

A Vision-based Experiment for Mechanical Engineering Laboratory Courses*

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A simple vision-based experiment has been designed which can be used to highlight various concepts and fundamental principles throughout the mechanical engineering curriculum. The experiment consists of a clear tank of water in which objects can be released from rest using an automated release mechanism. A vision system, using one or two standard video cameras, is used to track the falling object. The stereo imaging system, using two cameras, provides object tracking in three dimensions. Experiment control and image-processing software has been written using LabVIEW and IMAQ Vision. A series of images acquired at 60 Hz using one or two video cameras connected to IMAQ 1408 image acquisition boards are analyzed to resolve the instantaneous position of the falling object. Using a basic camera calibration procedure, the instantaneous position information is converted from pixel units to physical units. The object velocity and acceleration data can then be calculated numerically. The experiment has been designed and constructed by a group of three undergraduate students as part of a capstone senior design course. Utilizing the senior-level capstone design course provides a cost-effective means for laboratory improvement in addition to the educational benefits derived by the students from such projects. The approach taken at the University of Texas at El Paso (UTEP) for laboratory improvement is to develop simple experiments that can be used throughout the laboratory curriculum. The backbone of the strategy is the use of LabVIEW for experiment control and data analysis. LabVIEW provides a rapid prototyping tool for necessary software development. This paper describes the design and development of a vision-based experiment and the incorporation of the experiment in the mechanical engineering laboratory curriculum.

INTRODUCTION

QUINN [1] describes the importance of experimentation to the engineering profession, in response to declining emphasis placed on experimentation in undergraduate engineering programs over the last several decades. The most obvious reason for a decline in emphasis results from diminishing institutional resources available for laboratory maintenance and improvement. In addition, technological advancements in experimentation have placed financial burdens on institutions. For example, the introduction of the personal computer and PC-based instrumentation have mandated computer-controlled experimental data acquisition and control. Researchers can no longer submit publishable experimental research with manually obtained data, and students must be exposed to modern experimental techniques to remain competitive.

As a result, many institutions are investing in laboratory improvement, taking advantage of a number of corporate and private sources in addition to federal and state funding agencies that offer support on a competitive basis for laboratory improvement. These opportunities have provided interesting and creative strategies for laboratory development and improvement. A recent issue of

the *Journal of Engineering Education* (Volume 87, Number 5, 1998 supplement) was devoted exclusively to educational projects supported by the National Science Foundation. Examples of creative educational strategies involved transferring cellular manufacturing systems design and scheduling research experiences into the curriculum [2], developing Web-based computation and experimentation tools for internal combustion engines [3], and introducing micromechanical devices and systems technologies into the curriculum [4]. The commonality between these efforts is financial support. However, institutions without significant external support must also expose students to modern experimental techniques and take advantage of advanced educational strategies.

The University of Texas at El Paso (UTEP), like many others, has been investing in improving its laboratories [c.f., 5]. The UTEP approach for laboratory improvement has been to develop simple experiments that can be used throughout the laboratory curriculum, in an attempt to minimize the associated costs of laboratory improvement. The backbone of the strategy is the use of the graphical programming language, LabVIEW, for experiment control and data acquisition and analysis. LabVIEW provides a rapid prototyping tool, thus reducing software development time compared to traditional programming languages. This rapid prototyping aspect makes LabVIEW

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extremely attractive from an educational viewpoint in that students can generate much of their own code in a reasonable amount of time.

As a result, the UTEP laboratory improvement strategy also involves utilizing the senior-level capstone design course for experiment development; a strategy that has worked well for others [6]. Groups of two to three students are given well-defined projects that involve the design and development of computer-controlled experiments. Utilizing the senior-level capstone design course provides a cost-effective means for laboratory improvement in addition to the educational benefits derived by the students from such projects. In the following, the design and development of a vision-based experiment using LabVIEW and IMAQ Vision is more fully described.

VISION-BASED EXPERIMENT

Barat *et al.* [7] recently discussed the increasing importance and relevance of optical science technologies because of the wide applicability of these technologies in science and engineering. To demonstrate the application of vision-based measurements throughout the mechanical engineering curriculum, a group of three undergraduate students at UTEP developed a simple vision-based experiment that highlights various engineering concepts and fundamental principles. The experiment consists of a clear tank of water in which objects can be released from rest using an automated release mechanism. A vision system, using one or two standard video cameras, is used to track the falling object. If two cameras are used (referred to as a stereo vision system), the object's path can be tracked in three dimensions, while the use of one camera provides two-dimensional object tracking. Experiment control and image-processing software has been written using LabVIEW and IMAQ Vision. A series of images acquired at 60 Hz are analyzed to resolve the instantaneous position of the falling object.

