to the way the human brain recreates 3D scenes from stereo-imagery, for example as with a 3D movie. But with *iWitness* any number of images, any number of points, and a wide variety of camera viewing directions are accommodated in the 3D coordinate determination.

In order for the bundle of rays for each image to be established, it is necessary to determine the angular relationship between the rays, which all pass through the perspective centre of the camera lens. This is where the requirement to 'mark' (actually measure) image coordinates comes in, for although we might be marking the 2D location on an image, we are actually determining the angular direction of each ray with respect to the camera's pointing axis. This is illustrated in Figure 2. By thinking of the image measurement process as the forming of a bundle of rays with known relative directions, we make it easier to visualise the mutual fitting together of these bundles to form a 3D shape. This shape can have arbitrary scale (move the cameras stations apart and the shape enlarges) and an arbitrary 3D coordinate system. The assignment of scale, or size, and orientation and position of the intersected points P_1 to P_5 in a chosen XYZ coordinate system is termed 'Absolute Orientation' in photogrammetry.

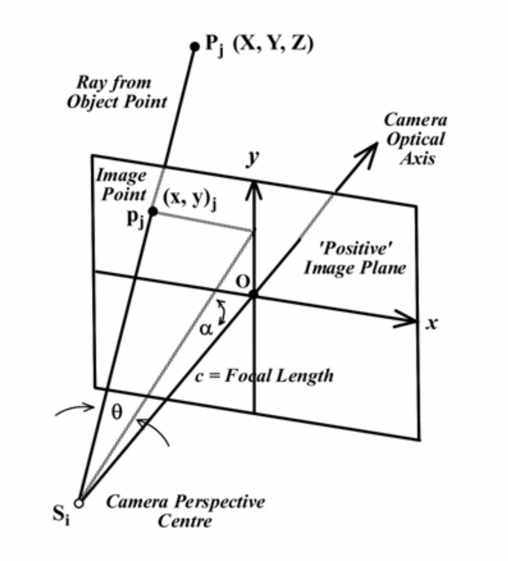

Figure 2. The camera as an angle measuring device.

So, the 3D feature point determination can be viewed as a four-stage process:

i) Record the two or more images from suitable camera viewpoints.

ii) Mark the x,y image coordinates to establish the angular relationship between rays forming each bundle of rays. The corresponding points are said to be 'referenced' when they are marked in two or more images.

iii) Relatively orient the images, ie bundles of rays, to recreate the geometry at the time of photography and so define the 3D shape of the array of referenced feature points.

iv) Assign a desired scale and XYZ coordinate system to the relatively oriented assemblage of bundles of rays, thus producing the desired outcome: scaled XYZ feature point coordinates.

2. What about camera calibration?

We need to state at the outset that photogrammetric measurement is both accurate and reliable, and the orientation procedures in *iWitness* are more robust, if the camera is calibrated. A very easy way to visualise the importance of calibration is through reference to Figure 2. As mentioned, the purpose of marking/referencing (x,y) image coordinates is to determine the two angles α and β shown for each ray. But, this cannot be done unless the distance S_i to O is precisely known, and this happens to be the focal length of the camera lens. More strictly, we talk of principal distance, c, rather than the focal length, which is typically a nominal value corresponding to infinity focus. Note that c changes with focusing, which is why it is imperative for accurate measurement in a project that images be recorded at a single focus.

Note also that the computation of the angles α and β will be influenced by how closely the camera optical axis intersects the assumed origin of the x,y coordinate axes (there are two 'Interior Orientation' parameters here). Furthermore, there is an assumption that the object point P, the image point p and the camera station S form a straight line, but lens distortion causes the ray to deviate from a straight line and thus there is a need to correct for such distortion effects. The topic of calibration is explained in more detail in the *iWitness* Users Manual. The purpose here is simply to highlight why calibration is important if the best possible accuracy and measurement reliability is desired.

3. What about the number of images and feature points?

In order to perform the relative orientation of one image with respect to another (corresponding points referenced to one another), there are two necessary conditions that must be fulfilled. The first is that the camera stations are separated such that the angle between the two intersecting rays at each point is greater than a few degrees (ie, the rays are not near parallel). The second is that there must be at least five corresponding feature points referenced for the two images and these cannot all lie within a straight line. While these conditions are necessary, they may not be sufficient to ensure a robust relative orientation, since the process of intersecting the bundles of rays is a complex mathematical estimation process, which can lead to either a failed solution, an incorrect solution or even multiple possible solutions in cases of very poor 'geometry'.

