

## **Hands-On Laboratory Experience via Remote Control: Jet Thrust Laboratory**

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### **Abstract**

This paper describes the development of a remote-controlled jet thrust laboratory for illustrating the fundamentals of compressible fluid mechanics as part of an undergraduate mechanical engineering curriculum. The laboratory is the first in a series to be developed jointly by faculty at Rutgers University and the University of Illinois at Urbana-Champaign. The sharing of resources significantly reduces the per institution development and maintenance costs, while making available a wide array of 'hands-on' laboratory experiences to students. Problems associated with implementing remote-controlled experiments, including control, visualization, data acquisition, student preparation, client-side compatibility, are discussed and workable solutions presented. Finally evaluation results of the educational outcomes of the remote-controlled laboratory compared against a control group are presented.

### **1.0 Introduction**

Recent years have seen enormous financial pressures on engineering departments struggling to cater to increased enrollments, static budgets, and the need to maintain educational quality. As departments look for ways to cut costs, 'hands-on' instructional laboratories, typically expensive to develop and maintain, are slowly being replaced with 'virtual' experiments<sup>1-6</sup>. Indeed as noted in a report by a task force commissioned by the American Society for Engineering Education, '[Engineering schools should adopt] cost effective approaches [that] make use of information processing and simulation technology' (ASEE, 1988). Recognizing the importance of 'hands-on' experimentation in the undergraduate curriculum<sup>7-13</sup>, several institutions have developed laboratories where students can gain 'hands-on' experience via remote control of physical experiments as a supplement to their existing laboratory curriculum<sup>14-19</sup>.

This paper describes the development of the first in a series of experiments controlled over the internet, that are being developed jointly by faculty at Rutgers University and the University of Illinois at Urbana-Champaign. This partnership forms the core of *The Integrated Remote Laboratory Environment (IRLE)*, where the two universities develop and host remote control laboratories that are then made available to their students. After a brief description of the motivation for IRLE, we will describe the remote-controlled jet thrust laboratory. In addition, we will discuss issues that are relevant to placing experiments online, and the evaluation of the

effectiveness of this laboratory compared to a similar laboratory conducted with the students physically present at the apparatus.

## 1.1 Motivation and Advantages of IRLE

The initial reason we considered developing IRLE in the Mechanical and Aerospace Engineering curriculum at Rutgers University is that there was a need (as confirmed by a recent ABET<sup>‡</sup> visit) to develop more laboratories for the undergraduate curriculum. Although the current laboratories were of high quality, it was determined that there were not enough of them to cover the broad range of topics in an undergraduate MAE laboratory curriculum. The first problem faced when considering additional laboratories, however, was not only the capital and maintenance costs of creating the experiment, but also the need for sufficient space for the students and equipment to run the additional laboratories.

Knowing that remotely operated laboratories could facilitate some of these difficulties and that there are other institutions with the same constraints, we decided to team up with the University of Illinois and create IRLE. IRLE presents several unique advantages:

- Reduced per institution development, maintenance, and laboratory supervision (teaching assistant) costs.
- Reduced space requirements (since only one experimental apparatus is needed to facilitate an entire class and no additional physical space is required for people to work).
- Institutions can rely on the expertise of each others faculty to create laboratories in fields in which they may not individually have current expertise.
- Although a given experiment may be facilitated by a single institution, each institution can tailor the experiment to their curriculum needs by creating an individualized set of cases for the students to run and individualized questions to be answered.
- As the experiment is conducted through a computer, the same computer resources can also be setup to include, interactive multimedia prelabs, laboratory operational explanations, and step-by-step derivation examples.
- Service to on-line universities and the creation of an environment where students can access the laboratory “any time, anywhere”.
- Laboratories can be made safer for students, reducing university liability concerns about experiments involving lasers, high pressures, harmful noise levels, or combustible gases.
- Demonstrations can be created from the same experimental apparatus for K-12 education and the general public.

There is no doubt that there are other advantages and disadvantages of remote laboratories. The primary disadvantage of IRLE specifically and remote-controlled labs in general, is the lack of physical contact students have with the instrumentation. This results in a lack of experience with

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<sup>‡</sup> Accreditation Board for Engineering and Technology, Inc.

typical experimentation tasks, for example, attachment of patch cables, trouble shooting experimental apparatus problems, familiarity with how components are wired together, etc.

