Particle Motion Tracking Utilizing a High-Resolution Digital CCD Camera

ABSTRACT: Digital imaging acquisition and processing is applied for the tracking of a two-dimensional assembly of disks. The disks are used to assemble models for studying granular material behavior for which the kinematics of the individual particles, and hence the disks' trajectory during motion, are of cardinal importance. Large particle size is dictated by photoelastic interparticle interaction analysis. Therefore, a sufficiently large representative number of particles results in a large physical model.

The system requirements of a sizable physical model comprised of a large number of particles, and simultaneous precise tracking of all particles, are achieved through the use of high-resolution digital CCD camera and semi-automatic image processing and analysis algorithms.

The physical system setup, image acquisition procedure, calibration, accuracy, and algorithms of analysis are described. The system’s performance is demonstrated through test results describing the displacement field along with the motion and interaction of individual particles.

The system’s advantages in providing detailed tracking of a large number of particles with minimal labor are unmatched by any other technique. The data obtained by such systems allow a better understanding of particulate media behavior with the ability to examine and calibrate numerical models on an individual grain basis.

KEYWORDS: image processing, granular material, particle, interface, shear, tracking, CCD

Particulate media possess unique characteristics differing from those of continuous media. Among these are the dilative nature during shear, the development of shear bands, and the ability to redistribute stresses bridging over yielding areas (arching). These characteristics are controlled at the micro level by the interparticle interaction. A detailed quantitative study of such interaction in three-dimensional natural or man-made particulate materials is currently unattainable.

A unique system has been developed capable of investigating the interparticle interaction in a two-dimensional array of ideal particles (Paikowsky and Xi 1997). This interaction is monitored via the interparticle forces (magnitude and orientation) employing photoelastic response and the kinematics (translation and rotation) of each particle. Both systems utilize digital imaging acquisition and analysis techniques. The present paper focuses on the principles and performance of the image tracking system aimed at providing the detailed motion of each particle.


The goal and performance of the presented system are different from tracking efforts utilizing X-ray (e.g., Phillips 1972) or photography (e.g., Gill 1991). In both techniques, tracers are used either inside the granular media (e.g., lead shots within sand) or on the boundary along a transparent surface. Such tracking enables one to follow the mass motion or independent individual grains. The present system is focused on studying the interaction between the particles following the trajectory of all particles, including the quantification of their rotation.

Experimental System

Overview

A schematic layout diagram, and a photograph of the experimental system are presented in Fig. 1. A light source provides illumination for the testing apparatus that contains a model. The model consists of particles fabricated from a photoelastic material placed between transparent walls. As a response to external loading, the particles in the model will displace and interact. The data collection and processing system acquires, stores, and processes the visual information of the particle motion as well as the interparticle contact forces. This system comprises two synchronized image acquisition and analysis tools, as the visual data contain different information regarding the motion (points) and the interaction (fringes).

The developed system is generic and can be used for various applications. The present study focuses on the fundamental mechanism that takes place at the interface between particulate materials and solid surfaces. As such, the testing apparatus includes a shear box (see Fig. 2) in which the particles are subjected to shear induced by the motion of a solid surface. The shear box includes a controlled upper boundary (of a constant vertical load), an interchangeably solid surface at the bottom and side walls capable of providing either direct or simple shear conditions.

Image Acquisition and Analysis Tools

Image acquisition is the primary data collection tool utilized in the presented research. An image is a two-dimensional “picture” generated by viewing, or more precisely, by sensing. From an image processing point of view, an image can be represented as a two-dimensional function \( f(x, y) \). The two independent variables \( x \) and \( y \) are spatial coordinates, and the values of the image function are usually referred to as the grayscale (of 256 levels) for black and white images. The image-sensing units (or simply, cameras) utilize two-dimensional area sensors, such as CCDs (charge coupled devices). Typical CCDs employ a rectangular grid of \( n \) by \( m \) storage sites, or “pixels.” Inherent in CCD technology is a charge transfer mechanism, which allows the conversion of the incident optical en-
FIG. 1—Experimental system: (a) schematic layout, (b) diagram, and (c) photograph.
ergy into electrical charge by the sensors. The acquired image, therefore, is the collection of analog or digital grayscale values of each pixel. For more information see, for example, Russ (1995) and Jähne (1997).

