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COMPUTER-AIDED ANALYSIS FOR THE MECHANICS OF GRANULAR MATERIALS (MGM) EXPERIMENT

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Computer-aided Analysis for the Mechanics of Granular Materials (MGM) Experiment

by

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Abstract

The Mechanics of Granular Materials program is planned to provide experimental determinations of the mechanics of granular materials under very low gravity conditions. The initial experiments will use small glass beads as the granular material, and a precise "tracking" of individual beads during the test is desired. Real-time video images of the experimental specimen were taken with a television camera, and subsequently digitized by a "frame grabber" installed in a microcomputer. Easily identified red "tracer" beads were randomly scattered throughout the test specimen.

A set of Pascal programs was written for processing and analyzing the digitized images. Filtering the image with Laplacian, dilation, and blurring filters then using a threshold function produced a binary (black on white) image which clearly identified the red beads. The centroids and areas for each bead were then determined. Analyzing a series of the images determined individual red bead displacements throughout the experiment. The system can provide displacement accuracies on the order of 0.5 to 1 pixel if the image is taken directly from the video camera. Digitizing an image from a video cassette recorder introduces an additional repeatability error of 0.5 to 1 pixel. Other programs were written to provide "hardcopy" prints of the digitized images on a dot-matrix printer.

Introduction

Experimental determinations of the mechanics of granular materials, such as powders, soils, grains, etc., have been conducted for many years. In these experiments a cylindrical specimen of granular materials is usually confined by a uniform pressure. Since the experiments are conducted on the earth, the test specimens are also subjected to 1 g of acceleration (due to gravity). Gravity induced body forces prevent the testing of specimens at low confining pressures of less than 1-2 psi since the specimen's weight dominates the system response. Determining the mechanics of granular materials at low confining pressures would significantly improve our understanding of many geotechnical engineering and geological phenomena, such as the behavior of soils during earthquakes, sand storms, and planetology.

The Mechanics of Granular Materials Experiment is currently planned for Space Shuttle flight in the next few years. In a series of experiments a variety of granular materials (initially small spherical glass beads) will be tested in the near-zero g (microgravity) environment of the Shuttle's orbit. The absence of gravitational forces will allow very low confining pressures (0.25 to 1 psi) which are not possible terrestrially.

One of the desired goals of the MGM experiments is to determine constitutive relationships between specimen loading and deformation. Determination of rigid body displacements of individual particles within the test specimen as a function of time would aid the development of these constitutive relationships. One proposed method for determining displacements of particles on the specimen surface is to record visual images of the system during a test. These visual images can come from either individual "still" camera pictures, or from continuous recording via movie or television cameras. When continuous recording is used a tremendous amount of data can be generated. A standard television camera generates images at the rate of 30 per second, which results in over 200,000 images during a single 2 hour test. Clearly, some type of computer-aided analysis would benefit researchers by reducing the amount of effort required to determine particle displacements from the visual recordings of the experiment.

Objectives

The overall goal of this project was to develop computer-aided analysis techniques for analyzing visual images of the MGM experiments. Within this broad goal are many specific objectives, such as:

1) determine if additional commercially prepared image processing software is necessary,
2) develop a means for generating "hardcopy" images on a variety of printers,
3) develop computer software for acquiring images of the experiment and determining particle locations in an individual image,
4) develop computer software for identifying and "tracking" individual particle displacements between successive images, and
5) test and evaluate the developed computer-aided analysis package with actual experimental systems.

Hardware & Equipment

The computer vision system uses an Imaging Technology PCVision Frame Grabber plug-in board. The frame grabber is mounted in an IBM PC AT microcomputer equipped with a 6 MHz Intel 80286 microprocessor, 640K of random access memory (RAM), and a 20 megabyte hard disk for permanent storage. The board digitizes a standard RS-170 television signal into a 512 by 512 pixel (picture element) matrix with a resolution of 8 bits ($2^8 = 256$ gray levels). The PCVision Frame Grabber can digitize images at the 1/30th of a second rate of the RS-170 standard, although permanent storage of the digital images on a hard disk requires several seconds.

A JVC model BY-110 color television camera is used for viewing the experimental setup. A VCR (video cassette recorder) is also available for recording images throughout the experiment. The PCVision Frame Grabber can digitize either the signal directly from the television camera or from the VCR.

The experimental setup used in this work consists of a 4 inch diameter by 6 inch tall "cylinder" of 0.3 mm diameter blue glass beads constrained by a thin latex membrane. The cylinder of beads is placed inside a rigid "plexiglass" or "Lexan" pressure chamber cylinder of approximately 6 inches inside diameter. The annular region between the bead specimen and the clear outer cylinder is filled with water, which is externally pressurized to maintain a constant confining pressure.

Several red glass beads (of the same size and weight) are dispersed among the blue beads. Since there are fewer red beads, it is possible to identify and track individual red bead motions from frame to frame as the experiment progresses. The specimen is mounted in a standard triaxial soil mechanics testing frame where it is subjected to a uniform confining pressure, see Figure 1. During the experiment the specimen is strained at a constant rate of approximately 1 inch per hour to a final value of approximately 30% strain. Additional experimental arrangements (such as different size beads, other strain rates, etc.) are planned for the actual flight experiment.

Printer (Hardcopy) Outputs

Two commercial software packages ("ImagePro" and "ImageAction") are available from Imaging Technology for use with the PCVision Frame Grabber. These packages provide menu-driven software for acquiring and manipulating video images. Both "ImagePro" and "ImageAction" were useful in early stages of the project for generating image processing steps that were later developed into dedicated programs. The general purpose nature of these packages limits their usefulness for the specific, application oriented analyses required in this project.

"ImagePro" provides a hardcopy (printer) output that "ImageAction" does not, although the quality of the printed pictures is extremely poor. However, digitized images stored by "ImagePro" are in a run-length-encoded form that is difficult to manipulate with other software. "ImageAction" stores the data in the form of consecutive rows (of 512 one byte pixels) with a small amount of preliminary information. The "ImageAction" storage format was used for all software developed in this project. This means that "ImageAction" can be used to generate images for subsequent processing and analysis, or that "ImageAction" can be used to display images generated by the processing and analysis programs.