Using a basic camera calibration procedure, the instantaneous position information is converted from pixel units to physical units. The object velocity and acceleration data can then be calculated numerically given the position and time information.

The experimental setup is depicted in Fig. 1. The falling object experiment includes the tank and tank stand, tank fluid (e.g., water), object release mechanism and associated automation equipment, and object. The imaging system consists of the video cameras with tripods, lighting system, image acquisition boards, and computer with LabVIEW and IMAQ Vision. The following subsections more fully describe the design of the experiment, the imaging system, and the costs of the two.

Falling object experiment design

For the falling object experiment, a tank is manufactured from 2-cm thick acrylic glass, and the tank stand is made of square steel tubing. Rectangular sections of acrylic glass were selected for the tank for ease of manufacture and to eliminate potential optical distortion due to wall curvature. The tank is thus square in cross-sectional area, providing easy access for the cameras when at 90 degrees separation. A tank height of 1.07 m was selected so that the falling objects could reach terminal velocity within the development region. The width of the tank is 0.46 m. All of the objects tested in the tank are released from the center of the tank and the largest object tested is a billiard cue ball with a diameter of 6 cm. With the cue ball, a minimum of three object diameters exists between the object and the tank walls. Using this width, the largest object does not impact the tank walls during its descent (During laboratory sessions, the effect of the tank walls is discussed with the students). The tank stand was designed to support the weight of the tank when filled with water. A stand height of 0.61 m was necessary for the cameras (mounted on tripods) to focus on the entire area of the tank.

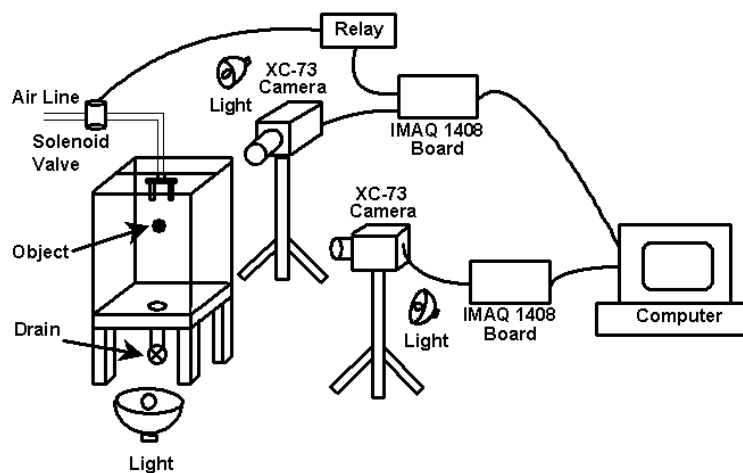


Fig. 1. Schematic of the stereo imaging experimental setup.

An automated release mechanism, located on top of the tank, is used to eliminate variability associated with manually releasing the object. A representation of the components required for the release mechanism and the gripping mechanism (gripper) are shown in Fig. 2. A Humphrey pneumatic actuator (gripper-model #HNHBRP-10) is used as the release mechanism. The single action gripper, with a 4-mm stroke, closes when the compressed air (operating pressure between 350 and 700 kPa) is allowed to flow through the system and is spring opened when the pressure is released.

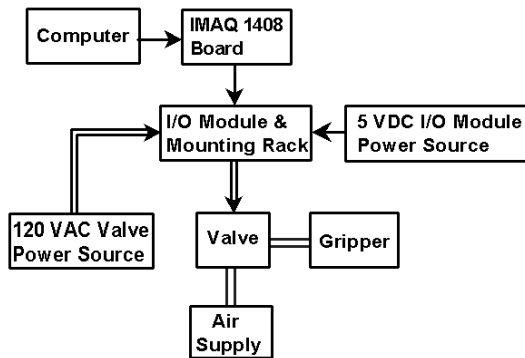


Fig. 2. (a) Schematic of the automated release mechanism with necessary control components.

