TIME MATCHING OF SEPARATE CINE CAMERA VIEWS FOR THREE DIMENSIONAL MOTION STUDIES

by

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Abstract

The purpose of this study was to evaluate the importance of time-matching separate cine camera views in three-dimensional motion studies and to develop analytical methods to accomplish the time matching. An image space was calibrated using twenty-four control points and motion picture films at about 60 frames per second were taken of a moving bar, and of a subject putting a shot. Combinations of correctly and incorrectly matched views were compared for their accuracy in determining the positions of six object points. An algorithm was derived which included the timing variable in the least squares solution for the X, Y, and Z coordinates. These "best fit" solutions for the timing and for the coordinate locations were compared with criterion values.

Alterations in the timing of views tended to introduce a bias into the coordinate locations. The magnitude of the bias was a function of the velocity of the object points and of the camera positioning. To keep final coordinate errors below 5% required the two views to be matched to within 0.008 seconds. The time matching algorithm was able to match the views to within 0.005 seconds. The corresponding coordinates could vary by an average of 2.4% from the correct ones. It was concluded that the analytical time matching algorithm could produce acceptable results if extreme accuracy was not required.

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Acknowledgements

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Introduction

The study of human motion in three dimensions using cinefilm is not a new idea (Miller, 1970; Van Gheluwe, 1973). Several techniques are available (Woltring, 1977; Walton, 1981; Dapena et al., 1982) which considerably simplify the procedures involved. One of the added complexities of three-dimensional techniques over two-dimensional ones is the need to time synchronize separate views. Although single view methods have been developed (Miller et al., 1980) they are of comparatively low accuracy and unique solutions are not always attainable (Woltring, 1981). Several time matching techniques are in use (as will be outlined later), but all lack general applicability to movements such as those that occur in real sporting activities.

Purpose

The purpose of this study was to evaluate the importance of time matching separate cine camera views in three-dimensional motion studies and to develop analytical methods to accomplish the time matching.

Methods

Theory

The simplest photogrammetric process used to locate an object point in three-dimensional space utilizes a pair of two-dimensional views. Intuitively, this leads to the conclusion that more information is provided in two views than is needed to solve the three-dimensional problem. This is confirmed when the problem is mathematically solved. Abdel-Aziz and Karara (1971) developed a mathematical model called the Direct Linear Transformation (DLT) to relate digitizer coordinates to object coordinates in real space. Walton (1981) applied a similar technique to problems in human movement. In Walton's method, solving the following four equations yields values for the three-dimensional coordinates of an object point.

$$(a_1-e_1u_1)X + (b_1-f_1u_1)Y + (c_1-g_1u_1)Z = (u_1-d_1) \quad (1)$$
$$(h_1-e_1v_1)X + (j_1-f_1v_1)Y + (k_1-g_1v_1)Z = (v_1-d_1) \quad (2)$$
$$(a_2-e_2u_2)X + (b_2-f_2u_2)Y + (c_2-g_2u_2)Z = (u_2-d_2) \quad (3)$$
$$(h_2-e_2v_2)X + (j_2-f_2v_2)Y + (k_2-g_2v_2)Z = (v_2-d_2) \quad (4)$$

(Where u_1, v_1, u_2, v_2 are the measured digitizer coordinates for a particular object point and coefficients 'a' to 'l' are known calibration values).

This system of equations is overdetermined, as there are four equations and only three unknowns (X, Y, Z).

If the experiment was error free, any three of the four equations would yield a correct solution. In reality, a "best fit" solution may be found by using a linear least squares technique. This solution, when substituted back into equations (1) to (4) results in residual errors. The square root of the sum of squares of the residuals for equations (1), (2), (3), and (4) is called the minimized euclidean norm of the residuals. This norm is an indicator of how well the four equations agree on the solution (Walton, 1981).

To calculate accurate coordinates the two sets of data must be time matched. When this is not the case the residual errors should increase, although experimental variations might obscure this fact for a single point. If, however, the norm is calculated for all of the points in a frame, an optimal time match should be revealed. An iterative procedure can be performed to determine which time match produces the minimum norm of the residuals.

There is one problem which must be overcome before the time matching of separate digitizer coordinates can be attempted. Each camera does not record events at the same instant of time, therefore a method for finding intermediate values for at least one camera must be found to enable matching between the views. Figure 1 illustrates the problem.

THE TIME MATCHING PROBLEM

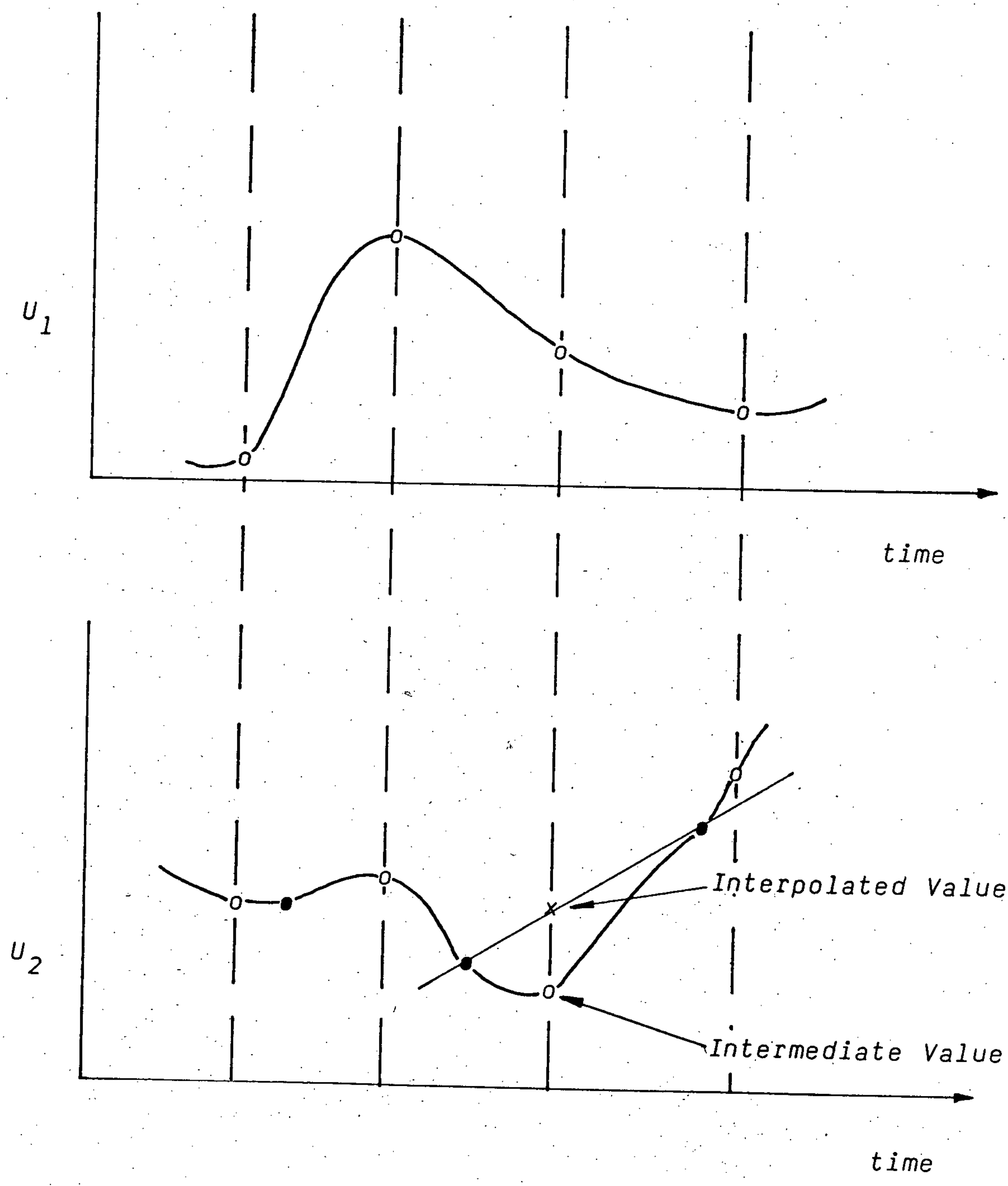

FIGURE 1.

In Figure 1, U_1 represents a digitizer coordinate for camera one, while U_2 represents a digitizer coordinate for camera two. The open circles represent the desired values from the camera two data while recorded data is indicated by solid dots. A linear interpolation between the two actual values will produce a reasonable approximation to the desired intermediate value (Walton, 1981).

Procedures

16 mm films were taken of two motions to investigate the time matching problem. Initially a 50 cm long wood bar was marked at 10 cm intervals. 24 beads spaced at 10 cm intervals were strung on cord to serve as control points for calibrating the camera. The control points defined a Cartesian Coordinate System with Z being vertical. A Redlake Industries Locam camera operating at 50 frames per second was used to film the bar after it was put in motion. Figure 2 is a diagram of the equipment set-up.

In test two , an unskilled subject was filmed while performing a shot put. Two Locam cameras were used, one operating at 60 frames per second and the other operating at 180 frames per second. The higher speed was used to permit a closer estimated time match between the views. The spacings between the 24 control points were increased to 20 cm to accommodate the large object space required for the shot put (110 x 108 x 100 cm). See figure 3 for a diagram of the set-up.

