2006-2364: A STEREO VISION-BASED WAVE SURFACE MEASUREMENT PROJECT

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Measuring the three-dimensional characteristics of the ocean surface has a variety of applications. For example, surface measurements of vessel wakes could be used for improving hull designs. In the study of ocean surfaces, accurate surface measurements could be used for verifying ocean wave models or in lieu of such models in the study of various surface properties (i.e. microwave backscatter, etc.). We present a vision-based wave sensing technique that can be used to measure water surface heights and compute pertinent wave characteristics, such as slope, height, or frequency. Using a commercially available stereo imaging system, students can acquire an image of a wave surface and accurately measure its characteristics. System configuration and data analysis methods are discussed. Data generated using this method can be verified using traditional wave gauges, and used for a variety of student project or laboratory experiments. We have used this system for a laboratory investigation in an Introduction to Computer Vision course, and as an experimental platform for independent study by Ocean Engineering students. Sample results from student projects in wave tank and natural water environments are presented.

Background

Measuring the shape of the water surface can be achieved with a variety of sensors. As reviewed in Jähne et al[1], research efforts to use stereo images of the ocean surface have been conducted for a century. A commonly referred to effort by Cox and Munk[2] used optical techniques to measure wave slopes based on sun glint. Obviously, computer-based processing of images has only been possible in recent years.

Pos et al[3]discuss techniques used for stereo measurements of wave heights and patterns for model harbor wave basins. Techniques include seeding the water with solutes and projecting a structured lighting pattern onto the water. All imaging was done at night to reduce the variability of illumination. Precisely located control points were used to calibrate the stereo camera system. Contour plots are generated, but wave properties are not computed.

A review of optical ocean wind wave imaging was done by Jähne et al[1]. Jähne (focusing on short wind waves) concludes that optical imaging of the water surface is a difficult experimental task that has not yet met with good results. Jähne concludes that techniques using reflection are best for deriving wave-slope statistics and refraction techniques are best for wave slope imaging. The authors also point out the correspondence problem (to be discussed later) restricts stereo photography to rough seas with many small-scale waves.

Most optical imaging has been limited to small surface areas; imaging by Keller et al[4], Grant et al[5], and Senet et al[6] ranged from 0.02 to 0.05m². Recently, Chou et al[7] used a CCD camera to acquire a sequence of water surface images for a 3.1m×5.75m area.

The system presented in this paper uses a commercially available stereo system that is capable of viewing areas on the order of tens of square meters. No solutes or particulates are added to the water, although a misting strategy is explained for the laboratory environment. The system is capable of producing three-dimensional measurements of the water surface.

Stereo Vision

Consider a simple stereo vision system consisting of two cameras as shown in Figure 1. The cameras with focal length f are aligned such that their x-axes are collinear and their y- and z-axes are parallel. They are offset along the x-axis by a baseline distance b. The location (X,Y,Z) of point P is computed by comparing the locations of the projections of P onto the two image planes, (x_l,y_l) and (x_r,y_r). Because of the geometry of the cameras, the left and right projections of P will appear at the same row and but at two different columns. The columnar distance in pixels is referred to as the disparity, *d*. Using simple camera geometry[8],

$$Z = \frac{fb}{d}$$

$$X = \frac{x_l Z}{f} = b + \frac{x_r Z}{f}$$

$$Y = \frac{y_l Z}{f} = \frac{y_r Z}{f}$$

From an image processing standpoint, the difficulty is in finding the pixel points that are corresponding (x_l,y_l) and (x_r,y_r) pairs. Some scenes are more difficult than others. Consider Figure 1 again. For the two cameras viewing an oncoming wave, there are many points along a crest or trough that look very similar. This image processing problem is commonly referred to as the *local correspondence problem* since the software is trying to find corresponding point pairs in the image. For this reason, the stereo rig was turned so that the baseline was not collinear with oncoming crests and troughs as shown in Figure 2.