During testing, digital synchronized images are acquired approximately every 10 s by two high-definition CCD cameras. The external synchronization assures that the data collected in the two images relate to the motion and interparticle forces starting at the exact same time. The two images are acquired using two PC-based systems comprised of CCD cameras, image capturing boards, controlling software, and external synchronization.

The CCD cameras are Kodak MP1.4 with a resolution of 1317 (H) by 1035 (V) pixels used for particle tracking, and Kodak MP4.2 with a resolution of 2029 (H) by 2044 (V) pixels used for photoelastic images. The actual acquisition time of an image is 0.145 s and 0.485 s with a maximum frame rate of the cameras being 6.9 and 2.1 frames per second, respectively. A camera control unit (CCU) allow the manual selection of both exposure and gain for each camera. The images are acquired using two IBM compatible personal computers equipped with Data Raptor-VL frame grabbers of BitFlow Inc. The Data Raptor-VL frame grabber is a single slot VESA local (VL) bus board, able to take advantage of the processing power and display capabilities of the host computer using the VESA local bus to transfer real-time high resolution image data. The images are stored on a hard drive immediately following their acquisition. This storage process is the most time consuming among all the data acquisition steps and dictates the minimal time (of 10 s) between sequential images. Other faster data storage procedures can enhance substantially the frequency of the obtained images. The synchronization of the two CCD cameras is accomplished by communication between the two computers via their serial ports. One PC acts as the host computer and whenever it acquires a frame of image it simultaneously sends out a signal through the serial port to the other PC and triggers it to acquire a frame of image as well.

The physical system was dictated by the requirements of a representative sample of approximately 30 by 30 particles, and the photoelastic image resolution that was possible for a minimum particle size of approximately 18.5 mm (0.73 in.). The use of a standard CCD camera of roughly 300 by 300 pixels resulted in a resolution of about 2 mm per pixel, which was unacceptable for particle tracking under the expected relatively small movements. For the chosen motion tracking CCD camera, the resolution of the system is approximately 0.42 mm per pixel and a corresponding rotational revolution of up to 5.5°. The actual accuracy exceeds the value of individual pixel size (to be discussed later), thus ensuring the accurate measurement of the particles’ position during motion. Further enhancement of the resolution can be achieved by focusing on a limited zone only, say 5 by 5 particles, increasing the resolution 36 times.

A commercial image-processing software with the trade name of Optimas has been employed in this research. Optimas has been proven to be an adequate tool for image acquisition as well as for object measurements. Optimas operates under Microsoft Windows. The main features of Optimas includes (Optimas 1995):

1. **Image acquisition**—Optimas supports functions to acquire, save, and open images. All the images are saved in the standard tagged image file format (TIFF).
2. **Image enhancement**—Image enhancement is often necessary in order to improve quality and increase the efficiency of the image processing. One of the major objectives of image enhancement is to reduce the noise or to increase the signal-to-noise ratio of images. Spatial filters can be employed as useful tools in image noise reduction.
3. **Object identification**—Optimas provides functions to identify certain types of (optical) objects, such as points, lines, and areas. The particle tracking technique utilized in this research is based on this feature and is further discussed below.
4. **Object measurements**—In order to obtain useful measurements of (optical) objects within an image, spatial calibration is essential. Calibration correlates the real-world scale to measurements. Spatial calibration can also correct for distortions due to physical conditions, such as optical distortion due to lens angle.
Specific details of the spatial calibration utilized in this research are discussed below. Numerous measurement functions are available in Optimas, such as area measurement, coordinates of the center of areas, length, and luminance.

5. Dynamic data exchange—Dynamic data exchange (DDE) is a communication protocol available as a standard feature of the Microsoft Windows environment. Optimas takes advantage of DDE to allow data communication with other Windows applications. For example, Optimas enables the measurement data to be transmitted via DDE into Excel spreadsheets where it can be conveniently modified into any desired format and saved for consequent post-processing.

