Precision of Digital Target Location

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ABSTRACT: Extensive investigations have been carried out on digital pointing to circular targets to determine the influence of image quality, pixel size in the image, quantization level, and noise on the precision of pointing. Under ideal circumstances, the precision of pointing can approach 0.01 pixel size; variations in image quality had no significant effect on precision while, for quantization levels below 5 bits/pixel and signal to noise ratio less than 5:1, the precision deteriorated. Asymmetry of the target profile may cause significant systematic errors in the pointing accuracy which can be minimized by selecting the appropriate threshold value.

INTRODUCTION

THIS PAPER DESCRIBES the results of extensive studies of the precision of circular target location on digital images and the systematic errors brought about by asymmetry in the target intensity profile. This task is required in the measurements of digital images in photogrammetry for control points. Wong and Wei-Hsin (1986) have developed a method for the location of circular targets on digital images, while Mikhail *et al*. (1984) have studied the detection and location of edges and cross-targets.

In this paper circular targets have been studied; therefore, the method adopted is a modification of the method of Wong and Wei-Hsin. A rectangular window of suitable size so that it covers the complete target and the surrounding area is approximately centered on a target and thresholding within the window is then carried out. Thresholding converts the window area to binary values with all pixels whose intensity is above a threshold set to 1, and the remainder to zero. This process identifies the area of the target. Intially, threshold was computed using the value of Wong and Wei-Hsin: i.e.,

$$\text{Threshold} = (\text{min pixel value} + \text{mean pixel value})/2. \quad (1)$$

Subsequently, this formula was modified as described later in an attempt to eliminate systematic errors caused by target asymmetry. Wong and Wei-Hsin then chose to computer the position of the target by taking the center of gravity using:

$$x = \frac{1}{M}\sum_{i=1}^{n}\sum_{j=1}^{m} j.g_{ij}$$
$$y = \frac{1}{M}\sum_{i=1}^{n}\sum_{j=1}^{m} i.g_{ij} \quad (2)$$
$$M = \sum_{i=1}^{n}\sum_{j=1}^{m} g_{ij}$$

where g_{ij} is the value of each pixel, either 1 or 0 located in row i column j.

However, target pointing by this formula was found to be subject to variations in window size and position and threshold value, which caused variations in the position of the target of up to 1/2 pixel. This was because low intensity pixels on the edge of the target but still above threshold had a disproportionately large influence on the location of the target. It was therefore necessary to add to equation 2 a weighting factor w_{ij} for each pixel which was equal to the intensity value of the pixel above the threshold as shown in Equation 3.

The central high intensity pixels therefore influence the determination of the pixel location more than the surrounding low intensity pixels: i.e.,

$$x = \frac{1}{M}\sum_{i=1}^{n}\sum_{j=1}^{m} j.g_{ij}\, w_{ij}$$
$$y = \frac{1}{M}\sum_{i=1}^{n}\sum_{j=1}^{m} i.g_{ij}\, w_{ij} \quad (3)$$
$$M = \sum_{i=1}^{n}\sum_{j=1}^{m} g_{ij}\, w_{ij}$$

PRECISION OF TARGET LOCATION

In an extensive series of tests, the precisions of target location using Equation 3 have been determined on artificially generated targets with varying characteristics. Blurred targets, typical of those which would occur on photography, were generated by convolution of circular targets of varying sizes and Gaussian spread functions with 2σ-widths ranging from 10 μm to 50 μm. Typical 2σ-widths of spread functions found on aerial photography range from 15 to 25 μm (Trinder 1984). The result of this convolution was a profile across the target which was symmetrical about the target center, as no asymmetry was introduced into the spread function forming the blurred image.

The process of digitizing for a one-dimensional target involves the determination of the area between the intensity profile of a target cross-section and the dimensions of the pixel, as shown in Trinder (1987). If the target is assumed to be two-dimensional, the volume contained within the dimensions of the square pixel and the surface describing the intensity of the target have to be computed. The computed profile for a one-dimensional target was therefore rotated about the target center and the pixel values computed in scan-lines across a square window centered on the target. In order to obtain an estimate of the precision of pointing to targets, a displacement was introduced into the starting position of the pixels along the scan-lines. This meant that the distribution of pixels and their intensities would not necessarily be symmetrical on the center of the target, as demonstrated in Trinder (1987). An interesting aspect of this study was to determine the effects of the asymmetric distribution of the pixels on the target, on the precision of target location.