TOP VIEW OF SET-UP FOR TEST ONE

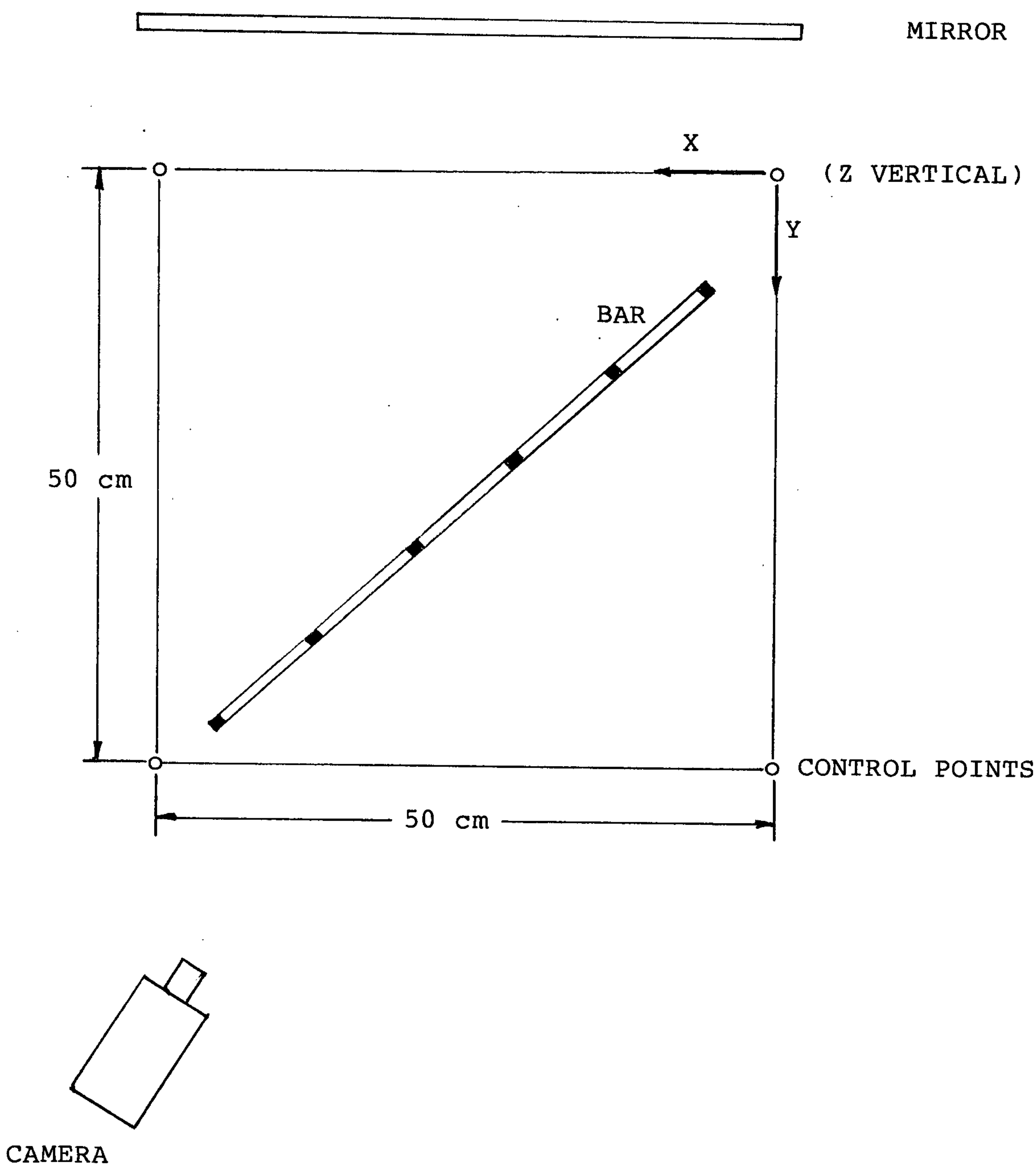

FIGURE 2.

TOP VIEW OF SET-UP FOR TEST TWO

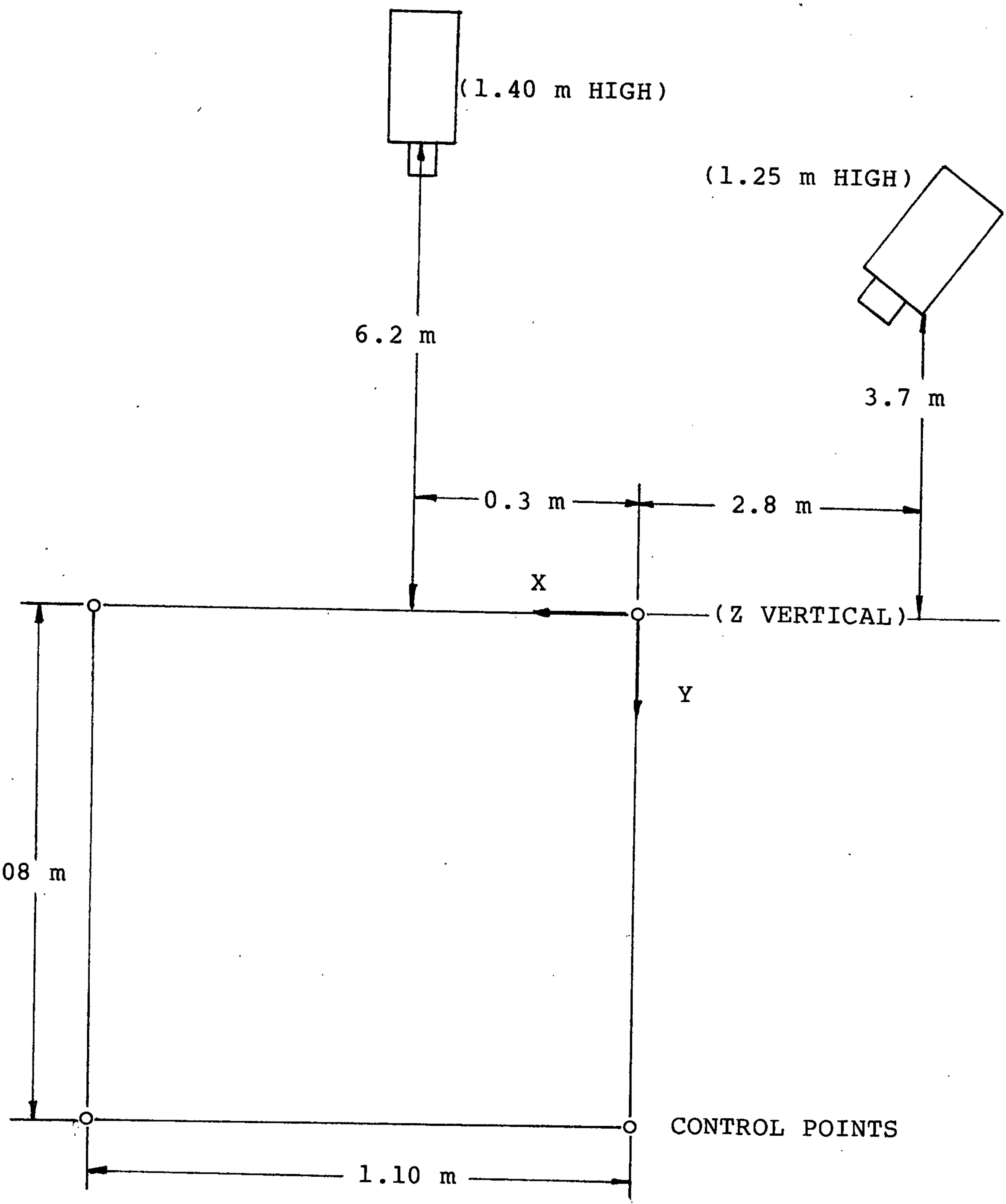

FIGURE 3.

Data Collection and Analysis

Films were projected at approximately 1/6 life size and digitized with a Numonics Graphics Calculator interfaced with a Micronova MP 200 computer (Data General). Test one was implicity time matched because both images were recorded on one frame at the same instant. To determine the most accurate time match for test two, the point of release of the shot for the slower camera (60 frames/s) was matched to the faster camera's (180 frames/s) release point. This should have been accurate to within one third of one frame, or .006 seconds. The six marks on the bar were digitized in the first test. For the second test markers at the wrist, elbow, hip, top of knee, bottom of knee, and ankle were digitized. As well, two of the control points were also digitized in each frame to provide an estimate of the noise in the data .

Two computer programs (JSW3D and JSWFILT) from Walton (1981) were modified to run on the Micronova computer. JSW3D was adapted to interpolate new U and V values from one digitized view and produce X, Y, and Z coordinates for a number of different time matchings. To obtain the minimal time match an interval one frame wide on either side of the best estimated match was defined. This was divided into three segments and the segment containing the minimum was isolated. This segment was then further subdivided into three parts for the next iteration. The procedure stopped when a change of less than 0.01 seconds was observed between iterations.

Results and Discussion

Noise in the Data

The coordinates of the control points in test two should have remained constant because they were stationary in the object space. Any apparent movement could only be due to noise from the digitizing or analysis procedures. The apparent movement due to noise, averaged over 30 frames, was 0.52 cm for X, 0.62 cm for Y, and 0.20 cm for Z. This compares favorably with values Wells and Winter (1975) found. Their data would predict a value of 0.4 cm for a 1/6 life size image. To express these errors in percentage terms, the dimensions of the object space were used as the maximum excursions a point could take. The object space enclosed by the control points had the following dimensions:

X = 110 cm, Y = 110 cm, Z = 100 cm.

Corresponding percentage errors would be:

X = 0.47%, Y = 0.57%, Z = 0.20%.

Interpolation Errors

The U and V coordinates used in the time matching algorithm were somewhat inaccurate due to interpolation error. The magnitude of this error was estimated by calculating the difference between actual and interpolated values for the 180 frames per second camera.

Using every third value to interpolate for the intermediate two resulted in an average difference of 0.5 cm, with a maximum difference of 1.2 cm. Since the actual interpolation interval would be 1/3 as large, the interpolation errors would also be expected to be 1/3 as large (0.4 cm maximum and 0.17 cm average). This is only about 0.15% error, thus interpolating seems to be a valid procedure.

Consequences of Mismatching the Timing

Figures 4 to 9 illustrate the effects of altering the timing for the wrist and elbow markers of the shot put test. Since the movement reached peak velocity in frames 17 to 36 this data was selected for the graphs. The lines marked by an 'x' are the coordinates for the best estimated time match. The lines marked by an 'o' are for a timing mismatch of 0.015 seconds (approximately one frame). The lines marked by a '+' indicate a mismatch in timing of 0.035 seconds (two frames). It is evident that the Y coordinate (Figs. 6 and 7) is affected the most by the time offset, although it is moving at about 1/2 the speed. The maximum difference in coordinate location that a mismatch of 0.015 seconds produced was about 12 cm (11% error). Note that the situations illustrated would be unlikely to occur in practice because a time mismatch of a full frame (0.0167 seconds) would be evident to casual observation.

