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TITLE AN ELECTRONIC SHADOWGRAPH STATION AND CONTROL SYSTEM

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AN ELECTRONIC SHADOWGRAPH STATION
AND
CONTROL SYSTEM

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Abstract

A proof-of-principle electronic shadowgraph station has been installed at the Aeroballistic Research Facility, Eglin Air Force Base, Florida, with encouraging results. This paper reviews the requirements for replacing a film system for aeroballistics measurements with an electronic imaging and processing system, with particular emphasis on using centroid and second moment of inertia algorithms to improve the accuracy. The proof-of-principle electronic shadowgraph station is described and results of comparative measurements at the facility between film and digitized video images show comparable accuracy.

I. Background

Why Electronic Imaging

Film cameras have their advantages for making measurements; high resolution and image quality, low cost, and reliability to name few. However, they also have their shortcomings; processing the film and reading information from the film is labor intensive and subject to human error. At the Eglin facility, the film processing, readings, and data reduction normally takes several weeks, since there are about 100 pieces of film to process for each shot.

The first major advantage of electronic imaging is that the image is digitized as it is captured, and thus is ready in a computer for processing. Conceivably, the same number of pictures as used in the film system could be processed in a few hours.

Another major advantage of an electronic image is that the entire image is digitized and may be processed by use of different algorithms to increase the accuracy of a measurement. Finding the centroid of an object is one such method for more accurately locating an object. Additionally, CCD electronic cameras usually have better sensitivity in the visual part of the light spectrum and a wider dynamic range.

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Electronic imaging has its drawbacks, though, just as film cameras do. Compared to film cameras, the imaging resolution is low. They also cost more, especially at high resolutions of 2000 x 2000 or even 1000 x 1000 pixels. Problems in using electronic cameras in place of film cameras depends on the application and measurements desired, and resolving whether or not the lower spatial resolution can be compensated for by processing algorithms.

Description of the Eglin Aeroballistics Range

A detailed analysis of the requirements for an electronic shadowgraph station in the Eglin Air Force Base Aeroballistics Research Facility was performed in 1985.¹ Briefly, this facility is 680 feet long and 12 feet wide for the first one third of the range, and 16 feet wide for the last two thirds. Projectiles and models of various shapes are fired down the range and photographed at 50 stations along the range to determine their stability, aerodynamic properties and other flight characteristics. A complete description of this facility and its capabilities are detailed in Reference 2. Each imaging station along the range, shown in Figure 1, captures two orthogonal shadowgraph images of the projectile as it passes.

Fig. 1 Typical Shadowgraph Station

The objective of the analysis discussed in Reference 1 was to provide system requirements and a conceptual design of a state-of-the-art high-speed electronic imaging system to improve the data acquisition and analysis of projectiles in flight. The projectiles vary in shape and may travel at velocities up to 3 km/sec. The required resolution was determined by measuring the

modulation transfer function (MTF) and optical illumination parameters of the existing system.

From the transfer function, the limiting resolution was determined to be 0.72 cycles per millimeter at the reflective screen. Illumination parameters were determined to ascertain the usefulness of the available spark-gap light source for large area arrays. Intensity and spectral characteristics of the source were also measured.

II. Requirements for the Electronic Shadowgraph

Accuracy

The initial study determined the resolution capability of the existing film system and then proposed to replace it with a comparable electronic imaging system. However, those stringent resolution requirements result in requiring area array electronic cameras with about 3500 x 1500 pixel resolution, which currently are not available. Instead of duplicating the film system capability, a determination of what measurements are actually needed at the Eglin facility were made. Basically, the need was to very accurately determine the absolute location of the projectile and its orientation (pitch, yaw, and roll) at each station. The accuracy requirements of the orientation was next determined.

The pitch and yaw of a projectile is now determined geometrically at Eglin. Since most models are symmetrical about one or more axis, a point at the front tip and at the tail on the same axis are determined. The angle of the line connecting these points is the angle of the projectile shadow. Since the images are actually projections of a projectile on a screen, three-dimensional geometry is required to determine the actual angle of the projectile from two orthogonal shadowgraph views of the same projectile. The projectile orientation is given as the direction cosines of the major axis through the projectile, and the location is the center of mass (cg) position relative to calibration points accurately known in the range. The accuracy requirements of determining the angle of the projection can be determined from the range accuracy.