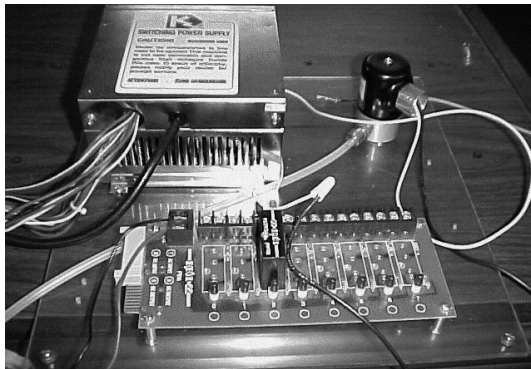


Fig. 2. (b) photograph of the input/output module, mounting rack, 5V DC power supply, and solenoid valve.

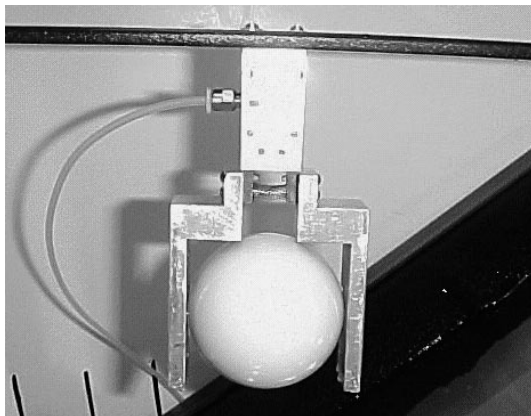


Fig. 2. (c) photograph of the object gripping mechanism (or gripper).

Fingers and spacers have been machined out of aluminum for a variety of spherical objects. The gripper mounting attached to the top of the tank allows the object to be submerged while the gripper itself remains above water.

The necessary control components for the release mechanism include a Humphrey air valve (model #062E1), an Opto22 I/O module (model #OAC5A) with an Opto22 mounting rack (model #PB8), a 5 V DC power source, a 110 V AC power source (i.e., wall outlet), and a computer with an IMAQ 1408 board. The solenoid valve, shown in Fig. 2b, is a 110 V AC two-way normally closed valve that operates within an allowable pressure range of 0 and 860 kPa. When the solenoid is energized, the valve is open and compressed air activates the gripper. In order to control (i.e., de-energize) the valve with a computer and release the object, an I/O module acts as a relay between the computer and the valve. The computer sends out a constant 5 V DC signal (high) via the IMAQ 1408 image acquisition board and IMAQ-A2514 cable adapter. A high computer signal applied to the I/O module does not allow the 110 V AC power to be applied to the solenoid valve. When the computer signal is reduced to 0 V DC the I/O module allows 110 V AC to be applied to the solenoid valve, allowing the pressure to be applied to the gripper. To release the object, the 0 V DC signal returns to 5 V DC, causing the 110 V AC signal to turn off, the solenoid valve to close, and the gripper to open. The valve has an exhaust port open to the atmosphere that relieves the pressure in the airline between the valve and the gripper.

Imaging system

The stereo imaging system consists of two video cameras with tripods, two camera lenses, a lighting system, two image acquisition boards, and one computer with LabVIEW and IMAQ Vision. Although any video camera will work with the system, two Sony XC-73 video cameras with 640×480 pixel resolution were selected for the imaging system. The lenses utilized were two Computar V1218 lenses with a 12.5-mm focal length. The cameras with lenses are placed approximately 2.5 m from the tank walls giving a viewable area (the entire tank) of about 0.5 m^2 . The cameras are placed at ninety degrees from each other, making the three-component position, velocity, and acceleration determination straightforward and easy (i.e., a simple vector addition).

Lighting is an important consideration when performing any vision-based measurement. In the particular falling object experiment, care was taken to ensure that no shadows appeared on the object during its path. This was achieved by placing a 75-W incandescent bulb and reflector under the tank and six 100-W halogen lights with reflectors from adjacent sides (three behind each camera).

To obtain the instantaneous position of the falling object in three dimensions, the two image acquisition boards must acquire images

simultaneously. The IMAQ 1408 image acquisition board was selected for this purpose. The IMAQ 1408 board has the capability of acquiring images from four different channels, however the board has only one analog-to-digital converter. As a result, two image acquisition boards were required to obtain two images simultaneously. To synchronize image acquisition, a real-time system integration (RTSI) cable connects the two boards. The use of the RTSI cable allows communication between boards, enabling simultaneous image acquisition (i.e., LabVIEW makes one board the master and the other board the slave, and the specific programming requirements will be discussed later).