POSITION OF THE WRIST IN THE X DIR. FOR TEST 2

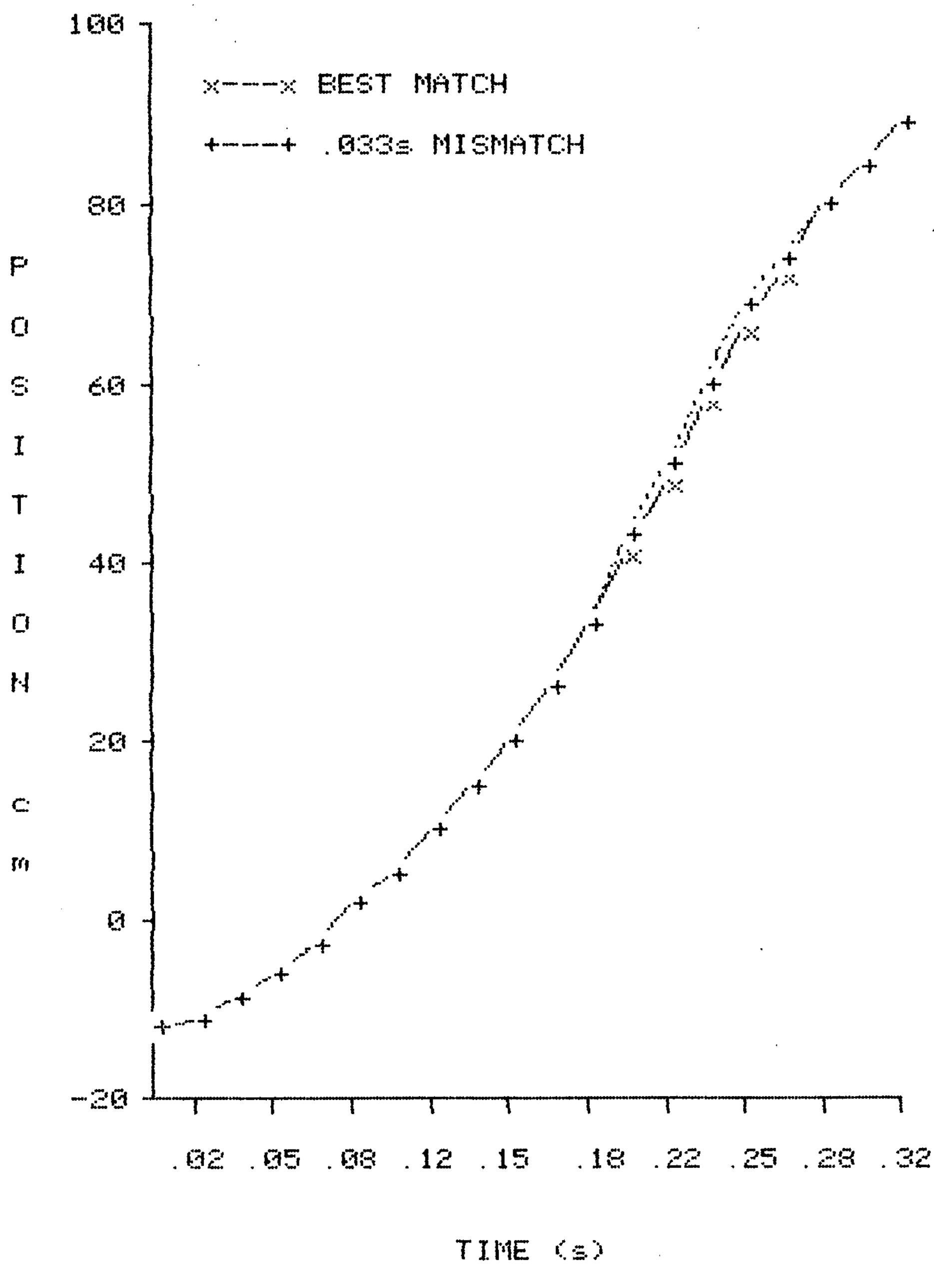

FIGURE 4.

POSITION OF THE ELBOW IN THE X DIR. FOR TEST 2

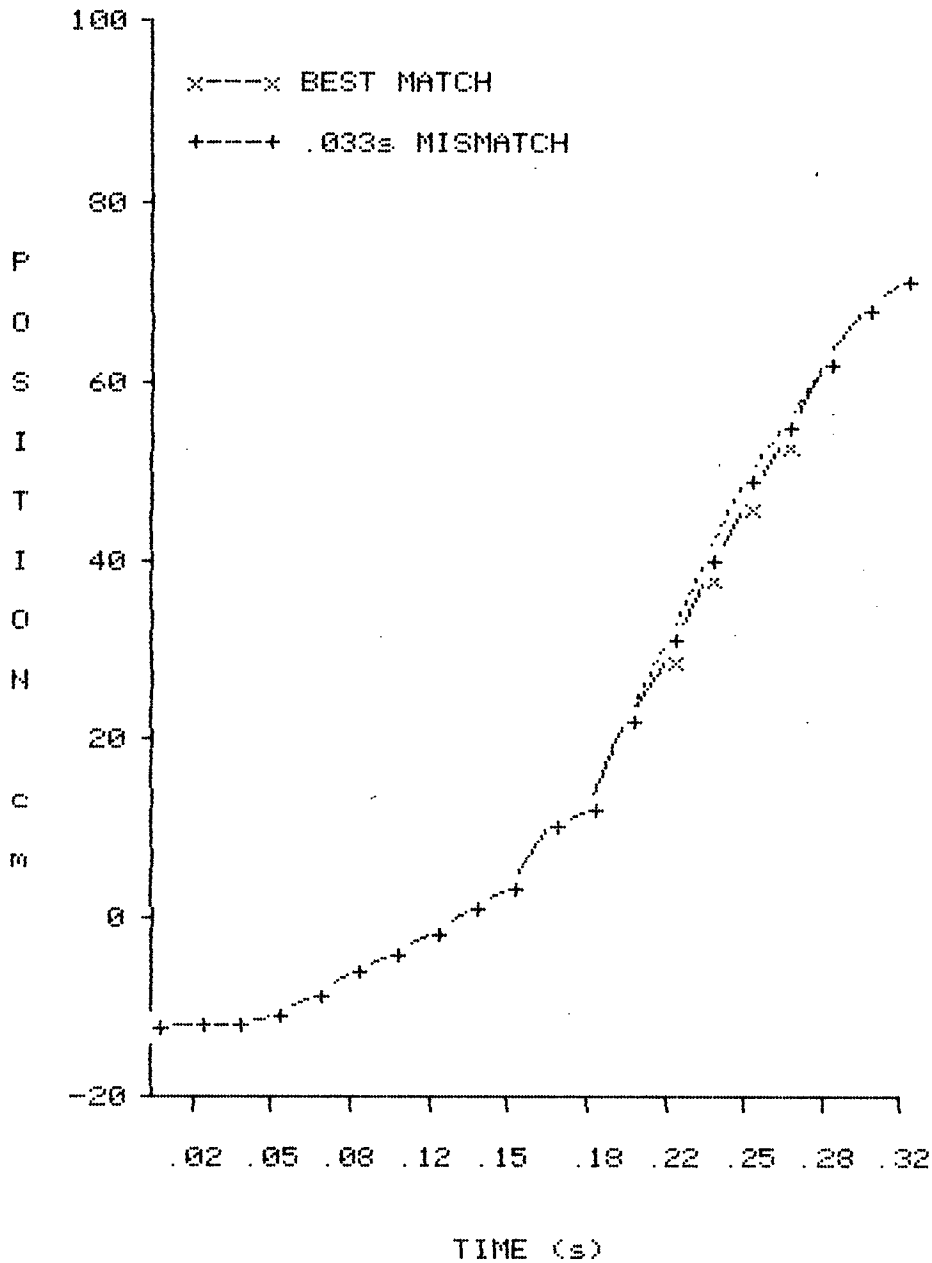

FIGURE 5.

POSITION OF THE WRIST IN THE Y DIR. FOR TEST 2

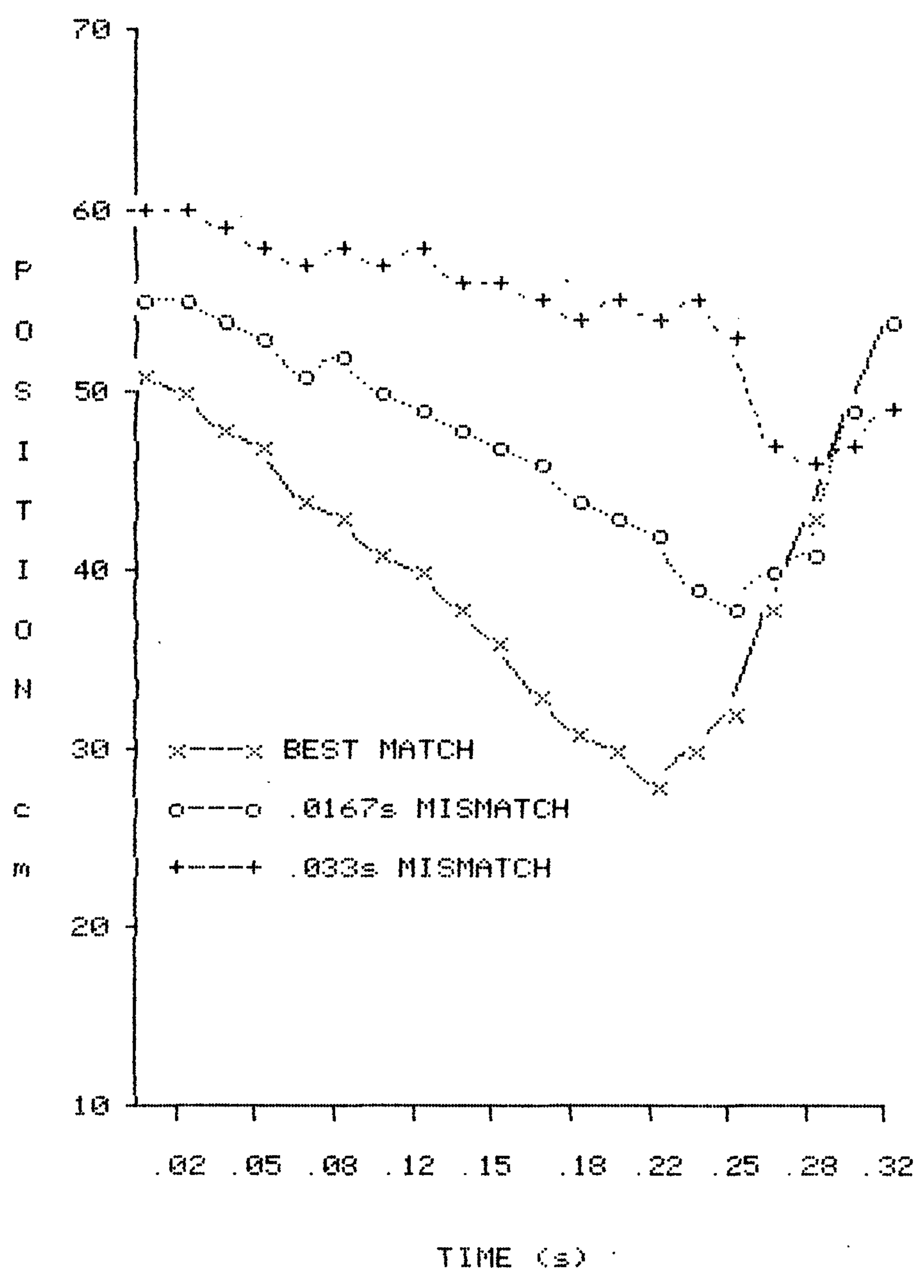

FIGURE 6.