Figure 2 shows a model projection with front (F) and rear (R) points selected, and a line drawn between them. The accuracy of the range was determined to be equivalent to an array camera with about 3500 x 1500 pixel resolution. This agrees relatively well with the system accuracy determined in Reference 2. A grid is superimposed to represent a 3500_v x 1500_h array used to acquire the image. A 2:1 aspect ratio is used because the shadowgraph screen dimensions are 96" high x 48" wide.

Fig. 2 Model Projection

The error in determining the actual location of a point on the projectile shadow is approximately ± 0.5 pixel. The maximum error of the angle of the line connecting the two points F and R is described by the equation:

$$\text{Error}_{\max} = \pm \sin^{-1} \frac{p}{L} \quad (\text{degrees}) \quad (1)$$

where p is the spatial resolution of a pixel and L is the length of the projectile. For the Eglin facility, the shadowgraph screen measures 2438.4 mm (96") high x 1219.2 mm (48") wide. The 1219.2 mm dimension at the screen maps onto the 1500 pixel dimension of the array, thus the horizontal spatial resolution of each pixel is:

$$p = \frac{1219.2 \text{ mm}}{1500} = 0.813 \frac{\text{mm}}{\text{pixel}} \quad (2)$$

The vertical spatial pixel dimension is the same as the horizontal. The location error then of ± 0.5 pixel is ± 0.406 mm.

The shortest projectile tested and measured at the Eglin facility is about 80 mm long x 20 mm diameter. Using Equation 2 for the pixel spatial resolution and $L = 80$ in Equation 1, we get an angular error of ± 0.582 degrees for the shortest projectile shadow. Keep in mind that this is the error when the front and rear points are located exactly. A one pixel error (operator error) in locating the front and rear points could result in three times the error determined above. However, for the comparison with the electronic imaging system it will be assumed that there is no location error. The angular error of ± 0.582 degrees and location error of 0.406 mm for the shortest projectile is the accuracy that the electronic imaging system must achieve to match the 3500_v x 1500_h array.

The electronic cameras must also work with the existing range components which are briefly described.

Spark-Gap Light Source

An open air spark-gap, Hi-Voltage model SS44P, with a capacitor discharge circuit charged to 4800 vdc is employed as a strob light source. The spark is discharged across a 2.2 mm air path, which is small enough to be considered as a point light source. The spark-gap is positioned adjacent to each camera and casts a well-defined shadow on the reflective screen. The spectral characteristics were reported in Reference 1. The output of the spark gap has a duration of about 300 nanoseconds.

Infrared Array Trigger

A narrow infrared beam about 8 feet high is projected onto the retro-reflective screen in order to detect the arrival of the projectile at a station. When the projectile enters the beam, a trigger is generated to flash the spark-gap light source.

Retro-Reflective Screen

A 3M No. 7610 screen, made up of tiny glass beads about 0.002" in diameter, is used as the surface on which a shadow of the projectile is cast. The shadowgraph formed allows the camera to be focused on a known object (screen) since the projectile can be anywhere in the 12-foot width of the range. Since the screen is retro-reflective, light from adjacent stations is not reflected into the camera. Also, the screen has a light gain over that of a Lambertian surface. The gain is dependent on the viewing angle to the source. A gain of about 40 is obtained in the Eglin facility with the spark separated by 5" from the camera viewing axis, but a gain of about 1600 is possible if the light source is viewed on axis with the camera. The light gain of the screen vs. viewing angle is shown in Figure 3.

Fig. 3 3M Screen Data

III. Reducing Resolution Requirements

Two primary methods have been investigated to reduce the resolution requirements to allow using a lower resolution, lower cost camera at the range. These methods are: finding centroids (first moment of inertia) and second moments of inertia of areas. Using centroids to locate an object is applied to both the projectile and the reference beads to improve accuracy.

