# Interactive Remote-Controlled Experiment for Instruction in Fluid Mechanics

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## Abstract

Just as the Internet has transformed communication and scientific research over the last decade, it is changing industry, commerce, social exchange, and education all over the world. Today engineers control complex systems that may have components in widely separated geographic locations all remotely controlled over Internet. In education, new avenues and methods for enhancing the overall learning experience as well as expanded educational opportunities for a larger pool of students have been enabled by the Internet. One such example is a remotely-accessed instructional laboratory experiment. Initial remote access development has been in the fields of computer science and electrical engineering where the Internet and related infrastructure are part of the curricula. Currently, these advancements are being adapted into engineering programs where a "hands-on" laboratory approach is essential.

This paper presents a "proof-of-concept" remote-controlled experiment developed at IIHR-Hydroscience & Engineering (formerly the Iowa Institute of Hydraulic Research) to illustrate a concept for an introductory undergraduate engineering course in fluids mechanics at The College of Engineering, The University of Iowa. The interactive, real-time fluid viscosity experiment allows individuals or groups of students to initiate, conduct, and conclude the laboratory experiment using physical hardware (http://vfl.iihr.uiowa.edu/atac/viscosity.html) from practically any place, at any time. Beyond the interactive learning environment and the related information (handout, experimental procedures, design and construction considerations, etc), the experiment is complemented with additional teaching aids (visualizations, course material, relevant Internet links, applets, etc.) to make it a stand-alone and tutorial assignment that can be accessed independently of the class lectures. This paper demonstrates that remote experimentation in conjunction with additional resources is a viable option for instruction in fluid mechanics by efficiently supplementing the on campus instruction and considerably assisting distance learning and non-traditional student education.

## Introduction

Rapid developments in computer science and network technology enhance the scope of possible activities in industry, training, research, and education. Engineers in today's industry can remotely collect massive amounts of real-time data through the Internet. Similarly, in today's education new avenues and methodologies for enhancing the experience of learning as well as expanding educational opportunities for a larger pool of students have been opened by Internet-based technologies. Currently, students are introduced to the new paradigm of remote experimentation. Remote experimentation, in the present context, connotes remote-controlled real-time fluid mechanics experiments conducted on actual equipment delivered over the network using a cluster of general-purpose and/or specialized instruments interfaced to personal computers[1,2,3].

Fluid mechanics is one of the most challenging areas of engineering sciences because it includes, for basically the same macroscale flow, a variety of interrelated, smaller scale fluid-fluid or fluid-boundary interactions that can be only understood with considerable intuition. Illustration of the concepts in moving fluids relies heavily on visualization and experimentations generally obtained using laboratory experiments. Computational Fluid Dynamics or simpler applet-based simulations provide extensive insight into a variety of fluid flow problems. While valuable learning experiences may be obtained with simulations, effective and complete learning in applied engineering requires a mixture of theoretical and practical sessions currently obtained in classroom and instructional laboratories. A recent educational innovation that could bridge the gap between simulations and conventional "hands-on" physical experiments is remote experimentation via the Internet. Remotely accessible laboratories for teaching are becoming more common, but most of them are fostered by educational areas where the Internet and related infrastructure were developed (i.e., computer science, robotics, telecommunication engineering). Fluid mechanics, as well as other engineering courses where a "hands-on" approach is essential, could greatly benefit from remote experimentation. Attempts to develop real-time controlled experiments in fluid mechanics instruction are scarce and those finalized to date (e.g., http://beam.to/welafi) are essentially flow visualization rather than participative laboratory experiments.

The paper presents a "proof-of-concept" remote-controlled experiment developed by IIHR-Hydroscience & Engineering (former the Iowa Institute of Hydraulic Research) for the Fluids Lab of the College of Engineering (CoE) at The University of Iowa (UI) through an Instructional Computing Awards project sponsored by the UI's Academic Technology Advisory Council. The interactive real-time fluid viscosity experiment allows individuals or groups of students to initiate, conduct, and conclude measurements using physical hardware located in a remote laboratory from practically any place, at any time, replicating step-by-step the experimental procedures used in the classroom. The experiment is housed at a dedicated website, http://vfl.iihr.uiowa.edu/atac/viscosity.html where experiment-related information and complementary teaching aids are assembled in a stand-alone instructional resource that can support traditional (in class) or autonomous (independent of the class) learning experiences.

