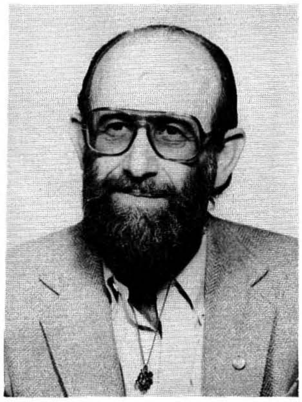
Award Lecture

IMAGE PROCESSING AND ANALYSIS FOR TURBULENCE RESEARCH



The ASEE Chemical Engineering Division Lecturer for 1986 is Robert S. Brodkey of Ohio State University. The 3M Company provides financial support for this annual lectureship award.

A California native, Robert Brodkey earned an AA degree in 1948 from San Francisco City College, a BS in chemistry and chemical engineering in 1950, and his MS in chemical engineering (also in 1950) from the University of California, Berkeley. At the University of Wisconsin he received his PhD in chemical engineering in 1952, doing a study in freeze drying. He then spent five years with Standard Oil of New Jersey in their Esso Research and Engineering Company's research facility and with Esso Standard Oil Company at their Bayway refinery. At Esso he worked on diverse chemical and chemical engineering problems, including chemical synthesis and chemical process. In 1957 he joined The Ohio State University as an assistant professor, became associate professor in 1960, and professor in 1964.

His work has been primarily in the field of fluid mechanics, with specialization in the areas of fundamental turbulent fluid flow, mixing, and rheology. He is the coinventor of ten U.S. patents and has written review chapters in four books. He is well-known for his graduate text The Phenomena of Fluid Motions *and the review book on mixing,* Turbulence in Mixing Operations, *which he edited. He has just completed coauthoring an undergraduate transport phenomena text which will be published by McGraw-Hill in their chemical engineering series.*

Professor Brodkey has won numerous university, national, and international awards for his teaching and research, and has held a number of national and regional committee posts in technical societies. He is also a member of a number of honorary professional societies and is listed in many national and international biographical references.

ROBERT S. BRODKEY
The Ohio State University
Columbus, OH 43210-1180

IMAGE PROCESSING IS THE reduction of visual data (in our case, usually data on 16mm films) to a form that is convenient to manipulate on a computer. Image analysis is further manipulation of the computer data to extract quantitative information. The analysis depends on the specific research problem and is a step beyond image enhancement where the visual material is modified for improved visual interpretation as is done by NASA with space pictures.

In many research areas there are operations in which understanding could be enhanced if simple photos or multiple photographic records could be analyzed easily. In the past, we have used films (both normal speed and high speed) to gain qualitative understanding of what is occurring, but were unable to extract additional quantitative information that would be very useful. Unfortunately, one cannot just take visual information, reduce it to digital form, and expect to obtain anything useful. One must first establish the type of digital information needed from the visual record and then develop the software necessary to extract that information in an efficient manner, recognizing that massive amounts of data are involved.

COHERENT STRUCTURES IN TURBULENT SHEAR FLOWS

In the field of mixing (either for blending of products or for the promotion of chemical reactions), the turbulence generated by the mixing unit can have a major effect on the time required and the degree of mixing obtained. While our understanding of turbulence in such mixing vessels is still relatively poor, the approaches used for turbulence research have changed drastically during the last fifteen years. The concept of using overall averages for the mean and fluctuating components has given way to a more fundamental view that turbulent shear flows are composed of a sequence of complex coherent motions or structures. Progress in turbulence research depends on better understanding of the mechanism of turbulent flows gained through the study of such motions or structures. Indeed, improvements in processes involving complex turbulent shear flows will require understanding the effect of coherent structures on the processes.