Centroid

Figure 4 shows a general case for determining the centroid of an area relative to a set of orthogonal axes, labeled x and y:

Fig. 4 Centroid of an Area

The equations for the centroid of the area A are given by:

$$C_x = \frac{\int X f_n dA}{\int f_n dA} = \frac{\sum_{n=0}^N X f_n \Delta A}{\sum_{n=0}^N f_n \Delta A} \quad (3)$$

$$C_y = \frac{\int Y f_n dA}{\int f_n dA} = \frac{\sum_{n=0}^N Y f_n \Delta A}{\sum_{n=0}^N f_n \Delta A} \quad (4)$$

Where ΔA is one pixel area, f_n is the fraction of each pixel area, ΔA , covered and N is the number of pixels. For digital systems, the integral is easily approximated by doing a summation. The fraction f_n corresponds to the pixel numerical value of the digitized image.

Example of Accuracy Improvement

An example of using the centroid to more accurately locate an object is demonstrated with the reference beads. One of the tasks of the imaging system at the Eglin facility is to accurately locate reference beads strung on Kevlar lines at each station, as shown in Figure 5.

Fig. 5 Shadowgraph Station Reference Beads

The absolute location of all beads in the range are accurately known, and thus provide a reference for determining the absolute location of the projectile shadow, since both the reference bead and projectile shadow, Figure 5, are contained in the same image. The detail of a typical reference bead is shown in Figure 6.

Fig. 6 Typical Reference Bead

The projected area of the bead on the screen, is about the same size as the bead, or 24.373 mm^2 , since the bead is located about $1/4"$ from the screen. Using a 2048×1024 camera array for our example, the pixel spatial resolution is $p = 1.19 \text{ mm/pixel}$. The bead projected area then covers about 17 square pixels ($24.373 / p^2 = 17.2$). Locating an edge of the bead by locating a point (without further image processing) would still have a ± 0.5 pixel error, or about $\pm 0.595 \text{ mm}$ ($0.0234"$) error.

However, locating the centroid of the bead projection on the shadowgraph is much more accurate than the geometric method described above. Each pixel of the bead image can be digitized to 12-bit accuracy (i.e., 1 part in 4096) in many good imaging systems. If the signal-to-noise ratio of the system is less than 40 db, the noise will be the primary contributor to the pixel value error, and the digitizer error can be neglected. A signal-to-noise ratio of 40 db, typical of many CCD cameras, is a voltage ratio of 100/1 equivalent to a pixel value error of $\pm$ one percent.

If each ΔA in the centroid calculation is accurate to $\pm$ one percent (due to noise contribution), then the sum of ΔA 's for 17 pixels (bead example with a 2048×1024 array) is accurate to ± 0.24 percent, assuming uncorrelated noise, since we approximately get the statistical improvement of $1/\sqrt{N}$ where $N = 17$. The location accuracy of 0.24 percent within a pixel dimension of 1.19 mm yields 0.0029 mm ($0.0001"$) accuracy, or about two orders of magnitude improvement over the ± 0.5 pixel or 50 percent accuracy computed earlier for locating a point. Therefore, we see that the centroid method of locating an object can be more accurate than just locating a point of the object, provided $N > 1$.

Second Moment of Inertia of an Area

Figure 7 shows a general case for determining the second moment of inertia of an area with respect to the centroid of the area. It turns out that finding the second moment with respect to the centroid, rather than to arbitrary axes, is simpler because the arbitrary axes moment terms do not have to be carried through the equations.

Fig. 7 Second Moment of Inertia of an Area

The equation for the angle of the axis through the centroid of the second moment of inertia of an area is:

$$\tan 2\theta = \frac{-2P_c}{I_x - I_y} \quad (5)$$

Where: $I_y = \int x^2 dA$ (second moment with respect to y axis)

$I_x = \int y^2 dA$ (second moment with respect to x axis)

$P_c = \int x'y' dA$ (product of inertia)

and θ = Angle of the axis of the second moment of inertia relative to the x' axis.

x' = Distance from the centroid to dA in the x direction.

y' = Distance from the centroid to dA in the y direction.