As with the image acquisition boards, the cameras also require synchronization. Video cameras require gen-locking for communication between cameras. In the particular case of the Sony XC-73 camera, the HD and VD pins from both cameras were joined and the internal camera boards were configured (one master and one slave). The result is synchronized communication between master board and camera and slave board and camera.

The experiment control and image acquisition and analysis programs are written using LabVIEW and IMAQ Vision. IMAQ Vision provides a variety of imaging tools that can be utilized within LabVIEW. The programs required to conduct the experiments are more fully described under the section entitled Software Development.

Costs

The costs associated with the reproduction of the experiment described in this paper are contained in Table 1. These costs have been divided into three categories, including computer and software, imaging system, and experiment. If one were to purchase everything required to perform the stereo vision experiment, a grand total of \$10,053 would be required. However, there are numerous ways of reducing these costs. For example, the computer and software make up nearly half of the grand total (\$4990). National Instruments recognizes the importance of educational projects for their software and provides educational software grants for projects such as the one described here. Thus, if one obtains a software grant and has access to a computer, the grand total is immediately reduced by \$4990.

To perform stereo imaging, all of the hardware listed under imaging system is required (a total of \$4032). However, many useful and similar experiments can be performed using only one camera. To perform two-dimensional measurements, the necessary imaging hardware includes one image acquisition board, one camera, one lens, and half of the lighting system, resulting in a total of \$1940 for 2-D measurements (further reductions can be achieved with less expensive hardware).

Finally, the experiment includes the tank and

Table 1. Total costs to develop falling object vision-based experiment.

PRODUCT	QTY	UNIT	TOTAL
LabVIEW 5.0 Full Devel. Sys.	1	1995	1995
Advanced IMAQ Vision	1	1995	1995
Pentium Computer System	1	1000	1000
sub-total (computer and software)			4990
IMAQ 1408 board	2	1075	2150
RTSI cable	1	22	22
IMAQ-A2514 cable	1	130	130
Sony XC-73 video camera	2	750	1500
12.5 mm Computar lens	2	105	210
lighting system	1	20	20
sub-total (imaging system)			4032
Tank and Tank Stand	1	630	630
Humphrey gripper	1	156	156
Humphrey solenoid valve	1	50	50
Release Mechanism Relay	1	150	150
Tubing and Fittings	1	30	30
Test Objects	3	5	15
sub-total (experiment)			1031
		Total	10053

tank stand and the automated release mechanism. To reproduce the experiment would require \$1031. Using a less expensive tank system (e.g., a fish tank) and manually releasing the object can reduce this total. Thus, if extreme financial constraints exist, the vision-based measurement techniques described here can be reproduced for less than \$2000.

SOFTWARE DEVELOPMENT

Experiment control and image acquisition and analysis software have been written using LabVIEW and IMAQ Vision. Three separate programs are required to conduct the experiments. The first program, *Image Acquisition*, operates the automated release mechanism, acquires images from both cameras, and writes the images to disk. The second program, *Threshold*, determines the threshold range needed to isolate the object, creates a binary image of the original, and determines which images to process. The final program, *Velocity Analysis*, determines the object position in physical coordinates, calculates object velocities from the position information, and saves the calculations on disk. These programs are more fully described in the following subsections. First, however, the configuration procedure for the image acquisition boards and the calibration procedure for converting camera pixel units into physical units are described.

Configuration and calibration

The video cameras used for the experiment are interlaced. Interlaced cameras divide the image array into even and odd fields. The camera scans the odd field first followed by the even field. Thus, if a camera is attempting to resolve a moving

object, the object may appear blurry because of the finite amount of time required to scan successive fields. As a result, the boards were configured to work in field mode, which only retains information from one field. *IMAQ Conf*, a configuration utility that is provided with the IMAQ 1408 board, was used to configure the IMAQ 1408 boards for field mode.