POSITION OF THE ELBOW IN THE Y DIR. FOR TEST 2

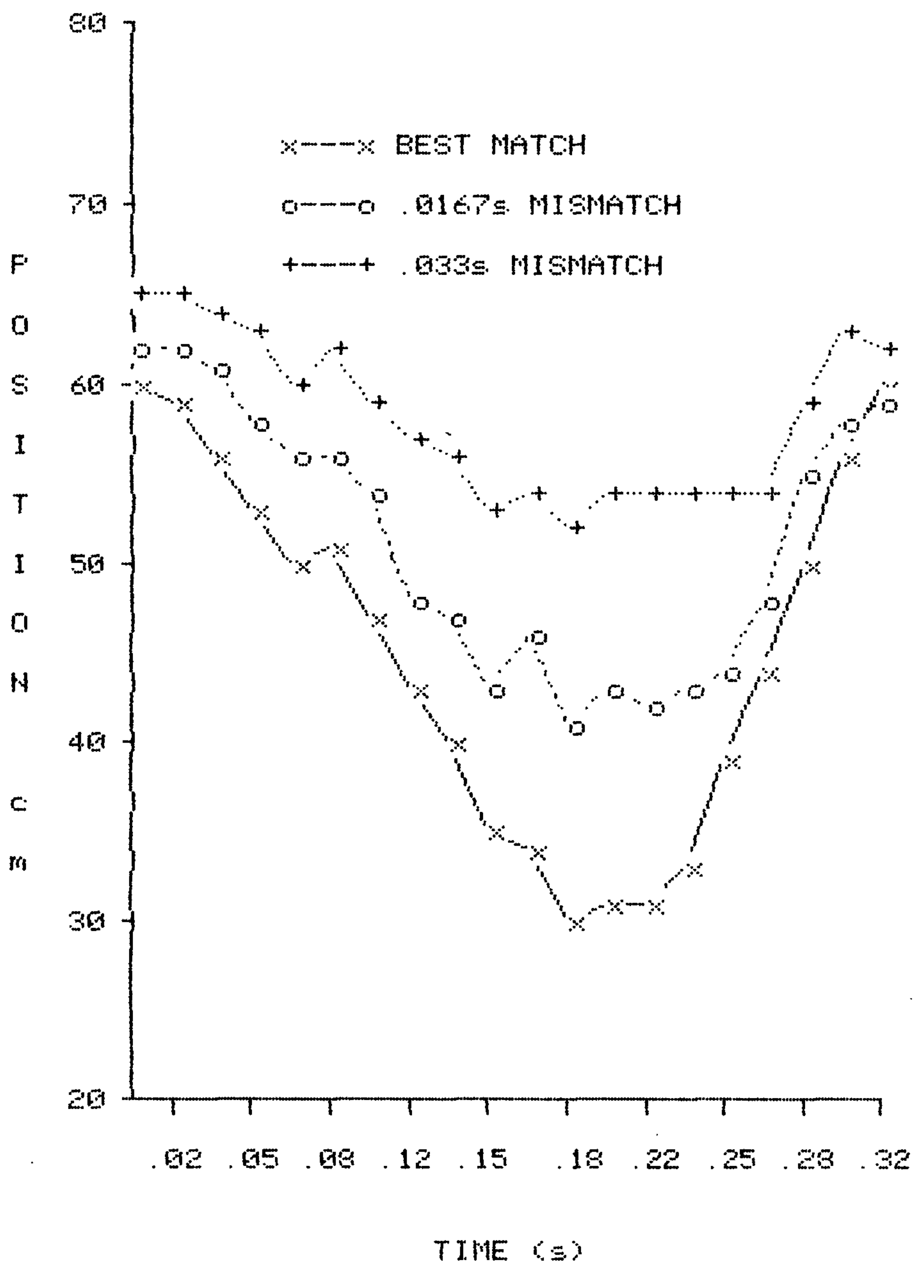

FIGURE 7.

POSITION OF THE WRIST IN THE Z DIR. FOR TEST 2

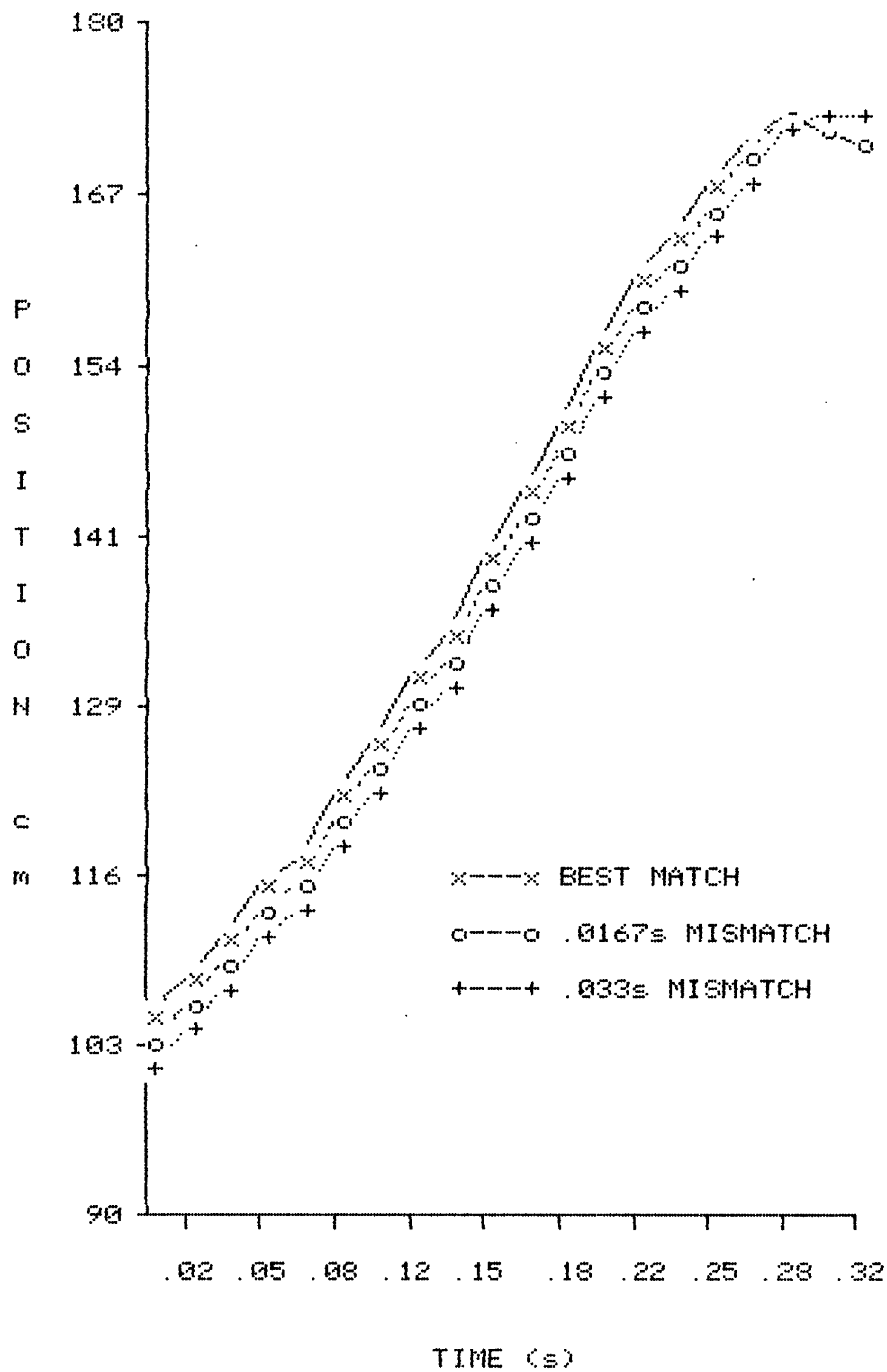

FIGURE 8.

POSITION OF THE ELBOW IN THE Z DIR. FOR TEST 2

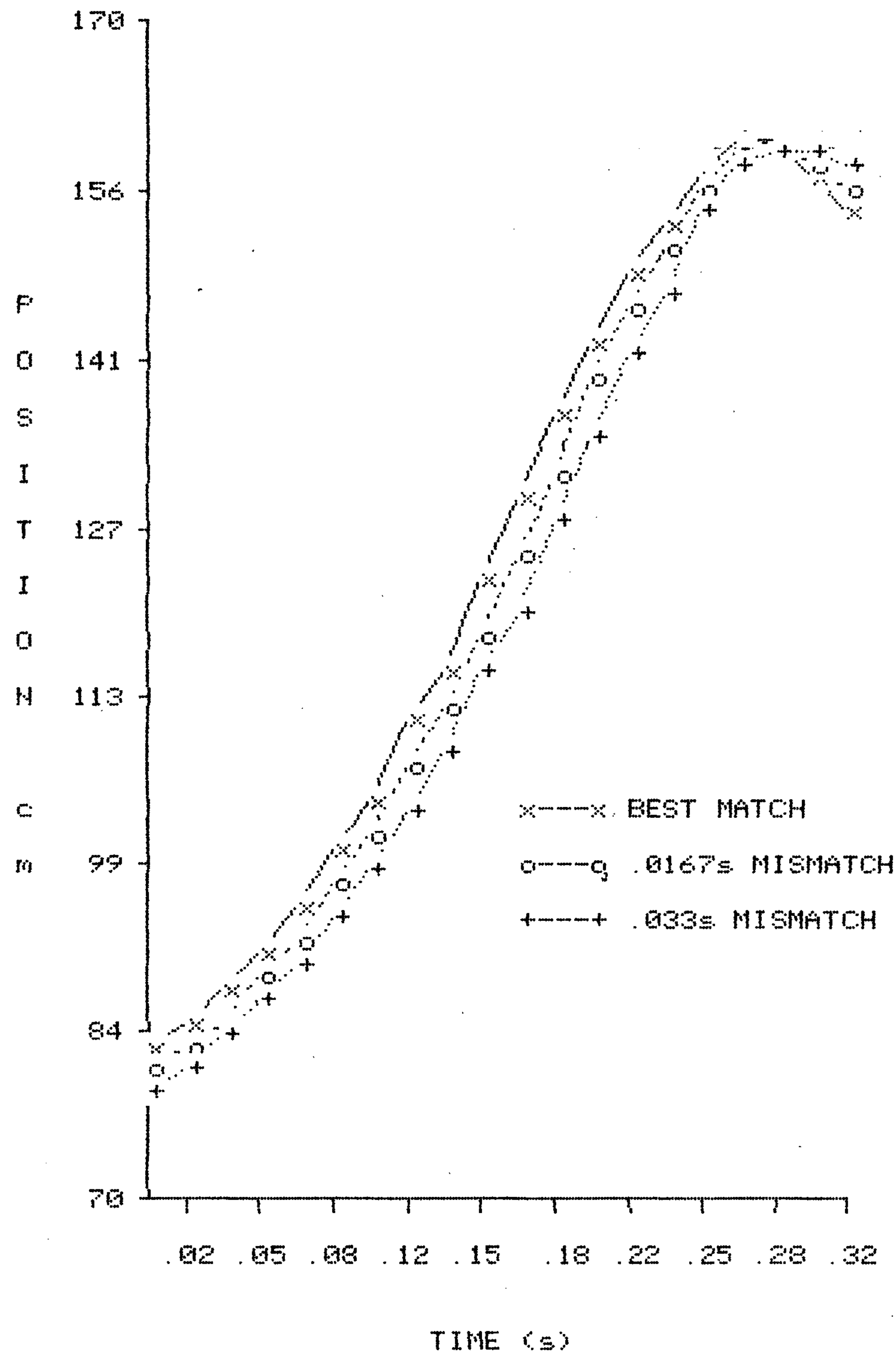

FIGURE 9.

There is, unfortunately, no simple explanation for the variance in effects. The Y coordinate might possibly have been most affected because both camera axes were closest to being in the Y plane. It is obvious that the digitizer coordinates of faster moving points will be more in error for a given timing mismatch, but due to the nature of simultaneous equations, this error could appear in any of the X, Y, or Z object coordinates. The camera positioning has a significant effect upon timing errors because it determines the coefficients of the equations.

It is also notable that the deviation in location is proportional to the amount of time offset. Thus, if the maximum errors due to timing in this experiment were to be kept below 1% (about 1 cm) the two views would have to be matched to within 0.0015 s (.014/11). If 5% errors were tolerable, matching would have to be accurate to within .008 seconds.

Effectiveness of the Time Matching Algorithm

Figure 10 illustrates the consistency with which the minimum norm corresponded to the correct time match for the first test. Since a mirror was used there is absolute certainty of correct time matching. Over the first 35 frames (0.6 s) the correspondence was quite poor, with maximum deviations of up to 0.06 seconds (3 frames).