Note that the result yields two axes 90° apart, being the maximum and minimum axes of the second moment of inertia of the area A . For our purposes, we are only interested in the axis of the minimum second moment, which is the same as the axis of symmetry through a projectile shape such as a bullet.

One might intuitively surmise that finding the angle of the second moment of inertia of an area is more accurate than the geometric solution due to the statistical improvement of using more data points. There is some additional help due to the fact that only pixels on the edge of the area are affected by noise. Interior pixels are known to be completely covered by the image, and so their values can be corrected (by image processing) to the full value with no noise. Rather than undertake an error analysis of the second moment of inertia for random uncorrelated noise on edge pixels, a simulation was used to demonstrate the accuracy of the technique.

Centroid/Second Moment of Inertia Simulation

Using the equations for the centroid and second moment of inertia of an area, a general case problem was created to simulate a typical condition in order to demonstrate the accuracy of the method. A simulation program was written to solve for the second moment axis and use randomly generated "noise" to affect the edge areas of the projectile. This allowed the determination of the effects of random errors on the ΔA values, and also to compute the standard deviation of the calculations, providing a feel for the accuracy one might expect from the second moment method.

Array Size

An array size of $512_y \times 256_x$ was chosen because it was close to optimum for maximum size/coat for available CCD camera, at the time of the simulation.

Projectile Shape

The projectiles generally tested at the Eglin facility are bullets, missiles, and shapes that fly without tumbling as they travel downrange. These are generally oblong shapes with the length much greater than the diameter. Also, the shapes tend to be symmetrical about the long (horizontal) axis. To make matters simple for the drawings and simulation area calculations, a bullet shape of 80 mm long by 20 mm diameter was chosen. This represents the smaller projectiles tested in the facility and casts a shadow whose area is easy to calculate.

Geometric Model

The representative model used is shown in Figure 8 with each small square representing one pixel of the imaging array. All units of measure are in pixel units.

Fig. 8 Simulation Model

The size of the projectile at the reflective screen was then mapped onto the 512 x 256 array using a spatial resolution factor of the field of view of 1219.2 mm horizontal + 256 horizontal pixels = 4.76 mm per pixel (same for the vertical dimension). The size of the model in pixel units is 16.8 pixels long by 4.2 pixels high. The model was angled at 20 degrees relative to the horizontal.

The interpretation of the shadow of the model overlaying the array is that it simulates the image of the projectile cast on a CCD array. The CCD array provides an output to the imaging system that digitizes to 12 bits with values between 0.0 and 1.0. Pixels fully covered by the shadow will have a value of 1.0 in the system with no noise or error because it is known that they are interior to the shadow. These are the pixels shown shaded in Figure 8. The pixels that are only partially covered by the shadow (edge pixels) will output a value between 0.0 and 1.0, with random noise added to the ideal value. The noise is a random value between 0 and $\pm$ the reciprocal of the signal to noise ratio (S/N). These are the white portions of pixels shown in Figure 8 that are inside the model shadow outline. The ideal value of each pixel output is proportional to the pixel area subtended by the shadow. To achieve a perfect shadow model, the values for all pixels were read manually from Figure 8, by estimating the number of subareas on a finer gridded graph paper. These areas were used in the simulator as baseline data

for pixel areas. The areas determined manually for all pixels were entered in the simulator for the standard measured values, with random noise then added to each pixel area.

Simulation Results

The parameters calculated from the "perfect" shadow with no noise added are:

$$\begin{aligned} \text{Total Area} &= 59.171, C_x = 10.020, \\ C_y &= 3.562, \theta = 19.963^\circ \end{aligned}$$

Table 1 shows the average values produced by the simulator with noise for the Area, C_x , C_y , angle θ , and the 3σ value for angle θ . The value for σ should be used as the probable error to be compared with the current probable error values for the range using the film cameras.