For many years visual photographic methods have been used to gain qualitative understanding of flow fields. We have pioneered in developing visual techniques suitable for studying turbulent structures, *e.g.*, utilizing stereoscopic, highspeed films of the flow. For quantitative measurements, probe methods have been the only techniques normally available. There are, however, limitations to the turbulence measurements made by conventional sensor techniques such as hot wires, hot films, or laser Doppler methods. This is especially true for complex measurements such as vorticity which involve derivatives of the velocity. Probes are good for time dependent information at a few points in the flow, but one can imagine the problem of probe interference that would develop if one wanted to place probes in a three-dimensional array. With the advent of modern image analysis, visual information can be converted into useful quantitative information that will enhance understanding of these very complex processes.

The immediate goal of our current turbulence research is to demonstrate that image processing and analysis of stereoscopic films is a feasible means of obtaining three-dimensional quantitative data to help establish a mechanistic picture of coherent structures in turbulent shear flows. This would help close the gap between visual observations and anemometry measurements. To accomplish this, the detailed nature of visually observed coherent motions needs to be converted into quantitative information. To obtain the proper information involves determination of the vector velocity field for individual events by high resolution image analysis and from this, establishing the vorticity and strain fields. This is not an easy task: recall that vorticity involves the difference between the velocity gradients. But once accomplished, it will be easier to identify coherent motions by alternate visual methods and by more extensive anemometry measurements. The former will provide the mechanistic picture and the latter will provide the statistical ensemble averages. The final step will be to incorporate the physical understanding obtained into an analytical model of the turbulent field and of the turbulent production and dissipation mechanisms.

THE FIRST PHASE OF THE IMAGE EFFORT

Rather than use our complex large scale flow loop to obtain new films of turbulent flows that would be adequate for image analysis, we chose to use a small fish tank and a simple mixer. This system was simple enough to set up, modify, and use so that we did not hesitate to make even small changes that would result in improved visual images. With this simple system, we could easily establish optimal lighting conditions, particle marker sizes, color of particles to aid in their identification, and other factors that might help in obtaining adequate films. We first tested any major changes with a video system to help establish the light levels and then recorded the flow for analysis with a variable speed disk camera and a Bolex stereoscopic lens. The camera could be adjusted between 16 and 400 fps and the lens was f2.8. The use of film was necessitated because of the need for high resolution, which cannot be obtained by video means. The neutrally buoyant particles ($\rho = 1.024$) were 20-35 micrometer Pliolite (trademark for polyvinyltoluene butadiene made by Goodyear Chemicals) particles and were the same as we had used in our previous visual studies. It was considered important in this initial work to determine if we could utilize color to help in matching the particles in the two views of a stereoscopic pair. The dyes tested were standard clothing dyes obtained at a local store. Some of these were fine, but most would not dye the polymer particles. This aspect of the research is continuing with the investigation of organic based dyes that can enhance the color and light output from the particles.

The immediate goal . . . is to demonstrate that image processing and analysis of stereoscopic films is a feasible means of obtaining three-dimensional quantitative data to help establish a mechanistic picture of coherent structures in turbulent shear flows.

A slightly modified Eikonix linear diode array camera was used for the digitization. The camera was not designed to digitize 16mm film and thus we modified it by building a 14″ extension tube that gave the desired magnification. It was necessary to mount the lens rigidly so that it would not vibrate and to make sure the spatial relation between the camera, lens, and picture being digitized did not move during the period needed to complete the digitization. This latter involved four passes: a neutral density filter, and red, green, and blue filters to establish the particle color. The particles could be easily identified in the raw data since they were about 10 pixils in diameter at the magnification used.

The data handling problem is difficult. The photodiode array is 2048 pixils wide and is mounted on an accurate stepping motor that gives 2048 positions across the image. The depth of digitization can be 8 or 12 bits. In this early work we used 12 bit depth simply because we did not know what would be necessary. You can always go from 12 to 8, but not the other way around. Since four filters were used at 12 bits each, a total of 32 mbytes of information was generated for each frame. This was a staggering amount of data even for our VAX 11/780. If the data were filtered and a binary output generated, there are known image compression techniques that could cut the data bank by a factor of two to four. But because of the binary output (*i.e.*, either black or white for each pixil), too much information is lost and the use of color becomes impossible. A better approach is to identify the particles in each of the stereoscopic views.