Pascal programs were written to provide hardcopy printouts of "ImageAction" digital images on both the Epson LQ-1500 (black and white) and ACT II (color) printers. The Epson printer simulates 8 shades of gray, while the ACT II displays 16 different colors. The PCVision Frame Grabber generates pixels with "brightness" values ranging from 0 (dark) to 255 (white). The printed gray shade (or color) for a particular pixel brightness is found by dividing the pixel value by 32 (Epson) or 16 (ACT II) and truncating the fractional part. The program for the Epson printer is named "Aspect.com" since it generates an almost exactly true aspect ratio (height to width ratio) for the printed image. The program for the ACT II color printer is appropriately named "Color_Pr.com" and it trims 56 columns from both sides of the image in order to have an almost true aspect ratio.

Two other printer programs were written for the Epson LQ-1500 printer. The program "Squish.com" prints a picture that is 1/4 the size of the one printed by "Aspect.com". This program prints only every other row and column, i.e. pixels with both even row and column numbers, so some resolution is lost. All images presented in this report were printed with "Squish.com". Another program ("Contur8.com") was developed for generating contour plots at 8 gray levels.

Image Processing

With only one exception (an assembly language routine) all software for this computer-aided image analysis project was written in Borland International's Turbo Pascal language. Turbo Pascal provides a convenient programming environment with the program editor, compiler, and error message generator integrated into a single package. One of Turbo Pascal's basic storage elements is an individual byte, and a single digital image generates over 240,000 bytes of data. Therefore, a considerable savings in storage is provided over languages such as BASIC or FORTRAN which typically use two bytes for integer storage. The only other logical choice for a programming language would be "C", but the programming environment is not nearly as "user-friendly" as Turbo Pascal.

The Pascal program for acquiring and processing the digital image into a usable form is called "Process". This program consists of a set of procedures (similar to subroutines in FORTRAN) for performing the required operations. The Pascal procedure for "grabbing" image frames from the TV camera (or VCR) is called "Snap". This procedure initializes the PCVision Frame Grabber board then "grabs" a single frame and places it in the PCVision memory. A procedure called "Store_Picture_in_Memory" stores the digitized picture in a 480 row by 512 column matrix of 1 byte values (in the IBM PC AT memory) for easy manipulation by other procedures. Although the PCVision system digitizes 512 rows, only the first 480 are displayed on the monitor, so the other 32 are not used by any of the image analysis programs or procedures. Another procedure called "Save_Picture_to_Disk" is used for storing the picture array in an "ImageAction" file format (which use the filename extension ".img").

In the original images the red beads display a noticeable diffraction pattern, which appear as the "cross-hatched" areas in Figure 2. Figure 2 represents the upper left quadrant (240 rows by 256 columns) of an image taken of an experimental specimen. Since the specimen is covered with a latex membrane, the red beads are somewhat difficult to see without image processing. Also, the PCVision system generates a black and white picture which would make it virtually impossible to distinguish red from blue beads without the diffraction patterns. Note that the left side of Figure 2 appears generally darker than the right side. The right side is near the center of the test specimen and a considerable amount of "glare" is present in this part of the image.

One of the basic image processing techniques used in this software involves convolving or filtering the digitized image with "operator masks" of various types. These operator masks are usually 3x3 or 5x5 matrices that are superimposed on each pixel of the original frame. Each value in the mask is multiplied by the pixel "under" it, and the sum of the 9 (or 25) multiplications becomes the pixel value at the center of the mask in the new, convolved image. As an example, consider the 4x5 digital "image" below along with the 3x3 Laplacian operator.

$$\text{Image:}\quad \begin{matrix} 5 & 7 & 10 & 4 & 3 \\ 6 & 9 & 8 & 2 & 4 \\ 4 & 5 & 7 & 1 & 2 \\ 7 & 6 & 6 & 2 & 8 \end{matrix} \qquad\qquad \text{Laplacian:}\quad \begin{matrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{matrix}$$

If we apply the operator mask to the image only where the mask completely covers part of the image, then the first pixel to be convolved is the 9 in row 2, column 2. Applying the operator to this first pixel gives:

$$\begin{aligned} \text{New Value} = {} & (-1)(5) + (-1)(7) + (-1)(10) + && \text{<- Row 1} \\ & (-1)(6) + (8)(9) + (-1)(8) + && \text{<- Row 2} \\ & (-1)(4) + (-1)(5) + (-1)(7) && \text{<- Row 3} \end{aligned}$$

or New Value = 20. If we apply the Laplacian operator to all usable points in the original image, the resulting convolved image is

$$\text{Convolved Image:}\quad \begin{matrix} 5 & 7 & 10 & 4 & 3 \\ 6 & 20 & 19 & -23 & 4 \\ 4 & -13 & 17 & -31 & 2 \\ 7 & 6 & 6 & 2 & 8 \end{matrix}$$

Notice that the pixels on the perimeter of the image are unchanged. Each time a convolution operator is applied to an image two rows and two columns of pixels are "lost" since their data is no longer meaningful.

The Laplacian convolution is the first to be applied to the video images since it enhances the visibility of the red beads while eliminating the blue beads. Figure 3 shows the image that results from convolving the Laplacian operator with the image in Figure 2. The cross-hatched areas of Figure 2 are replaced by vertical bands of alternating light an dark areas. This step is extremely important since the Laplacian convolution produces essentially the same pattern for all red beads, regardless of where they occur in the original image. The red beads located in the right hand side of Figure 3 are in the "glare" region of Figure 2, yet the convolved appearances are similar.

The next image processing step involves removing the dark bands from the Laplaced image. The operator here is called a "dilation" mask and it operates somewhat differently than the convolution mask. The dilation mask shown below is applied by the procedure "Dilate" to all pixels in the current image:

Dilation mask:
$$\begin{matrix} 0 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 0 \end{matrix}$$

If any of the pixels "under" a 1 of the mask are greater than a predetermined threshold (150 is the currently used value), then the center pixel is replaced by the largest value in the image under a 1 in the mask. If all surrounding pixels are less than the predetermined threshold, then the center pixel is left unchanged. This operation has the effect of thickening the light regions (greater than 150) of the banded areas by essentially eliminating the dark bands. Figure 4 shows the results of applying the dilation mask to the image of Figure 3. Notice that Figure 4 is similar to Figure 3 except in the red bead regions where there now appears a white "spot".