The development of a complete remote-controlled laboratory requires more than just the design and construction of the remote-controlled apparatus and support software. The entire lab must be pedagogically sound to ensure that the learning outcomes are as effective as 'in-person' labs, if not more. Therefore in order for the advantages of remotely operated laboratories to outweigh the disadvantages, the following criteria were proposed for experiments to be part of IRLE:

1. *The labs must have a high visual content.* Makes the experiment more interesting to run and allows students to better understand that they are running an actual experiment, not a simulation.
2. *Students must be able to run the labs using a regular web-browser without the need to install specialized software.* Allows students to run the experiments from their dormitories or from any university computing laboratory where it may be difficult or costly to have specialized software installed.
3. *The experiments must be sufficiently complex making simulation difficult or impossible.* Although many experiments can be simulated, it is important for students to observe and understand the differences between the simulation and “real-world”. One goal of IRLE is to highlight these types of experiments.
4. *The labs must provide an integrated environment.* Embodied in a pre-lab (provides background on experiment), remote access to the experiment and a post-lab (information necessary to complete the laboratory write-up) students should be able to perform the entire experiment, analyze the data and complete the necessary reports with minimal instructor intervention. IRLE should make maximum use of multimedia technologies to enhance the students' experience and allow the students to sign up for and run the experiments at any time.

Advantages and disadvantages associated with implementing remote-controlled experiments, including control, visualization, data acquisition, student preparation, client-side compatibility, are discussed and workable solutions presented in the context of a jet-thrust laboratory.

## 2.0 Aim of the Experiment

The aim of the jet thrust laboratory is to give students a laboratory experience in the general area of fluid mechanics, highlighting the integral control volume formulation of the governing equations, and general aspects of compressible flow. Figure 1 shows a schematic of the primary components of the jet thrust laboratory. The experiment consists of a 10.2 mm axisymmetric jet mounted on a balance allowing the direct measurement of the thrust using a load cell. The stagnation pressure of the jet is regulated with a computer-controlled valve. A pitot probe can be scanned across the exit of the jet using a stepper motor operating a linear traversing stage. The pitot and stagnation pressures are measured with transducers, which give a calibrated voltage output to the A/D board on the computer. A *schlieren* system has also been set-up so that the students can observe the shock pattern from the jet when it is operated at supersonic Mach numbers. All equipment is computer controlled through a LabView<sup>®</sup> program and will be described in greaster detail shortly.

Through this laboratory the students learn how to calculate the thrust from a jet using three different methodologies and verify assumptions made in the calculations. The three approaches are: direct measurement using a load cell, calculation of thrust from the pressure in the stagnation chamber of the jet, and calculation from a pitot pressure survey downstream of the exit of the jet. For the thrust calculated from pressure measurements (stagnation and pitot pressure survey), the students derive the thrust equation from a control volume analysis of the jet and test the incompressible flow assumption as it applies to the Bernoulli equation to determine the range of conditions in which the assumption is valid. Alternatively the students utilize the 1-D compressible isentropic equations to evaluate the velocity and thrust demonstrating when the incompressible assumption breaks down. In addition, the students operate the jet in the supersonic (underexpanded) flow regime and learn basic characteristics of compressible flow such as choked flow, shock waves, and expansion waves.