6. Programmable—Optimas supports a vector-based interpreted language, the analytical language for images (ALI) with syntax similar to the C programming language. ALI contains more than 500 functions and system objects, enabling the user to perform functions from the aforementioned five major features. The programs described in this paper were developed in ALI in order to enhance the effectiveness of image processing under specific circumstances.

Particle Marking

To accurately track the motion of each particle, it is required to monitor both rotation and translation. As such, at least two identifiable locations (points) need to be followed for each particle. This concept employs the fact that the particles’ deformation under the applied loading condition is negligible compared to the deformation of the whole assembly, closely associated with the motion of the individual particles. The contact relationship of a particle under uniaxial load application (between two half particles, see Paikowsky et al. 1999) is approximately 4100 N/mm. The normal contact forces are smaller than 200 N and hence result in a particle deformation smaller than 0.05 mm. Figure 3 presents the marking configuration used for the identification of two points on the 18.54 mm (0.73 in.) disks. Two black circles are marked; one of 4.76 mm (3/16 in.) diameter is placed at the center of the particle, and the other of 3.18 mm diameter (1/8 in.) is placed at the circumference of the particle. Those areas can be identified as optical objects (blobs) during image processing and hence apply automatic area identification based on edge detection algorithm. The size of and distance between the two blobs is dictated by the resolution of the image-capturing system, allowing easy identification and positioning of the two blobs for each individual particle. Each particle type (size and shape) was assigned different circle sizes and distance from the center. The location of the center of the central circle during testing enables tracking of the trajectory of the particle. The particle orientation and rotation along its trajectory can be assessed by the position of the center of the blob at the circumference relative to the central one.

Image Processing and Analysis

Each acquired image needs to go through several processes to allow detection, labeling, and tracking of the individual particles from image to image. A flow chart in Fig. 4 outlines the different stages from image acquisition to kinematics analysis.

Automatic Area Identification

The tracking camera images consist mostly of diffused light passing through the voids and the transparent particles (a.k.a., transmitted light images) and dark shadows (blobs) left by the marked circles. Figure 5 presents such images obtained by the tracking camera throughout a test. Adjusting the light level or digitization brightness and contrast (gain and offset level) enhances the contrast quality of the “live” image. By and large, the favorable physical environment allows most cases to produce high-quality images with sharp contrast between the background light and the foreground dark spots.

These images can be processed directly through automatic area identification using an edge detection technique based on the identification of a threshold in the optical field. This threshold (the “default” threshold) is set automatically according to the average gray scale of the foreground. All other gray-scale levels are regarded as background. Every group of connected pixels whose

FIG. 3—Particle marking for motion tracking.
values are within the foreground make up the identified blobs. Following this process all detected areas are marked. A visual inspection is then carried out to examine if all marker circles were identified and marked. If not, an assessment is made as to how many particles were "missed." If the number is less than about 10 (approximately 1.0% of the markers), the process is completed manually; otherwise, the image quality is enhanced and a new automatic area identification and marking are carried out. An additional visual inspection is then made to evaluate the number of "extra" identified areas due to optical noise. Again, if the number is less than say about 10 areas, a manual removal is carried out; otherwise, the image quality is enhanced and a new automatic area identification and marking is performed. At the end of the process the image is left with only the marker circles identified as area images ready for data extraction.

Image Enhancement

Different image operations can be carried out to enhance the image quality, which in this case means a sharp contrast between the white background and the dark foreground comprised of the markers only. The enhancement depends in part on the expected utilization. For example, "missed" markers can be better enhanced by varying the foreground threshold (for light/dark objects) or by using a filter of binary morphology and erosion or dilation processes. Optical noise, on the other hand, can be better handled through the
combination of spatial convolution filters, binary morphology, and image retouching.

Data Extraction

Once an optical object, such as the marker circle utilized in this research, is identified, numerous measurements can be performed. The measurement results are then extracted for analysis. For tracking purposes, the coordinates of each marker’s center are the requested data. These data, however, need to be sorted and labeled according to each particle and marker type (i.e., at the center or at the circumference) as discussed below.