There are about 3000 particles (we counted them once) in view and each particle has two positions (x and y) in each view for the stereoscopic pair. There is also a need to identify the color, which adds up to about 30 kbytes of information, a considerable reduction from the 32 mbytes previously cited. If the stereo particle pairs can be identified, then one needs only the three positions and a particle identifier or about 21 kbytes of information. This is for an entire frame and is a very modest computer storage requirement.

THE FIRST RESULTS AND THE PROBLEMS

With a new system (toy?) there are manifold unanticipated problems. The first color images were viewed digitally on a Megatek color graphics terminal that had 512 x 512 resolution and could provide up to 16 colors. The light balance was totally unsatisfactory (very low levels of blue); thus, we had to develop means of normalization of the light outputs from the three filters to obtain a reasonable color balance. We later learned that the unbalanced light problem was with a jumper that had been mistakenly left in place when the Eikonix system was installed. It was easily removed and the problem resolved.

A more critical problem was the low level of light available because of the 14″ extension tube used between the sensor and the lens. The 12 bit digitization depth helped here, but our accuracy was not great. We have now rectified this problem by using a fiber optic light source that was available for our visual studies. Our images are for the most part 16mm films and the physical size of the source need not be great. The standard Eikonix light source is large in order to accommodate a variety of subject formats. Once we converted to the alternate light source, we found that the 8 bit digitization was satisfactory and that we could utilize the entire digitizing range. We have just installed a modification to the Eikonix that allows further versatility by allowing the integration (and scanning) time to be adjusted as a function of the light level available. The combination of a variable high intensity fiber optic light source and a variable sampling time now gives us complete control.

A final and most difficult problem was the discovery of the limitations of digital terminals. Sixteen colors sounded like a lot, but in actuality are quite limiting when one wants to reconstruct an image in color. Digitally, every color, shade, mixture, etc. is a different color in the digital sense; thus, 16 colors do not go far. We spent many hours in attempting (actually more of value as a learning experience) to reconstruct a simple 10 color image that was photographed from the Megatek terminal after being constructed digitally, processed by Kodak (Figure 1a), digitized by the Eikonix, and reconstructed on the Megatek (Figure 1b). The results are not impressive and the lesson to learn is that total digital image analysis is not the best route. A workstation that provided a video output can handle the full range of colors and will be discussed later.

THE REAL PROBLEM

The real problem is a 16mm image pair that contain some 3000 particles in various colors. The job to accomplish is to exactly match each particle that exists in both pairs, determine from this information their locations in space, and track them frame to frame in time. Figure 2 is a picture of such a real frame. Figure 3 is a digitization through the red filter (as an example) of such a frame.

The information contained in four pictures (the neutral density image for the specific particle location

FIGURE 1a. Color construction photographed from a 512x512 terminal

FIGURE 1b. Fig. 1a, digitized, reconstructed and displayed on the same terminal

FIGURE 2. Two stereoscopic frames of a mixer flow reproduced from a 16mm film

FIGURE 3. Digitization of a small part of Fig. 2 through a red filter

FIGURE 4. False color analysis of Fig. 3 for the brightest group of particles

FIGURE 5. Compressed full resolution picture of one stereoscopic frame

FIGURE 6. Full color of a small section of the right hand pair at full resolution