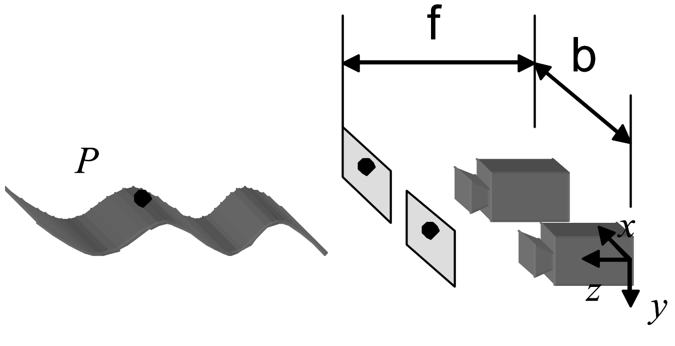

Figure 1 Geometry of typical stereo vision system viewing a point on a long-crested wave surface. The left and right cameras are separated by a baseline b and have a focal length f. It is difficult for the software to discern matching point pairs that correspond to Cartesian locations on the crest.

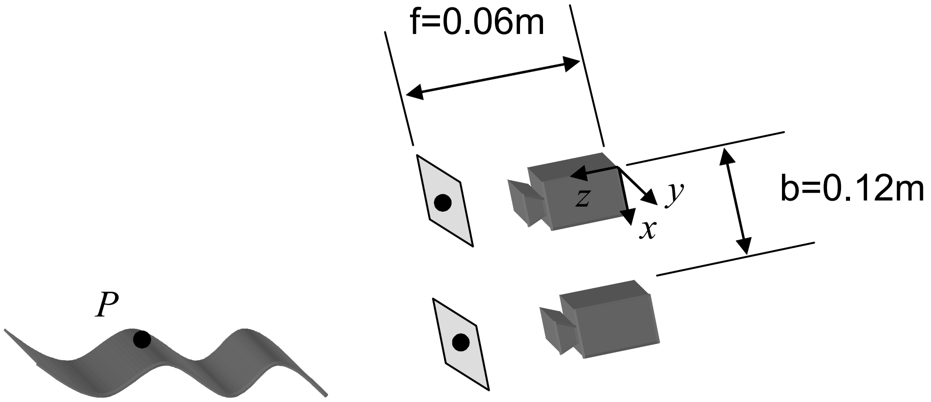

Figure 2 The stereo camera rig may be rotated so the camera baseline is not parallel with oncoming wave crsts and troughs. Thus the software is able to compute Cartesian locations for an increased number of image point pairs.

Commercially available stereo systems can be purchased with software that will acquire and process stereo images. These vendor supplied algorithms will solve the correspondence problem and compute Cartesian positions that correspond to objects present in the two images. The Cartesian data is suitable for further analysis such as computing wave height or frequency.

Experimental System

A wave sensing vision system will require a stereo vision camera, a computer (preferably a laptop for transportability), and a tripod or other camera mount. An inclinometer is useful for determining the orientation of the camera and a measuring tape is useful for determining the approximate height of the camera system. If working at an outdoors location without power, you will need a generator. Lighting can sometimes be useful in indoor locations for illuminating the surface of the water.

Water poses some unique challenges for stereo image processing in the laboratory environment. Unlike most naturally occurring wave surfaces, the waves created in a wave tank feature a smooth glassy surface. From an image processing standpoint, these waves pose an unusual challenge; both the reflected ceiling and the wave tank floor are visible in the image. This results in few distinguishable surface features which can pose a difficult correspondence problem. The problem with reflectance can be solved by simply texturing the wave surface with a fine mist. Garden sprayers are an inexpensive and effective way of misting the water. The mist minimizes the reflections and the transparency of the surface, resulting in successful identification of corresponding visual features for the stereo vision algorithms.

The work demonstrated in this paper uses the Bumblebee stereo camera from Point Grey. Point Grey's Digiclops Software Development Kit (SDK) is used to acquire images and create point cloud data files. A C/C++ compiler is necessary for tailoring the Digiclops software to your needs. The data may be analyzed using commonly used analysis tools such as MATLAB (used here) or Microsoft Excel.

Interpreting Cartesian Data

The point cloud file simply contains Cartesian points that correspond to the observed surfaces. These points are with respect to the camera's coordinate frame with the z-axis parallel to the optical axes of the stereo cameras. For analysis purposes, it is useful to transform the data to another coordinate frame. Figures 3 and 4 show some possible arrangements for the Bumblebee camera system.