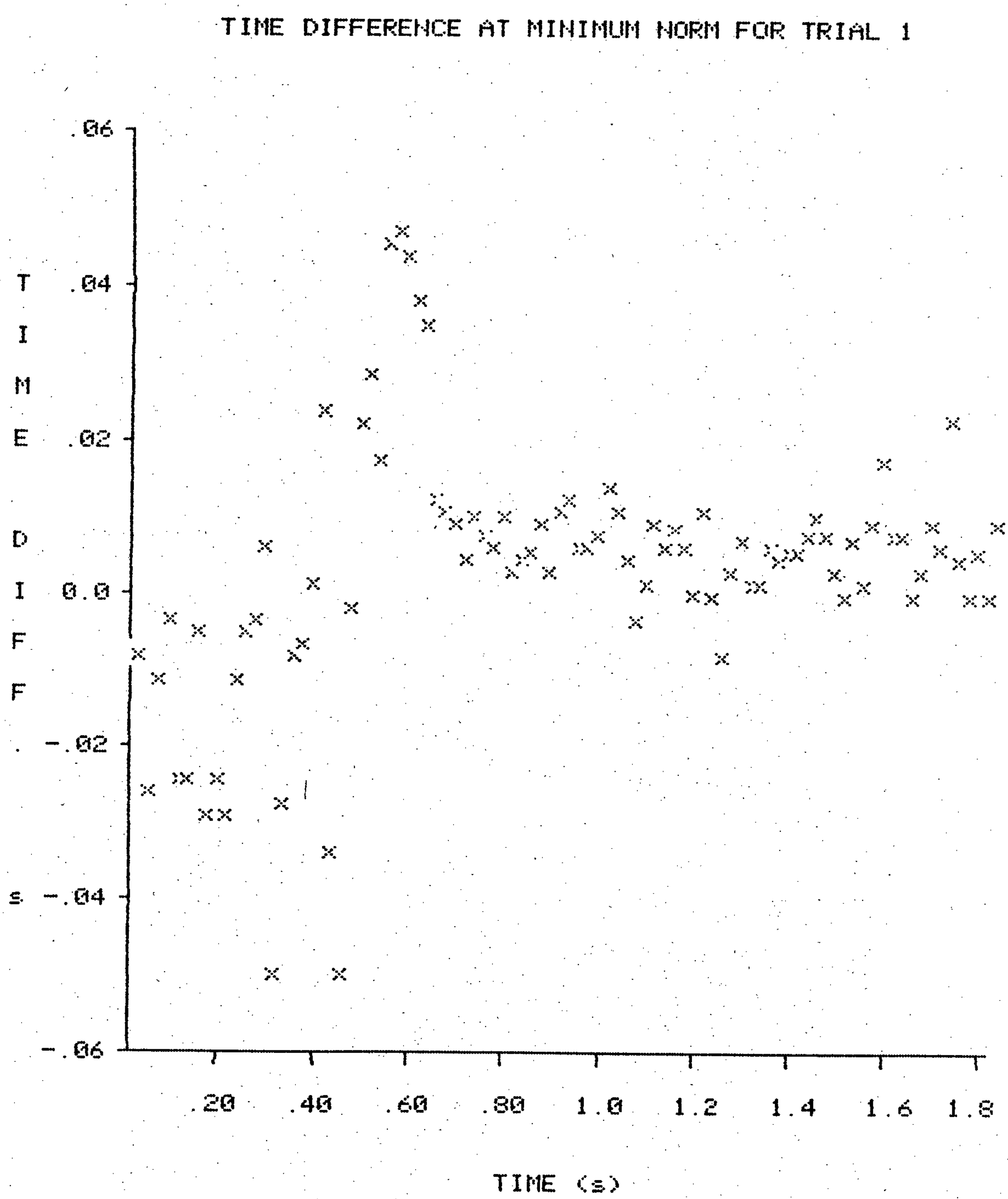
TIME DIFFERENCE AT MINIMUM NORM FOR TRIAL 1
TIME DIFF. s
.06
.04
.02
0.0
-.02
-.04
-.06
.20
.40
.60
.80
1.0
1.2
1.4
1.6
1.8
TIME (s)

FIGURE 10.

The match from frames 35 to 95 was substantially better. Observation of the film revealed that the bar reversed direction at frame 18, and thus, moved very slowly in that time period. This made differentiation between frames difficult. The mean time match over 95 frames was 0.005 seconds different from the exact value. This is approximately one quarter of one frame at 50 frames per second.

The time match at a minimum norm for the film of a shot put is illustrated in figure 11. Although the mean (-0.007 s) approaches the estimated exact value, individual times vary by up to 0.04 seconds, as indicated by the large standard deviation (0.016 s). There is also a low frequency variation in the values obtained, which does not seem to be due to random noise.

Figures 12 to 17 show the effects these time variations have on the calculated coordinates. The best estimates of the coordinate locations are the same as those in figures 4 to 9 ("x" points), while the coordinates at a minimum norm are shown by "+" points. The X and Y coordinates deviate considerably from the closest estimated path. Although the best estimated path may not be exact, it is clearly more accurate than the one derived from the time matching algorithm. The mean deviation for the X coordinate was 2.4 cm. with a maximum of 8 cm. The mean deviation for the Y coordinate was 2.9 cm. with a maximum of 12 cm.

TIME DIFFERENCE AT MINIMUM NORM FOR TRIAL 2

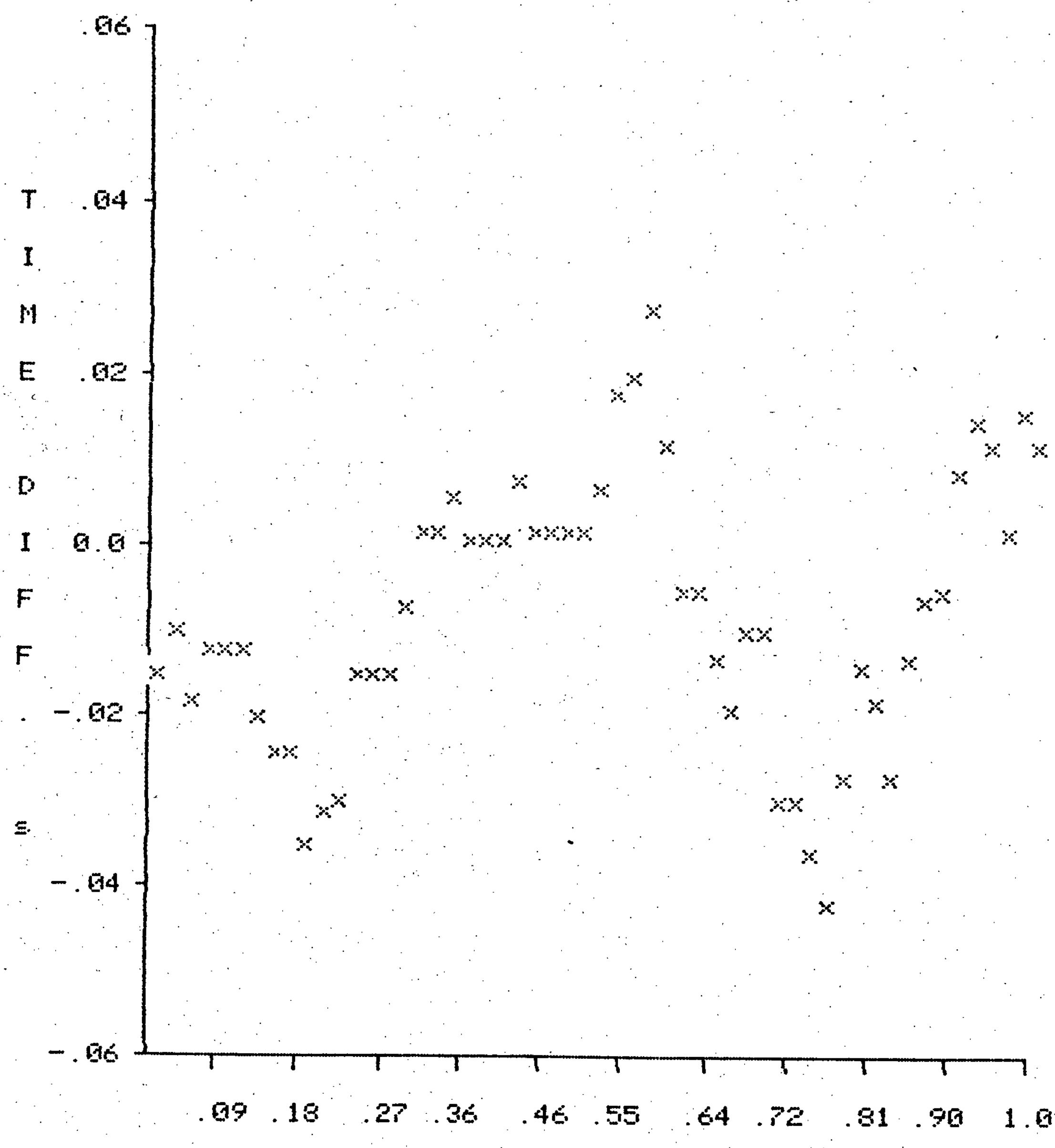

FIGURE 11.

X COORDINATE VARIATION AT BEST MATCH FOR THE WRIST

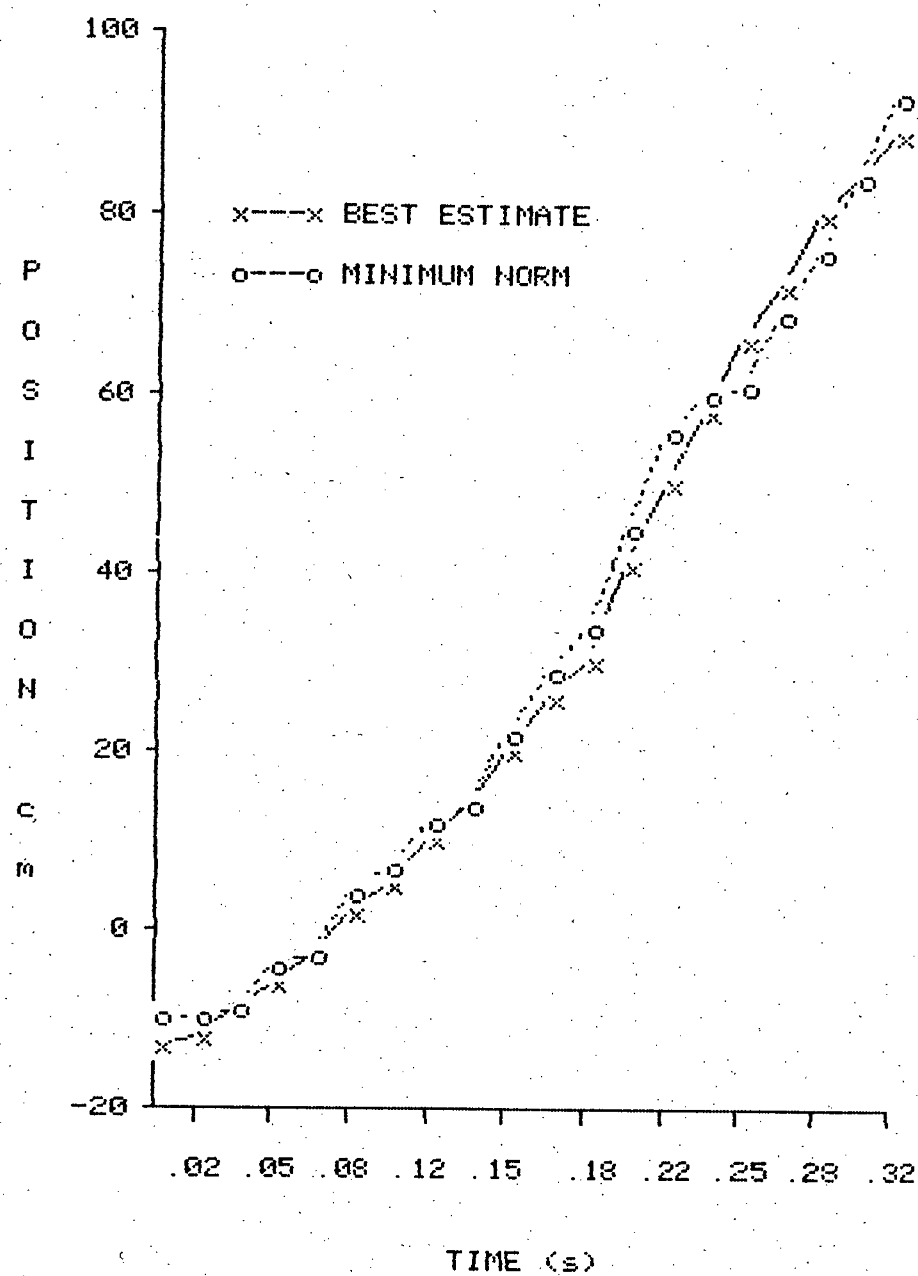

FIGURE 12.