## Implementation

*Experiment principle and design*

The experiment adapted for online remote access is aimed to demonstrate and support understanding of the viscosity concept for an introductory undergraduate engineering course in fluids mechanics. The experiment is currently used in an undergraduate course on Mechanics of Fluids and Transport Processes at UI. Three additional undergraduate and introductory graduate courses of greater complexity offered at CoE, namely, Principles of Hydraulics, Intermediate Fluid Mechanics, and Inviscid Flow can readily include the experiment in their activities as a demonstration or complete experiment.

The experiment principle is based on the effect the kinematic viscosity of a liquid has on a falling object. For this purpose, a sphere is released in a long transparent cylinder filled with glycerin, as illustrated in Figure 1. After the sphere has fallen a long enough distance so that it attains the terminal velocity, the length of time required for the sphere to fall through a pre-established distance is measured.

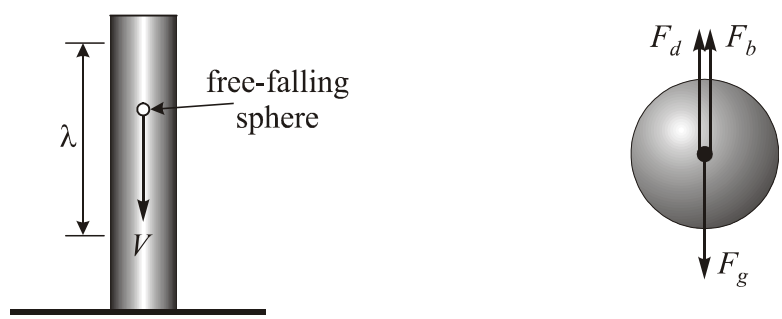


Figure 1. Experimental principle

Once terminal velocity is achieved, the gravitational ($F_g$), drag ($F_d$), and buoyancy ($F_b$) forces acting on the sphere must balance. The drag force for the above situation is described by the Stokes law which is valid for Reynolds numbers, $Re = VD/\nu << 1$, where $V$ is the terminal velocity, $D$ is the diameter of the sphere and $\nu$ is the fluid kinematic viscosity). Equating the forces allows for calculation of the fluid viscosity

$$\nu = \frac{D^2 g\left(\rho_{sphere}/\rho_{fluid} - 1\right)t}{18\lambda} \qquad (1)$$

where $g$ is the gravitational acceleration, $\rho_{sphere}$ is the density of the sphere, $\rho_{fluid}$ is the density of the fluid, $t$ is the time for the sphere to fall a vertical distance $\lambda$. The fluid density in Equation (1) is obtained repeating the experiment for two spheres of different densities (e.g., teflon and aluminum)

$$\rho_{fluid} = \frac{D_t^2 t_t \rho_t - D_a^2 t_a \rho_a}{D_t^2 t_t - D_a^2 t_a} \qquad (2)$$

where subscripts $t$ and $a$ refer to the teflon and aluminum spheres, respectively. Given the density of the two sphere materials, the students have to measure $\lambda$, $D_t$. $D_a$, $t_t$, and $t_a$. For the in-class experiment, students consecutively release spheres in one cylinder and recording the experiment independent variables.

The central consideration in designing the remote experiment was to mirror step-by-step the procedures applied by students during the class experiment. Two cylinders are simultaneously used for conducting the experiment, as illustrated in Figure 2. Each of the cylinders contains one sphere type, i.e., teflon and aluminum. The two cylinders are mounted on a common support that rotates in the vertical plane. The plexiglass cylinders contain inserts at each end that release the spheres along the cylinder centerline.

