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BRL

APPLICATION OF DIGITAL MEASUREMENT TECHNIQUES TO ANALYSIS OF RANGE SHADOWGRAPHS

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Range shadowgraphs have been digitized using a solid state video camera and a relatively unsophisticated personal computer-based frame grabber board. Image processing, including edge enhancement and level discrimination were used to provide data files for further analysis. A simultaneous multiparameter least squares fitting program was used to determine position and angle of the projectile in the image relative to fiducial markers. Analysis of accuracy and guidelines for future production systems are given.

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1. INTRODUCTION

The acquisition of data on flight characteristics of various projectiles of interest to the Army is obtained in the same manner as has been the case for many years; that is, short flash duration light sources are used in free-flight ranges to produce a shadowgraph image on a sheet of film (Murphy 1954; Rogers 1958; Braun 1958; Schmidt 1983; Clay et al. 1989). By arranging a well measured fiducial system of markers from which shadows are included in the same image, measurements of the position and angles of the projectile can be obtained as a function of time and location downrange. The accuracy required from these measurements is 0.001 foot and 2 minutes of arc (Murphy 1954); this distance number translates to approximately 0.001 inchs on the range film. Since the films also record shock patterns for supersonic projectiles, additional information about the flight characteristics can be obtained.

Presently at the Launch and Flight Division (LFD) of the Ballistic Research Laboratory (BRL), the information is obtained from the photographic records by manually measuring the position of the shadow image of the projectile body in relation to the fiducial markers. The possibility of using an alternative technique to digitize and measure the same parameters using computer numerical techniques had been suggested previously both here and at other laboratories, and even designed conceptually (Brown and Parker 1984), but because of a lack of both funding and the required experience with apparatus and techniques, no tangible progress was made in that direction at BRL.

Although those persons responsible for the overseeing of the data reduction have long been aware that digital image techniques were probably a superior approach, resources were not available to explore their application. The authors had earlier developed digital image measuring techniques for an unrelated effort. Discussions with LFD personnel led to an unfunded project to explore applying these techniques for Transonic Range (LFD) photo data reduction, with the obvious extension to Aerodynamic Range (LFD) photos if successful. The main goal was to demonstrate whether digital image techniques were appropriate, and if so, to define the level of resolution required for a useful system. This report is the summary of that study.

2. DESCRIPTION OF APPARATUS

The system used to digitize the image and measure the parameters was based on an IBM PC/AT computer equipped with 512 kilobytes of memory. The camera used was a Pulnix model TM-3400 charge coupled device (CCD) monochrome television camera, with 384 vertical by 485 horizontal rows of pixels. The pixels have an aspect ratio of 1.712:1. As an order of magnitude estimate, if the imaged area is approximately three inches square, and the camera is approximated by a 400 by 400 pixel device, then each pixel would map onto a 0.0075-inch square. The image was digitized to 8-bit precision, stored, and displayed on a separate monitor by a Datacube model IVG-128 frame grabber. The memory of this plug-in board was designed to map the CCD pixels onto a 512 by 512 byte memory area on a one pixel-to-byte basis, with the extra memory ignored and not displayed. This frame grabber plugged into the PC bus and was addressed as segment nine of the available memory space. This architecture limits the computer to a maximum of 512 kbytes of memory. Because of this limitation, this board is now obsolete.

A package of range shadowgraphs was provided by the LFD. Each image is a 4 x 5 inch (10.2 x 12.7 mm) negative of reasonably high contrast. The images measured were part of round number 30490, a re-creation of the 155-mm Paris Gun projectile. The round was fired at the BRL Transonic Range Facility. Digitization was done by placing a negative on a light box, varying the camera distance until a suitable image was observed on the monitor, at which time the image was saved.

The software used to control the image acquisition and manipulation process was developed in-house as part of earlier efforts. The menu choices include standard image processing algorithms such as edge enhancement, calculation and display of the histogram of gray levels, selection of pixels with only certain gray levels, remapping the gray levels to fill a chosen dynamic range, writing the coordinates of selected points to an ASCII data file for further analysis, and image storage, refresh, and retrieval. Because of the research orientation of the team who developed this software package, there is much flexibility and control over the execution of functions. Much of this flexibility was important to the timely and efficient exploration of critical elements of the data reduction and fitting. The image analysis software will not be described in more detail, since it was written for a specific board.