Having obtained the pixel values from this simulated process of digitizing, the next step required was quantization into a selected number of grey scale values which would be typically used in the process of digitizing an image. Eight different quantizations were selected for separate tests, giving $2^8, 2^7, \ldots, 2^1$ grey scale values, which means encoding into 8,7,. . ., 1 bits, respectively. Following quantization, the precision of target location was determined by repeating the pointing process 50 times for each target with the commencement of the scanning displaced for each new digitizing process by a random number varying up to ±1 pixel. Obviously, the exact position of the target was known on the artificially generated targets. A stan-

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dard deviation of pointing and the systematic error in target location could therefore be computed from the 50 pointings.

Noise was also introduced into the values of the pixels following digitizing but prior to quantization. The noise was computed as a random number within a positive and negative range of a certain percentage of the maximum intensity value of the target. The percentages chosen were 10 percent, 20 percent, 40 percent, and 80 percent, equivalent to signal to noise ratios (SNR) of 10:1, 5:1, 2.5:1, and 1.25:1, respectively.

Because this test was based on artificially generated targets, parameters of target size, image quality defined by the Gaussian spread function, pixel size, and noise level could be varied and the precision of pointing determined. In addition, it was possible to introduce targets whose profiles were subject to asymmetry in image quality, that is, different slope characteristics on one side of the target intensity profile than on the other. Subsequently, the effects on pointing accuracy and precision were determined.

The results of these investigations are presented in Figures 1, 2, 3. For the cases where image quality was symmetrical, there was no effect on the precision of pointing as the 2σ-width of the Gaussian spread function varied from 10 to 50 μm. In Figure 1 precisions of pointing are shown for a target size of 100 μm, and pixel sizes of 12.5 μm, 25μm, and 50μm against the number of bits used for encoding the data. In Figure 2 the variation in precisions are shown for ratios of target size/pixel size indicated and different levels of quantization. Larger targets were tested, but precisions of pointing to these targets were similar to those shown in Figure 2 for a ratio of target/pixel size of of 8. In Figure 3 are shown the variations in precisions of pointing due to random noise expressed in terms of SNR, for the ratio of target/pixel sizes shown on the curves, for a quantization of 8 bits.

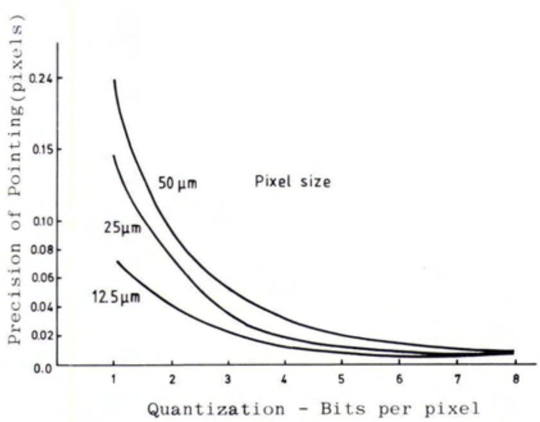

FIG. 1. Relationship between pointing precision and quantization level for a 100-μm target digitized with pixel sizes of 12.5 μm, 25μm, and 50μm.

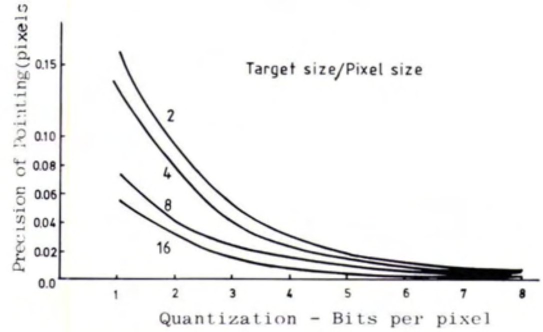

FIG. 2. Relationship between pointing precision and quantization level for target/pixel size ratios shown on the curves.