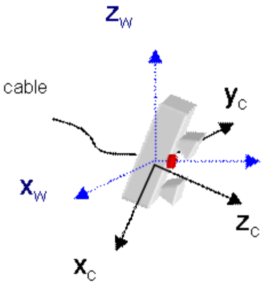

Figure 3 Camera oriented vertically and at an angle looking downward.

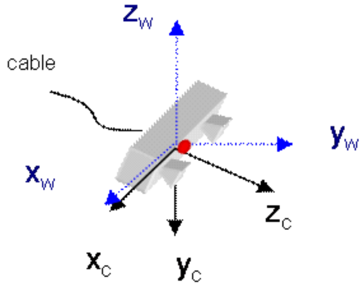

Figure 4 Camera oriented horizontally and looking downward.

If the camera is oriented vertically and at an angle (one camera on top of the other) the coordinate frames are aligned as shown in Figure 1. An inclinometer is used to determine the angle θ between z_w and z_c. As shown the angle should have a positive value. A Cartesian point ${}^{c}p$ can be rotated into the world frame, denoted by ${}^{w}p$, by using the following equation.

$$ {}^{w}p = Rot\left(z, \frac{\pi}{2}\right) Rot(y,\theta)\ {}^{c}p $$

where

$$ Rot(z,\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ and } Rot(y,\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} $$

If the camera is oriented horizontally and angled downward, the coordinate frames are aligned as shown in Figure 2. Again, an inclinometer is used to determine the angle θ between z_w and z_c. As shown the angle should have a negative value (the angle is measured about x_w using the right hand rule.) The relationship between the world and camera frames is given by the following equation.

$$ {}^{w}p = Rot(x,\theta)\ {}^{c}p $$

where

$$Rot(x,\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$$

For other configurations, draw the camera and world coordinate frames. The z_c. axis comes out of the camera along the optical axis. Decompose the motions necessary to take the world frame to the camera frame into a series of fundamental rotation about the x, y, or z axes. Write down the first rotation (about x, y, or z) using the fundamental rotation matrices provided above. Then add more rotations as necessary. If the rotations are with respect to the moving frame, post-multiply additional rotations. If it is with respect to the fixed frame, pre-multiply. This will allow you to compute the matrix ${}^{W}R_c$.

$${}^{w}p = {}^{w}R_c\,{}^{c}p$$

Once the data has been rotated to a world coordinate frame, it is in a format that is suitable for analysis.

Analyzing the Wave Surface Data

MATLAB's data analysis and visualization tools are useful for interpreting the data. Some examples include generating and plotting an interpolated surface using the point cloud data. Significant wave height can be computed using the standard deviation of detrended (zero mean) data. Data from a wave tank can be averaged across the width of the tank and analyzed for wave number or wavelength using a Periodogram or Fast Fourier Transform (FFT). Advanced analysis of data taken from a natural water body could include a 2-D FFT of the interpolated surface to compute predominant wave direction and frequency

In the natural environment, sun glint can have an interesting effect. The specular reflection can be interpreted as objects that are deep below the water surface. One way to handle this is to simply ignore any points that could not plausibly be part of the water surface due to an incongruous height.

Sample Projects

A good first experiment is to view a solid model of a wave surface. (For best stereo imaging success, cover the solid model with a patterned surface rather than a solid color.) An initial test for a known wave shape allows students to easily calibrate their system and test out the algorithms. For example, Figure 5 shows the Cartesian data and interpolated surface as represented in MATLAB. After generating this figure, the students were able to observe that at the current camera angle; only the oncoming side of the wave was viewed.