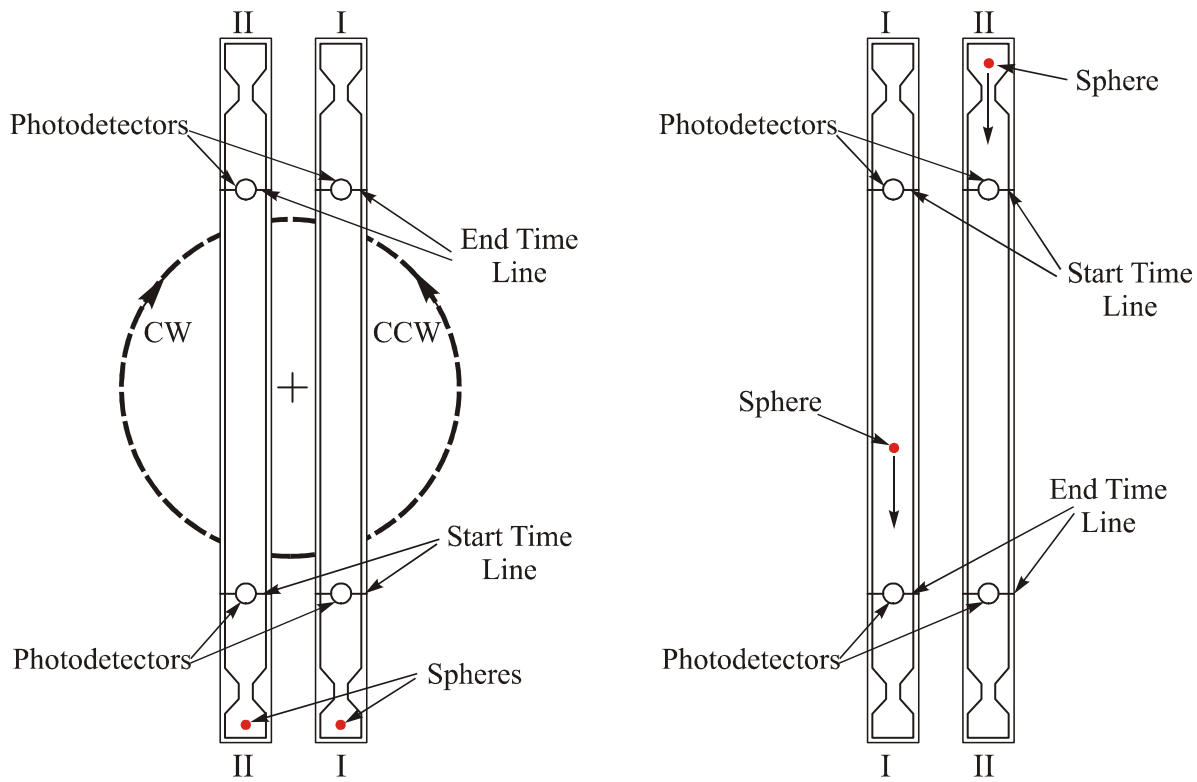


Figure 2. Remote experiment design: a) the setup in the standby position; b) the setup position during measurements.

*Web-enabled platform configuration*

The configuration of the experimental setup is shown in Figure 3. It consists of a Windows® PC, embedded controller, and the relays and switches that control the motor that rotates the cylinder platform. The firmware on the embedded controller has a simple command-line interface, and can be accessed via a terminal emulator. One can type in commands such as "+" for *Nudge CW*, "-" for *Nudge CCW*, and so on, without using the web interface. This makes it easy to test and debug the system.