FIGURE 7a,b,c. Red, green, and blue sequence of filters of Fig. 6

FIGURE 8a,b,c. Edge enhancement of Fig. 7 by use of simple cut off

FIGURE 9.; Four window composite of Figs. 6 and 8

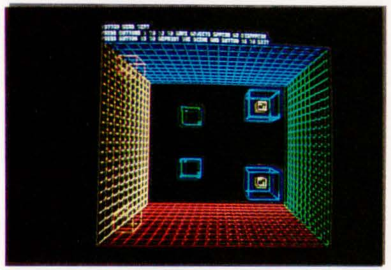


FIGURE 1a

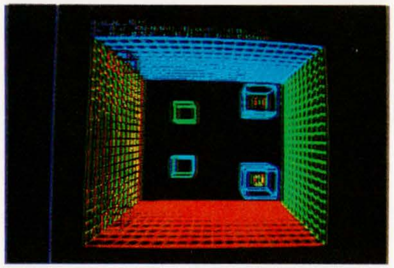


FIGURE 1b

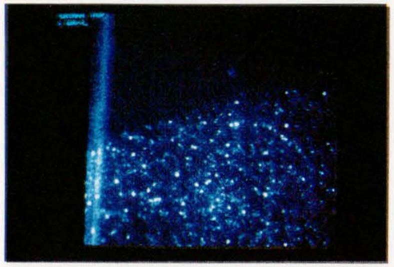


FIGURE 2

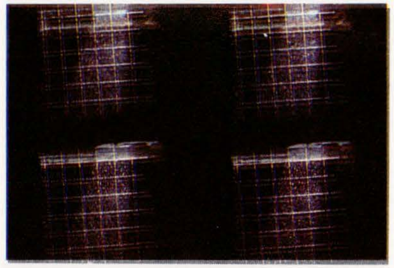


FIGURE 3

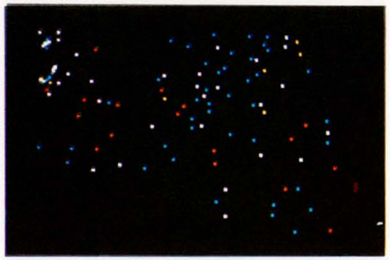


FIGURE 4

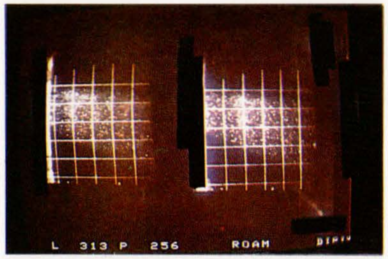


FIGURE 5

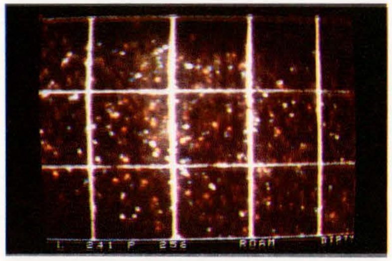


FIGURE 6

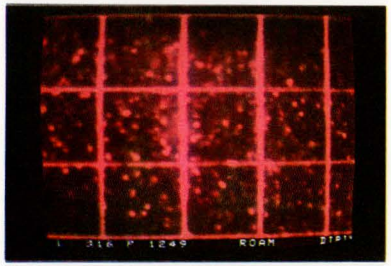


FIGURE 7a

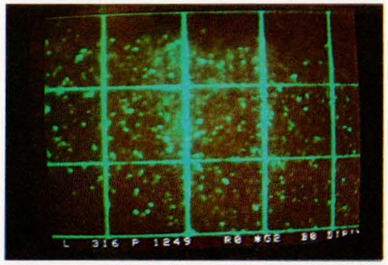


FIGURE 7b

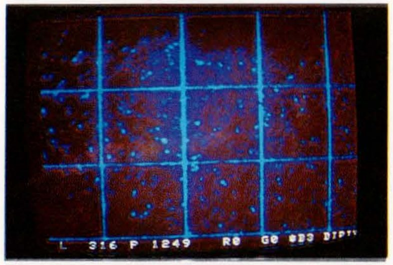


FIGURE 7c

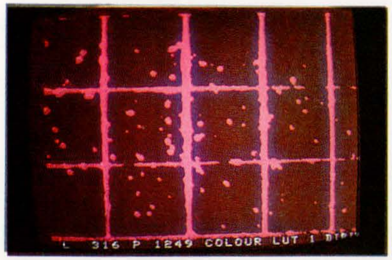


FIGURE 8a

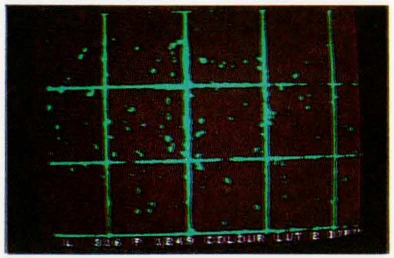


FIGURE 8b

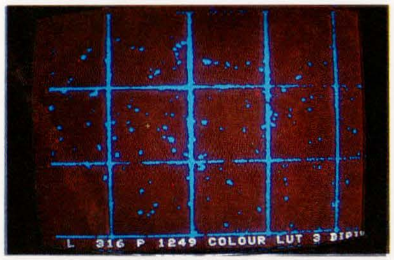


FIGURE 8c

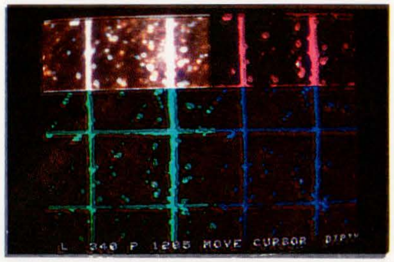


FIGURE 9

We learned the limitations of the equipment and how to improve or circumvent the problems introduced by these limitations.

and the color filter images for the color) was processed to determine the location and specific color of the particles in view. Forty (40) particles were selected directly from the 16mm film and were selected as representative of several groups: bright, medium, and faint particles that were not dyed (white) or were dyed red or blue, or were unknown (only three colors were used in this initial effort). This was the learning test for automatic identification. These forty particles were used as the control for making sure the computer program could properly identify the particle location and color. Once satisfied that these particles could indeed be identified correctly, then the entire digital image was processed. The processing of the digital image involved using a simple cut-off filter for the background and a threshold level for edge enhancement. If the level was set high, then only a few particles were located. Figure 4 is an example for the brightest group of particles (108). If the brightest 50% of the particles were considered, the number rose to 619. It should be understood that only the crudest of image processing techniques were used in this initial effort.