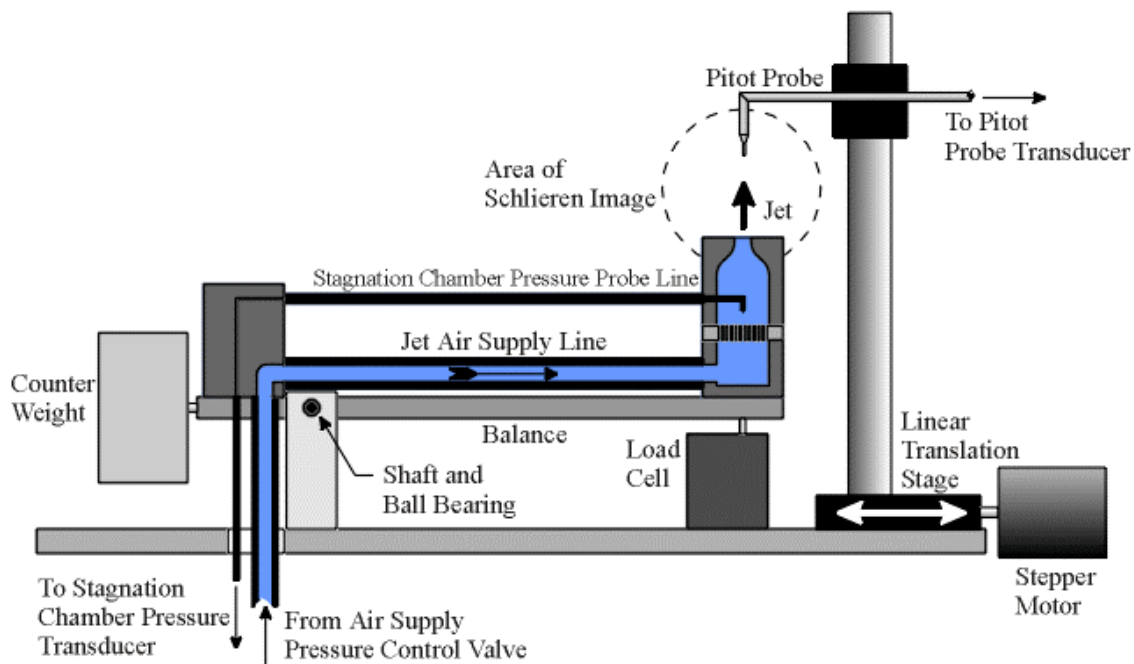


Figure 1. Schematic of Experimental Apparatus

### 3.0 The Instructional Remote Laboratory Environment (IRLE)

One of the key considerations in designing the Instructional Remote Laboratory Environment (IRLE) was to have it modular in nature, i.e. experiments controlled by different types of computers and software in disparate locations could easily be added or removed from the system with minimal effort. To achieve this, IRLE was divided into three basic components connected via the internet as illustrated in Figure 2: the gatekeeper server, the experimental apparatus and the experiment servers. Each will be discussed in detail in the following sections.

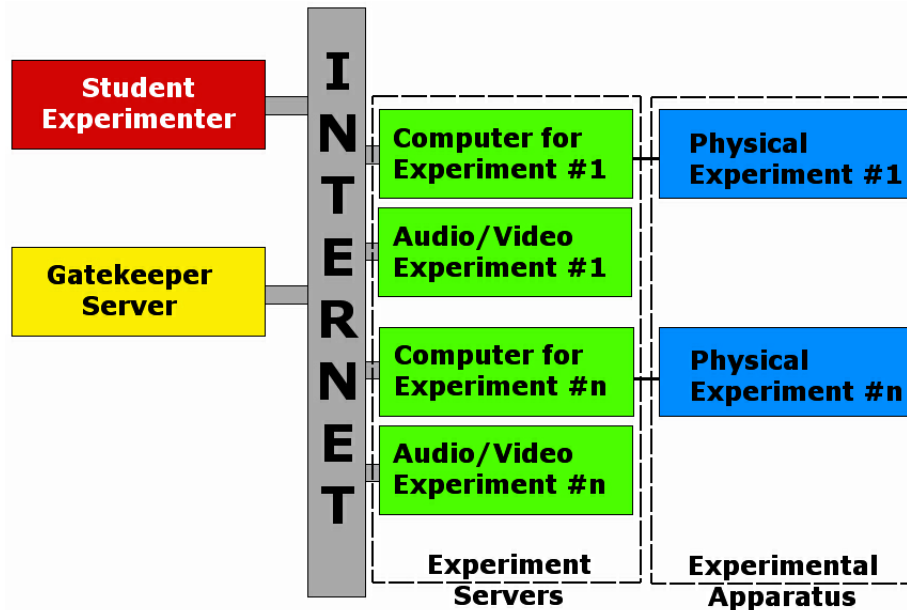


Figure 2 The Instructional Remote Laboratory Environment's (IRLE) basic structure

### 3.1 The Gatekeeper Server

The *gatekeeper server* is the students' entry point into IRLE. Each student has their own account into which they can login in at any time. Once logged in the students have a choice of menu items:

1. *Sign up to run a laboratory*<sup>1</sup>. One of the key advantages of the remote-access laboratories is allowing students to sign up and run the labs at anytime, from anywhere. A Filemaker<sup>®</sup> database program, with a built-in web server, powers the Gatekeeper server that controls the student accounts and access over the web. The combination allows the serving of static pages from *.html* files or dynamic custom pages directly from the database. The option to sign up and run the lab is available up and till the time the students actually run the lab, allowing them to change a previously scheduled lab time if the need arises.
2. *Select and view the prelab materials for a particular experiment*. The prelab contains a motivation section which gives the history and examples (with *MPEG* movie clips) of thrust, thrust measurement, and supersonic flow. This is followed by detailed step-by-step examples of how to calculate thrust from a control volume analysis. Then the experiment and components are described in detail with schematics, pictures of the apparatus, and short video clips of each major component. This option is available all the time. As students view each page in the pre-lab materials, the date and the amount of time they spend on each page is noted in a Filemaker<sup>®</sup> database. This information allows us to determine how much time

<sup>1</sup> For the current academic year, this feature was disabled. We had the students run the experiments in the department computer lab during specific times to allow us to observe how they interact with each other and with the system during the experiment. These observations allowed necessary adjustments to be made to the laboratory instructions, making the experiment easier to conduct.

each student spent on the pre-lab and correlate that to how well they do in the laboratory. In addition, it provides quantitative information on which pages are appealing to the students, based on the time spent on that page, and which ones are not. Information on the latter allows corrections to be made. Quantitative data collected in this way is also then compared to qualitative evaluations performed at the end of the laboratory in the form of student questionnaires, to try and determine their attitudes towards various features of IRLE.

3. *Run the experiment.* When students select this option, they are transferred to the computer that controls the experiment. This option is only available during the time the students signed up to run the experiment. Once they have run the experiment, this option is no longer available.
4. *E-Lab Notebook.* As the students run the experiment, all their experimental data is automatically stored for them. In addition students can make comments on any observations, problems or about the data itself at various points in the experiment. This information is later used during their laboratory write-up. On completion of the experiment, the students have access to all their data and comments from the e-lab notebook resident in their individual accounts. The e-lab notebook is available all the time once the students have performed the experiment.
5. *Post-Lab.* This contains instructions for completing the laboratory write-up, and is available all the time.

## 3.2 Experimental Apparatus

A schematic of the experimental apparatus is illustrated in Figure 1. It can be divided into several main systems described below.

### 3.2.1 The Air Control System

Pressurized air at ~80 psig is routed to the experiment through a pressure control valve so that the air available to the jet can be throttled. The control valve accepts voltage from 0-10 VDC, opening proportionally from 0 to 90 degrees. To account for a time lag in opening the valve, a potentiometer attached to the valve outputs a 0-10 VDC signal indicating the valve's current position. After the control valve a flexible hose directs the air through the force balance system near the pivot point of the balance. The proximity of the hose to the balance's pivot point reduces the residual forces it might produce and subsequently be measured by the load cell as the hose is pressurized. After passing through an elbow, which turns the flow 90 degrees, the air continues to the stagnation chamber of the jet through a 1 inch diameter stainless steel tube.

### 3.2.2 The Jet

The jet consists of four parts: stagnation chamber, flow straightening section, converging nozzle and pitot probe (refer to Figure 3). As the air enters the jet from the left it is introduced into the *stagnation chamber* where the flow slows down and to a first approximation stops. In the stagnation chamber the flow is turned upward and passes through the *flow straightening section*. The latter consists of small tubes that dampens out any turbulence created by unsteady eddies and swirling air in the stagnation chamber. Air exiting the small tubes enters a small *settling region* where the flow is allowed to equilibrate before being accelerated by smoothly decreasing

the area through a converging nozzle with an exit diameter of 10.2 mm. The air then exits as an axisymmetric jet expanding into the atmosphere. The total pressure of the jet is measured using an upstream facing small diameter *pitot pressure probe*, located in the settling region.