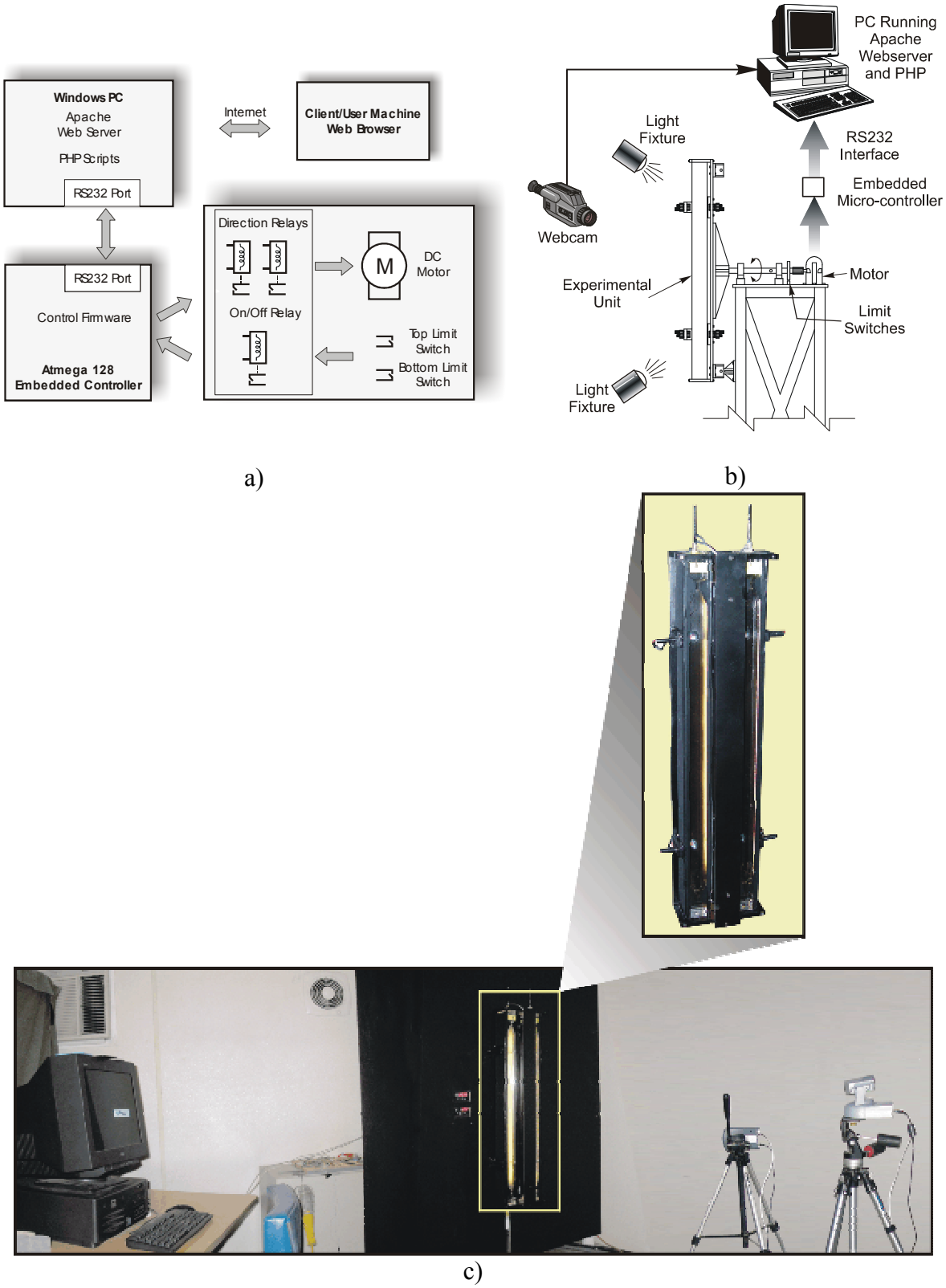


Figure 3. Remote experiment configuration: a) control system; b) electro-mechanical assembly; c) rendered photograph of the experiment

Users interact with the system via a web browser. The PC runs an Apache (www.apache.org) web server configured with PHP (www.php.net). When a user clicks one of the buttons, for example the *Run CW* button, a PHP script on the server is invoked that generates the corresponding ASCII command that is sent through the PC's serial port to the embedded controller. The firmware on the embedded controller interprets the commands and turns on the appropriate relays to make the motor turn left. The limit switches are for safety, and open when the apparatus reaches the mechanical limit. This automatically turns off the motor. The embedded controller also senses the state of the limit switches. If the motor reached the limit via a left rotate/nudge, the system will only respond *to Run CW* and *Nudge CW* commands. If the motor reached the limit via a right rotate/nudge, the system will only respond to *Run CCW* and *Nudge CCW* commands.

Real-time video is streamed from the experiment site to the user location, where one can see the experiment progress in real-time. Students can be involved in changing various parameters in the experiment, in observing the process, in data collection, in downloading the data and the analysis. Commands are queued and executed in the order of the incoming requests. Users logging in during a test may view experiments being carried out by others.

*User Interface*

A suite of visual interfaces stored on the experiment website was developed for introducing the learner to the experiment configuration, experimental procedure and the actual conduct of the experiment. Separate interfaces include experiment handout, description of the experimental cycle, experimental procedures, and on-line experiment. It is suggested that the user review the preparatory material before conducting the experiment. The online experiment interface is organized into different areas responsible for managing and displaying distinct streams of information, as illustrated in Figure 4.

*Visualization area* (central) provides a video feedback of the physical process using two screens. The left screen is provided by a fixed webcam. The screen allows the user to observe the setup status and to prepare the measurements. The screen on the right is provided by an adjustable webcam that features "zoom in" and right-left, up-down adjusting capabilities. This camera is used to actually conduct the measurements, by allowing the user to focus on the sphere that needs to be timed in its fall.

*Control area* (bottom) allows the user to start and conduct the experiment. The stand-alone Apparatus Control interface rotates the cylinders 180˚ clockwise or counter-clockwise using *Run CW* or *Run CCW* commands, respectively, or rotates them with incremental steps using *Nudge CW* or *Nudge CCW* commands. *Stop* command interrupts rotation. *Reset* command brings cylinders in the standby position. The control area also contains a virtual stopwatch that that is used to record on screen the time it takes for the spheres to travel between the two markers.

Cylinders are equipped with four photodetectors-lasers pairs that sense sphere passage at the marker location. A digital oscilloscope follows the time evolution of the photodetector signals to provide an automated measurement of the falling time. This feature (not implemented in the interface yet) will allow the comparison of the accuracy of the student measurement with a more

precise timing alternative. This last feature exceeds the capabilities of the existing in-class experiment and plays an important role in conducting the uncertainty analysis where sources of errors need to be estimated as part of the uncertainty analysis.