X COORDINATE VARIATION AT BEST MATCH FOR THE ELBOW

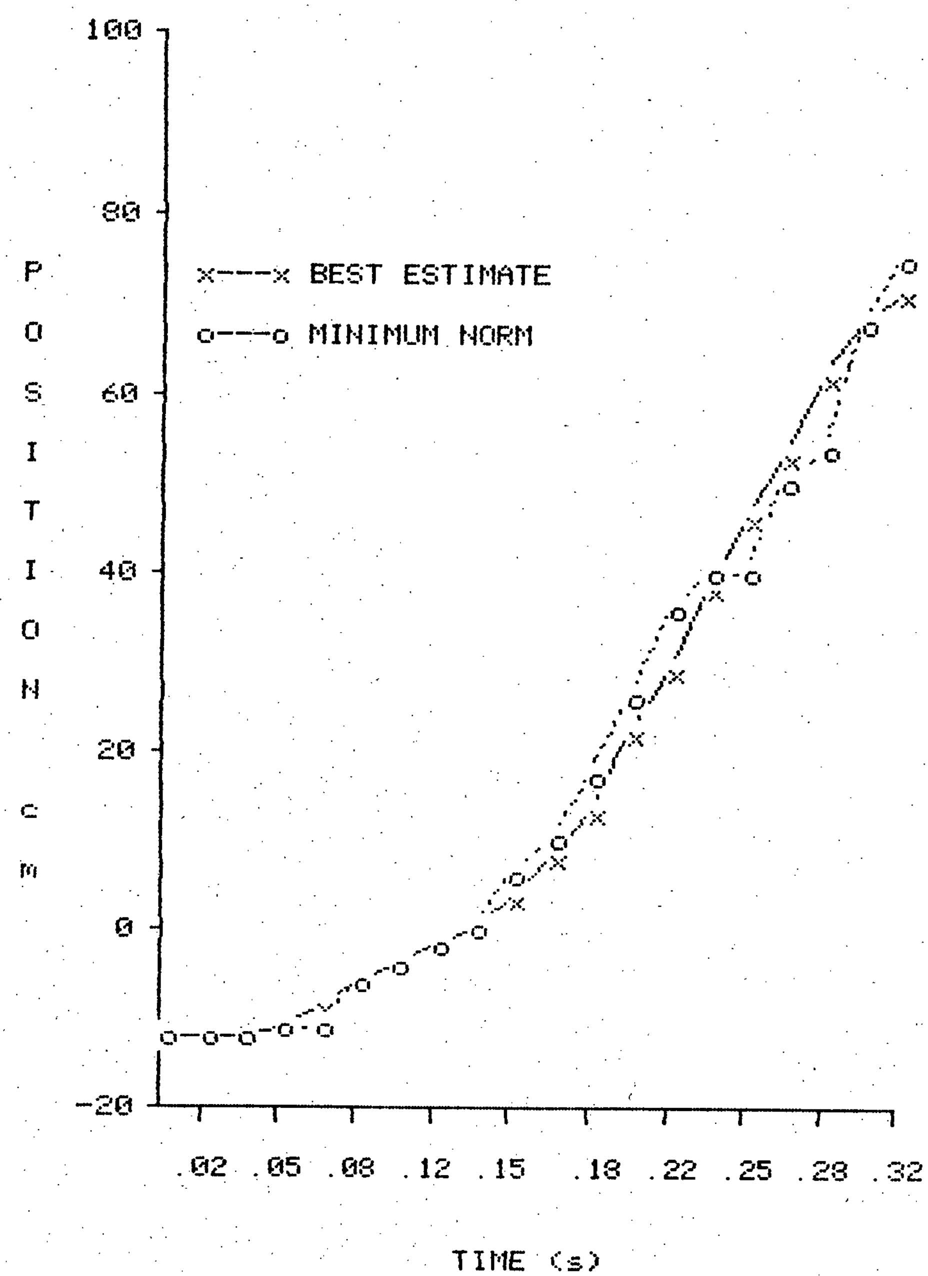

FIGURE 13.

Y COORDINATE VARIATION AT BEST MATCH FOR THE WRIST

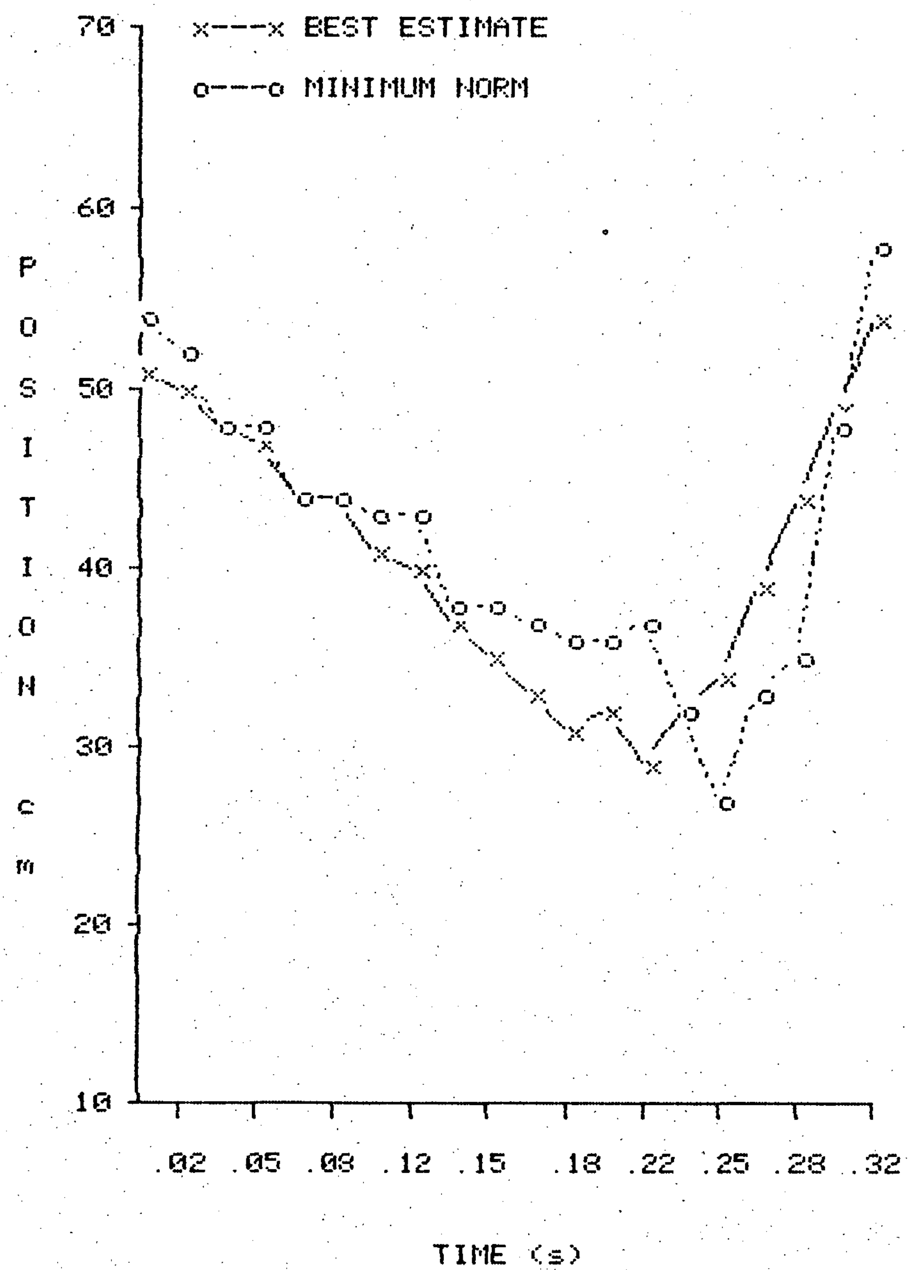

FIGURE 14.