One of the features of *iWitness* is its very robust determination of photogrammetric orientation, but there are still a number of simple rules the user can follow to aid in ensuring a correct and accurate orientation of the many images forming the network of camera stations and feature points. These include:

a) For the first two oriented images, ensure that the camera station separation is at least 10-20% (or more) of the average distance to the array of feature points.

b) Ensure that the referenced feature points used for initial orientation are as well spread as possible in two directions, and preferably three. It can be expected that there will be less problematic relative orientations in situations where the feature points do not all lie within the same plane.

c) Be conscious of the fact that, generally speaking, the larger the angle of intersection of two or more rays, the more accurate will be the XYZ coordinates.

d) Where possible, try to have the object point field fill as much of the image format as possible (this will increase accuracy and likely orientation reliability as well).

e) Always opt for more marked and referenced feature points rather than less. Although in theory a minimum of 5 per image in a stereo pair is required, and *iWitness* expects at least 6 for reliability purposes, a reasonable minimum of referenced points per image should be 12 or more.

f) Record more images rather than less. Images not needed do not have to be referenced to others in the network, but the recording of an insufficient number of images is a more difficult situation to recover from. We need to ensure that all feature points are imaged in a sufficient number of images (2 is the minimum but 4 with good geometry should be a working minimum). Not all points need to be 'seen' in all images, of course, but each feature point must be 'seen' by enough images.

4. How does image marking/referencing and orientation proceed?

The procedure for importing images into *iWitness*, marking and referencing image feature points, performing the photogrammetric orientation, assigning scale and an XYZ coordinate system, and finally exporting 3D coordinate data is further detailed in the *iWitness* Users Manual. To set the scene, however, we briefly review the marking/referencing and computational processes within *iWitness*:

a) We start with the assumption that the user has recorded 'a network' of images of an object upon which the 3D coordinates of feature points are to be determined. We further assume that the network of images and points forms a favourable geometry for image orientation, as per the guidelines in the previous section. The object scene may have natural feature points of interest, or artificial targets, or indeed both. Also, the digital camera may be either calibrated or uncalibrated.

b) The images are stored within the desired Folder on the PC and *iWitness* is started. The first step is to select from the images recorded those desired to be marked and referenced. These are simply 'dragged and dropped' into the project. In the likely event that the images are JPEG (*.JPG) files written by the digital camera, *iWitness* immediately determines the camera type which recorded the images. The program will then assign the correct camera parameters to the images. Shown in Figure 3 is the user interface of *iWitness*, with project images on the left, the icon of the automatically recognized camera above these, and two selected images being referenced in the main working window.

c) The next essential step is to establish the relative orientation between two suitable images in the network (eg the two shown in Figure 3). This involves the referencing of common feature points. We can think of referencing as the linking of two corresponding marked points. After six or seven points have been referenced, an initial relative orientation is automatically performed and the user can view a graphical display of the network of feature points and the two camera locations, as shown in Figure 4. With the completion of the initial two-image orientation, a 3D set of measured object points within an arbitrary XYZ coordinate system is established. Additional object points can then be added to the point array, through both further referencing in the initial two images and through extending the referencing to additional images.