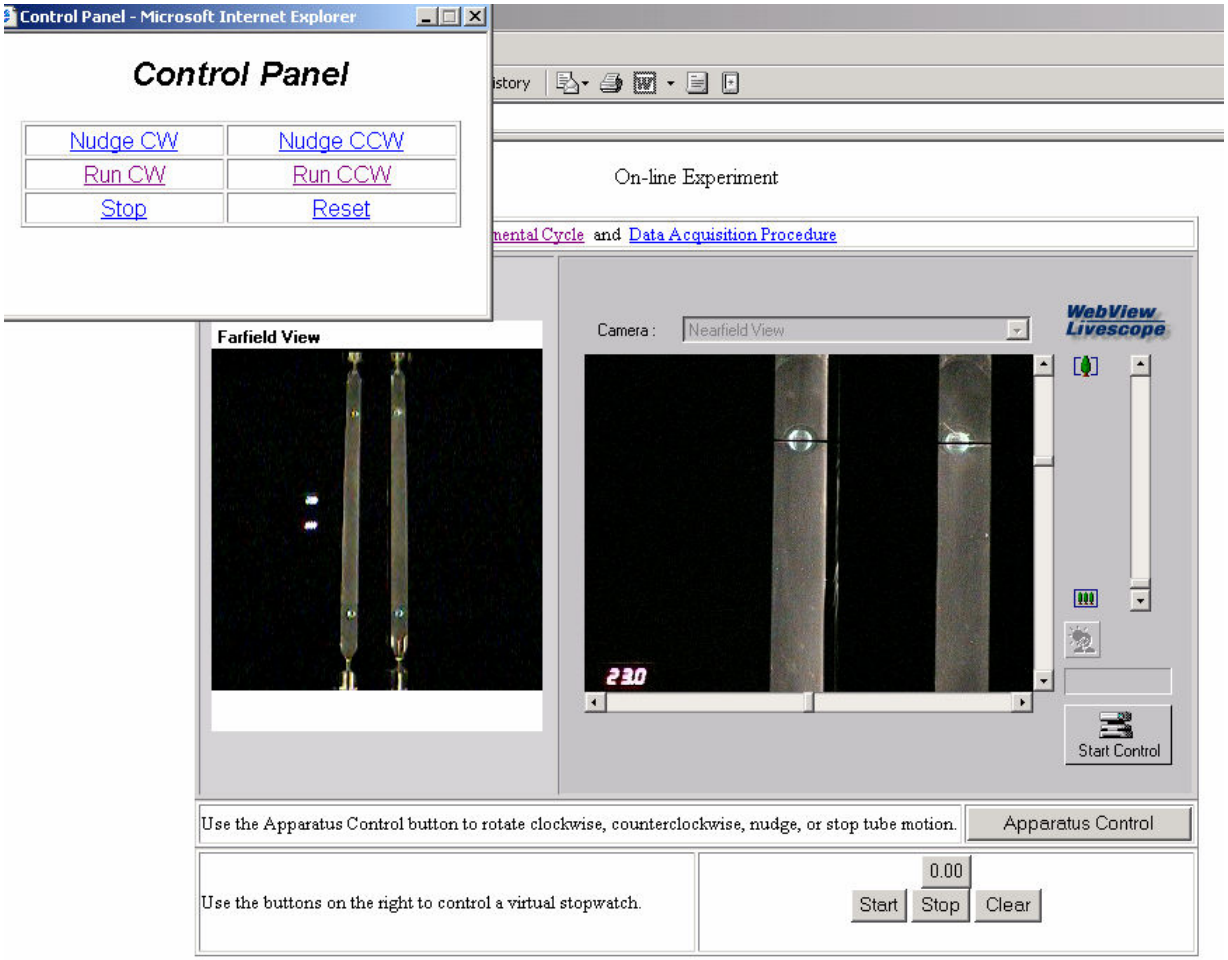


Figure 4. The On-line Experiment Interface

*Experiment Website*

The remote experiment described above is part of a more general curricular improvement initiated in the last decade by IIHR for instruction in fluid mechanics at the CoE of UI. Central to this pedagogical initiative is integration of simulation technology into undergraduate education through complementary computational fluid dynamics (CFD), experimental fluid dynamics (EFD), and uncertainty analysis (UA). Elements of this development are included on the CoE' Fluids Lab website http://css.engineering.uiowa.edu/fluidslab. The ultimate vision of IIHR's educators and researchers is the creation of a subject-center, multilevel, modular teaching and learning environment where digital courseware, experiments, numerical simulations, and cutting edge information and multimedia communication tools and activities are synergistically combined for providing an interactive learning environment that could assist class lectures or be shared by multiple users over the network for self-paced learning.