Particle Numbering and Labeling

Particle numbering is necessary not only for the convenience of tracking, but also for organizing and manipulating image data efficiently. Particle numbering is performed only for the first frame of the image. Each particle is assigned an exclusive number according to its location in the model field, which is divided into layers. Particles in layers of higher elevation have larger numbers. In the same layer, particles with smaller horizontal coordinates are assigned smaller numbers.

Particle labeling consists of two components: one for the frame number of the analyzed image and the other for the circular markers. The center markers are labeled by the number “1” and the circumferential markers by the number “2.”

Tracking and Matching Criteria

The marking and the spatial calibration process (to be outlined in the following section) allows the accurate positioning of objects in the model field. The aforementioned numbering assignment is carried out for each particle and its markers based on the initial image. The tracking of multiple particles in motion requires an additional step to match (trace back) the particles to their positions at the previously analyzed image. To do so, the updated (“current”) particle positions need to be compared to the previous ones. The criterion used for this comparison is that the translation increment of a particle (at the center) between two consecutive images does not exceed the radius of the particle:

\[ | \Delta_{i-1} | \leq r_p \]

where

\[ r_p = \text{radius of particle (long axis for ellipse)}, \]

\[ \Delta_{i-1} = \text{translation of the particle between image } i - 1 \text{ to } i, \]

and

\[ \Delta_{i-1} = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}. \]

This criterion is utilized by the tracking algorithm but is achieved by controlling the rate of shear relative to the frequency of the image acquisition. The actual solid surface pull-out rate ranged between 10 to 20 mm/min (constant throughout the test) and was found to satisfy the above criterion without exceptions.

Once a particle is identified in the “new” image, its circumferential circular marker can then be identified based on the fixed distance between that marker and the center location.

Kinematics Analysis

The orientation \( \theta \) of each particle can be defined according to the centroids of the central and circumferential (side) markers \((x_c, y_c)\) and \((x_s, y_s)\), respectively:

\[ \theta = \arctan \left( \frac{y_s - y_c}{x_s - x_c} \right) \quad (0 \leq \theta < 2\pi) \]

Knowing the particles’ position and orientation for any two images (frames) of interest allows the evaluation of the particles’ kinematics. The translation increments \( \Delta^x \) and rotation increments \( \Delta \theta \) between the two time instances, say frames \( i \) and \( j \), can then be readily calculated by:

\[ \delta = | \Delta^x | = \sqrt{(x_{ij} - x_{ci})^2 + (y_{ij} - y_{ci})^2} \]

and

\[ \Delta \theta = \theta_j - \theta_i \] (counterclockwise positive)

Three types of kinematics analyses were typically conducted in the presented research: (1) displacement fields describing the incremental translation and rotation components of all particles between two selected positions along the test, (2) distribution of displacements with elevation based on averaged displacement

FIG. 5—Acquired images for particle tracking (a) initial position (Frame 7), and (b) position at peak interfacial shear resistance (Frame 10).
components of each layer of particles, and (3) detailed motion of a selected group of particles constituting a representative cell (as a portion of the sample), enabling the system to reflect critical displacements in greater detail.

System Accuracy and Spatial Calibration

The accuracy of the physical measurement depends on the resolution of the image-capturing system, the physical size of the acquired image, and the calibration of the system to handle various distortions. The system used for particle tracking provided a resolution of 1317 by 1035 pixels for a physical model of 556 by 387 mm. The immediate resolution is therefore approximately 0.4 mm per pixel.

The CCD light-sensitive unit itself is an electronic chip approximately 8.98 mm (H) by 7.04 mm (V). A 24-mm lens is used in order to capture the image of the physical model. The camera is positioned at about 2.2 m away from the object slightly off center (of the model) due to the physical requirements of accommodating two cameras. The obtained image is, therefore, slightly distorted and a parallax correction (spatial calibration) is required to procure accurate measurement. The spatial calibration is accomplished by associating a set of measured fiducial points in a target coordinate space with their corresponding coordinate values. Fiducial points can be of any kind of optical objects, such as spots, holes, or lights, that can be found by capturing an image. The points can be arranged in a grid consisting of an evenly spaced array. A finer by grid, namely more fiducial points over the same space, usually yields more accurate measurements. To facilitate the calibration process, a matrix consisting of 11 by 11 holes of 4.76-mm diameter (3/16 in.) evenly spaced both ways (50 mm apart on center) was drilled in a tooling steel plate. The design of the spatial calibration plate is described in Fig. 6.