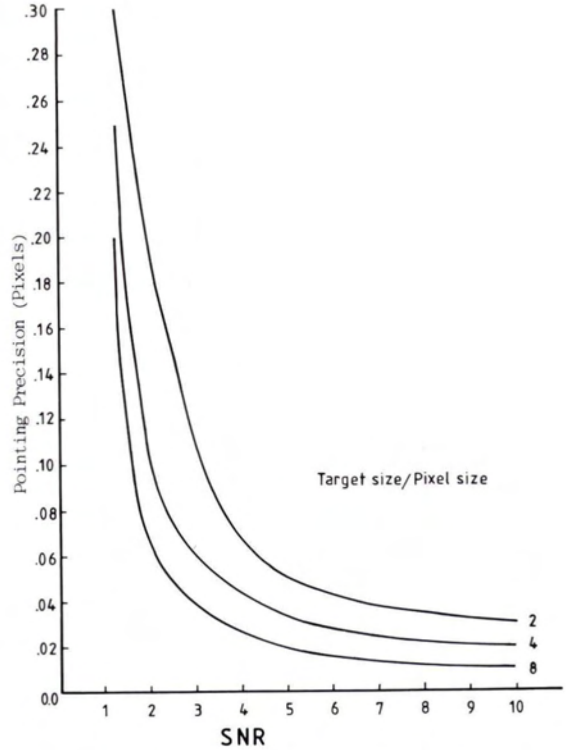

FIG. 3. Relationship between pointing precision and SNR for target/pixel size ratios shown on the curves.

The precision obtainable by digital pointing is approximately 0.01 pixel size and slightly better on certain occasions, as shown in Figure 1. This result has been obtained consistently for all target sizes and for all pixel sizes for quantization levels of 8 bits/pixel. There is a general deterioration in precision as quantization levels decrease, especially below 4 bits/pixel, but also as pixel sizes increase. Figure 1 indicates that a pixel size of 12.5 or 25 μm would result in consistently high precisions for quantizations greater than 4 bits/pixel. The influence of the relative dimensions of the pixel in relation to the target size is shown in Figure 2. It can generally be concluded that, if target sizes are too small, e.g., less than about 4x pixel size, the pointing precision will deteriorate. The precision also improves as the target size increases to 200 μm and indeed larger.

Defining Q as quantization, the sections of curves in Figure 1, for a quantization below 5 bits/pixel may be expressed by

$$\text{Precision} = Q^{-1.4} \cdot K \text{ [pixels]} \qquad (4)$$

where K is non-linearly inversely proportional to pixel size.

The variation in precision in terms of SNR in Figure 3 demonstrates that, for SNR greater than about 5:1, the precision is very similar to that with no noise, but below SNR of 5:1, clearly the precision deteriorates rapidly. This deterioration is even greater as the target size becomes smaller in relation to pixel size.

Curves in Figure 3 for SNR below 5:1 can be approximated by

$$\text{Precision} = (\text{SNR}^{m}.L)^{-1} \text{ [pixels]} \qquad (5)$$

where m varies from 1.7 to 1.2 for targets of 50 to 200 μm in size and L varies linearly with target size. For target size of 300 μm and greater, the relationship does not hold however.

The results of digital pointing obtained in this study particularly with regard to target image quality and size disagree with those shown in Trinder (1984) for visual observations, where pointing precisions deteriorate as target sizes increase and as image quality deteriorates. In addition in Trinder (1987) it was demonstrated that, for hardcopy digital images, RMS errors of 1/5 pixel size were introduced into the visual target pointing due to the asymmetric distribution of the pixels on the target. Such errors do not occur in digital pointing. It is also significant that in Trinder (1984) the SNR below which visual pointing precisions for circular targets deteriorated was about 5:1. There is therefore a striking similarity in both cases of visual and digital pointing in the levels of noise which affect pointing precision.

ACCURACY OF TARGET LOCATION

The accuracy of target locations derived in the above studies was of the same order as the precision. That is, for repeated pointings on symmetrical targets, the mean position of the target was the correct center within the precision of pointing. However, as the target profile becomes asymmetric, a simple pointing operation using the threshold in Equation 1 will result in significant errors in pointing. This phenomenon was investigated thoroughly by convolving the target with different spread functions on each side. Three nominal spread functions were adopted for the right hand side of the target, *viz*, 10,25, and 50 μm. Then the spread function defining the profile on the left hand side of the target was varied in steps of 5 μm from 5 μm to 50 μm. The systematic errors in target location were then derived. In addition, the threshold values were varied to investigate their effect on target location.

The deterioration in pointing accuracy as the asymmetry in the target profile increased is demonstrated in Figure 4. For threshold levels set at 0.14, 0.23, and 0.29 of the maximum pixel value (i.e., grey scale values, T, of 37, 58, and 74, respectively for 8-bit data), the target location varied significantly for different levels of asymmetry in target intensity profile. The investigations in this study revealed that, for a particular target size and the level of asymmetry, a threshold can be chosen at which the systematic error approaches zero, as shown by A and B on Figure 4. Similar graphs can be drawn for other sizes of targets, but it was found that the relationship is inversely proportional to target size. The overall relationship between target size and asymmetry in the target profiles is however, complex and therefore a simplified approach was investigated.