The next operation on the digital image is applying a "blurring" convolution mask (procedure "Blur"). This mask is a 5x5 array with the values:

Blur mask:
$$\begin{matrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 2 & 2 & 2 & 1 \\ 1 & 2 & 1 & 2 & 1 \\ 1 & 2 & 2 & 2 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{matrix}$$

The resulting value is divided by 33, which is the sum of all values in the blur mask. Blurring is essentially a smoothing or averaging operation that has two main effects on the dilated image. First, it reduces the effect of small spots of white (usually "noise") by spreading the pixel value over a larger area. Secondly, it smooths the edges of the red bead areas by averaging the dilated pixel values with surrounding darker areas. Figure 5 shows the image of Figure 4 after the blurring operation.

The three image processing operations of Laplacian, dilation, and blurring are provided in the ImageAction software. However, the Pascal routines written for this project run from 30% to 50% faster than the equivalent ImageAction routines. Also, the ImageAction convolution mask routines have a small "bug" in them. The result of an ImageAction convolution is placed one pixel to the left of where it is supposed to be. After three convolutions the entire image has been shifted to the left by three pixels. Images processed by the ImageAction routines should not be compared to other images for measurement purposes since this shifting has taken place.

After the image has been blurred, a "thresholding" operation is applied. All pixel values greater than a threshold value (currently 150) are set to 0 (black). All other pixel values are set to 254 (white). The thresholding operation results in a binary image which clearly identifies the red beads as dark spots on a light background. The subroutine for thresholding is written in Microsoft assembly language for fast operation, but could be written in Pascal with only a small penalty in execution speed.

The resulting binary image is then "segmented" into non-touching objects or "blobs" by a set of Pascal routines. Although humans can automatically determine which ones of the approximately 240,000 pixels form an individual object, a computer has no intrinsic way of doing this. An algorithm for grouping neighboring pixels into unique "blobs" was developed after several trials, and is implemented in the procedure "Segment". The essential steps of this algorithm are:

1) Initialize a parameter (Next_Object) to 1 and scan the first row of the image from left to right searching for pixel values of 0 (dark).
2) If a value of 0 is found and its left-hand neighbor pixel value is a 254, then replace the current pixel value with the value of Next_Object and increment Next_Object.
3) If the left-hand neighbor is less than 254 (which indicates that it used to be a 0), then replace the current pixel value with the value of its left-hand neighbor.
4) Continue steps 2-3 until the first row is finished.
5) Scan the next row looking for pixel values of 0.
6) If a value of 0 is found and the left-hand neighbor is a 254, check (in succession) the pixel values in the row above that touch the current pixel (to the left, straight up, then to the right). Replace the current pixel value with the <u>first</u> one of these that is not a 254.
7) If a value of 0 is found and the left-hand neighbor is less than 254, then replace the current pixel value with the value of its left-hand neighbor. Check (in succession) the pixel values in the row above that touch the current pixel (to the left, straight up, then to the right). If any of these are less that 254 and are different from the current pixel value, replace <u>all</u> instances of the different value with the current pixel value.

8) If a value of 0 is found and none of the surrounding pixel values are less than 254, then replace the current pixel value with the value of Next_Object and increment Next_Object.
9) Continue steps 4-8 until finished with all rows.

After this algorithm is run, each individual "blob" will be identified by a set of pixels with a unique value between 1 and 253. All pixels with the same value belong to the same object. Note that no more than 253 "blobs" can be found by this method (actually quite a few less).

Now that individual "blobs" have been identified, parameters such as area, "roundness", and height to width ratio can be calculated. These parameters are used to determine which "blobs" are actually legitimate red beads and which are simply "noise". The area of each individual "blob" is calculated and compared to predetermined thresholds. All areas smaller or larger than the target red bead area range can be automatically eliminated. The smaller areas usually come from noise in the picture, while the larger areas can result from "glare" in the original image or from two or more touching beads.

"Roundness" or "circularity" of an object is defined to be the ratio between the perimeter length squared and the area. For a perfect circle the circularity ratio is 4π. In a procedure called "Circle" all "blobs" with a circularity greater than 15 are eliminated. Similarly, a procedure called "Ratio" eliminates all "blobs" with a height to width ratio greater than 1.

All remaining "blobs" are considered to be valid "red beads" and are re-numbered starting with 1. A procedure called "Center" calculates the centroid of each bead. The X axis is assumed to be along column 0 while the Y axis is assumed to be along row 0 (Y is positive down). The bead centroids and areas are written into a data file (with a user-specified name) along with the number of beads. The current software determines bead centroids to within 0.1 pixel, although this has some aspects of "false accuracy". Determining centroids to any greater precision would be meaningless, which will be shown in a later section of the report.

Image Analysis

After the original images of the experiment are processed and bead centers are located, the analysis shifts to determining individual bead displacements between successive images. The current software for performing this analysis treats all bead displacements as relative motions between a single pair of images. Displacements are calculated from the first to the second image in a sequence, then from the second to the third, then from the third to the fourth, etc. However, the bead motions from the first to fourth frames can easily be determined by simply adding the three relative displacements between these two images.

The bead "tracking" algorithm is relatively simple, and is performed by a program called "Analysis". The user is prompted for the names of two bead center data files prepared by the "Process" program. The data from these files is read into arrays. Bead centers are displayed on the video monitor as "+" signs for the first image and as "x" signs for the second image. The user is then prompted for the X (horizontal) and Y (vertical) "pixel to inches" conversion factors. The bead center in the second frame "closest" (in a least squares fashion) to each bead center in the first frame is then identified. The distance between them is compared to a threshold value (which is currently 0.1 inch). If the distance is less than this threshold, then a "match" is assumed and relative X and Y displacements can be calculated. The "matched" bead centers in the second frame are then discarded so that they cannot be used for subsequent processing. The displacement analysis continues until all beads in the first image have been checked.

One important limitation of the algorithm outlined above must be remembered, <u>displacements between successive frames must be relatively small</u>. Motions on the order of half a bead diameter would be approximately ideal since the matching algorithm would work well with little opportunity for mis-matching. Displacements larger than one bead diameter could easily lead to erroneous results, especially if two beads begin to approach each other. Very small relative motions should also be avoided since calculated displacements will be greatly contaminated by inherent measurement "noise" (discussed in the next section).

The bead "size" information is recorded in the data files along with the horizontal and vertical center locations. This information could also be used to help in the "tracking" analysis, but is not used currently. Bead sizes should not change greatly between successive frames, so a matching algorithm based on both size and distance criteria could be developed.