3. THE RELATION BETWEEN DIGITIZATION RESOLUTION AND MEASUREMENT ACCURACY

A major issue to be determined by this study was the pixel density required when digitizing the image in order to get the necessary accuracy. Although a thorough analysis effort could have been done, it was decided that with the number of uncertainties involved it was better to try some sample photographs and evaluate the results. One exception was made; the variation of accuracy in fitting the image of a straight line as a function of the angle of the line with the pixel rows was explored. This was done by writing a simple Pascal program to generate synthetic data and then fitting these data with the FITTER program. (This program, the creation of A.J. Kotlar, is a vigorous simultaneous multiparameter least squares fitting program which has been adapted to a wide range of spectroscopic and physical/chemical functions, but has never been documented in a form to be referenced.) Although the projectiles do have important curved contours, much of the preliminary fitting will involve straight lines. As will be seen, these lines can also give good insight to the importance of angular variation.

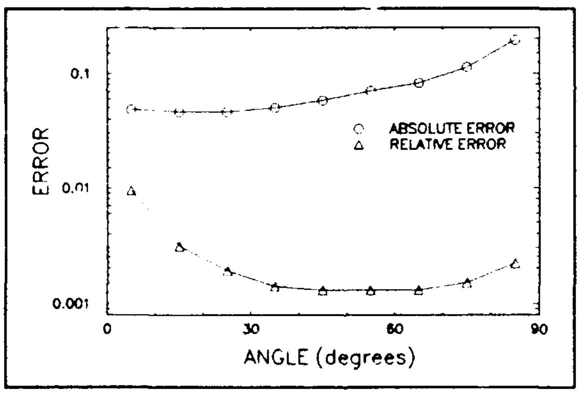

Figure 1. The Absolute and Relative Angular Error for a Fixed Length (1 Inch) Line Five Pixels Thick.

The lines used in the first part of these "experiments" were approximately 5 pixels high and one inch long, assuming magnification ratios as described above. Figure 1 shows that the absolute error is not a strong function of the angle of the line, with the relative error a minimum when the line is at 45 degrees with respect to the pixels. Thus one would desire that the dominant lines of the image to be digitized are oriented near 45 degrees to the pixel columns if possible.

Figure 2 exhibits the calculated absolute error in slope (angle) and intercept (position) for lines which are 5 pixels thick but of varying length. Significant in Figure 2a is that the number of pixels has a larger effect an absolute error than the angle, as shown in Figure 1. Figure 2b shows that the effect of angle with the pixels is more important with shorter lines in uncertainty in the position of the line. This figure also shows that if the line is oriented near 45 degrees to the pixels, large numbers of pixels do not give greatly decreased absolute position error.

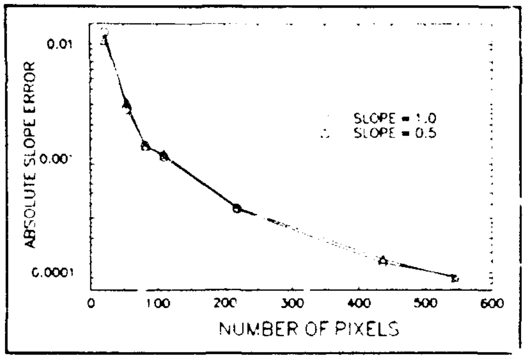

Figure 2a.

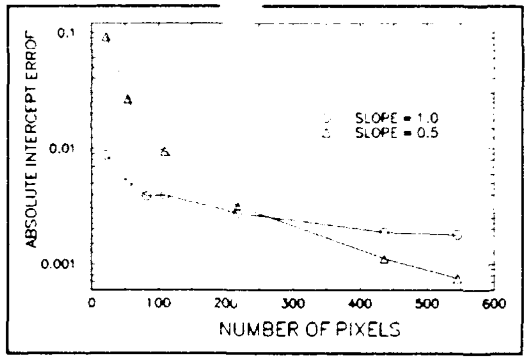

Figure 2b.

Figure 2. The Variation in Error of (a) Slope and (b) Intercept as a Function of the Length of Line in Pixels for Slopes of 1.0 and 0.5.