The calibration plate is positioned at the model’s location and illuminated from the back. An image of the calibration plate with the grid of holes is acquired and the coordinates of the four corner holes of the grid are supplied. A normalized least-squared fit is carried out to obtain various degree polynomial coefficients describing the relation between the detected fiducial points and the actual coordinates. This fit need not be higher than a second degree in both (X and Y) directions. To check the quality of the calibration, the positions of the fiducial points are measured under the calibrated coordinate system. Knowing the exact locations of all the fiducial points, the measured coordinates are compared to their physical location. Table 1 presents the results of a calibration process in which different combinations of fiducial grid dimensions and degrees of the polynomial fit were investigated.

The data in Table 1 suggest that the arrangement of 11 by 9 fiducial points along the horizontal and vertical directions, respectively, with a second degree fit in both directions, provides the most satisfactory performance. The average errors of 0.298 and 0.250 mm are lower than the actual distance per pixel (0.422 and 0.374 mm) in the horizontal and vertical directions, respectively. These errors are associated with standard deviations of 0.175 and 0.172 mm in the horizontal and vertical directions, respectively.

Example of Test Results

One test in which circular particles were subjected to interfacial shear along a rough solid surface is used as an example. Figure 7 depicts the specimen’s setup in a test containing 708 round, 18.5-mm (0.73-in.)-diameter particles. Relevant results from the processed images are provided, demonstrating the abilities of the presented system.

Displacement Fields

Figure 8 describes each particle incremental translation starting with the particle’s initial position (following the application of the vertical load) to the peak shear resistance. The information provided in Fig. 8 is based on the analysis of the images presented in Fig. 5. The length of each vector in Fig. 8 is directly proportional to the particles’ translation. The vector points at the direction of motion starting and ending at the particle’s position initially and at the end of the analyzed time period. In the presented case, this period extends from the images captured on Frame 7 to Frame 10, along 32-s and 5.5-mm displacement of the solid base movement. Figure 9 presents the relationship between the measured pull-out force of the solid base and its displacement in the form of the system’s global response as a function of time.

Visualization of the displacement field in Fig. 8 allows the identification of the particles’ translation patterns and the underlying mechanism. For example, based on the information pre-

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**Table 1**—Result of spatial calibration of the tracking CCD camera.

<table>
<thead>
<tr>
<th>Degree of Polynomial</th>
<th>Best Fit Fiducial Grid</th>
<th>$e_x$</th>
<th>$e_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>First degree</td>
<td>2 by 2</td>
<td>0.365</td>
<td>0.386</td>
</tr>
<tr>
<td></td>
<td>3 by 3</td>
<td>0.326</td>
<td>0.459</td>
</tr>
<tr>
<td></td>
<td>6 by 5</td>
<td>0.363</td>
<td>0.321</td>
</tr>
<tr>
<td></td>
<td>11 by 9</td>
<td>0.340</td>
<td>0.275</td>
</tr>
<tr>
<td>Second degree</td>
<td>3 by 3</td>
<td>0.353</td>
<td>0.301</td>
</tr>
<tr>
<td></td>
<td>6 by 5</td>
<td>0.308</td>
<td>0.262</td>
</tr>
<tr>
<td></td>
<td>11 by 9</td>
<td>0.298</td>
<td>0.250</td>
</tr>
</tbody>
</table>
FIG. 7—Model setup in a test of round particles sheared against a rough solid surface with detail particle numbering of the representative cell.
FIG. 8—Particles’ incremental displacement field from initial position (following vertical load application) to the location at peak shear resistance.