The image acquisition setup must also be calibrated so that the acquired images can be converted from pixel units to physical units. A simple camera calibration procedure is used for this purpose. A calibration grid with 1-cm² boxes is placed within the measurement region (i.e., inside the tank). Several images are acquired using *IMAQ Conf* and the length between grid points in pixel units is determined using *Extract ROI* (a VI from reference 8). The number of pixels between grid points divided by the physical distance (1 cm) determines the pixel ratio. More sophisticated calibration techniques exist but this simple procedure worked sufficiently well for this experiment (as determined by placing the grid in different locations within the measurement region).

Since the object could only appear within the tank, a region of interest was determined prior to acquiring any images. This served to limit the memory required to obtain and save the images to disk. An image was acquired and a rectangle (region of interest) encasing the tank area was determined. It should be noted that the cameras were positioned to maximize the number of pixels available to resolve the object (i.e., the cameras were positioned to utilize 640 pixels for the longest tank direction). The pixel ratio and the pixel coordinates of the region of interest are used as controls in the other sub-programs.

Image acquisition

The first sub-program, *Image Acquisition*, has three main functions. *Image Acquisition* triggers the release mechanism, acquires the images, and saves the images on disk. The front panel for *Image Acquisition* is shown in Fig. 3. When the computer turns on, the IMAQ 1408 trigger line automatically sends 5 V to the relay board via the IMAQ-A2514 cable. A high signal causes the solenoid valve to turn off, which in turn maintains the release mechanism in the open position. When the user places the spherical object in the release mechanism, the user presses the *Close Trigger* button illustrated in Fig. 3. This button reduces the trigger line to zero volts, opening the valve and closing the release mechanism. When ready to acquire images, the user clicks the *Start Acquisition* button, which returns the trigger line to 5 V, closing the valve, opening the release mechanism, releasing the object, and acquiring the user-specified number of images. The user also inputs the pixel coordinates of the region of interest determined previously.

Images are acquired using a function called *IMAQ Grab*, which provides sufficient image acquisition rate and allows for triggering the release mechanism. The *IMAQ Grab* function worked simultaneously with *IMAQ Trigger Drive* and *IMAQ Configure Trigger* resulting in the desired synchronized acquisition. *IMAQ Trigger Drive* specifies the IMAQ 1408 master board, and *IMAQ Configure Trigger* specifies the slave board. The block diagram for the synchronized image acquisition operation is provided in Fig. 4. Every time the master board acquires an image, *IMAQ Trigger Drive* sends a signal to the slave board through the RTSI cable. *IMAQ Configure Trigger* prepares the slave board to acquire an image every

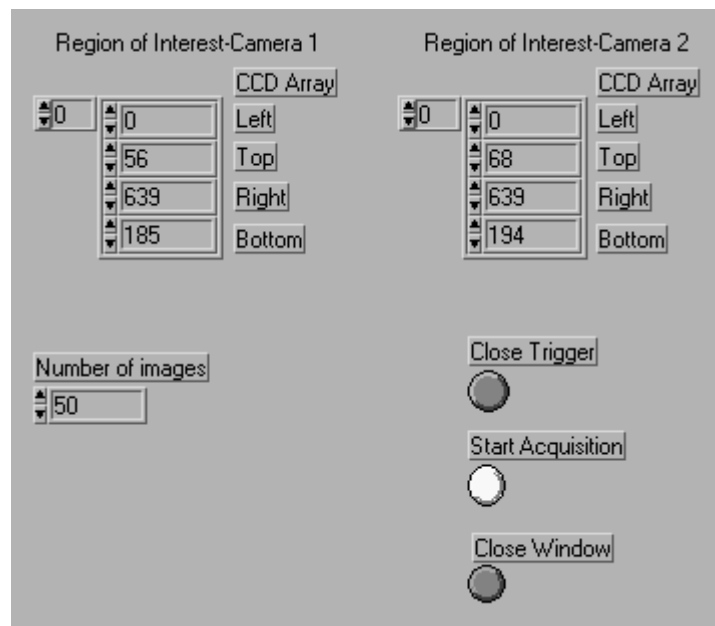


Fig. 3. Control panel for *Image Acquisition* program.