Considering practical applications of this work, it can be safely assumed that for most circumstances the asymmetry in the target intensity profile will not be greater than 20 percent. It can also be assumed that the approximate value of the spread function will normally be known. If it is not, then the spread function should be determined approximately because it influences the accuracy of the pointing process. A simple formula for the computation of the threshold has been derived assuming quantization to 8 bits, as follows:

$$\text{Threshold} = 74.(\text{SF})^{1.3} A^{-1} \quad (6)$$

where SF refers to the 2σ-width of the Gaussian spread function and A the target size. The maximum intensity value for quantization to 8 bits is 256.

Because the threshold value is dependent on the determination of the target size (it is assumed this is unknown in practical applications), an initial pointing was made on the target based on an assumed threshold. From this, the target size was computed and a new threshold value assigned according to Equation 6 for the final computation of the target center. This computation therefore involved two iterations of the pointing algorithm, which affected the processing time as shown in the next section.

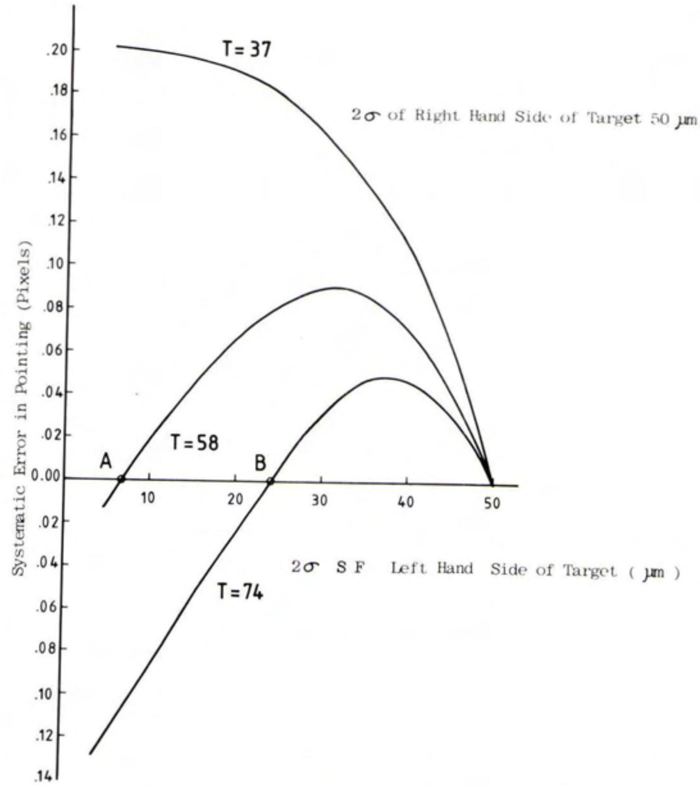

FIG. 4. Relationship between asymmetry in image quality of a target 100 μm wide and systematic error in the target location. Abscissa scale describes the 2σ width of the spread function defining the left hand size of the intensity profile of the target, while the right hand intensity profile of the target is derived by a spread function with a 2σ width of 50μm. Quantization is 8 bits (maximum value is 256). T defines the threshold chosen in the pointing computation.

Tests of this algorithm demonstrate that the choice of threshold is effective in reducing the systematic errors to 0.01 to 0.02 pixel with and without noise introduced into the data, except for cases where the target is small in relation to size of the spread function. Indeed, if the target size is very small, and the image quality asymmetric, it is impossible to locate the target accurately because the target profile becomes so distorted.

In Trinder (1984), the recommended optimum target sizes in relation to spread function width are given for visual observations. Such rules cannot be applied directly to digital pointing because different phenomena affect pointing precision in both cases. From the study of systematic errors in this paper, it is recommended that targets sizes should at least be 4 times the 2σ-width of the spread function of the system. Provided this rule is followed, systematic errors in pointing will be less than 0.02 pixel, if the correct threshold value is incorporated in the computation.