Y COORDINATE VARIATION AT BEST MATCH FOR THE ELBOW

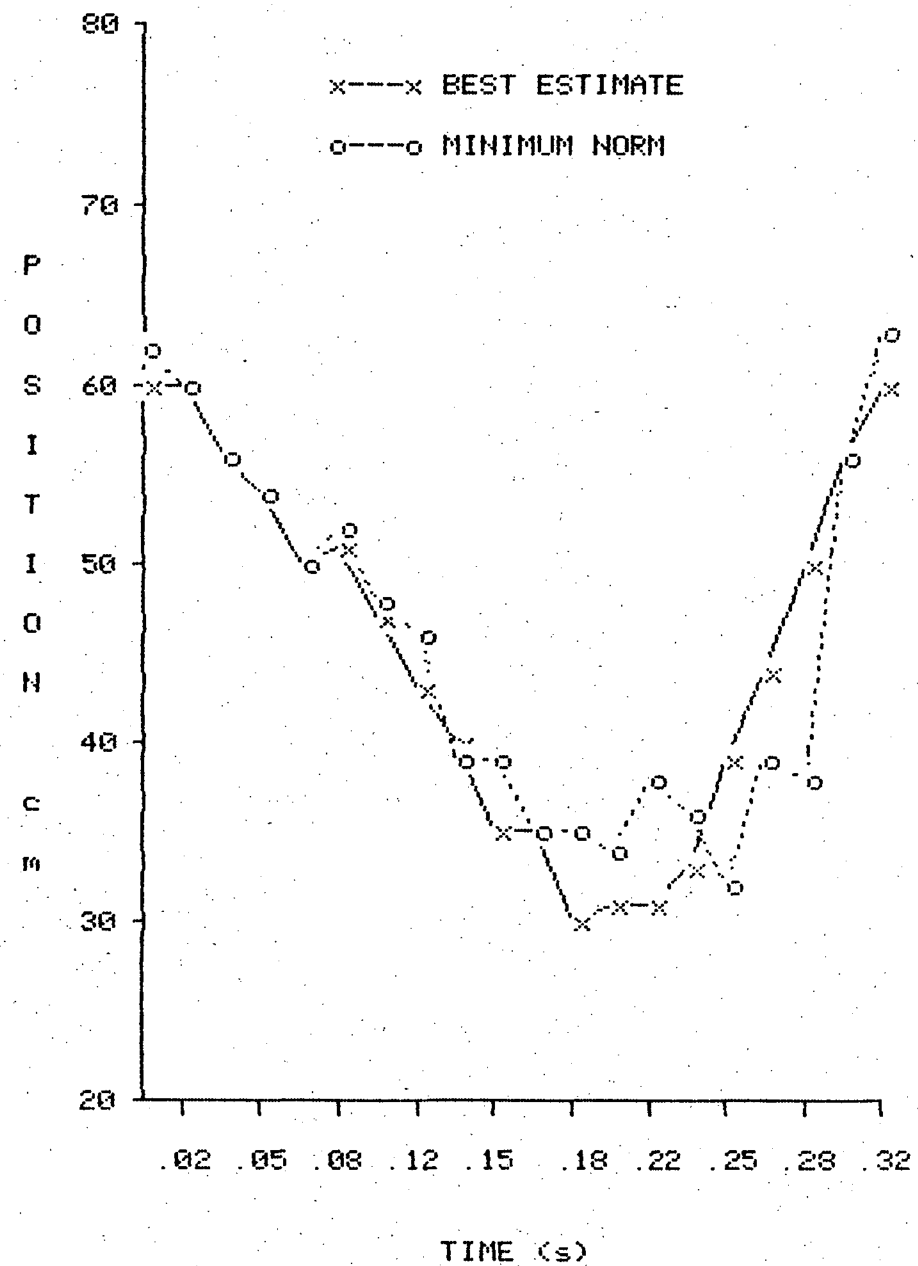

FIGURE 15.

Z COORDINATE VARIATION AT BEST MATCH FOR THE WRIST

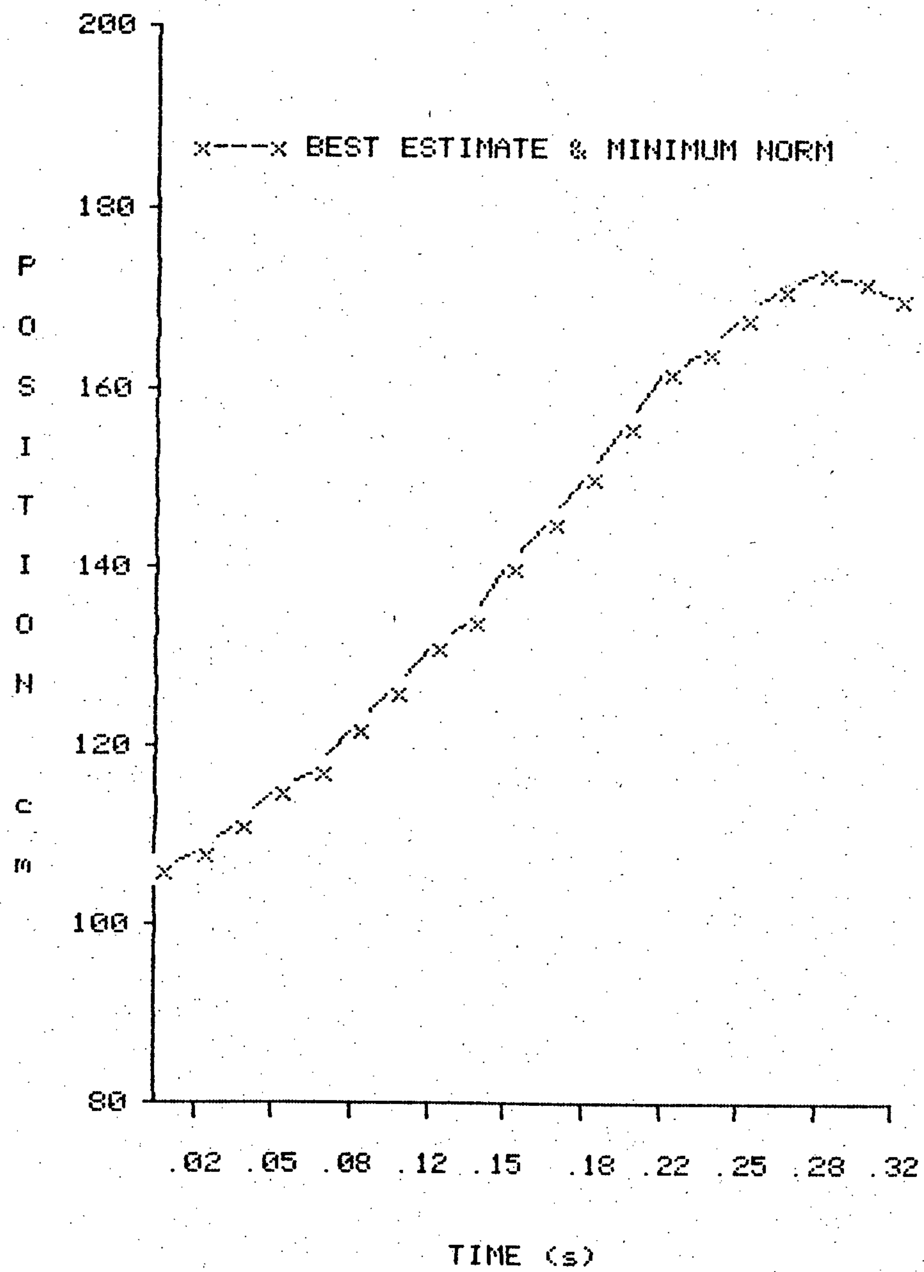

FIGURE 16.

Z COORDINATE VARIATION AT BEST MATCH FOR THE ELBOW

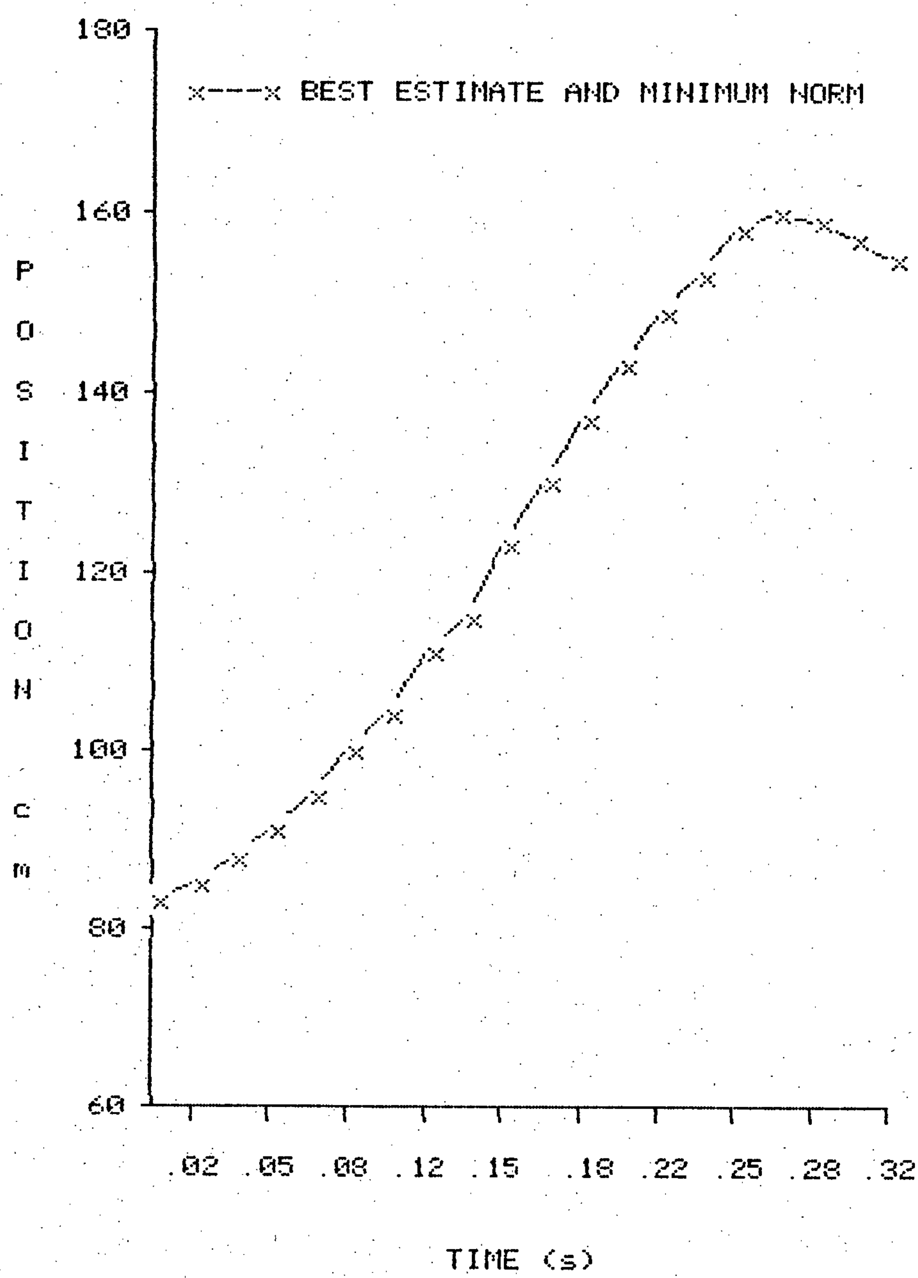

FIGURE 17.

There was no discernable difference between the two curves for the Z coordinate. These errors expressed as a percentage of the object space dimensions are X = 2.2% error and Y = 2.7% error.

If mistakes of logic in the mathematical theory are discounted, the only factor which can account for the observed variability is experimental error. The greatest errors are most likely found in the projection and digitization procedures. The error in reconstructing the measured locations of the control points averaged 0.5 cm in each plane. Noise introduced into the results by the data collection and reduction process would limit the effectiveness of the time matching methods.

Conclusions

The data presented above support the following conclusions:

1. Time matching methods used in three-dimensional cinematography should be accurate to within plus or minus eight milliseconds to limit coordinate errors to less than 5%.

2. The time matching algorithm presented was able to time match two views to within 5 milliseconds of the correct value.

Recommendations

Based on the understanding gained as a result of this study, the following recommendations for the investigation of timing in three-dimensional cinematography are suggested.

1. A movement should be filmed from several different angles to evaluate the effects of camera positioning on time mismatching.

2. The noise which appears in the raw data must be reduced to a lower level, perhaps by digital filtering, or with superior equipment.

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APPENDIX 1 - DEFINITIONS OF TERMS

(from Walton,1981)

ACCURACY: The amount any stated value differs from it's true value is termed it's accuracy.

CONTROL POINT: An object point for which the object-coordinates are known a-priori is referred to as a control point.

DIGITIZER COORDINATES: An ordered pair of numbers, expressed in digitizer units, and used to describe the location of a point in a real or virtual secondary image relative to the digitizer-reference-frame, are referred to as digitizer coordinates.