The "Analysis" program also has another output. Bead centers from the second data file that "match" bead centers from the first file are written to a new data file. This new data file has the same name as the second data file, but the new extension is "upd" (for UPDated). Each bead ID is changed to match the ID of the bead it was matched with from the first data file. For example, assume that bead #6 of the second data file ("No2.dat") matches bead #4 from the first data file ("No1.dat"). The centroid and area data for bead #6 of the second file is then written to the new data file ("No2.upd") with a new identification as bead #4. Beads from the second data file that have no "match" from the first file are not written into the new file.

With this scheme bead centers <u>from the first image</u> can be tracked throughout an entire series of images. Suppose that four data files (No1.dat, No2.dat, No3.dat, and No4.dat) have been created by "Process" from four successive images. First use "Analysis" to determine displacements from "No1.dat" to "No2.dat", which creates a new data file entitled "No2.upd". Next use "Analysis" to determine displacements from "No2.upd" to No3.dat", which creates a new data file entitled "No3.upd". All displacements determined for a given bead "i" from the second analysis refer to the same bead "i" from the first analysis. Finally, use "Analysis" with the files "No3.upd" and "No4.dat". Again, all displacements determined for a given bead "i" from this third analysis refer to the same bead "i" from the first analysis.

Analyzing a series of images in this fashion does have some potential problems. If a bead "disappears" in one image of the sequence and then "reappears" in a later image, no connection between these two beads will be made. A given bead could "disappear" in one of two ways. If a bead begins to move radially toward the center of the specimen, then the "size" of the bead appears to decrease. If it decreases below the threshold size of the "Process" program, then it is removed from the set of possible bead centers. Also, if two red beads move together and touch, a single large "blob" is generated by the "Process" procedures and can be removed by the circularity or ratio criteria.

An additional program which uses the data files written by the "Process" program is called "Sequence". This program prompts the user for the name of a data file, then displays small circles on the video monitor at each bead center location. The program can then display other sets of bead centers concurrently. This program can be used to "animate" the motion of beads at speeds several times that of the original experiment.

Experiments and Calibration

A series of tests were conducted in order to establish the validity of using video digitization as an analysis technique for the MGM experiment. In the first test a set of 20 red beads (of 3 mm or 0.12 inch diameter) were rigidly attached (glued) to a test plate. The plate was mounted to the triaxial test machine, but it was not behind the water or the "plexiglass" pressure chamber cylinder. The plate was displaced vertically (as a rigid body) five times in 0.100 inch increments. Digitized images were taken directly from the video camera at each increment. The digital images were then processed using the software discussed in the previous sections ("Process" and "Analysis"). The data from the first test (0.1 inch input displacement) is given in Table 1, while the data for the last test (0.5 inch input displacement) is given in Table 2.

Table 1

Experimental Measurements with 0.1 inch Input Displacement

Bead	Horizontal Displacement (pixels)	Horizontal Displacement (inches)	Vertical Displacement (pixels)	Vertical Displacement (inches)	Net Displ. (inches)
1	0.2	0.003	8.4	0.099	0.099
2	-0.2	-0.003	8.5	0.100	0.100
3	-0.2	-0.003	8.4	0.099	0.099
4	-0.6	-0.009	8.4	0.099	0.099
5	-0.3	-0.004	7.7	0.091	0.091
6	0.4	0.006	8.2	0.097	0.097
7	-0.6	-0.009	8.5	0.100	0.101
8	-0.5	-0.007	8.0	0.094	0.095
9	-0.2	-0.003	8.8	0.104	0.104
10	-0.3	-0.004	8.3	0.098	0.098
11	0.3	0.004	8.4	0.099	0.099
12	0.3	0.004	8.7	0.103	0.103
13	-0.4	-0.006	7.8	0.092	0.092
14	0.1	0.001	8.1	0.096	0.096
15	0.0	0.000	8.4	0.099	0.099
16	-0.1	-0.001	8.5	0.100	0.100
17	0.1	0.001	8.3	0.098	0.098
18	0.2	0.003	8.5	0.100	0.100
19	0.3	0.004	8.5	0.100	0.100
20	0.2	0.003	8.0	0.094	0.094

Average bead displacement = 0.098 inches
Standard deviation = 0.0033 inches

Table 2

Experimental Measurements with 0.5 inch Input Displacement

Bead	Horizontal Displacement (pixels)	Horizontal Displacement (inches)	Vertical Displacement (pixels)	Vertical Displacement (inches)	Net Displ. (inches)
1	1.2	0.017	42.0	0.496	0.496
2	1.5	0.022	42.4	0.500	0.501
3	1.1	0.016	42.5	0.502	0.502
4	0.5	0.007	41.8	0.493	0.493
5	2.0	0.029	42.1	0.497	0.498
6	1.2	0.017	41.8	0.493	0.494
7	1.5	0.022	42.7	0.504	0.504
8	0.5	0.007	42.1	0.497	0.497
9	1.7	0.024	42.9	0.506	0.507
10	1.0	0.014	42.2	0.498	0.498
11	1.6	0.023	42.9	0.506	0.507
12	1.8	0.026	42.7	0.504	0.505
13	1.2	0.017	41.4	0.489	0.489
14	1.2	0.017	41.0	0.484	0.484
15	1.4	0.020	42.5	0.502	0.502
16	1.4	0.020	42.5	0.502	0.502
17	1.3	0.019	41.6	0.491	0.491
18	1.4	0.020	42.1	0.497	0.497
19	1.9	0.027	42.4	0.500	0.501
20	0.7	0.010	41.5	0.490	0.490

Average bead displacement = 0.498 inches
Standard deviation = 0.0062 inches

The 0.2, 0.3, and 0.4 inch input displacement cases showed average measured displacements of 0.199, 0.300, and 0.400 inches respectively with standard deviations of 0.0042, 0.0052, and 0.0059 inches respectively. The data indicate that the average measured displacements are quite accurate, but that individual beads may deviate somewhat from the average. The "worst-case" deviation for the 0.5 inch input is 0.014 inches, which is approximately a full pixel height.

One possible source of error can be seen by comparing individual bead displacements in Tables 1 and 2 to the average displacements. The displacements of beads 1, 2, 3, 4, 7, 9, 11, 12, 15, 16, 18 and 19 in Table 2 are greater than the average of 0.098 inches. In Table 2 beads 2, 3, 7, 9, 11, 12, 15, 16, and 19 have displacements greater than the average of 0.498 inches. These nine beads from Table 2 also have greater than average displacements in Table 1. The displacements shown in both tables are measured with respect to the same original image. Any errors in determining the starting bead centers from this image would tend to remain throughout the analysis of several images.