The S/N ratio is calculated using the root-mean-square (RMS) value of the random noise generated, which is a continuous function, and using the voltage ratio of the signal and noise. The signal range is 0 to 1 volt. For each S/N ratio, the simulator was run 25 times to provide a good statistical sample. The standard deviation is based on these 25 runs.

Table 1. Simulation Results vs. S/N

S/N	C_x	C_y	θ	σ	3σ
3.5	10.031	3.573	19.082	0.7931	2.3793
5.2	10.007	3.560	19.995	0.5614	1.6842
6.9	10.055	3.567	19.782	0.4198	1.2594
8.7	10.021	3.557	19.879	0.3596	1.0788
10.4	9.991	3.554	20.054	0.2658	0.7974
12.1	10.011	3.559	19.899	0.2357	0.7071
13.9	10.016	3.564	19.984	0.2389	0.7167
15.6	10.018	3.563	20.001	0.1920	0.5760
17.3	10.017	3.562	19.984	0.1225	0.3675
26.0	10.016	3.561	19.974	0.0992	0.2976
34.7	10.020	3.562	19.950	0.1021	0.3063
52.0	10.016	3.560	19.968	0.0617	0.1851
69.3	10.020	3.562	19.964	0.0399	0.1197
86.7	10.020	3.563	19.967	0.0199	0.0597
121.3	10.021	3.562	19.964	0.0192	0.0576
173.3	10.020	3.563	19.969	0.0172	0.0516

Figure 9 shows a plot of the 3σ angle θ error vs S/N taken from Table 1. It also shows equivalent plots for 5 and 10 degree angles, showing insensitivity to model orientation.

Fig. 9 3σ Angle θ Error vs. S/N

Error vs. Array Size

Next, in order to look at the effects of array size on the angular error, the simulator was modified to accommodate various array sizes. Simulations were run for 2048 x 1024, 1024 x 512, and 512 x 256, as the three most likely array sizes to be used. Figure 10 shows the angular error (3σ) vs. S/N for the three array sizes. These plots assumed random noise over the entire projectile image, so the errors in general are higher than those calculated previously.

Fig. 10 Angle Error vs. S/N for Various Arrays

Comparison With the Film Method

The previous Los Alamos National Laboratory report³ contains an analysis of the Eglin Aeroballistics Research Facility. That analysis showed that the resolution capability of the film camera system used at the facility has a limiting resolution of 0.72 line pair/millimeter at the screen. This is 1.39 mm/line pair or 0.69 mm/line. This means that an object 0.69 mm wide can just be discriminated, or 0.69 mm is the "error limit" of the film system. Using that number for the error dimension for locating a point on each end of a line, and using a length of 80 mm for the shortest projectile, we can calculate the error in finding the angle of a line on film by using Equation 1. The calculation is shown in Equation 6 and is slightly better than the estimate used earlier in this paper.

$$\theta = \sin^{-1} \frac{\text{Error Limit}}{\text{Length}} = \sin^{-1} \frac{0.69 \text{ mm}}{80 \text{ mm}} \quad (6)$$

$$= 0.494 \text{ degrees}$$

The θ error of 0.494 degrees is based on the assumption that an operator can locate the end points of the line perfectly, resulting in $\pm$ one error limit of resolution. The error for a digital imaging system with an array of 2048_v x 1024_h resolution is about $\pm$ 0.852 degrees with no operator error in locating the end points of the line.

By comparison, a 512_v x 256_h array with a S/N of 20, which is realizable with the Eglin reflective screen and typical CCD cameras, will yield an angular error of about 0.40 degrees. It can be seen, then, that using the second moment of inertia algorithm with a 512_v x 256_h CCD array will yield angular accuracies of about what the

present film system can, and more than twice the accuracy of a 2048_v x 1024_h array camera using the geometric method. A 1024_v x 512_h array camera then can yield angular determinations better than the film system.

IV. Electronic Shadowgraph Station at Eglin AFB

The proof-of-principle electronic shadowgraph station for high-speed electronic imaging was delivered to the Aeroballistics Research Facility at Eglin Air Force Base on May 18, 1987.