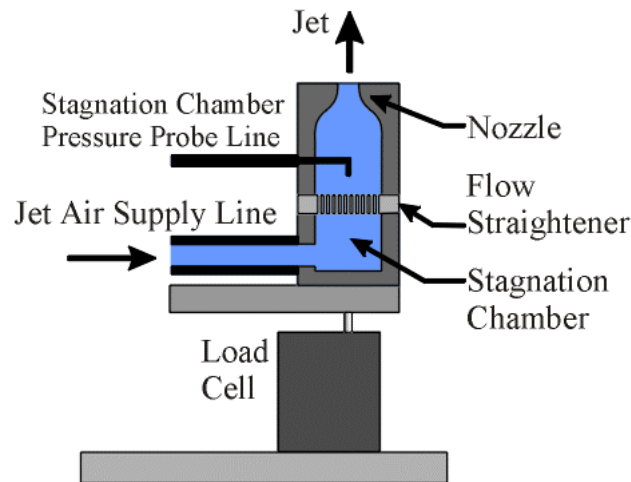


Figure 3. Schematic of the Jet

### 3.2.3 Traversing Pitot Probe System.

One measurement the students make during the experiment is a *pitot pressure profile* downstream of the jet exit. A pitot probe is therefore attached to a traversing stage as illustrated in Figure 1. Since the flow in front of the pitot probe stagnates, the total pressure can be measured at various locations in the jet and the jet velocity can be calculated using the Bernoulli equation (which is accurate for the incompressible regime at low Mach numbers) or 1-D compressible isentropic equations with the Mach number definition. The pitot probe is traversed across the diameter of the jet using a linear translation stage powered by a stepper motor. A Linear Variable Differential Transformer (LVDT) outputs a voltage proportional to the position of the pitot probe as it traverses across the jet.

### 3.2.4 Direct Thrust Measurement.

To measure the thrust of the jet directly, a load cell is utilized. To minimize other forces that would be registered by the load cell, the jet is placed on a counter balance as illustrated in Figure 1. The weight of the jet is negated by a counter weight placed on the other side of the balance. By counterweighting, a more sensitive load cell can be used since it is only measuring the thrust with the other extraneous forces (weight of the jet and beam) minimized. It should be noted that there is a third variable force created by the hose when it is pressurized. By placing it near (2 cm) the pivot point, its effects are minimized.

### 3.2.5 The Schlieren System.

With reference to Figure 4, the Schlieren system consists of a point light source placed at the focal point of the first of two concave mirrors (collimating mirror), forming a collimated beam



that is directed across the jet. The second concave mirror (imaging mirror) focuses the beam down to the focal point and then into a CCD camera. At the focal point of the second mirror, a knife-edge is adjusted approximately halfway into the beam. The density gradients in the flow deflect the light rays, from this point in the flow more into or away from the knife-edge. The result is that the image appears brighter or darker at locations where there are density gradients in the flow field, therefore capturing compressible flow features such as the jet, shocks, or expansion waves. Figure 5 displays a typical schlieren image that may be observed in the course of the experiment. The bright circle in the middle of the image is due to the fact that the collimated beam is formed from a circular concave mirror, which sets the diameter of the interrogation region. Since the knife edge is oriented horizontally, the system is most sensitive to vertical density gradients.

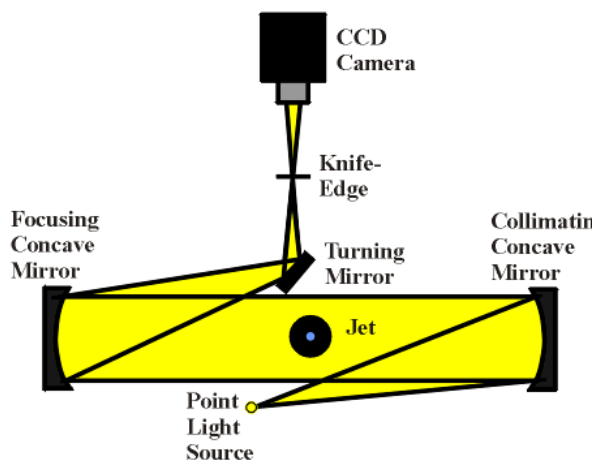


Figure 4. Schematic of Schlieren System (top view)