From this perspective, the remote experiment recently finalized was embedded in a website where additional comprehensive resources are available for traditional or autonomous learning (http://vfl.iihr.uiowa.edu/atac/viscosity.html). The website structure is illustrated in Figure 5. To date, the experiment website includes the interface for conducting the real-time experiment as well as experiment-related information (handout, procedures, design and construction considerations, etc), customized numerical simulations, visualization clips, a "canned" version of the experiment, analysis and discussions, and other relevant information regarding the experiment concept under consideration (course material, flow visualizations, relevant Internet links, and interactive applets). Given that this development work is undergoing, not all of the education resources have been finalized and incorporated in the website.

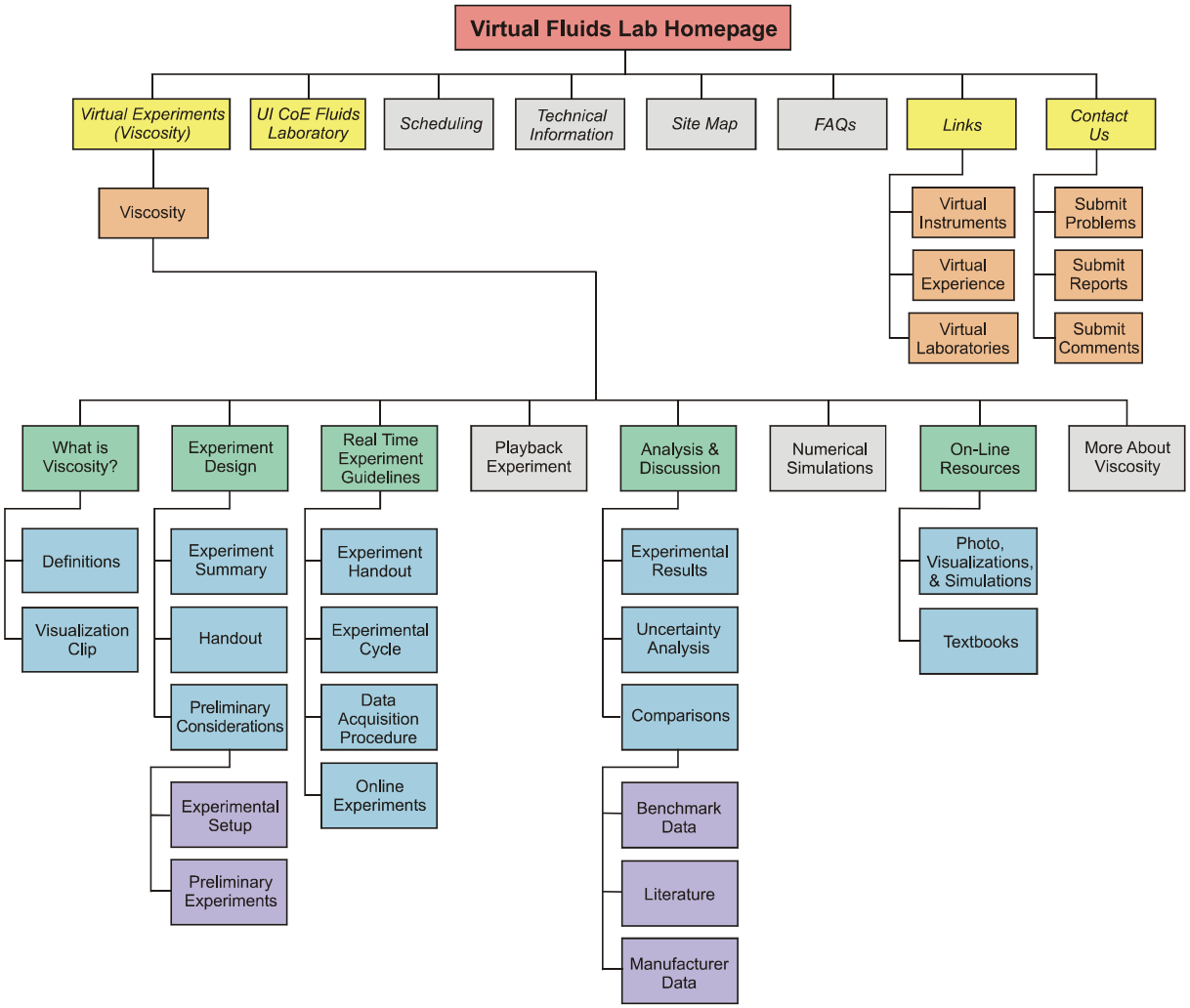


Figure 5. Structure of the website dedicated for the viscosity experiment

## Lessons Learned and Outlook

In the last decade, remote access of equipment components or laboratory experiments have steadily increased in engineering instruction. However, most of the development has occurred in disciplines at the forefront of remote control development, such as robotics and

