Measuring distances using digital cameras

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Abstract

This paper presents a generic method of calculating accurate horizontal and vertical object distances from digital images taken with any digital camera and lens combination, where the object plane is parallel to the image plane or tilted in the vertical plane. This method was developed for a project investigating the size, density and spatial distribution of shrubs growing as hedges.

The geometry of objects projected on to parallel and oblique image planes was used to develop an equation for calculating horizontal and vertical distances from image pixel counts. Images of a grid were taken with a variety of digital cameras at different focal lengths, image-object distances and vertical tilt angles. The equations were also tested by taking a set of photos of shrubs in a hedge field experiment.

The results show a very strong correlation between calculated distances and physical measurements across a range of cameras, focal lengths, distances and vertical tilt angles. A small constant error was found in two of the three cameras tested suggesting that effective image size may vary from published sensor dimensions in some cameras. Cameras should be calibrated to check for any constant error before using the equations described in this paper.

Introduction

Digital imaging is regularly used to measure distances in horticultural and related experiments. Some of these uses involve images that are not perpendicular to the object being photographed; for example, many photographs of trees taken from ground level require the camera to be tilted up to capture the whole canopy. When the camera is tilted in the vertical plane, vertical distance measurements will be affected by the vertical tilt angle (Clark et al., 1998). However, this also affects horizontal measurements. Imagine a photograph of a tall building where the camera is tilted up: the top of the building appears narrower than the base of the building on the image.

There are two digital imaging techniques commonly used to measure distances in horticultural experiments:

1. A specific camera/sensor/lens combination used in an experimental spatial configuration is calibrated against actual object measurements using a regression analysis.
2. Turn-key third party solutions are used which have the regression analysis embedded in the supplied software.

The disadvantage of these methods is that they rely on specific proprietary hardware and/or software solutions that may not be readily repeatable and are often quickly made obsolete by technological advances.

This paper presents a general solution for measuring distances that can be applied to experiments using any consumer or professional digital camera in an experiment where the image plane is at any vertical tilt angle to the object plane. This method was developed for a project investigating the size, density and spatial distribution of shrubs growing as hedges, however it could be applied to a range of other applications such as measuring tree canopy heights and widths.

Materials and methods

A distance measured on an image is proportional to the distance on the object being photographed according to the equation:

$$O = \frac{ID}{f}$$

where O is the object dimension (in mm), I is the image dimension (in mm), D is the distance from the image plane to the object plane (in mm) and f is the focal length of the lens used (in mm).

When analysing digital images on a computer, distances are measured in pixels. Pixel distances can be converted to millimetres if the size of image sensor is known. Sensor pixels and dimensions vary in both the horizontal and vertical planes. Thus, object distances can be measured from image pixel counts when the image and object are parallel using the equations:

$$O_x = \frac{xS_xD}{fP_x} \text{ and } O_y = \frac{yS_yD}{fP_y}$$

where O_x is the horizontal image dimension (in mm), x the horizontal image dimension (in pixels), S_x the horizontal sensor size (in mm), P_x the horizontal sensor size in pixels. O_y is the vertical image dimension (in mm), y the vertical image dimension (in pixels), S_y the vertical sensor size (in mm) and P_y the vertical sensor size in pixels.

The geometry of how an object is projected on to an oblique image plane is shown in Figure 1.

In the experiment, these equations were developed, since the distances d, h and f are known and O_x and O_y can be calculated using the formulas

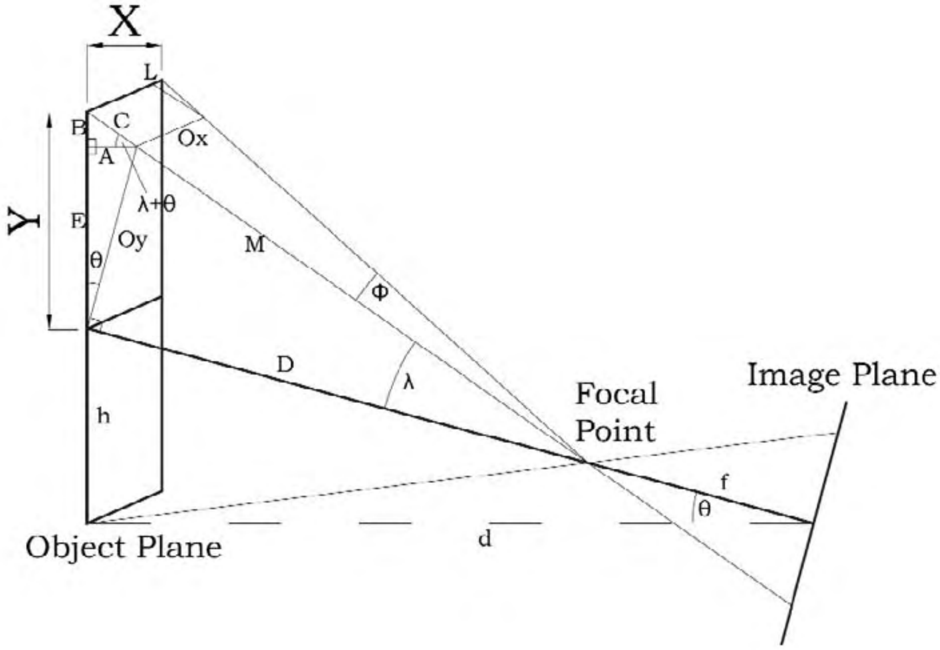

Figure 1. The camera is tilted up at an angle of θ (the vertical tilt angle), where d is the distance from the centre of the image plane to the object (in mm), h is the distance above the perpendicular of the centre of the image at the object plane (the tilt height, in mm), f is the focal length (in mm), O_x is the calculated horizontal distance from the centre of the object (in mm) and O_y the calculated vertical distance from the centre of the object (in mm). X is the true horizontal distance on the object plane (in mm) and Y the true vertical distance on the object plane (in mm).