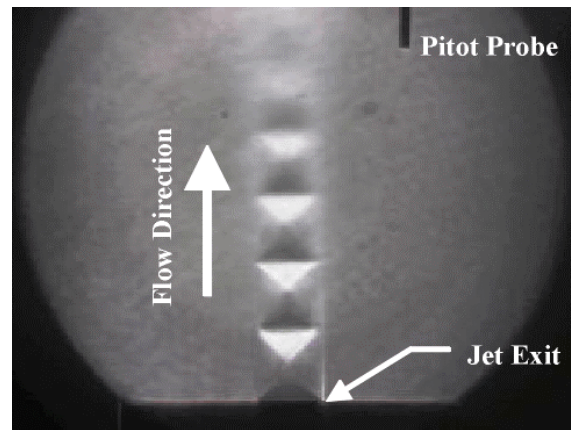


Figure 5. Sample Schlieren photograph from experiment

### 3.2.6 Control of the Experiment

The experiment is controlled through a LabView<sup>®</sup> Virtual Instrument the front panel of which is illustrated in Figure 6. The top portion of the panel consists of the instrument controls to start the program, tare the system, adjust the control valve position, and set the pitot pressure profile parameters (i.e. number of points to be taken, start data collection and return the probe position to home). There have been limits programmed into the controls so that the jet can be safely operated and the equipment not damaged. As a back-up, timers have been programmed to automatically shut the air-control system valve and terminate the program after an hour elapses from the start of the experiment. It should also be noted that the experiment automatically closes the valve using a battery backup if the power to the system is interrupted or the door to the laboratory is opened. The latter is especially important to avoid harmful noise levels which any unauthorized person entering the room while the experiment is in progress might experience.

Below the instrument controls portion of the panel (shown in Figure 6) are the instrument readouts that give instantaneous numerical and graphical feedback of the valve position, stagnation chamber pressure, pitot probe pressure and position, and load cell value. Below the numerical readouts is a graph in which the pitot pressure profile, stagnation chamber pressure,



and thrust can be viewed as they are recorded. While a pitot profile is being taken, the program limits the control of the user by hiding unused displays and controls to prevent changes being made during data collection. All the data is automatically written to a file with a unique file name, which can be downloaded by the student at any time from their e-lab notebook.

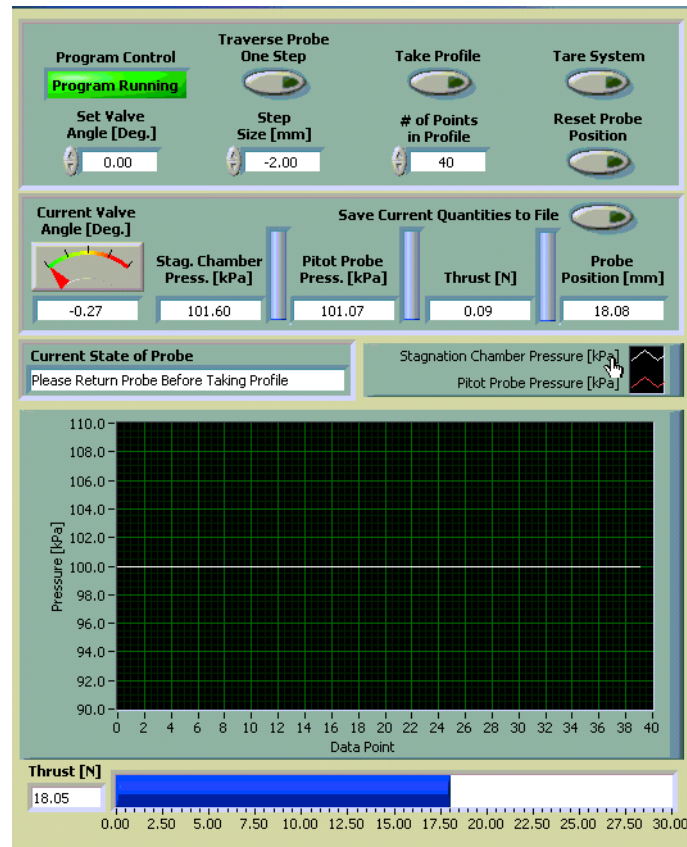


Figure 6. Labview<sup>®</sup> control panel for jet thrust laboratory.

### 3.3 Experimental Servers

Three servers simultaneously send information to the student during the course of the experiment (refer to Figure 7). The servers individually provide control of the experiment, step-by-step instructions and streaming video of the Schlieren images.