In the second test of the imaging system, frames (or images) were captured from a video cassette recording of an experimental specimen. The specimen was mounted in the triaxial testing frame and the pressure chamber was filled with water. Several red beads were randomly scattered throughout the specimen. The specimen was not moved or strained during the video recording. Four different digitizations of the same "identical" image were made. Thirty-three (33) beads were correctly identified in each of the four images at essentially the same X and Y coordinates. However, four smaller beads were identified in some of the digitized images but not in others. Some of these beads were eliminated from the final analysis because they fell below the size or area threshold.

Three sets of "displacements" were calculated for the 33 beads common to all four images by subtracting the positions of the first image from the second, third, and fourth images. The <u>average</u> displacement calculated in this fashion was essentially zero in both the horizontal and vertical directions. However, the standard deviation was 0.57 pixels in the horizontal direction and 0.41 pixels in the vertical direction. Histograms for the horizontal and vertical displacements are shown in Figures 6 and 7 respectively. Gaussian distributions with the same standard deviations are also plotted for reference purposes. The data indicate that using the VCR for recording video images prior to digitization does contribute additional error in the form of reduced repeatability. This error is approximately one half to one full pixel in both the horizontal and vertical directions.

Results

The extensive amount of data generated from the Mechanics of Granular Materials experiment will require computer assistance for effective data analysis. No commercial software packages are available for performing the specialized and specific analyses required.

A set of Pascal programs for determining individual bead motions from digitized video pictures of the MGM experiment has been developed. The original image is passed through Laplacian, dilation, and blurring filters before thresholding creates a binary (black on white) image. Image segmentation separates the black pixels into contiguous sets or "blobs". Further processing eliminates some "blobs" on the basis of size, circularity, or height-to-width ratio. All remaining "blobs" are assumed to represent valid beads. This image processing for a single picture takes approximately 3-4 minutes after the digital image has been stored on the hard disk. The output of this software is a data file containing bead centroids measured from both the X and Y axes (top and left sides of the image respectively).

Testing of the video digitization equipment and image processing software indicated that measurements with average measurement errors of essentially zero can be made. However, standard deviations in the measurements made directly from the television camera indicate that the accuracy is on the order of one half a pixel. Also, images digitized from VCR recordings are of significantly lower quality than ones digitized directly from a television camera. Repeatability in measuring "identical" images from VCR recordings was within one half to one full pixel.

Additional software was written to provide "hardcopy" output for the digitized images on a printer. Programs were developed for printing full size images on the Epson LQ-1500 (black/white) and ACT II (color) printers. Other programs provide contouring and quarter size copies on the Epson LQ-1500.

Recommendations

Several recommendations for further work on this project are given below. The recommendations are given in roughly the order of priority and/or practicality with highest priority first.

The currently used JVC BY-110 color camera is too large and bulky for use in the actual shuttle experiments. Much smaller black and white cameras are available, but they must be checked to see if the "diffraction" pattern is generated for the red beads. The "diffraction" pattern is an critical requirement of the current analysis software.

The use of special filters should be considered if other cameras do not generate the required "diffraction" patterns. A filter that passed only red light could be used to give an image in which red beads could be easily identified.

The experimental arrangement used in the test cases could not discriminate bead motion from relative motions between the camera and test specimens. Small stationary identifying points or "landmarks" should be added to the experimental system. Measurement of these "landmarks" in the image could then be used to correct for any "jitter" from the VCR or changes in angular orientation between the camera and test specimen.

The water which fills the space between the specimen and the "plexiglass" pressure chamber magnifies the image to some degree. This magnification is difficult to determine and may change as the experiment progresses. The exact effect must be evaluated to determine the inches-per-pixel ratios required for both the horizontal and vertical directions.

Significantly more testing of the entire imaging system (hardware and software) is needed to conclusively prove the utility of this approach. The digitized images are of higher quality in the center 50 - 60% of the specimen image. This portion of the image is not significantly affected by the effects of projecting a three-dimensional scene (the specimen) onto a two-dimensional surface (the video frame). The outer portions of the test specimen image must be discarded or correction factors must be developed for generating valid information.

The current 3 to 4 minutes required for processing each image can be reduced somewhat by different methods. The Turbo Pascal programs used in the current software are fairly well optimized for fast execution. Replacing the IBM PC-AT's standard 12 MHz clock crystal with a 16 MHz crystal would increase the AT's operating frequency from 6 to 8 MHz. Since disk access times would not be significantly improved, a 25% to 30% faster analysis could be expected. A more time-consuming option would be to convert the image processing routines to the "C" language for future porting to a faster microcomputer (such as the IBM RT-PC or a Motorola 68000 based system).

The PCVision frame grabber provides a useful resolution of 480 "rows" and 512 "columns". A 7% improvement in the imaging resolution could be easily obtained by turning the camera 90 degrees such that there are 512 "rows" and 480 "columns". The current software would not be changed, except possibly to re-label the X and Y axes. This arrangement would also better use the full video screen, since the MGM test specimens usually have height-to-width ratios greater than one.

The final recommendation is the most esoteric. Pattern matching and artificial intelligence techniques could be developed to identify red beads directly from the original or Laplaced images. These same techniques could also be used to accommodate the problems encountered with adjacent (touching) red beads. These beads are eliminated by the current algorithm, but could provide valuable information from the actual experiment.