telecommunications [3,4,5]. Students are introduced to a new instruction paradigm [6,7,8]. Similar to traditional laboratories, remote experimentation allows students to interact with real equipment and conduct analysis on real data, and use the trial and error approach. Despite many features in common with traditional methods, there remains considerable skepticism among faculty, and even among students about implementation of remote experimentation in engineering because most of the programs, and rightly so, are perceived as a "hands-on" disciplines [3]. In order to emphasize the remote experimentation developmental needs, a summary of its advantages and disadvantages compared to traditional laboratory experiments is provided in Table 1.

Table 1. Comparison of advantages and disadvantages of remote experimentaion and traditional laboratory experiments [9,10,11]

| Advantages | Disadvantages |
|---|---|
| Multiple user access to different experiments any time, any place | Inability to provide qualitative answers to open-ended problems and student questions |
| Operational safety | Less impact than direct hands-on student interaction |
| Cost effective operation and upgrading | Significant initial effort and operation costs |
| No physical presence for student required | Must request queuing and scheduling time |
| Experiment repetition possible | Limited participative (hands-on) learning |
| Acquire and process automatically the data | Limited means to enforce independent student work |
| Prepare for the future workplace environment | |

Given that the remote experiment described above has not yet been subjected to a rigorous evaluation [12], objective criteria for properly assessing its pedagogical effectiveness are not available. The experience gained by the authors during the development of their first remote experiment, however, has led to a wide range of lessons learned in this demonstration (mostly of a technical nature) that should prove invaluable to future efforts to expand remote experimentation for instruction. These lessons include:

- How to integrate the existing instructional material (usually in hard copy form) within an interactive web-based interface. The materials must be visually attractive and completely self-explanatory (in contrast, materials intended for classroom discussion often omit items for clarification or expansion during class).
- How to design a generalized template for the experiment including instructional materials, a theoretical background and with the potential for future expansion to include numerical simulations.
- The need for clarity. Since all of the materials and instructions for the conduct of the experiment must stand alone, they must be clear and unambiguous. Instructions need to be intuitive. There is a need for extensive testing with unsophisticated users in order to make this a reality.
- The need for the experiment to be robust. This means that the programming must be flawless, all of the possible key combinations must be checked to ensure proper execution. Further, the equipment itself must be robust, capable of repeated operation without human intervention. It must always fail in a safe way that will ensure no damage to the equipment. It must fail in a way that can be recovered on-line by an inexperienced operator.
- Visualization is key. The ability to see what is happening is a key part of the on-line laboratory experience. How to reconcile the need to see the big picture as well as details of the sphere crossing the lines was a major item of discussion and exploration. This problem is

also strongly tied to the problem of bandwidth since the real-time cameras are the largest users of data transmission capability. Given that all users will not have the kind of bandwidth we have at the university that allows us to use multiple cameras in real time, what kind of bandwidth should be assumed? Can we strike a balance between likely user capability and the need to see what is happening?

- Pedagogical aspects are critical. Use of remote experimentation changes in pedagogical methods such as structure, presentation, and information organization. The current pedagogical trend aims toward student learning autonomy through development of flexible and distributed tutoring resources disseminated through e-learning platforms, teaching assistants, and educators. There should be clear objectives, pertinent information, and precise stages. Management of space and time should provide combined solutions with office hours and on-line support.

These lessons will be important for us as we extend the current lab into more, diverse, and increase the degree of complexity experiments.

Solutions to some of the implementation issues listed above have already been addressed in the developmental work of other investigators, but they have not been applied yet. For example, efficient enhancement of the synchronous access to the experiment can be attained through the method suggested by Gillet et al. [12]. This will provide users with adequate perception of real-time events. Live video, for instance, can be augmented with virtual objects, which are in turn driven by real measurements. To avoid schedule conflicts, a virtual gateway can be developed to assign priorities and reserve particular time slots [12]. Suggestions for solving logistical problems occurring during website operation, such as handling task scheduling, conflict resolutions, equipment and network failures, are recommended by Esche [8]. Increased "hands-on" features to the remote experiments can be obtained by adopting adequate system architecture, programming environment, and user interface elements as suggested by Wang et al.[3]. Some of the technical issues listed above can be efficiently addressed using LabVIEW, software for automated data acquisition systems that increasingly includes web-enabled capabilities [13].