The purpose of the system was to demonstrate the feasibility of either replacing or augmenting the current film camera system presently operating in the facility with solid state video cameras. This demonstration was to show the measurement resolution capability for locating projectiles as they fly down the range and also to demonstrate proper sensitivity and operation in situs at the range using existing range timing, controls, and spark-gap illumination.

Another purpose of the demonstration was to show the effects of special purpose algorithms and image processing on improving the accuracy of the measured projectile location.

Configuration

The study detailed earlier has shown that 1024_v x 512_h resolution electronic imaging cameras have sufficient accuracy, when used with centroid and second-moment-of-inertia algorithms, to yield measurement results comparable to the film system. Based upon that, the proof-of-principle system simulated a 1024_v x 512_h camera system by using zoom lenses on 512 x 512 resolution cameras to reduce the field of view to achieve equal spatial resolution.

The 1024_v x 512_h cameras had to be simulated, because a camera with the right resolution and price was not available. The proof-of-principle system was then configured as follows:

1. Two GE Model 2250 charge-injection device (CID) cameras with 12.5 to 75-mm zoom lenses, 512_v x 512_h resolution, single-frame integrate-mode operation.
2. Two Poynting Products Model M5250-PC controllers for the GE cameras, interfaced to an IBM PC/AT computer.
3. IBM PC/AT computer with 1-mb memory, running PC-DOS vs 3.1, with a monochrome monitor.
4. Imaging Technology Model FG-100-AT-1024 image processing card, with 1 mb memory. The PC card was installed in the IBM AT.
5. Sony 19" color monitor with 512_h x 480_v resolution. The color monitor was connected to the FG-100 PC card.
6. Werner-Frei "Imagelab" image processing software for the FG-100.⁶ This includes a

subroutine library "Toolbox" with subroutines usable from Fortran programs.

7. Microsoft Mouse and Mouse driver software. This is a PC card installed in the IBM AT, along with the driver software. The Mouse is used by the Werner-Frei "Imagelab" operating system to select menu commands or areas in an image for processing.

8. Infrared filters installed in the zoom lenses to filter out the IR screen light used at the facility. The filter cutoff is about 700 nm.

Software

Additional software was also written to provide some image processing capability not provided by Werner-Frei. The two algorithms (centroid and second-moment-of-inertia) were also coded. Software to operate the cameras was also written and menus for operation were embedded in the "Imagelab" operating system.

The system and software were tested by operating the cameras, processing images, and by calculating the centroids and second-moments-of-inertia of several objects of known size and orientation placed directly in memory (not imaged by a camera). The algorithms and software all seemed to work with very high accuracy.

Installation at Eglin AFB

Figure 11 shows the IBM AT computer and the Sony color monitor located in the control room at the Aeroballistics Research Facility. Cables were run overhead in cable trays to the cameras in the firing range and to the control console in the same control room.

Figure 12 is a photograph of the Hall camera installation at Station 1. The film camera is at the top, the spark gap is the circle in the center, and the IR emitter/detector unit is at the bottom right of the picture. The GE camera is at the lower center and is mounted closer to the spark gap than the film camera to compensate for the lower CID sensitivity. Tests have shown that the CCD camera is about three lens f-stops more sensitive than the GE CID cameras. This picture shows that the electronic imaging camera can be installed alongside the existing range cameras and equipment without disturbing their installation. This allows the film system to remain intact and operational while the electronic imaging system is installed.

Figure 13 shows the Pit camera installation, which was slightly different from the Hall installation, in that a turning mirror was used because of the different mount configuration for the Pit camera. This causes the image to be backwards, but that was reversed by the computer software.

Part of the spark gap can be seen between the film camera and the mirror. The Pit does not have an IR emitter/detector unit, because its spark gap is triggered from the corresponding Hall IR unit.