Although not a major part of the initial effort, we tracked a few particles frame by frame to make sure that the filming speed was in the range where particle tracking would not only be possible but relatively easy; *i.e.*, a range in which the particles do not travel far from one frame to the next, so that there would not be mistakes in following individual particles. Once established as true, nothing further need be done with this information until the time comes when the particles in a series of frames have all been identified.

By this initial effort we learned a great deal. We learned the limitations of the equipment and how to improve or circumvent the problems introduced by these limitations. We learned that we could produce high quality color films that could be adequately digitized so that location and color could be established. And very importantly we learned of a need for an image analysis workstation that would avoid the need of reconstruction of the images digitally and allow most of the calculations to be done on it in a parallel manner rather than directly on the VAX 11/780. This latter conclusion resulted from the time estimates for our various programs to run on a full (2048 x 2048) color frame and the neutral density counterpart. For example, about 12 minutes were needed to digitize the full image, about 50 minutes to identify the particle positions, less than 5 minutes to classify the particles and assign their colors, and several hours to put it all together into a displayed final reconstructed image. Not very efficient.

THE DIPIX ARIES III IMAGE WORKSTATION

For a great deal of money, most of the preceeding problems can be avoided and one can operate in near real time by using one of several commercially available workstation systems. After much debate and comparison, we chose the Dipix Aries III system. This system, when used in conjunction with the Eikonix camera, forms a powerful tool for the obtaining and modification of visual information. It would be nice to show a number of familiar images to demonstrate the versatility; however, the cost of color reproduction makes that impossible. The best way to see it is to come to Columbus and see for yourself. But some examples are necessary to illustrate the capability and these will be taken from our particle identification work.