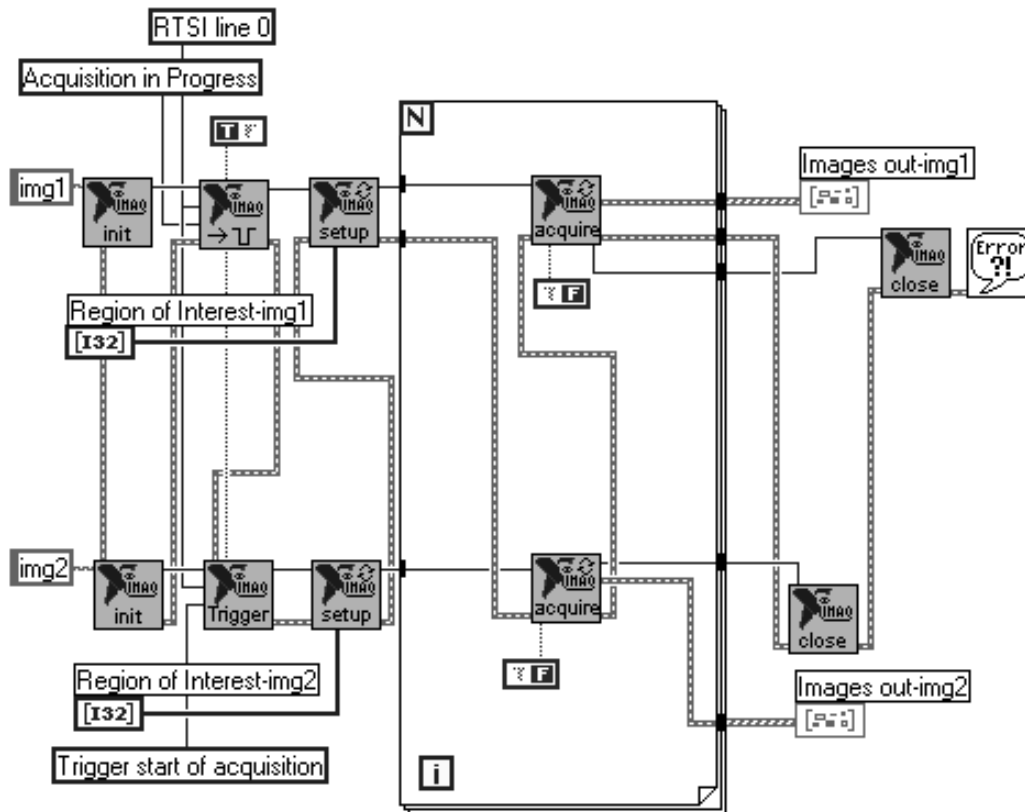


Fig. 4. Connection of VI functions within *Image Acquisition* program required for synchronization of two IMAQ 1408 boards.

time a signal is received. The particular program sequence shown in Fig. 4 ensures that the slave board is configured prior to receiving any signals from the master board.

After acquiring the user-specified number of images, the images are placed in two image arrays, one for camera 1 and the other for camera 2. Finally, the image arrays are saved in a particular directory on the hard drive for later use.

Threshold

To process the images, it is necessary to identify the object in each image. A simple thresholding procedure is used for this purpose. The second sub-program, *Threshold*, determines the threshold range necessary to isolate the object in each image. The block diagram for *Threshold* is illustrated in Fig. 5. When the video camera acquires an image, it collects light intensities in a two-dimensional array of sensors inside the

camera 480 units high and 640 units wide. For an 8-bit camera such as the one used here, each sensor gives the light intensity a numerical value ranging from 0 to 255 (0 being black and 255 being white). *Threshold* looks into this array of intensities and using *IMAQ Threshold* converts each intensity within the threshold range to 1 and anything outside the range to 0. This turns an 8-bit image into a binary image of black and red (red being anything inside the threshold range). The program is run continuously to determine a satisfactory threshold range.

Velocity analysis

The final sub-program, *Velocity Analysis*, obtains the images created and saved by *Image Acquisition*. The first part of the program imports each image and performs a threshold on the images using the threshold range determined in the *Threshold* program. Several morphology functions are then used to polish the images (shown in Fig. 5).

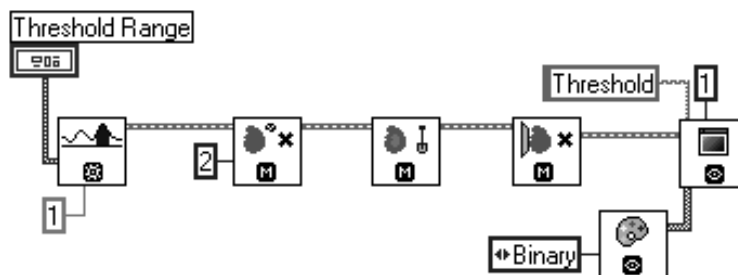


Fig. 5. Connection of morphology functions used within *Threshold* program.