represented in Fig. 8, three distinctive particle displacement (or flow) patterns can be recognized. Particles in the bottom layer translated horizontally along with the rough solid surface. Particles in the second (and possibly third) layer moved in both horizontal and vertical directions, and particles in the third layer and above displaced mostly upwards in the vertical direction. It is also noted that particles along the front boundary (with respect to the solid bar motion) displaced diagonally. This is a result of the concentrated force band that transfers the shear force to the front boundary wall. This unique particle displacement information suggests that internal shear takes place in the particulate material and not along the interface between the particles and the rough solid surface. This observation is consistent with the interface mechanics of shear along granular material and rough surfaces and its relationship to surface roughness (e.g., Paikowsky et al. 1996). Furthermore, the data suggest that the movement of the particles in the second layer induces the dilation of the specimen in response to the interfacial shear. This information is complemented by the distribution of particle rotations presented in Fig. 10. Contours of particle rotations in absolute values are provided for the testing period that is related to the data presented in Fig. 8. The obtained contours indicate a concentration of intense rotations at the second layer of the specimen only. Combining the patterns observed in the translation and rotation fields, it is recognized that the rolling of particles in the second layer dominates their motion. Hence it can be concluded that the shear failure is governed by the rolling of particles in the second layer.

More detailed understanding is achieved by focusing on the motion of individual particles, especially around the interface, and the analysis of the interparticle forces. The latter is beyond the scope of the present paper. The detailed displacement of particles, in particular at the vicinity of the rough solid surface, is investigated through a selected group of particles marked as the representative cell.

The Representative Cell

The representative cell is depicted in Fig. 7. Translation as well as rotation of particles in the representative cell under local coordinates is presented in Fig. 11. The particle motion described in Fig. 11 relates to the entire testing period (from initial to residual states) and hence the scale used to describe the horizontal motion is ten times larger than the one used for the vertical motion. The quantitative details provided in Fig. 11 confirm the observations made from Fig. 8 and 10. The two disks in the bottom layer of the specimen (disks Nos. 15 and 16), translated with the rough solid surface in the horizontal direction with limited or undetectable rotations. The lateral motion (local x) in Fig. 11a,b closely agrees therefore with the horizontal axis describing the global response in Fig. 9. The disk in the second layer (disk No. 45) underwent a large rotation in which it rolled over disk No. 16. As a result, the translation of the disk’s center underwent a trajectory of an arc with the same diameter as that of the disks. The disks in the third row (disks No. 74 and 75) and above (disks No. 103, 133, and 134) translated vertically upwards with minor or no rotations at all. Moreover, the par-
FIG. 9—Sample global response as a function of time prior to shear (left-hand side) and during solid surface displacement (Test No. D-AR100-D73-SS-R): (a) vertical load, (b) vertical deformation, (c) solid surface force.

ticle displacements indicate that the peak shear takes place following very small solid surface and resulting particle movement (about 2 mm, see Fig. 9 and the related details in Figs. 11a,b), while the dilation and shear plane follow the continuation of motion beyond the peak shear resistance.

Conclusions

Analysis of images from a high-resolution digital CCD camera system provides a unique approach towards the research of the fundamental mechanism of particulate materials. Results from the image analysis of a test demonstrated the capabilities of the developed experimental system to carry out the detailed tracking of each individual particle.

The system’s advantage in providing detailed tracking of a large number of particles with minimal labor is unmatched by any other technique. The data obtained by such systems allow the researcher to examine and calibrate numerical models on an individual grain basis (Paikowsky et al. 1996, 1998).

Acknowledgment

The presented research was possible through the support of the Air Force Office of Scientific Research (AFOSR Grant F49620-93-1-0267), the National Science Foundation (NSF, NYI Grant MSS-9358090 and NSF Grant MSS-9020526), and the University of Massachusetts at Lowell.

Acknowledged for their technical help are Frank Modica and Gary Howe, former and current laboratory directors of the Civil and Environmental Engineering Department, David Rondeau and Furui Tang, the machinists of the College of Engineering. Also acknowledged are the former graduate students, Kevin DiRocco, who helped lay the framework for the theoretical analyses and the early photoelastic and imaging techniques, and John Regan, who assisted Dr. Paikowsky in the design of the testing apparatus. Mr. Avner Butnaro of BitFlow assisted in developing the concepts for the image acquisition and motion tracking.
FIG. 10—Contours of particle incremental rotations in absolute values from initial position (following vertical load application) to the location at peak shear resistance.

FIG. 11—Displacement of particles in the representative cell: (a) local translations, and (b) local rotations.
References