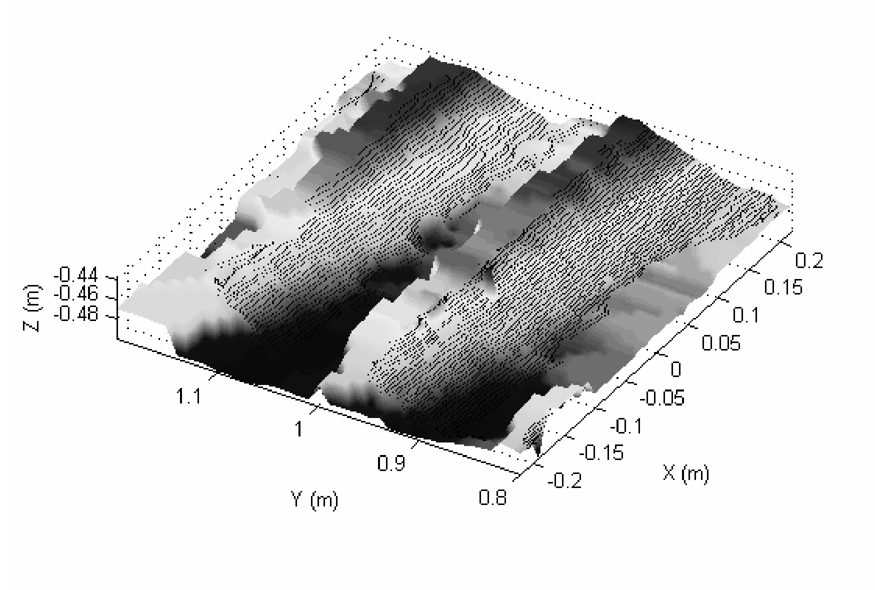

Figure 5 Data from stereo measurements of a solid model of a wave surface. The camera angle was insufficient to adequately view the back side of the wave.

Continued testing may be done in the laboratory or natural environment. As part of a senior-level independent study, a series of images were taken at a variety of wavelengths in the 300ft (91.3m) wave tank at the Davidson Lab at Stevens Institute of Technology. While the system was positioned to see a large area of the tank, the usable surface data encompassed a roughly 0.5m×3.5m swath. Three different wave frequencies were tested with wave periods of T = {1.1, 1.2, 1.3}s and a sequence of images was taken for each wave period. Figure 6 shows a MATLAB interpolation of the Cartesian data from the T=1.1s experimental run. As mentioned earlier, texturizing the water surface with sufficient mist or spray is essential to getting good results. Figure 7 shows the Periodogram of the averaged data from Figure 6. The peak corresponds to a predominant frequency wavelength of 1.71m for this run. The average wavelength for the entire sequence of images was 1.93m; this shows excellent agreement with the wave gauge wavelength of 1.90m.

In another experiment, a series of stereo images were taken along the United States Naval Academy seawall near the mouth of the Severn River. The experimental setup is shown in Figure 8. A wave gauge located near the camera was used to collect wave height data for comparison. It should be noted that the wave gauge provides height versus time for one point in the water, and the vision system is measuring heights spatially over a large surface. A stereo image pair and surface reconstruction are shown in Figure 9 and Figure 10. Taken at a resolution of 240 × 320, the data extends out to 12 meters away from the camera. Other resolutions and camera angles were able to measure points up to 70 meters away from the camera system.

Conclusion

A system for making three-dimensional measurements of the water surface can be assembled using stereo vision system. Successful results depend on a basic understanding of the stereo algorithms and transformation between coordinate frames. Adequate lighting and surface texture are also necessary. This system would be ideal for cross-disciplinary student projects and could incorporate computer scientists, electrical, or mechanical engineers on an ocean engineering project. While the results presented here are for a static camera, further investigations could look at vessel-based measurement systems.

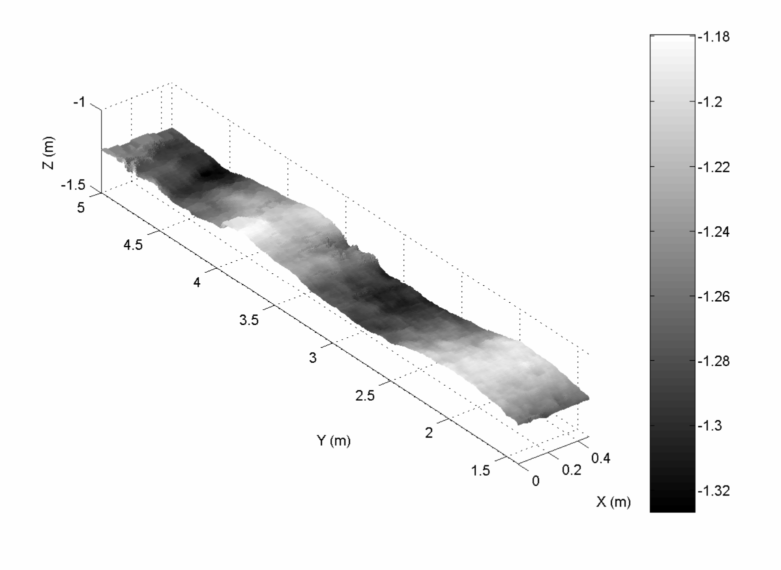

Figure 6 Surface reconstruction of (x,y,z) data retrieved from stereo vision system for a T=1.1s regular wave.