4. METHODOLOGY OF FITTING IMAGES

The image data were analyzed in a manner that was somewhat labor intensive, but adequate for this exploratory study. Images were digitized using the equipment described previously. A digitized image was then manipulated to enhance the projectile edges and the fiducial beads and wire. The level of enhancement varied from image to image as well as being different for fiducials as compared with the projectiles. Typical examples are discussed with more specific information and reasons for choices. After digitization, five files were created consisting of the cartesian coordinates and intensity of the selected (enhanced) points from the top fiducial bead, bottom fiducial bead, top edge of the projectile, bottom edge of the projectile, and base of the projectile. The five files were then consolidated into one file with identification of the points carried within the file (i.e., top bead points were known to be from the top bead and so fitted). A function was written for FITTER to fit this data set in the usual simultaneous multiparameter least squares manner to the corresponding set of two points (fiducials, and parallel sides and perpendicular base of the projectile. The latter three lines were assumed to be straight lines, which was not precise but was adequate for this study.

5. FITTING OF SYNTHETIC IMAGES

The results of the brief study above suggest trends with regard to angle and number of pixels digitized. However, the interplay of these various factors could be extremely complicated in a complete image. In order to get a better feel for how well this technique works without the disadvantages of a potentially noisy actual range photo, two images were drawn of a simple bullet-shaped projectile with the fiducial marks (dots) on a line passing through the projectile (perpendicular to its axis) and on a similar line passing well ahead of the projectile front. Since these images were high contrast line images, no image analysis or modification was required after digitizing, as with the actual photographs. In the first case, the image of the projectile can be digitized with a much larger number of pixels, while in the second case fewer pixels are available because much of the image area is used to record the fiducials. These two images provide an opportunity to compare the effect of pixel number in the digitizing device by using different numbers of the available pixels to digitize the projectile. In both cases, the image was oriented such that the axis of the projectile was aligned at about 45 degrees to the pixels. The results of this exercise are summarized in Table 1. As can be seen, the angular uncertainty (one standard deviation) is greatly reduced when the image of the projectile covers more of the pixel area. Level of uncertainty of Figure 3a is certainly well within the range of required values. It is not immediately clear why the corresponding uncertainty obtained for the intercept is larger for the same case. Most of the real photographs to be analyzed are much like the "front" case, since the flash lamps are triggered so that the projectile does not obscure the image of the fiducial beads.

Table 1. Fits to Synthetic Data

LOCATION OF FIDUCIAL DOTS	ANGLE (deg)	INTERCEPT
FRONT (Figure 3b)	6.17 ± 0.14	191.7 ± 0.2
SIDE (Figure 3a)	3.292 ± 0.008	253.7 ± 0.4

6. ANALYSIS OF RANGE SHADOWGRAPHS

The range negatives were digitized as described previously. A series of relatively simple image enhancements were then performed. The first was to stretch the histogram of the digitized image to fill the 8-bit dynamic range of the display device. While this step does not change the information content of the image, it does make the contrast higher and allows the operator to see components better. The examples shown here are for image 12W (station 12, wall camera).

Figure 4 shows the histograms before and after this operation. As can be seen, before the operation a large number of the pixels are in the top third of the dynamic range, which indicates a picture that is "overexposed". By mapping those pixels over the entire dynamic range, as shown in Figure 4b, the image is clearer on the display.

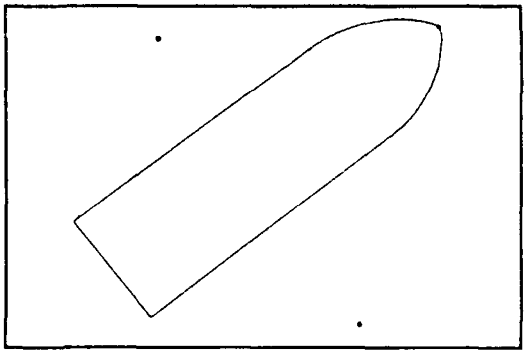

Figure 3a.

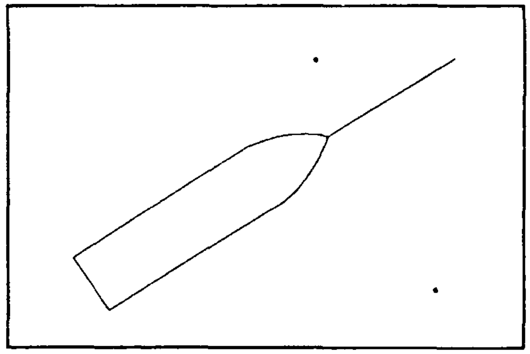

Figure 3b.