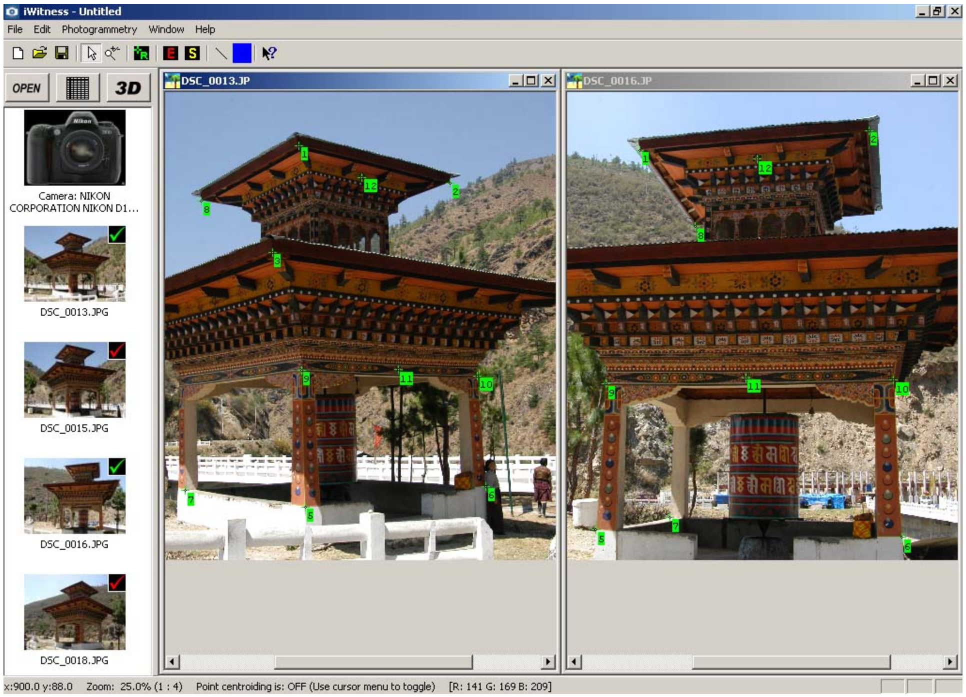

Figure 3. User interface of *iWitness*.

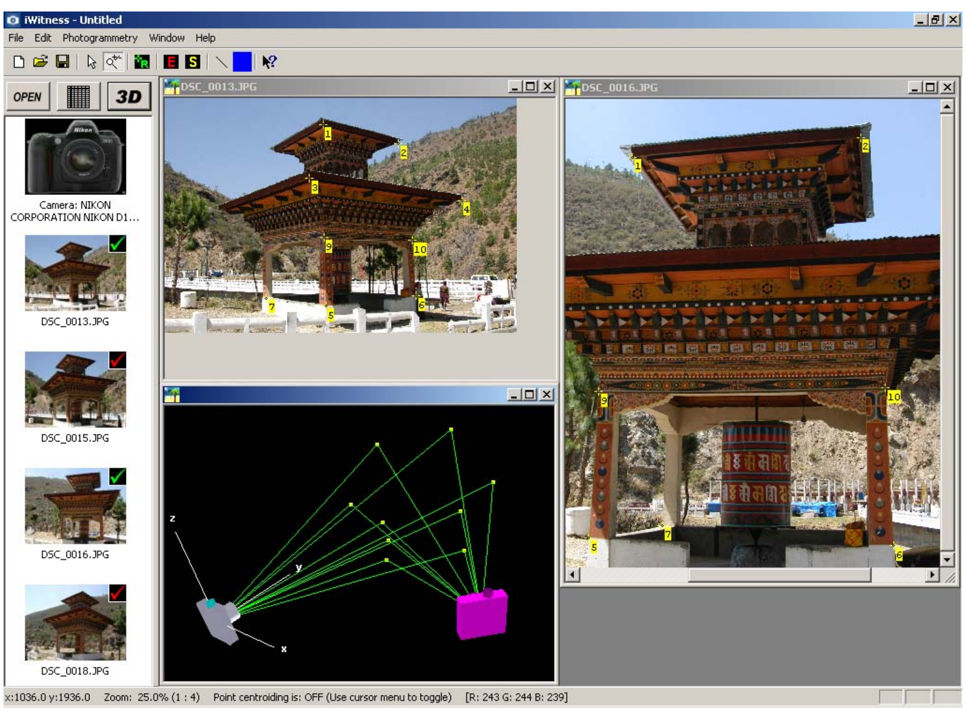

Figure 4. Relatively oriented stereo images in *iWitness*.

d) The third and subsequent images are processed one at a time, in combination with a previously referenced image. The sequence is typically as follows: The new image is referenced to an already oriented image. As soon as the referencing of four suitable points is carried out, *iWitness* automatically computes the spatial orientation of the new image. At this point, the predicted locations of as yet unreferenced feature points are displayed to aid in further referencing. Then, as further points are referenced, the coordinates of these are determined as each measurement is performed. Thus, at any time beyond the referencing of the first four or so points for the newest image, the 3D graphical display will depict all measured images and points. The ability to keep the full image orientation and object point determination current, with automatic updating accompanying any measurement, is a major feature of *iWitness*. Processing does not have to be manually selected; instead it happens automatically and continuously, not just following the completion of all measurements on some or all images, as has been the traditional approach.

e) The operator can continue to sequentially build the network of oriented images and object points, and at any time can choose to assign a particular scale (true size) or coordinate system alignment to the object feature points. By selecting options within the 3D graphical display, scale is set by assigning one or more point-to-point distances, and the coordinate system is set according to the '3-2-1' procedure. Here, three points are highlighted: the first defines the XYZ coordinate system origin, the second the X-axis and the third the XY plane and the direction of the Z axis. These two concepts are illustrated in Figure 5.