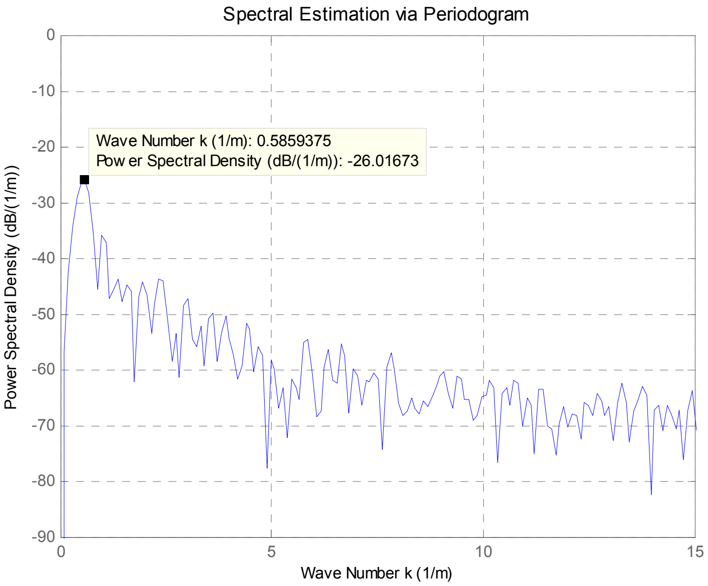

Figure 7 Spectral content of the average surface height shown in

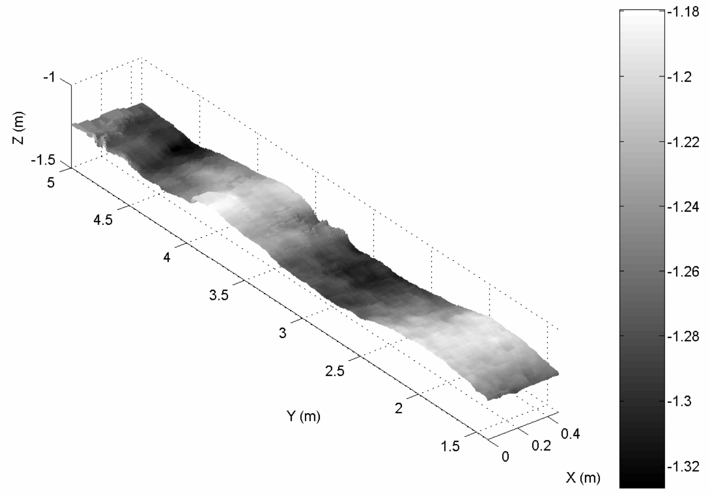

Figure 6. The peak corresponds to a wavelength of 1.71m. The average wavelength for a sequence of images was 1.93m; this shows excellent agreement with the wave gauge wavelength of 1.90m.

Figure 8 Experimental setup showing Bumblebee stereo camera, tripod, and wave gauge along the Severn River at the United States Naval Academy, Annapolis, MD.