Figure 3. Synthetic Images Used to Demonstrate the Effect of Having the Fiducial Beads at the Side and in Front of the Projectile.

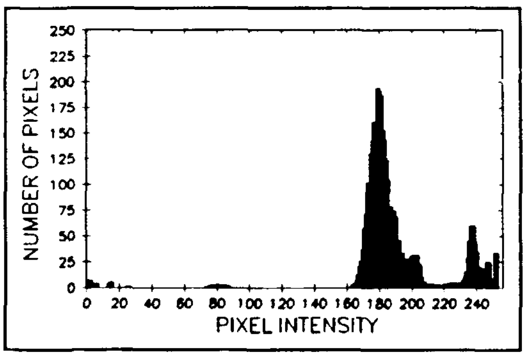

Figure 4a.

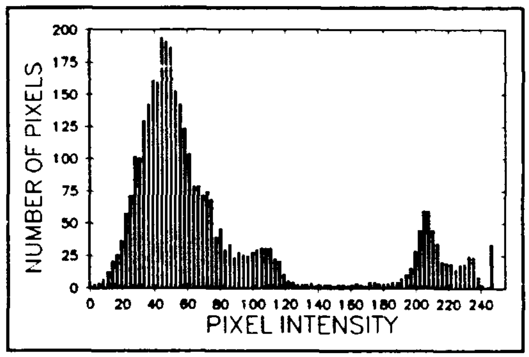

Figure 4b.

Figure 4. Histograms of Pixel Intensity (a) as Acquired and (b) Stretching the Histogram Over the Full 8-Bit Dynamic Range.

Figure 5 is a photograph of the display screen showing the digitized image with the modified histogram. In addition to the shadow of the projectile and the shock waves from it, which are in focus, the projectile itself is partially visible, but out of focus. Perpendicular to the axis of the projectile and just ahead of its nose is the piano wire which holds the fiducial beads, one of which is visible just in front of the actual projectile.