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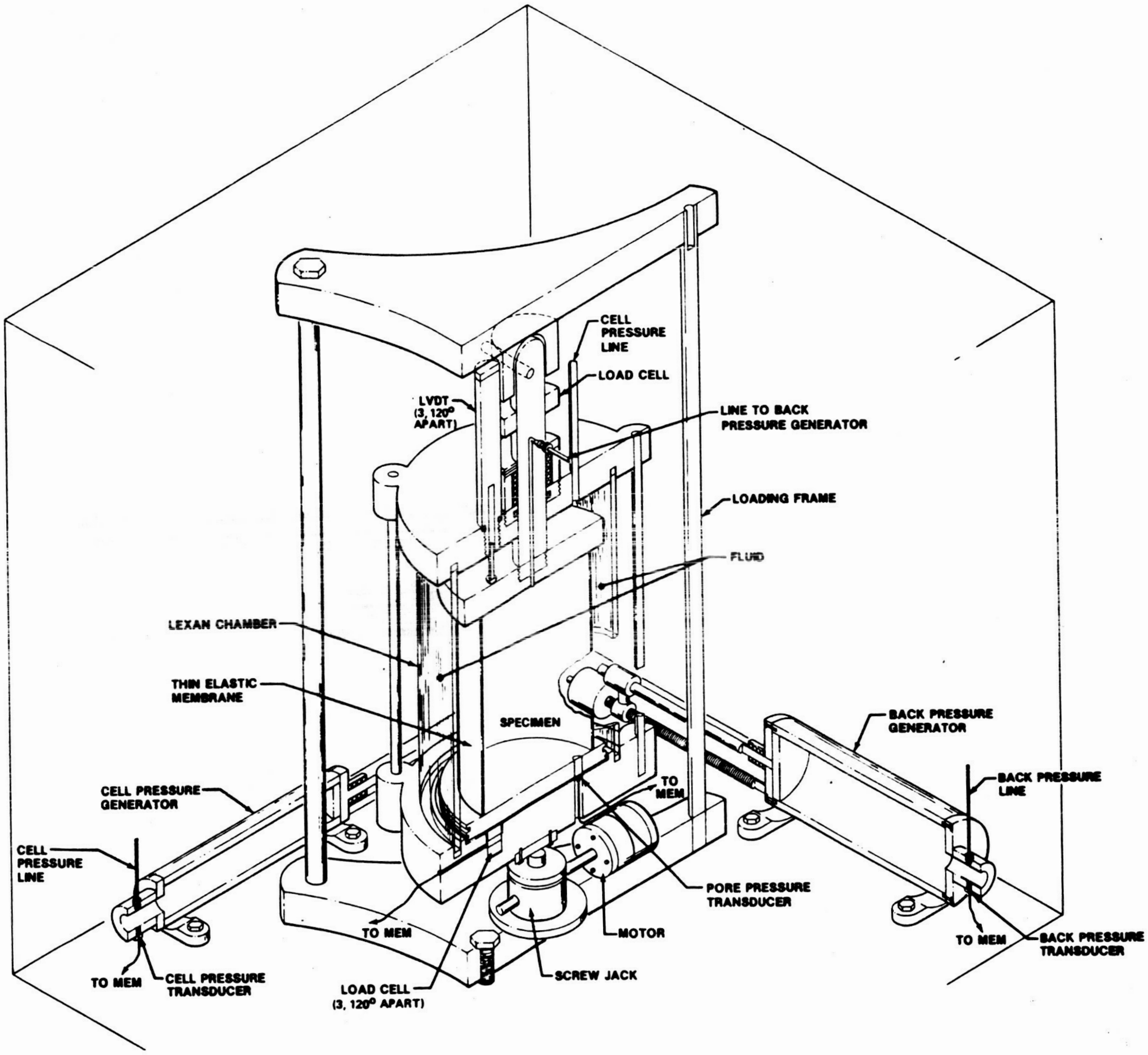

Figure 1 - MGM Experimental System

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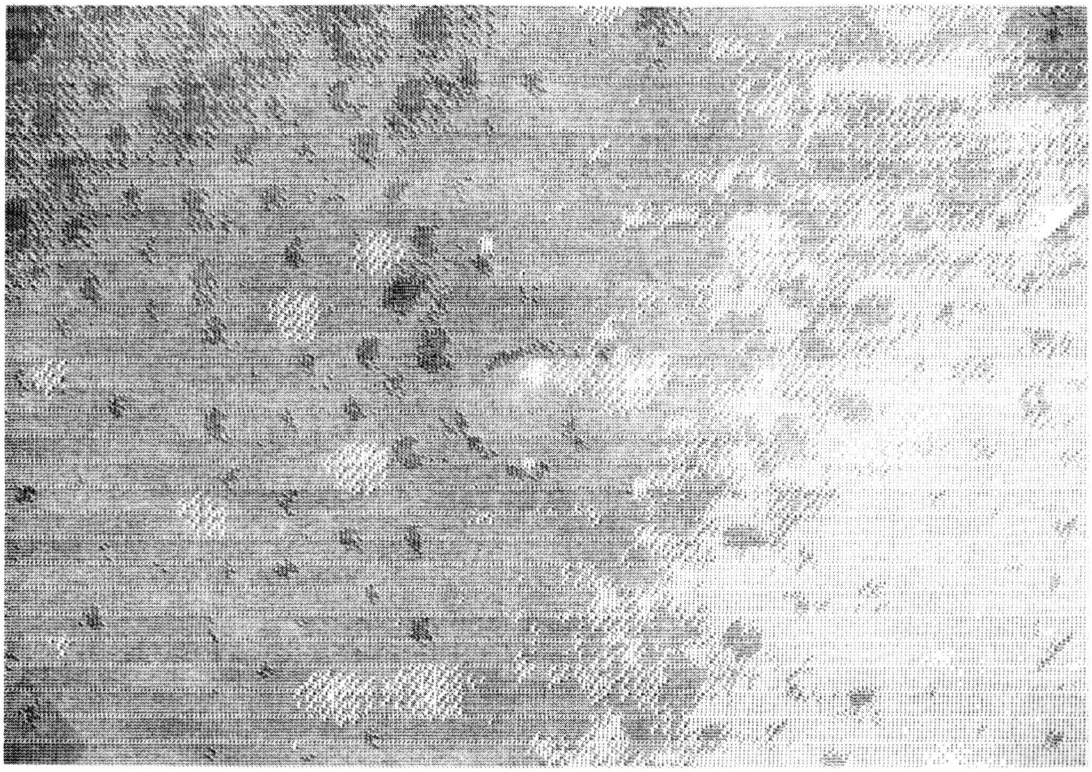