#### 3.3.1 Control of the Experiment - VNC Server.

As explained previously, the experiment is controlled through a LabView<sup>®</sup> Virtual Instrument. To allow the laboratory to be controlled remotely a *Virtual Network Computing (VNC) server* is installed on the experiment computer. The VNC server allows the 'desktop' environment of the experiment computer to be viewed from anywhere on the Internet through any Java-capable browser. It allows the remote 'real-time' transmission of keyboard commands and mouse movements as if one were sitting at the host computer. Some of the key attractions of the VNC server include:

1. 'Crashing' or restarting of the remote computer has no effect on the host computer. Once a connection is re-established the user can continue where they left off. This is critical in this particular application where if the remote students' computers disconnects from the Internet or freezes up, they must be able to continue the experiment once a connection is re-established.
2. It does not require the installation of any specialized software on the remote-machine.
3. As it essentially facilitates the remote control of the laboratory computer, it can be used to stream the control panel of an experiment based on any commercial or in-house software.
4. It is free!<sup>‡</sup>

As the remote-user has control of the experiment computer, safeguards must be put in place both on the control panel and the VNC server to restrict the user's activities to running the experiment.

### 3.3.2 Step-by-Step Instructions: Filemaker® Server

During the experiment, students receive step-by-step instructions served up by a Filemaker® database program with a built in web-server. E-lab notebook entries during the course of the experiment are stored in the database. This information and the students' experimental data, automatically logged by the LabView® program, can be retrieved at any time through their IRLE accounts. The program also automatically logs how long it takes to complete each step and notes if certain steps are repeated. This information is used to improve the general flow of the experiment and for scheduling purposes - determining the length of the time slots.

The Filemaker® database is also used to control access to the experiment. We wanted a system that would, (a) allow students to run the laboratory only once, and only during their scheduled time slot, and (b) allow re-entry to run the lab if the remote-user's computer becomes disconnected before the lab is complete. The developed program, therefore, grants access to the experiment if the time a group attempts to run the experiment falls within their scheduled time slot. When access is granted for the first time, a 'start time' entry is made. At the successful completion of the experiment an 'end time' is noted. An 'end time' entry will deny that group further access to the experiment. On the other hand, if the group's remote computer disconnects from the experiment before the laboratory is completed, they would be able to reconnect due to the absence of an 'end-time' entry, so long as the attempted reconnection time falls within their scheduled time slot.

### 3.3.3 Schlieren Images - Camera streaming video Server

The Schlieren images are streamed using an Axis 2100 CCD camera with a built in Linux-based web server. As a result no PC or specialized software was required to achieve crisp quality MPEG streaming video at ~ 10 frames/second. Although a video streaming component using a

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<sup>‡</sup> The vnc server is developed by AT&T and available for download at <http://www.uk.research.att.com/vnc/>

web-cam and specialized software could have been added to the experiment computer, response time would have been significantly impacted as the experiment computer is already burdened with streaming the control panel, serving the step-by-step instructions, and controlling the experiment.

#### 4.0 Sample Results

Before evaluating the teaching effectiveness of the remote controlled jet thrust laboratory we will present a few of the results from the experiment to briefly demonstrate the accuracy of the measurements and that the trends and characteristics which are desired to be taught can be observed with this set-up. Figure 8 shows a graph of the velocity computed from the pitot pressure profile for a range of equivalent Mach numbers, i.e., the Mach number that would theoretically be achieved if the jet was to isentropically expand from the stagnation pressure to atmospheric pressure. The velocity was calculated using the Bernoulli equation assuming an incompressible flow and a 1-dimensional isentropic analysis. As expected the two methods are in agreement at low Mach numbers, but as the Mach number increases above  $M=0.5$  the discrepancy between the calculations becomes apparent due to compressibility effects.

In addition, the students can see in the Schlieren image (refer to Figure 9) the effect on the velocity profiles at supersonic Mach numbers when a shock is formed in front of the pitot probe. The students are also asked to describe the characteristics of the jet in the Schlieren images taken over the range of stagnation pressures including the compressibility effects such as the observed shock/expansion diamonds (Figure 9).

Figure 10 shows the thrust calculated using three methods over a range of stagnation pressures (or equivalent Mach numbers):

1. Direct measurement using the load cell. This is considered to be the standard measurement for this experiment. Students also evaluate sources of uncertainty.
2. From the jet exit conditions determined from the stagnation pressure using the Bernoulli equation (assuming incompressible flow) and using isentropic relationships (assuming choked flow for the supersonic cases).
3. From the integrated pitot pressure profiles.