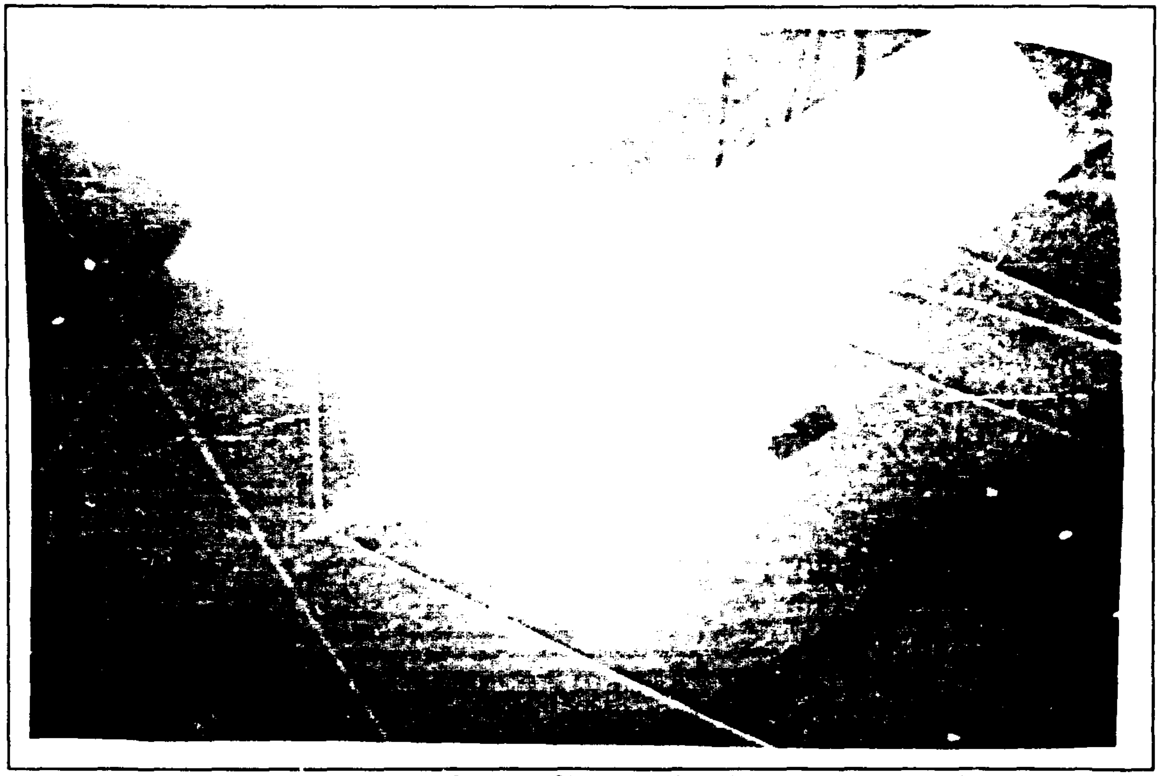

Figure 5. Photograph of Display Screen Showing Digitized Negative 12W.

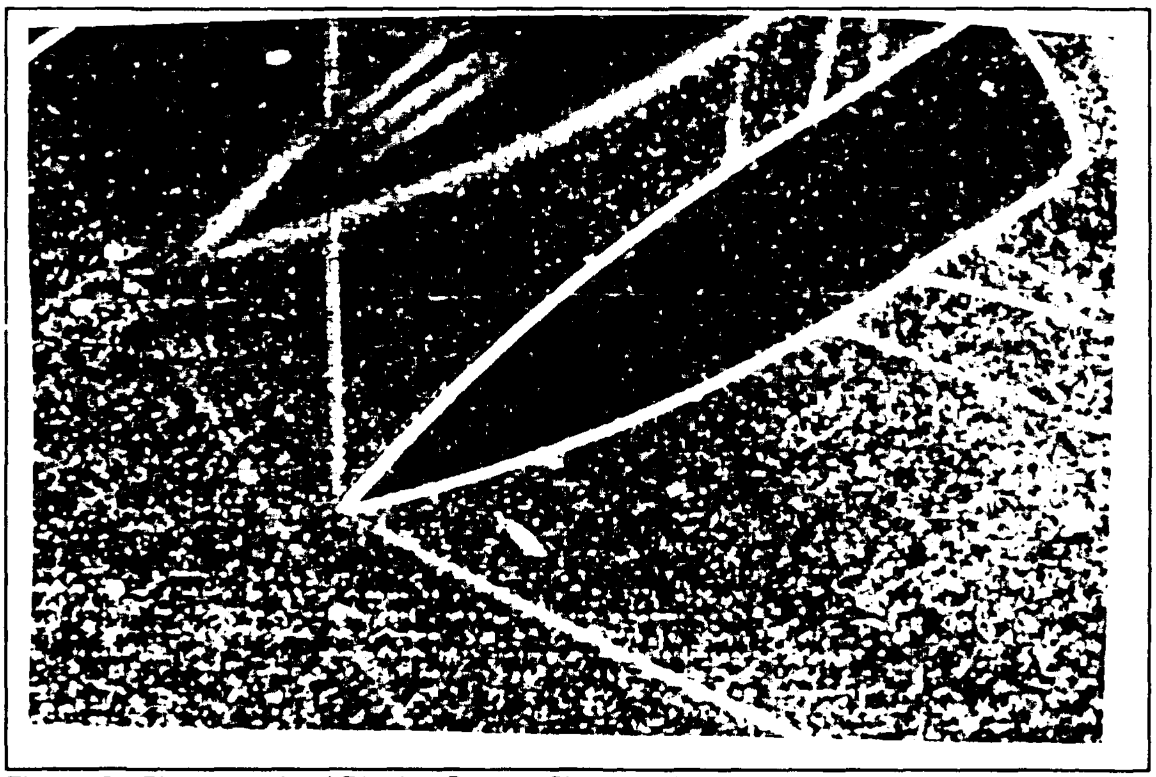

Figure 6. Photograph of Display Screen Showing Edge Enhanced 12W.

In order to do a computer analysis of the information which a human eye quickly comprehends in an image such as Figure 5, we need to reduce the content greatly. The first step in this procedure was to enhance the edges in the image; that is, to make a new image in which the edges of the original are highlighted and other features are suppressed. There are several standard ways of doing this operation. The most effective, and the one used here, is to take a local 3-point derivative in four directions (horizontal, vertical, two diagonals) at each pixel and replace the pixel with the maximum of those derivative values. The result of this operation on Figure 5 is shown in Figure 6. This figure shows a sharply defined outside edge of the projectile, a bright spot for the bead, and a great deal of clutter which can be easily eliminated. The contrast is even greater on a typical display screen where pseudo-color is used to enhance differences in intensity. Note that the wire which holds the fiducial beads is very weak in the edge-enhanced picture.