Figure 5 is a stereo-pair taken at full resolution, but compressed here by a factor of four in both the horizontal and vertical direction so that it would fit. Figure 6 is a color segment at full resolution of a small part of the right hand stereo-view of Figure 5. The sequence shown in Figure 7 are the individual filtered pictures of Figure 6 and Figure 8 shows the application of a simple cut off of the same data to enhance the edges. Far better edge detection schemes are available, such as maximum derivative detectors, and we are in the process of investigating these. The enhanced images can be overlayed to give a false color representation of the individual particles to aid identification. Rather than this we show Figure 9, which is a four window composite of the same information. Careful studies of these images show that it is easy, even with this simple image processing, to identify the individual particles and their color. There should be no problem in doing this automatically with the computer.

Beyond these simple techniques we have a full bag of tricks to help us in the particle identification task. One experimental effort that is under way is to improve the dyes being used and the light source so that the particles act as intense sources of light at any selected color. The use of organic dyes (we would use mixtures of red, blue, and green dyes to form any output color desired) in conjunction with ultraviolet light shows promise.

Spatial filter techniques can be used to process the image to eliminate the background noise of particles that are not in the field of view and the grain of the film, etc. Gradient edge enhancement techniques can be used to outline the particles more reliably. Warping or rubber sheeting can be used to alter and match the two views to a standard grid scale so they exactly match each other and an easy to use reference grid. Colors can be identified as we have done and then a series of false colors can be assigned. Sizes can be estimated as well as orientation, roundness, roughness, etc., that subsequently can be used to help identify the corresponding particle in the other stereoview and thus set the stage of the three-dimensional location of the particles. But all this is for the months to come.

THE FUTURE

The three-dimensional location of each particle in the field of view is in the future, but it is our immediate goal and we fully expect to have this task accomplished shortly. But where from there? For accurate positioning, account will be taken of the bending of the light rays as a result of slight differences in the viewing angle. This is a well known calculation and can be taken into account when the position is determined from the positions in the two stereoviews.

For tracking we are working on careful and accurate registration of the films frame to frame so that the tracking will be accurate. An old 16mm film projector has been obtained from surplus and is being modified into a frame registrar device. The old lens is now the fiber optic light source and the Eikonix looks at the film from the side of the old light source. During tracking we must take into account the possibility of particle overlap or blocking. This may involve an iteration and backtracking in time so that we can accurately estimate the particle location in the frame in question. We have seen partial blocking in some of the frames already, but we do not know the extent of the problem. The velocity can be determined by standard multipoint sloping techniques that give the best estimate of a slope from five or seven points.. We will look into the representation of the isovelocity contours by three-dimensional mapping techniques. This would be a better approach than trying to determine vorticity directly from the particle path data. If the contours can be established with the desired degree of accuracy, then derivative methods can give the velocity gradients and thus the vorticity and strain fields. Finally, CAD graphic techniques will have to be utilized to display the vast amount of information about the flow field that will be obtained.

ACKNOWLEDGMENTS

There are two groups of very important people that have made this work possible. Kris Lakshmanan is the author of the preliminary studies and helped evaluate and select the image workstation. My current students involved with this project are L. Economikos, K. Russ, and C. Shoemaker; the present and the future are in their hands. The second group are those who have helped support our effort. The Erna and Victor Hasselblad Foundation of Sweden provided the funds to obtain the Eikonix camera. The Atlantic Richfield Foundation and The Ohio State University have made obtaining the Dipix Aries III system possible. The Dipix company made significant contributions in the form of hardware and a cooperative agreement to obtain source code material as needed. The Megatek 1650 color graphic terminals came to us through the generosity of the university, the College of Engineering, our department, and the Megatek Corp. The university has been a major factor in the support of the previously cited students. Finally, the personnel of the Koffolt Computer Graphics Laboratory, Jeff Hulse and Dave Jones, have been most helpful both in managing the facility and in programming the special needs as they develop. □