IMAQ Remove Particle removes any unwanted edges from the main object. *IMAQ Fill Hole* fills any holes inside the object, replacing any zero pixel inside the object's area with a one pixel. Finally, *IMAQ Reject Border* removes any object located, such as the release mechanism, along the border of the image.

The binary images are then processed by *IMAQ Basic Particle*, which determines the global rectangle in pixel form around the spherical object. The coordinates of the global rectangles are stored in an array, and the centers of the global rectangles are calculated. The object center is assumed to coincide with the center of the global rectangle. These centers then provide the position of the spherical object in every image.

The distance traveled from image to image is calculated by subtracting the centers of successive images giving Δd . Since the cameras acquire images at 60 Hz in field mode, the time between images is known. From these two numbers, the velocity of the spherical object is calculated using $v = \Delta d / \Delta t$, where v is velocity, Δd is object separation and Δt is the time between images. Also, the position of the object in physical space is determined relative to the initial position of the object prior to release. These data are saved in Excel format for any future processing, such as may be required for lab reports. The program also plots the measured velocity versus position information for each camera in the vertical and horizontal direction on the front panel, as can be seen in Figure 6. The sections 'Spherical Object Properties' and 'Water Properties' on the front panel contain controls used to calculate a predicted velocity in the vertical direction based on a vertical summation of forces and an assumed object drag coefficient. This allows the user to compare predicted velocities to the measured velocities. The

section 'Image Parameters' contains controls required for the measured velocity calculation.

LABORATORY INTEGRATION

The falling object experiment described in this paper has been used in an undergraduate fluid mechanics laboratory to investigate terminal velocity, dimensional analysis, drag, and the concept of added mass. An example of the measured instantaneous velocity for a falling spherical object using the stereo imaging system is shown in Fig. 7. In the figure, the vertical velocity component is provided along with the vector magnitude of the velocity. Examination of the figure illustrates a number of interesting features of the measurement technique.

For example, the data in the figure do not appear to be 'smooth'. The data scattering is a result of errors in identifying the center of the object in successive images. For example, using our technique for object identification, we have found errors of up to three pixels in identifying the object center (i.e., errors of 1, 2, and 3 pixels occur in identifying the object center). The velocity error associated with errors in identifying the object center (which is an integer number) can be calculated using the 60 Hz image acquisition frequency and the camera resolution in physical units. In our setup, one camera pixel corresponds to 0.125 cm in physical space yielding potential velocity errors of ± 7.5 cm/s per pixel. Discussion and calculation of these errors can be a useful exercise included in the laboratory report.

The simple object identification routine can be improved by using more sophisticated image processing techniques that can be part of a graduate experimentation course or as another senior design course. In an undergraduate measurements and instrumentation laboratory,