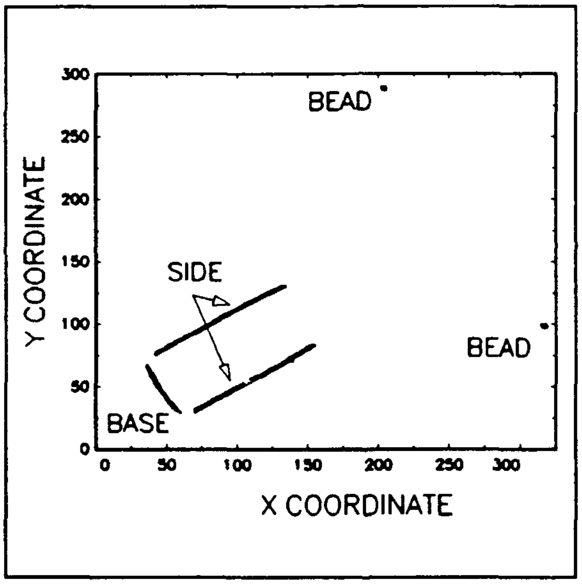

Figure 7. A Plot of the Basic Data Set From Images Shown in Figures 5 and 6.

The next operation is to threshold the image, that is, to zero the intensity of pixels which are not above a selected value which will include most the lines which we want to retain. This operation removes most of the background clutter in the image. In this manual selection exercise, the operator then singles out in turn the data in five rectangular regions to be fit (top bead, bottom bead, projectile top, bottom, and base) and writes the coordinates of the nonzero points to disk files. The use of rectangular regions to select the data points for fitting made discrimination against noise pixels somewhat difficult. Although the edge-enhanced image of the projectile was required for the computer fit to these photographs, the original image was better for analysis of the fiducial beads (and the connecting wire when it was used). Thus, the data set fit by the model was a composite of the edge of the projectile and the beads. A plot of these five components for photo 12W is shown in Figure 7. There are a total of 1141 points in this data set.

The FITTER program has a provision for rejecting data points that are too far from the fitted result; the criterion is specified in either absolute term or as a multiple of standard deviations of the overall fit. Because there are some outlying points which the eye would clearly like to reject, but which are not easily discriminated against in the data set selection, this option was used (carefully) to improve the fit of the model to the data. Two fitted values were tracked: the angle listed is the angle of the centerline of the projectile with respect to the normal to the line connecting the fiducial beads; the intercept is the intercept of the line fit to the top edge and bottom (assumed to be parallel). Thus, these two values, and in particular their uncertainties, give a good indication of the statistical uncertainty in the fit of the model to the image data. A list of the values with different rejection criteria is given in Table 2. Rejection with more stringent criterion, such as 1.5 standard deviations, resulted in only 26 data points remaining and a correspondingly poor fit. As can be seen from this table, most of the gain in statistical precision is achieved in the rejection of points which lie at least three standard deviations from the fit. This rejection process is done in an iterative manner so that points can move back into the fitted data group as the value of the parameters varies.

Table 2. Effect of Rejection of Outlying Points on Fit to Image 12W

POINTS INCLUDED (number)	ANGLE (deg)	INTERCEPT (pixels)
ALL POINTS (1141)	-1.1 ± 0.2	313.3 ± 0.5
WITHIN 3σ (1071)	-0.74 ± 0.08	312.0 ± 0.2
WITHIN 2σ (950)	-0.73 ± 0.07	312.1 ± 0.1
WITHIN 1.75σ (696)	-0.63 ± 0.06	311.7 ± 0.1
WITHIN 1.65σ (283)	-0.38 ± 0.04	310.82 ± 0.07