PROCESSING SPEED

Target location is a fundamental task which should be undertaken in near real time if camera positions are to be determined rapidly. Two computer configurations were tested with the same FORTRAN program code on an IBM AT (8 mhz) computer with and without optimization in the software and on an IBM 3090 main frame computer running at 18 MIPS with and

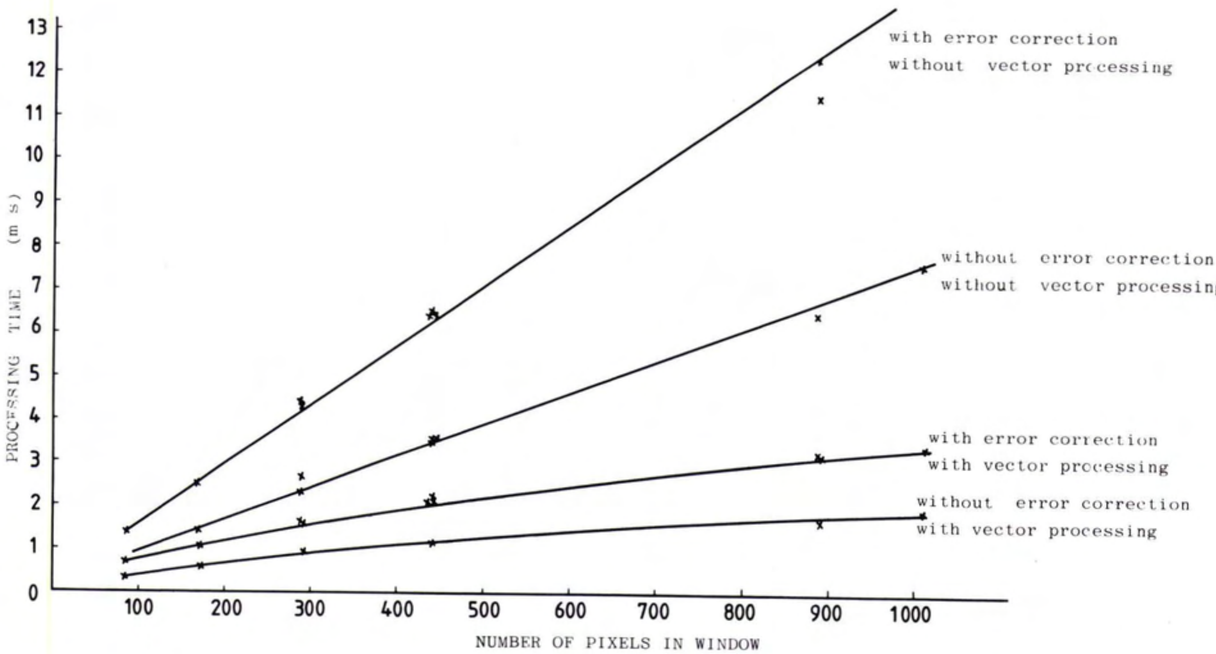

FIG. 5. Processing time for target pointing expressed in terms of the total number of pixels in the window for an IBM 3090 mainframe computer.

without vector processor. The vector processing in the software involved optimization by the operation system, but no special modification to improve the efficiency of the program. Results of the timing tests on pointing to various targets are presented in Figure 5 for the IBM 3090 computer, against the number of pixels in the window. Separate tests were done with and without error correction as described in the previous section. As expected, processing time is linearly dependent on the number of pixels in the window except when the vector processor is incorporated on the IBM 3090 where the processing time tended towards dependency on the width of the target window only. From these figures it is clear that processing time for location of small targets can be as little as 1 ms for the IBM 3090. A similar pattern of results was obtained for an IBM AT computer, but the average processing time is of the order of 1s.

CONCLUSIONS

The paper described tests carried out on the digital location of artificially generated circular targets of various sizes subject to a range of levels of blurring, noise, and quantization. The conclusions reached from these studies are:

Pointing Precision:

- within the ranges of image quality tested, there is no deterioration in pointing precision due to image quality;
- quantization at less than 5 bits/pixel will result in a deterioration in the precision of pointing;
- the precision of target location is affected by noise when the signal to noise ratio (SNR) is less than 5:1;
- where the quantization is equal to or greater than 5 bits/pixel, the precision will be a function of the relative sizes of the pixel and the target, and can approach 0.01 pixel in the best cases; and
- targets sizes should be chosen so that they are larger than 4 x pixel size and 4 x the 2σ width of the spread function of the system.

The systematic error in target location can be significant if there is substantial asymmetry in the target intensity profile. A procedure has been developed to reduce the effects of this asymmetry by the selection of an appropriate threshold, which is dependent on the average image quality of the optical system used to acquire the images.

Computing times for target location on PC and mainframe computers have been determined and found to to vary linearly with the number of pixels in the window. Processing time can be as little as 1 ms for small targets on a mainframe computer.

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