described above. The distance D from the focal point to the centre of the object can be calculated as:

$$D = \sqrt{d^2 + h^2} - f$$

The angles θ, λ and ϕ can be calculated from these known values:

$$\theta = \sin^{-1}\left(\frac{h}{D+f}\right);\ \ \lambda = \tan^{-1}\left(\frac{O_y}{D}\right);\ \ \phi = \tan^{-1}\left(\frac{O_x}{M}\right) = \tan^{-1}\left(\frac{O_x \cos\lambda}{D}\right)$$

The real object dimensions can be calculated from these angles and the known values as follows:

$$Y = B + E = A\tan(\theta+\lambda) + O_y\cos\theta = O_y\sin\theta\tan(\theta+\lambda) + O_y\cos\theta$$

$$X = O_x + L = O_x + C\tan\phi = O_x + \frac{A}{\cos(\theta+\lambda)}\tan\phi = O_x + \left(\frac{O_y\sin\theta}{\cos(\theta+\lambda)}\right)\tan\phi$$

To test these equations, photographs were taken of a grid using three digital cameras with different sensor sizes and pixel resolutions (the 5 million pixel Nikon 5400 compact digital, the 6 million pixel Nikon D70 digital SLR and the 3 million pixel Canon A70 compact digital), three image-to-object distances (400 mm, 600 mm and 1000 mm), three tilt heights (0 mm, 85 mm and 140 mm). The Nikon 5400 was tested with its lens zoomed to its narrowest and widest focal lengths (5.8 mm and 24 mm), the Canon A70's lens zoomed to its narrowest and widest focal lengths (5.4 mm and 16.2 mm) and the Nikon D70 was tried with three different lenses (the 18 mm setting on an

18–70 mm zoom lens, a 24 mm prime lens and a 50 mm prime lens). Object distances were calculated using the equations described above and compared to the real object distances using a regression analysis. At least five horizontal and five vertical distance measurements were calculated from each image.

A set of images of the plants used in the hedging trial were taken (a total of 200 plants) using the Nikon 5400. Heights and widths were calculated from the images and compared with manually measured heights and widths and the results analysed using a regression analysis.

Results and discussion

The camera calibration results were analysed using a regression analysis and showed excellent results across the board with R-square values (the proportion of variation explained by the regression equation) close to 100% (see Table 1). All cameras had a negligible regression constant and a regression coefficient close to 1, indicating that the distance equations were excellent predictors of measured distances. The Nikon 5400 showed almost perfect correlation at all distance and focal lengths. The Nikon D70 had a regression coefficient of 0.93 on both horizontal and vertical axis. The Canon A70 had a slightly different regression coefficient in the vertical (0.96) and horizontal (0.98) axis.

It is not clear if these coefficients were a result of the active sensor area varying from the published sensor dimensions, or some other factor was involved. Further investigation using other cameras, sensors and lenses may clarify this issue. For the purposes of the hedge study, the coefficient was corrected by applying it to the published sensor image size (see Table 1).

The height and width calibration was verified by regressing physical and calculated heights and widths for each plant (Table 2). This again gave excellent correlation, showing a strong relationship between measured and calculated height and width. The lower R-square value for the width calculations is a result of the difficulty in clearly identifying the canopy edge when canopies have merged into a hedge.

Table 1. Regression analysis results for the camera/sensor combinations shows excellent prediction of distance measurements from the pixel count equations. All results are significant at $P < 0.001$, $n = 115$ for Nikon 5400, $n = 169$ for Nikon D70 and $n = 133$ for the Canon A70. P is the predicted distance from the regression equation and C is calculated from the distance equations.

Camera	*Axis*	*Sensor pixels*	*Sensor size (mm)*	*Regression equation*	*R-square*
Canon A70	horizontal	2048	5.27	$P = -0.3 + 0.98C$	99.8%
Canon A70	vertical	1536	3.96	$P = -0.1 + 0.96C$	99.9%
Nikon D70	horizontal	3008	23.7	$P = 0.3 + 0.93C$	99.9%
Nikon D70	vertical	2000	15.6	$P = -0.9 + 0.93C$	99.8%
Nikon 5400	horizontal	2592	7.18	$P = -0.9 + 1.00C$	99.6%
Nikon 5400	vertical	1944	5.32	$P = -0.8 + 1.00C$	99.7%

Table 2. Regression analysis results for the calculated vs measured distances showing a strong correlation. All results are significant at P < 0.001, n = 200 plants.

Measurement	Regression equation	R-square
Height	$P = 26 + 1.01C$	96.1%
Width	$P = 10 + 1.02C$	84.2%

The largest measurement errors in the hedge experiment using this method would be due to camera-to-hedge distance errors (d in Figure 1), the error in tilt height (h in Figure 1) and the natural variation in canopy shape (a hedge is never a perfectly regular shape). Branches were often closer or further away than assumed in the equations. However, the relatively large distance between the hedge and the camera (1000 mm) reduced the significance of these errors.

Conclusion

The results show a very strong correlation between calculated distances and physical measurements across a range of cameras, focal lengths, distances and vertical tilt angles. A small constant error was found in two of the three cameras tested suggesting that effective image size may vary from published sensor dimensions in some cameras. Cameras should be calibrated to check for any constant error before using the equations described in this paper.

References

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