Although these values were close to acceptable, a look at the original image, as seen in Figure 5, shows that we are not using all of the data present. In particular, much of the angular uncertainty was found to arise from the poor definition of the reference line through the two beads. In order to define this line better, the obvious next step is to include the image of the wire which holds the beads. Although the eye sees this as an obvious straight line, attempts to separate it from the background clutter using simple algorithms were not successful. Thus, an image file was written to include the line and the surrounding noise pixels, as shown in Figure 8. In part, this lack of discrimination was due to the nonuniformity of the light box illuminating the negative. The data files were written with the two rectangular areas included with the adjacent bead. The beads are indicated by arrows in the figure. The total number of data points in the image file is 2959. A fit with all of these points does not draw an acceptable line through the beads, so fitting was started by fixing the line through the beads (from an earlier fit using only the beads), and rejecting the outlying points to get rid of the obvious clutter. Figure 9 shows the data that remain with the three standard deviation criterion applied. Table 3 shows the results of these fits to data.

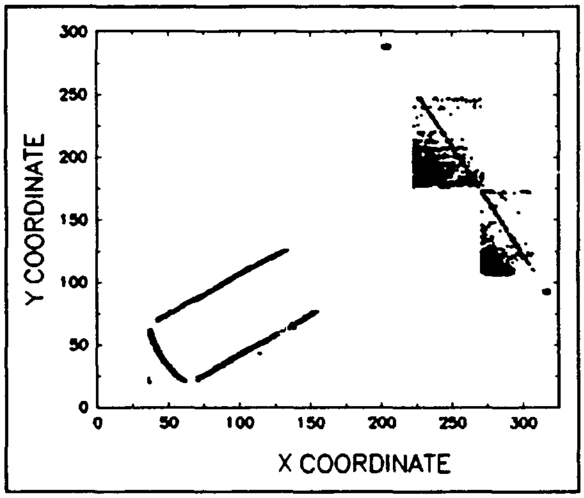

Figure 8. The Expanded Data Set From Figures 5 and 6 with Inclusion of Wire Connecting Beads and Surrounding Area.

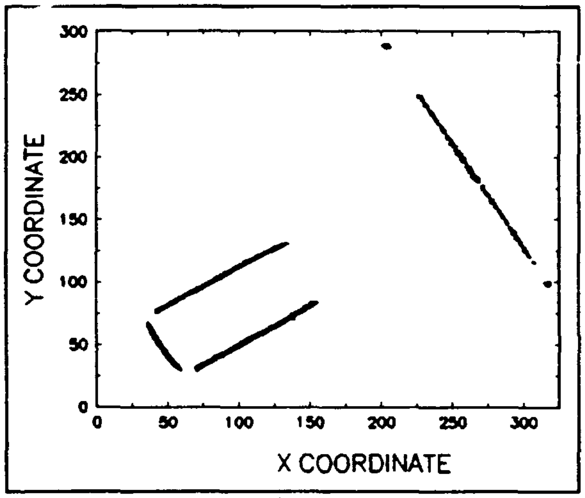

Figure 9. The Data Set for Figure 8 After Rejection of Points 3 Standard Deviations Outside of Fitted Values.

Table 3. Fit to Data with Inclusion of Wire Between Beads

POINTS INCLUDE (number)	ANGLE (deg)	INTERCEPT (pixels)
WITHIN 4σ (1534)	-0.6 ± 0.1	312.1 ± 0.3
WITHIN 3σ (1455)	-0.57 ± 0.08	312.0 ± 0.2
WITHIN 2σ (1248)	-0.59 ± 0.06	312.1 ± 0.1
WITHIN 1.5σ (53)	-0.43 ± 0.009	311.6 ± 0.02

In the values given in Table 3, compared with those in Table 2, the standard deviations of the fits were slightly better, but the fitted value of the angle changed by almost 20 percent. The intercept, which is generally less of a problem, remains the same. The second method contains more information and should be a better fit. This result will be discussed in more detail below.

7. DISCUSSION

If this technique is to be applicable to the photographs which must be measured, two points must be addressed. The first is whether the required accuracy can be attained. The second is the effect of discarding data, as in the previous section.

The precision of these measurements is directly related to the statistical uncertainty of the values from the fits to the image files. For comparison, the stated accuracy for manual measurement of the photographic plates is 1×10^{-3} in (on the plates) for position and 5×10^{-2} deg for angle (Rogers 1958). (These values are the manufacturer's stated accuracy of the measuring device and do not reflect uncertainty due to the judgement of the operator. There are no available data on reproducibility of the measuring techniques.) Since a pixel side dimension corresponds approximately to 7.5×10^{-3} in on the film, an accuracy of 0.2 pixels, as in Table 3, corresponds to about 1.5×10^{-3} in, or slightly worse than the presently quoted equipment specification value. This uncertainty can be reduced by about a factor of two with a higher resolution device where each pixel corresponds to a smaller dimension on the film.