Figure 2 - Original Digitized Image

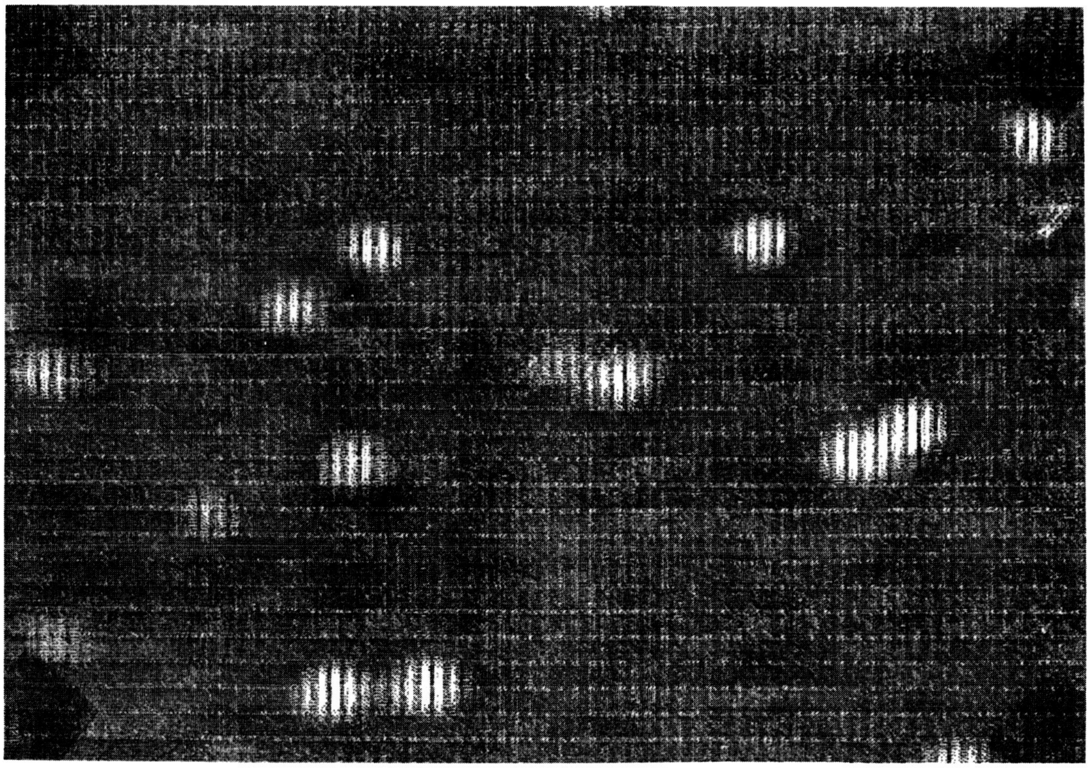

Figure 3 - Digitized Image after Laplacian Filter

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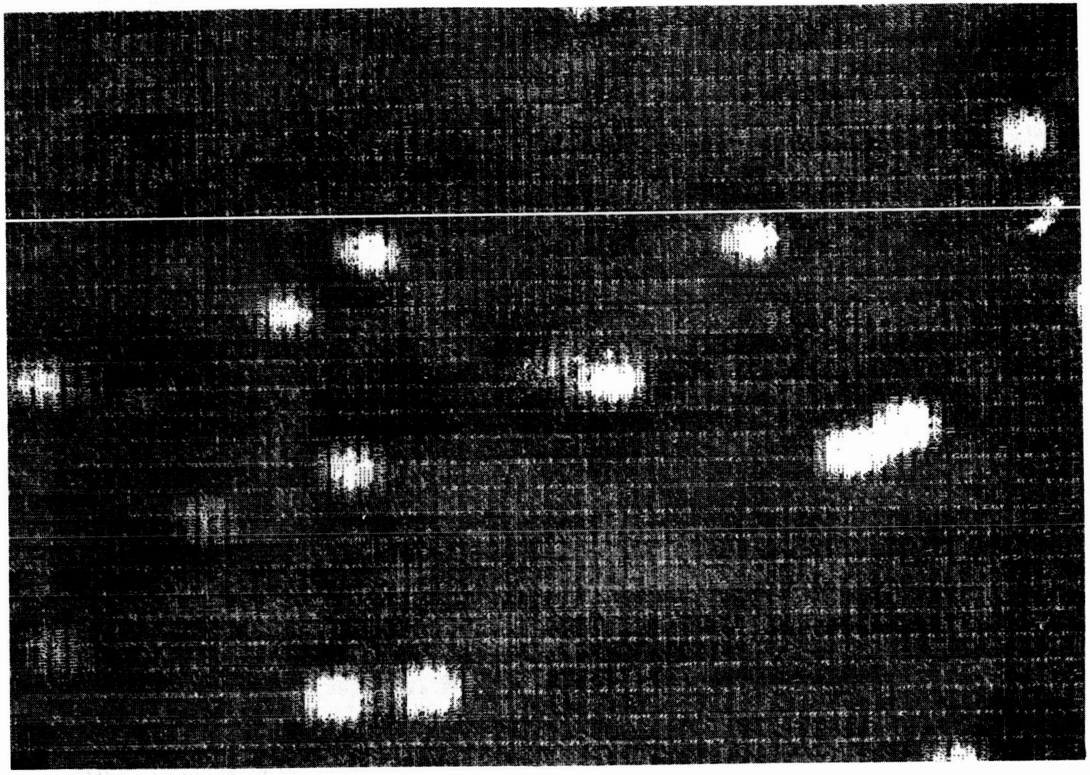