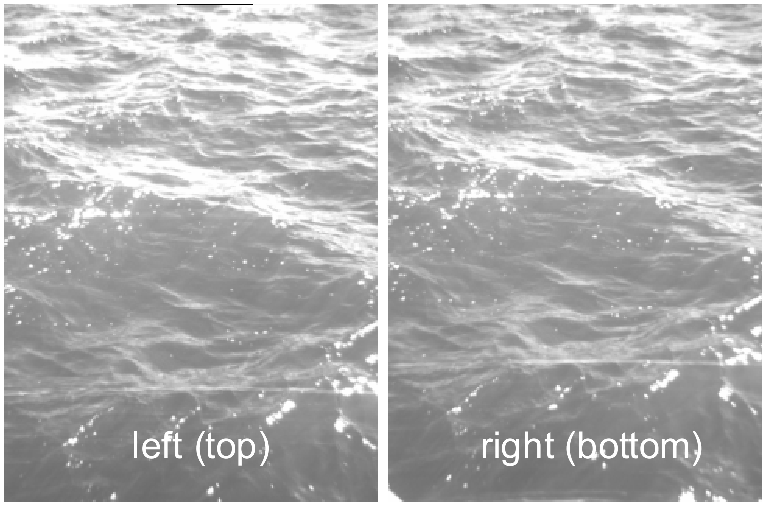

Figure 9 Stereo image pair natural water taken at 240 × 320 resolution. The camera angle is 120.9°. The images have been rotated for ease of viewing.

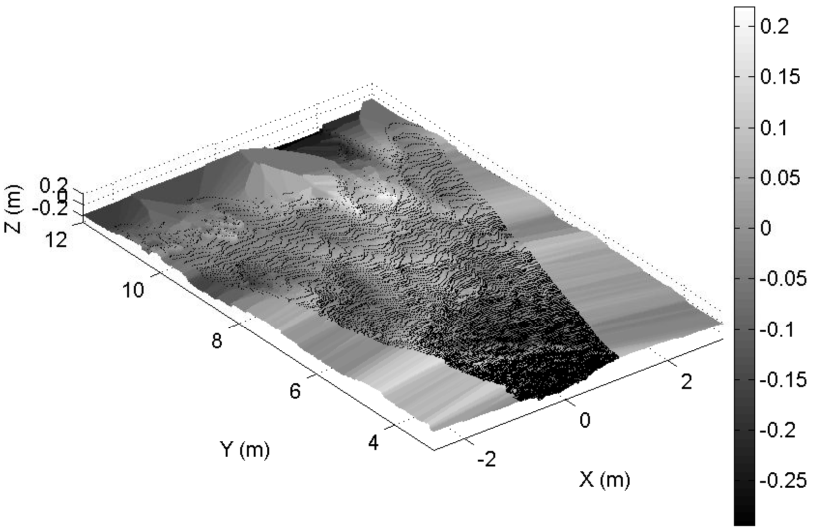

Figure 10 A water surface plot for stereo image pair shown in Figure 9. Data is detrended for a zero-mean height. The grayscale surface represents a MATLAB interpolation and the data points are from the point cloud generated by the stereo processing algorithm.

Bibliography

1. B. Jahne, J. Klinke, and S. Waas, Imaging of short ocean wind waves: A critical theoretical review, *J. Optical Society of America A*, vol. 11, no. 8, pp. 2197.2209, August 1994.

2. C. Cox and W. Munk, Measurement of the roughness of the sea surface from photographs of the sun's glitter, *J. Opt. Soc. America*, vol. 44, pp. 838.850, 1954.

3. J. Pos, L. Adams, and F. Kilner, Synoptic wave height and pattern measurements in laboratory wave basins using close-range photogrammetry, *Photogrammetric Engineering and Remote Sensing*, vol. 54, no. 12, pp. 1749-1756, 1988.

4. M. Keller, B. Gotwols, W. Plant, and W. Keller, Comparison of microwave backscatter with optically-derived cross sections from wind generated waves in a wavetank,, in *International Geoscience and Remote Sensing Symposium*, 1994, pp. 2424-2426.

5. I. Grant, Y.Zhao, G. Smith, and J. Stewart, Split-screen, single-camera, laser-matrix, stereogrammetry instrument for topographical water wave measurements, *Applied Optics*, vol. 34, no. 19, pp. 3806-3809, July 1995.

6. C. Senet, J. Seemann, and F. Ziemer, Dispersive surface classification: Local analysis of optical image sequences of the water surface to determine hydrographic parameter maps, in *Oceans 2000 MTS/IEEE Conference and Exhibition*, vol. 3, 2000, pp. 1769-1774.

7. C. Chou, J. Yim, and W. Huang, Determining the hydrographic parameters of the surface of water from the image sequences of a CCD camera, *Experiments in Fluids Experimental Methods and their Applications to Fluid Flow*, March 2004.

8. L. Shapiro and G. Stockman, *Computer Vision*. New Jersey: Prentice Hall, 2001.