Fig. 11 Computer and Image Processor

Fig. 12 Hall Camera Installation

Fig. 13 Pit Camera Installation

Controls and Operation

Controls for the electronic imaging system were simple. The operator selected the ARM CAMERAS command from the menu on the monitor, and the computer set the cameras into the integrate mode of acquiring a single frame. This was done twenty seconds prior to firing. The camera controller hardware then looked for start and stop signals to trigger the cameras. Two control signals from the range control panel were used to start and stop the camera integration period, similar to opening and closing a film camera shutter. The timing of these signals was controlled from thumbwheel switches on the existing control panel. A CCD camera integration period of 700 milliseconds was used, which did result in some dark current noise accumulation, but it was acceptable for this test. In the final range installation, that time could probably be shortened. As soon as the model was fired, the computer was then accessed, and an image put on the monitor within a few seconds.

Live Tests

During the installation and testing period, a number of images of live projectiles fired down the range were taken and stored on disk. Lighting from the spark-gap light source seemed to be adequate to get pictures with the video cameras.

1024v x 512h CCD Camera System

In conjunction with the studies and algorithm development, a vendor was invited to demonstrate a prototype 1024_v x 512_h CCD camera during the testing of the shadowgraph station. The CCD camera had been previously interfaced to a Megavision image processor, therefore it was suggested that they bring that system with them.

The Megavision/CCD Camera system was interfaced with the range control signals, and managed to capture one test image of a projectile fired in the range. Many other images were obtained of static projectiles for calibration purposes and later those images were transferred to the IBM AT system, where calculations were performed. The Megavision system provided an easily adaptable interface to the CCD camera and also demonstrated image processing capability that would provide the necessary functions for the range.

V. Measurements at Eglin AFB

The only measurements taken at Eglin, due to time limitations, were centroids of beads and spatial locations of reference objects. These reference objects were thumbtacks mounted on the screen itself. The tack locations relative to the beads are shown in Figure 14.

Fig. 14 Bead and Tack Locations

The diameters of the two tacks, designated as points 5 and 6 in the image, were measured in order to relate their centroids to the measurement between the inside edges of the tacks.

Figure 15 is a photograph of the Sony monitor showing an image of the screen taken with the CCD camera. The two bullet shapes are a projectile and its shadow. The tacks and beads are also indicated in this figure.

Fig. 15 CCD Camera Image

The Plan

Ideally, it was desirable to accurately measure the distance between the two thumbtacks to use as a standard for comparison with the same

measurement obtained by the shadowgraph station and by the film cameras. Therefore, the plan was:

1. Measure the distance between the tacks with a calibration transit used by the personnel at the Aeroballistics Research Facility in making range measurements of actual bead locations. This system is accurate to about $\pm 0.005"$.

2. Photograph the same screen with the film camera and measure the distance between the tacks using the normal film reading procedure used at Eglin. That measurement should have a probable error of about $\pm 0.023"$, under ideal conditions, determined by the Los Alamos study by measuring the MTF of the film camera system.³

3. Measure the distance between the tacks with the GE and CCD cameras using the centroid algorithm.

Film Measurement of Tacks

A photograph of the screen was taken and numerically coded in the normal fashion, except points 5 and 6 were added, as shown in Figure 14. Of course, for statistically more reliable data, this measurement should be repeated 10 to 15 times. But for the case reported herein, it was read only once during this process.

Since the inside edges of the beads are set $36.000"$ apart when they are assembled on the Kevlar line, any error in that assembly will cause an absolute error in measurements in the range. But the beads are assembled very carefully on pre-stretched line using a machined fixture, therefore it was assumed that no error in this measurement existed. Measuring the distance between inside edges of the beads on the film, and using $36.000"$ as the actual distance, permitted the establishment of the spatial resolution factor for all measurements.

Because the beads and tacks in the image may be tilted with respect to the camera, simple geometry can be used to find the straight-line distance between them. For the beads, r_b is the straight line distance shown in Figure 16, b_b and a_b are the x and y image dimensions.