The angular uncertainty with the digital method is typically 0.8 degrees. However, as was seen with the "synthetic images," if a sufficiently large array of pixels is used, precision of better that 0.01 degrees is readily achievable.

Of considerable concern is the variation in the fitted angle values of Tables 2 and 3. These are in contrast to the intercepts, which appear to be fairly stable for reasonable choices of rejection criteria. The first problem of note is the difference in the angle values between Table 2 and Table 3; those in the former are consistently larger than in the latter. Since these results are all from fits to the same data, one could get a false sense of accuracy based on the standard deviations of the fits. Even with a "man in the loop," it might seem reasonable to accept results such as in Table 2. The principal difference between these two tables is in the definition of the reference line from which the angle is measured. Although not explicitly mentioned, it was quite clear throughout this study that beads-on-a-wire are a less than desirable type of fiducial for digital imaging. They were apparently chosen to be small so that they could be mounted near the projection screen but not have overlap between the image and shadow. Thus, a manual measurer can probably distinguish the center of the bead with reasonable accuracy, whereas the digital (automatic) system is combining the bead image and shadow together and drawing the reference line through the combination. With the incorporation of the image of the piano wire that holds the beads, the line becomes well-defined for angular purposes and the beads are needed only for spatial reference, for which they are adequate. This observation suggests that it might be desirable to develop a different fiducial system based on shapes that are easily sensed and fitted by a digital system. For example, two lines that intercept at a well-known vertex could be fitted with moderate resolution and the orientation of the digital image fixed with excellent accuracy. Such changes should be part of a well-considered effort that includes the possibility of incorporating modern measuring techniques such as interferometry or laser radar to calibrate the position of the fiducial object. If one were to idealize the direct digitization of the image without a film intermediate, then a computer controlled system could place the camera pixels in space with superior accuracy and in a manner subject to ready verification.

The second point of note in the Tables 2 and 3 is the variation of angular values as "outlying points" are rejected. It is possible that the variations in Table 2 are largely due to the inclusion of image and shadow in the data set (correctly only the shadow should be included). The data of Table 3 are much more like that anticipated in a production system, and show reasonable consistency until large percentages of the data are rejected. For this study, it is reasonable to reject outlying data points at the three standard deviation levels. Part of the difficulty lies in the inherent width of the edges of the projectile (typically five pixels) as well as uncertainty in the fiducial marker positions. It is easy to conceive of a system that allows more precise manual discrimination of the desired image data points and therefore eliminates any need for computer discard of data. Keeping a "man-in-the-loop" as part of the analysis system would be desirable from this point as well as having an immediate check of the results by projecting the calculated fitted image values onto the original digitized image.

8. RECOMMENDATIONS

Based on these exercises and discussions, the following recommendations are made for the design of a semiautomatic system to make position and angle measurements from range negatives.

Imager:

A fixed dimension solid state imager with excellent geometric stability is required.

The imager should be least 1000 pixels square.

Pixel dimensions are not critical.

Greater numbers of pixels will improve accuracy.

Fiducial markers:

The beads are adequate but far from optimum for this type of semiautomatic measuring system.

A fiducial marker with lines intersecting at a vertex could be placed with much greater accuracy.

Modern metrology techniques should be incorporated if a new design is pursued.

Man-in-the-loop:

Human interpretation remains highly desirable for the first generation system.

The level of training should be greatly decreased, and a moderately skilled operator should be able to exceed the best operators using the present technique.

Other desirable features:

An on-line storage system using compressed data which allows the firing engineer to review the images with computer fits might allow insights in data analysis.

Baseline data should be obtainable for a future system which uses multiple solid state imagers at each station. Such a system should become economically feasible some time after the introduction of consumer high definition television products (HDTV) which are now under development.

9. SUMMARY

An inexpensive desktop computer-based image processing system has been used to define the accuracy available from digital measurement of range photographs. The results show that a system could be assembled from readily available commercial hardware and custom software that would provide a routine measurement capability comparable with the results of the best trained operators of the present measuring system.

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