EXPOSURE TIME: The period during which a photographic emulsion is exposed to light is known as the exposure time. In cinematography, the exposure time is determined by the equation:

$$\text{exposure time} = \frac{1}{(\text{Frame Rate}) \times (\text{Shutter Factor})}$$

FIELD OF VIEW: The field of view of a camera (with a particular objective) is that portion of the object space which can be recorded by the camera.

FRAME RATE: The frequency with which a cine camera records distinct images is known as the frame rate of the camera.

INTERMITTENT CAMERA: An intermittent camera is one in which the film is held still while each exposure is made.

OBJECT COORDINATES: An ordered pair or triplet of numbers which are expressed in object units and used to describe the location of an object point with respect to the object reference frame are referred to as object coordinates.

OBJECT POINT: Any point in the object space which is subjected to photographic examination is referred to as an object point.

PHOTOGRAMMETRY: Photogrammetry is defined as the science or art of obtaining reliable measurements by means of photography.

SHUTTER FACTOR: In cinematography, the ratio of the total time between successive frames to the exposure time per frame is known as the shutter factor.

TIMING MARKS: In some cine cameras there is a provision for marking the border of the film by exposing it to a small, pulsed light source. These marks are called timing marks.

APPENDIX 2 - SYMBOLS USED IN THIS PAPER

a,b,c,d,e,f,g,h,j,k,l - The eleven calibration coefficients needed to transform digitizer coordinates to object coordinates.

u - The horizontal coordinate measured from a film (in digitizer units).

v - The vertical coordinate measured from a film (in digitizer units).

X,Y,Z - The three coordinates of a Cartesian system (in object units with Z vertical).

Appendix 3 - REVIEW OF LITERATURE

There are many techniques that have been used in the field of biokinematic data acquisition. Woltring, (1984) surveys electrogoniometry, ultrasound, stoboscopic photography, optoelectronics, accelerometry, and cinematography. This discussion will deal only with cinematographic techniques, or those concerned with analysing data recovered from cine film of an athletic performance.

Time Matching Methods

The time matching problem is not one which has recieved extensive analysis in the literature. Only one study deals directly with the time matching problem (Garnov and Dubovick, 1965). These authors developed expressions for finding the number of matched pairs of photos to be expected from two cameras running independently.

Investigators who have completed three-dimensional studies of human movement have used three methods to time match their data. The "split image" technique (Pierrynowski, 1981; Van Wijk and Ziemann, 1976) involves recording two separate views on one film with the use of mirrors or prisms. Figure 18 is an illustration of the set-up used by Pierrynowski (1981).

EQUIPMENT SET-UP FOR SPLIT IMAGE PHOTOGRAMMETRY
(as used by Pierrynowski, 1981)

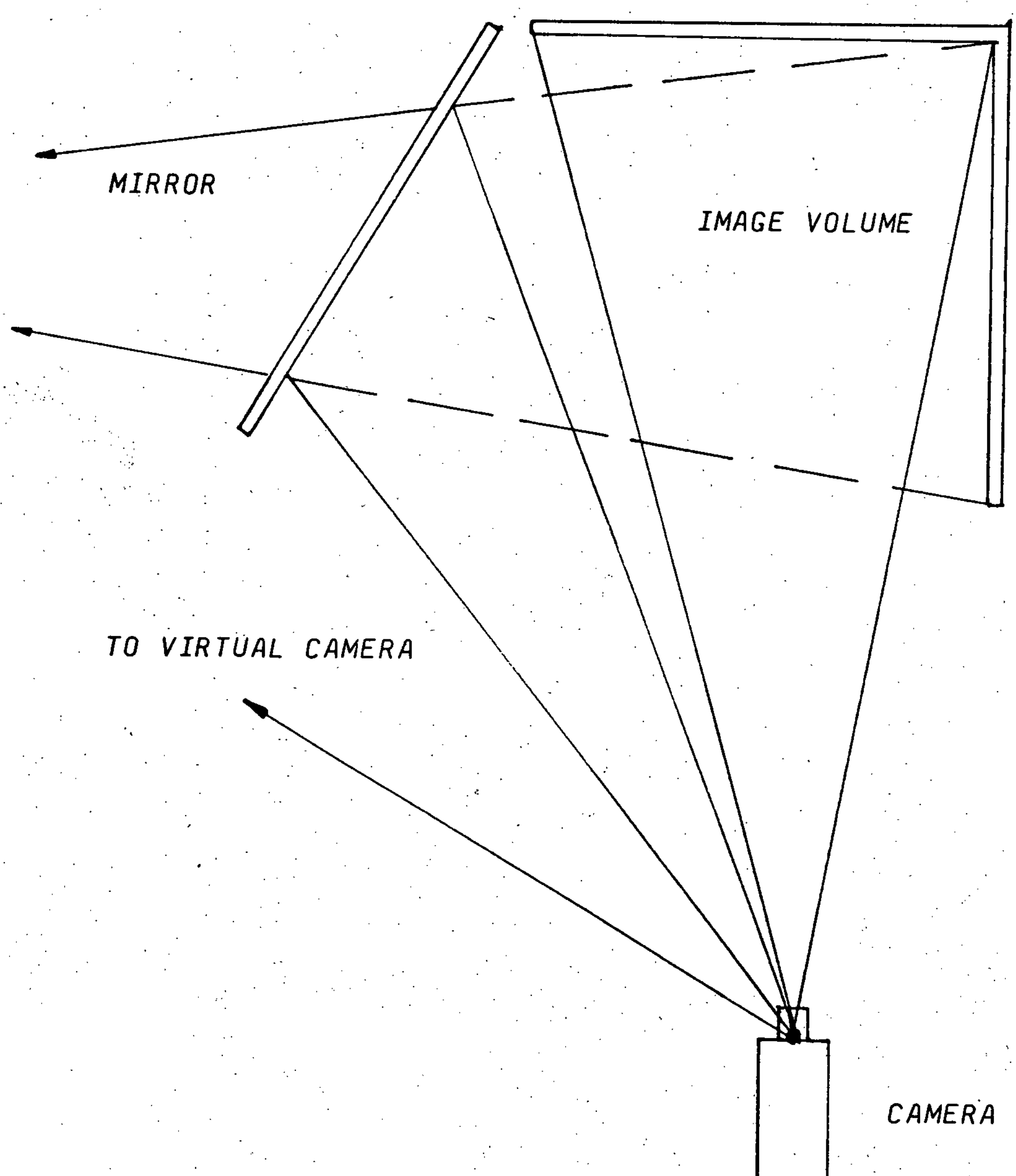

FIGURE 18.

The limitations of this method include:

(1). The large mirrors needed are expensive, cumbersome, and are likely to introduce distortions.

(2). The image size in the film frame is halved, reducing the signal-to-noise ratio of the data.

(3). The method is simply impractical in some situations such as larger scale movements in sporting activities.

The second method involves placement of an identifying mark on the film so synchronization can be completed later. There are several variations of this technique, ranging from an external light visible in both cameras, to internal timing lights built into the cameras.

The most basic method uses an event signal, often a light, which is visible to separate cameras. Fukashiro et al. (1981) used this method to coordinate eight cameras in their two-dimensional study of the triple jump. Hobart and Provenza, (1983) and Ben-Sira et al. (1971) avoided the problem of visibility by using a bright flash to overexpose the film in separate cameras. The flash, however, would only be visible in low light situations.

The problem with these methods is that they can only be accurate to the nearest half frame. The first frame on each film where the light is visible can be matched, but if the illumination occurs when one shutter is closed, there would be some error. Ben-Sira et al. (1971) acknowledge this when they state "... the procedure is not sufficiently accurate for critical three-dimensional analysis." A variant of this method used by Miller et al. (1980) is subject to the same inaccuracy. Miller used two Locam cameras operating at 100 Hz., and simultaneously fired their internal event marking lights. He noted that the intermittent motion of the film in the gate of the camera introduced an uncertainty of plus or minus one frame in the matching.

Pierrynowski (1982) attempted to reduce the uncertainty by matching the closest frame of one Locam running at 160 Hz. with another Locam running at 40 Hz.. This method may have enabled him to decrease his error to within plus or minus 1/4 frame at 40 Hz., which is equivalent to a time period of 0.006 seconds. This method places limits on the speed ranges allowed and increases costs.

An improvement upon simply recording an event mark is the inclusion of an actual time record on the film. This is possible via an internal or external timer. Blievernicht (1967) provides plans for an external mechanical timer but it has a low resolution of 0.01 seconds. Walton, (1970) describes an electronic timing unit of 0.001 seconds resolution. This device includes a master unit and several slave units for separate cameras. Walton (1981) used this timer to record a time for each film frame during digitization. Coordinates from separate films were then matched using linear interpolation. Walton further smoothed the timing record using the assumption that his cameras were running at a constant speed. He found the assumption was valid for AC powered cameras, but DC powered cameras did not have stable frame rates. Borms et al. (1973) also used a timer visible to both cameras in his study of the twisting somersault. These methods achieved an accurate time match quite successfully. The only disadvantage was in ensuring that a timer was visible to each camera.

A slightly different approach was used by Newton et al (1977) which involved the use of a split lens to simultaneously film a stopwatch. His resolution was only 0.001 seconds and difficulties in including the same stopwatch in several camera views are anticipated.

The third and most elegant solution to the time matching problem is to use electronically synchronized cameras. Walton (1981) describes two such systems that are available. The large capital costs and cable connections between cameras are the only drawbacks to this solution.

To summarize, these three time matching solutions seem to be the only ones in use. Their limitations are recognized, which contributes significantly to the lack of widespread acceptance of three-dimensional analysis.

Effects of Noise

The ability to achieve an accurate time match by searching for the minimum norm of residuals should be dependent only upon the experimental accuracy. Several authors have analyzed the characteristics of the noise to be expected in a cinematographic analysis of human movement. Capozzo et al. (1975) asserted that the error introduced by multiple and independent causes can be assumed random with normal distribution. Wells and Winter (1980) assessed the expected noise levels under filming conditions varying from a controlled laboratory setting to an outdoor sports event. They found noise in a 1/3 life size image to be 2 mm, while that in 1/14 size image was 1 cm. Atwater (1981) attributed most of the systematic errors which might appear to the digitizing procedures. She recommended monitoring the skill and precision of the digitizing personnel. Lanshammar (1982) determined that measurement noise would be white if it changed by several quantization steps between samples.

These authors seem to agree that most of the expected noise should be random. If this is true, the averaging procedures proposed would allow the time matching algorithm to produce an accurate result.

Several authors have evaluated methods to reduce the amount of noise in biomechanical data. Pezzack et al. (1977) concluded that digital filtering could effectively remove most high frequency noise. He considered polynomial curve fitting to be insufficiently accurate. Soudan et al. (1979) advocated the use of spline functions followed by determination of the Fourier coefficients. The main advantage of spline functions over digital filtering is the accommodation of gaps and discontinuities in the data.

Hatze (1981) provides an extensive review of the use of Fourier series for eliminating noise. He notes their advantages as computational efficiency, and automatic filtering parameter selection. Disadvantages are listed as the equidistant data spacing requirement, and no data may be missing.

Miller et al. (1980) evaluated several smoothing techniques and concluded that digital filtering, Fourier analysis, and cubic splines are each best suited to distinct situations.

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