Fig. 16 Bead Location Geometry

From the film measurements, the distance between the inside edges of the tacks were obtained as:

$$D_{T(film)} = 35.475" \quad (6)$$

Electronic Image Tack Measurement

Measuring the tack and bead positions using the centroid algorithm is not as straightforward as it may seem, because of the very important influence of noise in the image. In this case, noise is anything other than the object to be measured. Thus, the Kevlar line, projectile, handprints, and random noise (both optical and electrical) are all "noise." In the electronic imaging system, noise affects the accuracy of the processing algorithms, so any noise minimization will be helpful. This requires filtering or other noise reducing techniques to be used, and places a great emphasis on careful selection of image processing techniques that must be employed to provide a clean image while not affecting measurement accuracy. Also, if the background noise can be eliminated (by image processing), then the centroid can be calculated on the entire image instead of defining the area (projectile) on which to process. This can also greatly simplify any image processing which automatically finds the projectile and determines its location and orientation.

The procedure, then, is to eliminate all extraneous information in the image, taking care not to destroy any measurement information in the process. Any image processing filters or thresholding applied to the image must be such as to comply with the stated procedure. Some of the experiments were efforts to derive some filtering methods to eliminate all the background (set to zero value) and to leave the object (tack or bead) intact. Some procedures were derived, but much image processing development for these measurements still needs to be done. This seems to be a relatively new, or at least unpublished, area of image processing; that is, most image processing has to do with improving how an image looks to the human eye, but not in improving measurement capability within an image.

Taking some simple tries at processing an image for eliminating the background, two different images acquired by the two different cameras (GE CID and CCD) and digitizing systems were operated on to measure the distance between the tacks.

GE Camera Image

The centroid data were measured with the GE CID camera. Calculating the distance between the two tacks resulted in:

$$D_{T(GE)} = 35.454" \quad (7)$$

CCD Camera Image

The centroid data were measured on the CCD camera similar to that measured with the GE camera. The distance measured was:

$$D_{T(CCD)} = 35.465" \quad (8)$$

Measurement Results

Results of the various methods of measuring the tack spacing is shown in Table 2.

Table 2. Measurement Results

<u>Method</u>	<u>Tack Measurement</u>
Film	35.476"
GE CID	35.454"
CCD	35.465"
Transit	35.380"

Summarizing the measurement results, the electronic imaging camera measurements resulted in differences of 0.022" and 0.011" from the film system measurement. The error for the film measurement, using the transit measurement as the standard, was 0.096". The errors for the GE and CCD cameras were 0.074" and 0.085", respectively, with the electronic shadowgraph measurements from both cameras closer to the transit measurements than was the film measurement. Not too much should be made of these results, because they are based on so few measurements and they were fairly coarse. Two electronic imaging measurements, from different systems, with pixel resolutions of about 0.085" agree within 0.011" and they were only 0.011" and 0.022" different from the film measurement, which must contain some error. Since the film measurements are so much different than the transit measurements, something very basic could be wrong with the system or the measuring devices. However, these results for the electronic cameras look very encouraging, and are certainly within the realm of accuracy of the present film camera system.

VI. Conclusions

The work reported in this paper has accomplished several things that were desired from the beginning, though some results were not anticipated:

1. An electronic shadowgraph system can achieve equal or better accuracy than the film camera system (using geometric methods), provided that adequate image processing be accomplished and the centroid and second moment of inertia algorithms be used.

2. Solid state cameras, as opposed to vidicon cameras, are required for their sensitivity to work with the existing Eglin spark-gap as part of an electronic shadowgraph. Vidicon cameras have several deficiencies, the worst of which is inadequate sensitivity for this application.

3. When using the centroid and second moment of inertia algorithms along with image processing that does not degrade the measurement information in the image, solid state cameras of 1024 x 512 resolution can be used to replace or augment the film camera system.

4. All measurements made during the proof-of-principle installation were of a coarse nature and should be verified, but look good in accuracy comparisons with the film system. They do not show what the ultimate accuracy of the electronic camera system could be.

5. Significant development of processes to adequately prepare the images for the application of the measurement algorithms must be done before higher accuracy measurements can be a reality.

6. An electronic shadowgraph system can be implemented very easily alongside the film camera system, using existing range timing and controls.

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