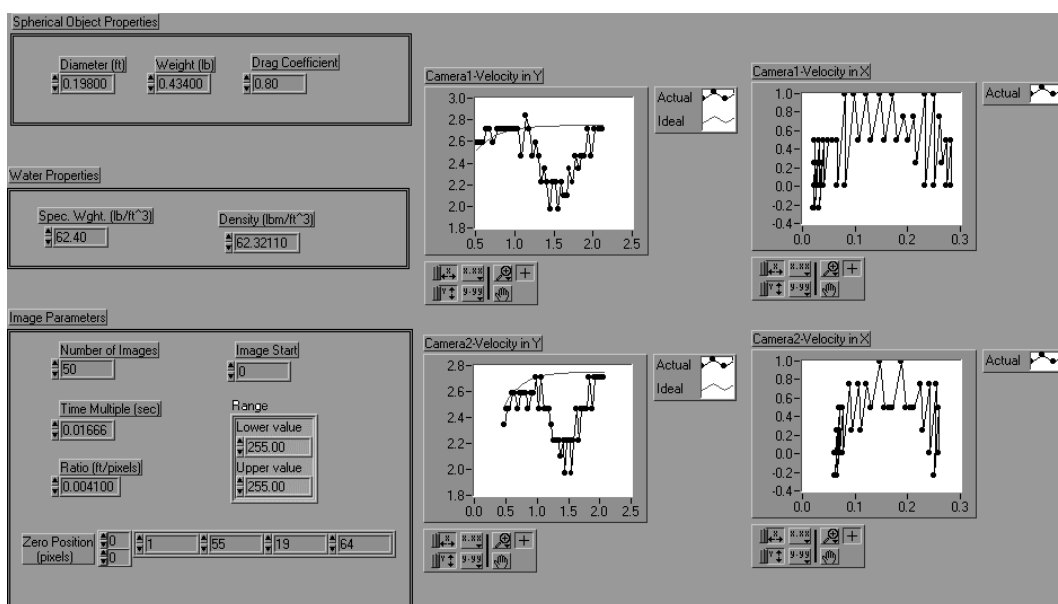


Fig. 6. Control panel for *Velocity Analysis* program.

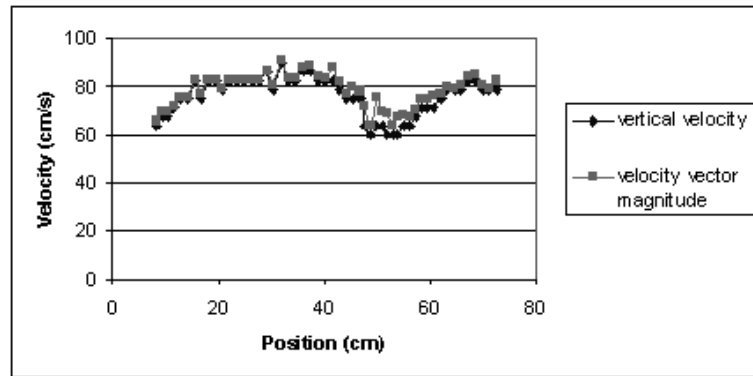


Fig. 7. Example of velocity information obtained for a falling spherical object.

the vision-based measurement technique and the errors associated with these measurements can be highlighted. Topic areas for discussion include modern video and digital camera technology, optics, image and data acquisition, object identification and image processing, resolution, and two- and three-dimensional machine vision.

This experiment can be used to illustrate other topics in the laboratory curriculum. In an undergraduate controls laboratory, for example, students can generate useful control software using LabVIEW for the release mechanism and perhaps an automated object retrieval mechanism. The students can also learn about experiment and hardware synchronization. At the graduate level, students can determine the frequency of vortex shedding in the wake behind the falling object and the instantaneous drag as a function of Reynolds number.

CONCLUSIONS

A simple vision-based experiment has been designed that highlights various concepts and fundamental principles throughout the mechanical engineering curriculum. The experiment consists of a clear tank of water in which objects can be released from rest using an automated release mechanism. A vision system, using one or two standard video cameras, is used to track the falling object. The stereo imaging system using two cameras provides object tracking in three dimensions. Experiment control and image-processing software has been written using LabVIEW and IMAQ Vision. A series of images acquired at 60 Hz using one or two video cameras connected to IMAQ 1408 image acquisition boards are analyzed to resolve the instantaneous position of the falling object. Using a basic camera calibration procedure, the instantaneous position information is converted from pixel units to physical units. The object velocity and acceleration data can then be calculated numerically.

The experiment has been designed and constructed by a group of three undergraduate students as part of a capstone senior design

course. Utilizing the senior-level capstone design course provides a cost-effective means for laboratory improvement in addition to the educational benefits derived by the students from such projects. The approach taken at the University of Texas at El Paso (UTEP) for laboratory improvement is to develop simple experiments that can be used throughout the curriculum, in an attempt to minimize the associated costs of laboratory improvement. The backbone of the strategy is the use of LabVIEW for experiment control and data analysis. LabVIEW provides a rapid prototyping tool for necessary software development, making LabVIEW extremely attractive from an educational viewpoint; students can generate much of their own code in a reasonable amount of time.

The falling object experiment described in this paper has been used in an undergraduate fluid mechanics laboratory to investigate terminal velocity, dimensional analysis, drag, and the concept of added mass. The student responses to this and other automated experiments have been overwhelmingly positive. As a result, UTEP is actively engaged in developing additional laboratory experiments and curricula.

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