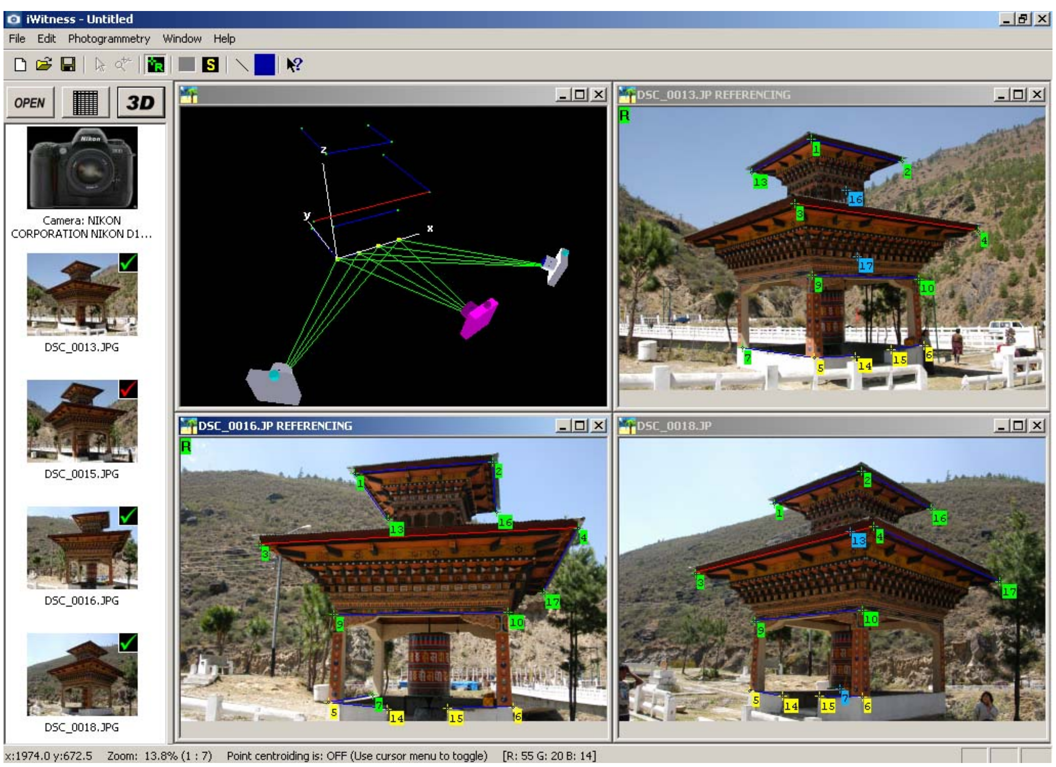

Figure 5. 3-image network showing assigned XYZ system, 3D points and scaled distance.

f) Although there are a number of object point analysis features in *iWitness*, the primary purpose of this photogrammetric processing system is to generate a 3D array of feature point coordinates which can be exported to either a CAD or alternative modeling system Thus, the final output from *iWitness* is an exported DXF and/or ASCII formatted file of 3D coordinates.

g) One very important feature worthy of highlighting at this point is that as well as accurately producing the desired 3D XYZ object point coordinates, *iWitness* can precisely calibrate the camera or cameras used, as an integral and again fully automatic component of the overall photgrammetric processing. This is not always a desired feature, and it does require special consideration of camera station geometry, but it is nevertheless a very important component of high-accuracy feature point measurement.

5. Summary

The purpose of this brief overview of the operational stages involved when performing image-based 3D measurements with *iWitness* has simply been to introduce the potential user to the basic concepts of image-based 3D measurement. This coverage helps set the scene for application of the powerful, easy-to-use *iWitness* system in a host of 3D object measurement tasks ranging from traffic accident reconstruction, through engineering measurement, to the recording of heritage sites and structures.