Figure 4 - Digitized Image after Dilation Filter

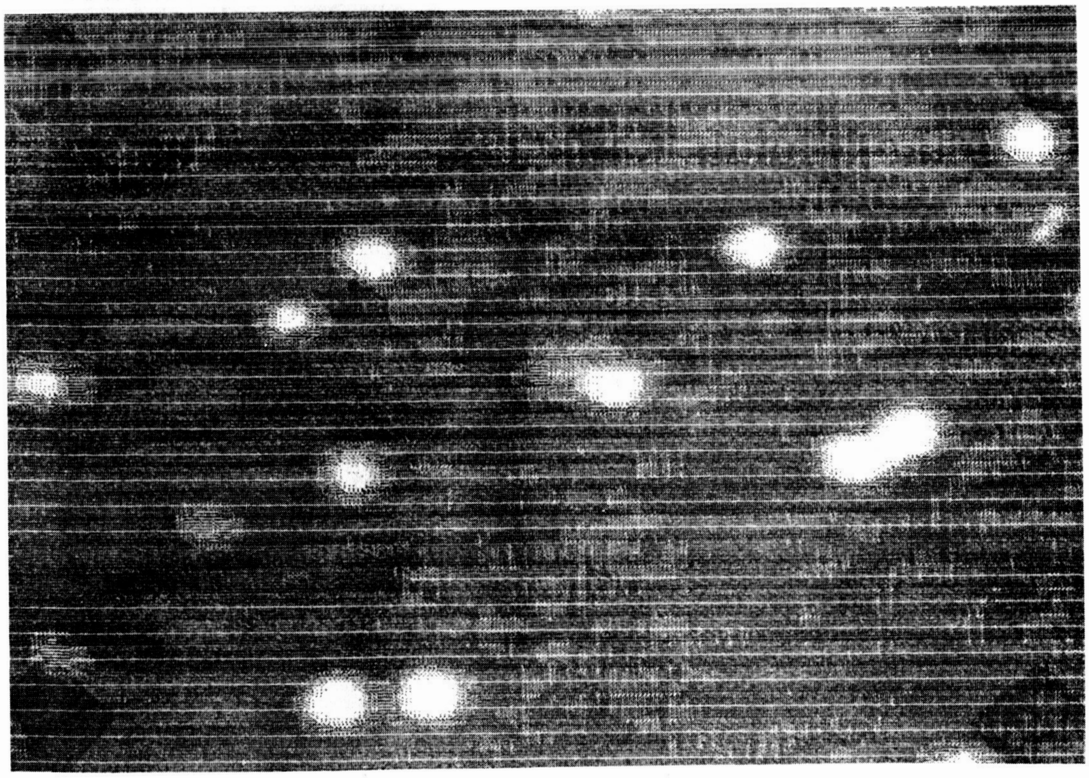

Figure 5 - Digitized Image after Blurring Filter

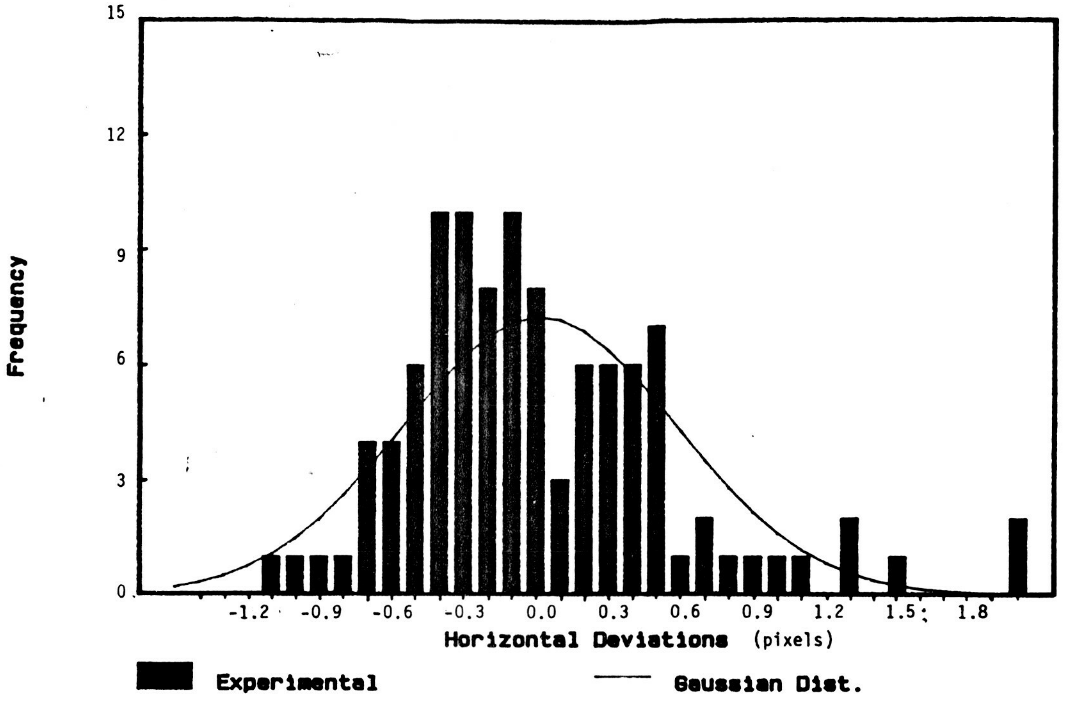

Figure 6 - Histogram of Horizontal Displacements

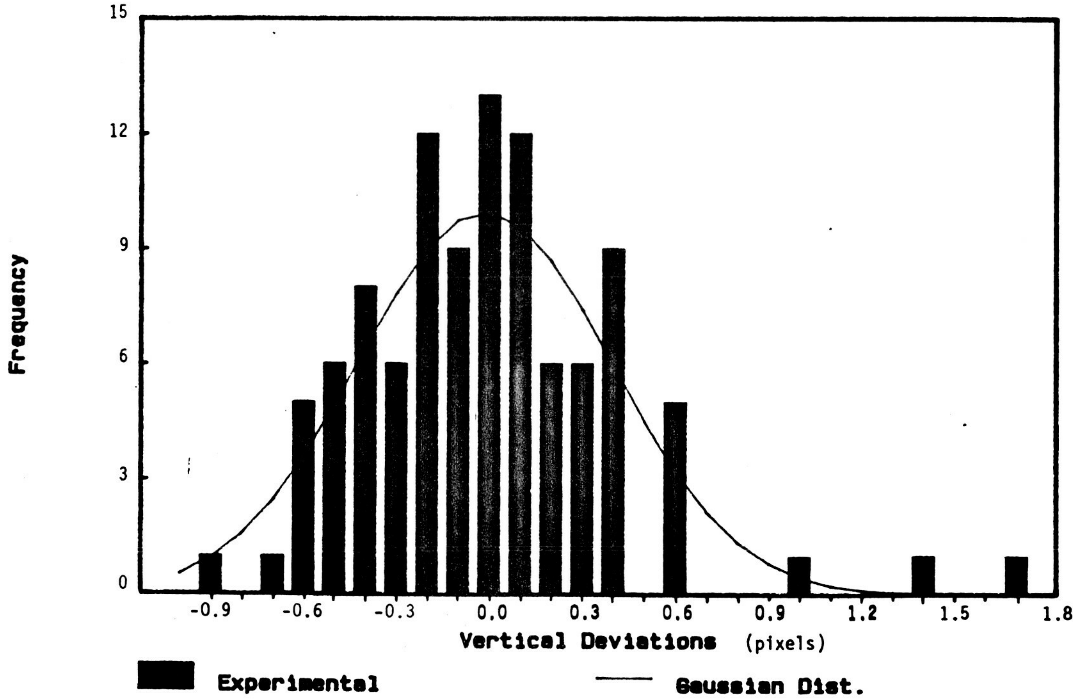

Figure 7 - Histogram of Vertical Displacements