Despite the continuing debate of the effectiveness of remote experimentation in engineering, it is anticipated that in the future, the demand for remotely located facilities for real-time instructional purposes across national boundaries is likely to grow considerably, including curricula with strong requirements for realistic laboratory experiments (e.g., fluid mechanics, thermodynamics, environmental engineering). Further developmental efforts to make these learning tools more feasible are growing, motivated in principal by the fact that building laboratories requires considerable time, expertise, and financial resources (http://etnet.vub.ac.be/eLABS/). Particular attention needs to be given to technical aspects such as modularity, expandability, scalability, compatibility with existing communication standards, and computer platform independence [9]. Remote experiment design should increasingly adapt user-friendly interfaces, inquiry-based procedures, and methods that enhance interactivity and accommodate teamwork. Emphasis should be given on implementation of remote experiments features that increase the joy of learning experience, raise motivation, and more accurately resemble configurations and functions of the emerging cyberinfrastructure-based workplace environment.

Remote experimentation will impact students, faculty, and administration. For students, the excitement of having unrestricted access to sophisticated real laboratory instruments can only

enhance student interest and foster further creativity and self-exploration. Experiments can be repeatedly viewed, paused, or partially reviewed providing a capability not possible in the classroom experiments. The "any time/any place" feature of the remote experimentation can resolve issues related to individual learning styles and wide ranging levels of student preparedness. Instructors can access exemplary demonstrations and experiments without the burden of designing, constructing, and maintaining expensive laboratory facilities. Reducing the need for facility duplication can free up considerable time, expertise, and financial resources. For administrators, the web-enabled environment greatly reduces the cost of setting up laboratories and provides opportunities to share high-quality teaching experiments with secondary schools (via demonstrations), two-, and four-year colleges (via complete experiments) irrespective of the location and local facilities of the institution. Overall, the practically unrestricted access (anybody, anytime, anyplace) to the teaching/learning environment considerably maximizes the efficiency of the instructional infrastructure (otherwise only sporadically used when dedicated exclusively to teaching at one location) and greatly supports instruction in small universities and via distance learning to non-traditional students who seeks carriers in engineering areas.

From the pedagogical point of view, remote experiments have additional implications:

- The unrestricted accessibility and interaction with the web-based experiments promote the "learning by doing" approach developing student capabilities and motivation to engage in lifelong learning.
- There is a "hands-on" aspect of the remote-controlled experiments consisting in the real feeling the student experience while manipulating buttons on the computer screen to control real time the experiment. This feature is often missing for distance-learning students who passively view video, CDROM of previously recorded physical experiments, or numerical simulations. Moreover, remote experimentation preserves the copes with the experimental imperfections that usually are not reflected in the textbooks and numerical simulations that is essential part of educational experience.
- Foster professional development for multidisciplinary faculty in engineering through adaptation and implementation of innovative instructional methods supported by state-of-the-art information and communication technologies.

**Conclusions**

This paper demonstrates that remote experimentation is a viable option for instruction in fluid mechanics by efficiently supplementing the instruction on campus and considerably assisting distance learning and non-traditional student education. We are aware that nothing can replace the value of direct hands-on laboratory experience. Remote experimentation, however, can provide a rewarding experience through its interactivity, visual feedback, unrestricted repeatability, and authentic views of the experiment. Despite the opportunities that remote experimentation capabilities provide to supplement traditional teaching, final acceptance by the academic community depends on its correlation with curricular needs, pedagogical soundness, ease of use, and reliability.

Remote experimentation creates a unique connection between the lab bench of the past and tomorrow's cyberinfrastructure-based science and engineering. This technological approach

greatly reduces the cost of setting up laboratories and makes remote individualized laboratories available where none existed before. Coordination of developmental efforts is suggested to inaugurate an outstanding instructional resource in fluid mechanics centralizing the best expertise and facilities available worldwide. The final set of experiments can be shared through inter-departmental, inter-institutional, and international cooperation for curriculum upgrading, faculty professional development, external evaluation, and planning future developments.

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TAO XING received his Ph.D. in Mechanical Engineering from Purdue University in 2002. He is a Postdoctoral Associate at the hydraulic laboratory at The University of Iowa with main expertise in the area of computational fluid dynamics.