As shown in the graph the methods for calculating the thrust from both the exit conditions and the pitot profile have good agreement with the direct measurement of thrust, except for the Bernoulli equation method which over predicts the thrust as compressibility effects are not accounted for. The students are also asked to evaluate the uncertainty of all measurements which vary from 1 to 2.6% for the velocity and 3 to 5% for the thrust.

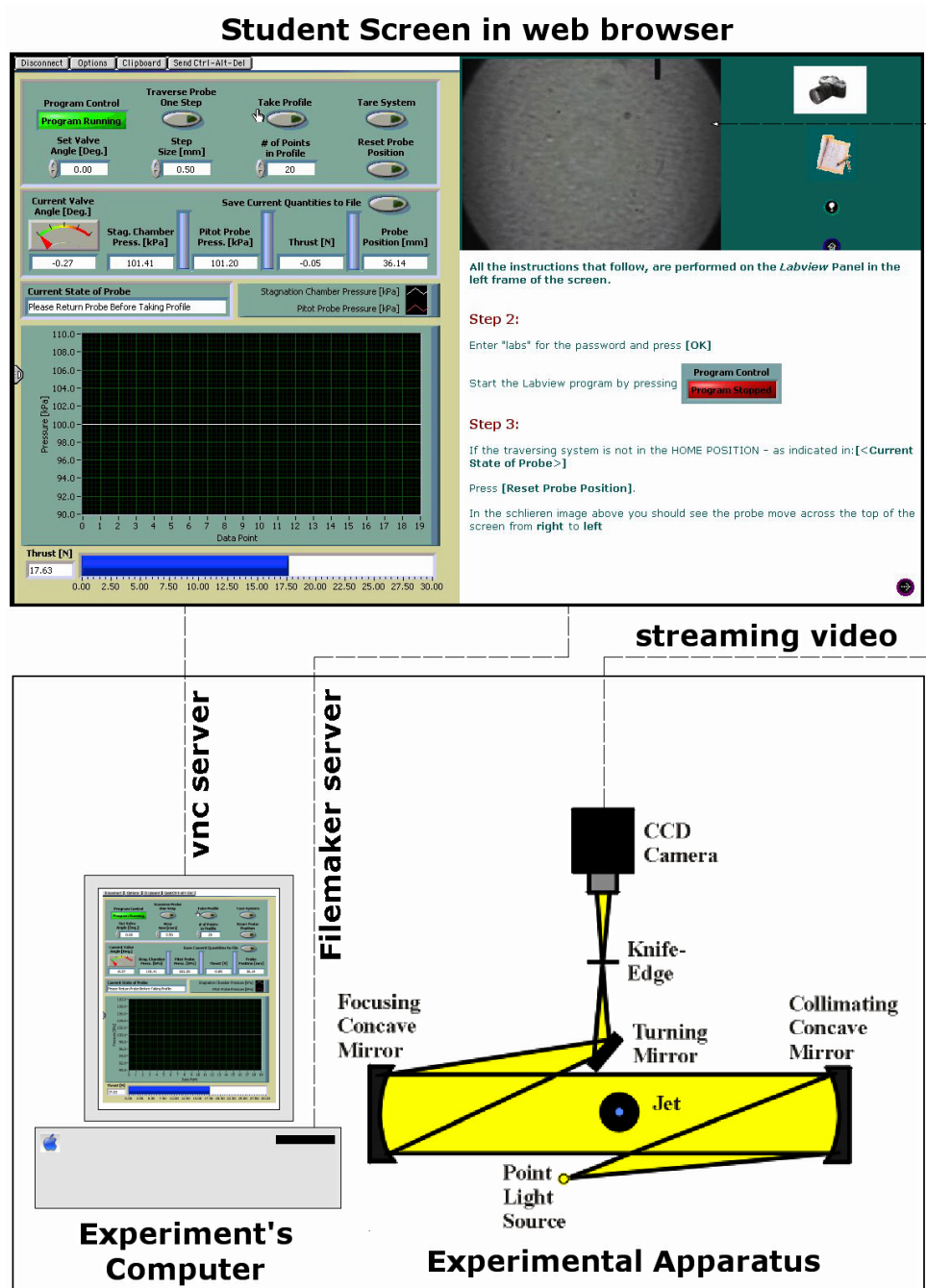


Figure 7. Screen shot of experiment page as seen by the students through a web-browser. The page is divided into three frames: the control panel, streaming video and step-by-step instructions. Also shown are the three servers providing content for each of the three frames.

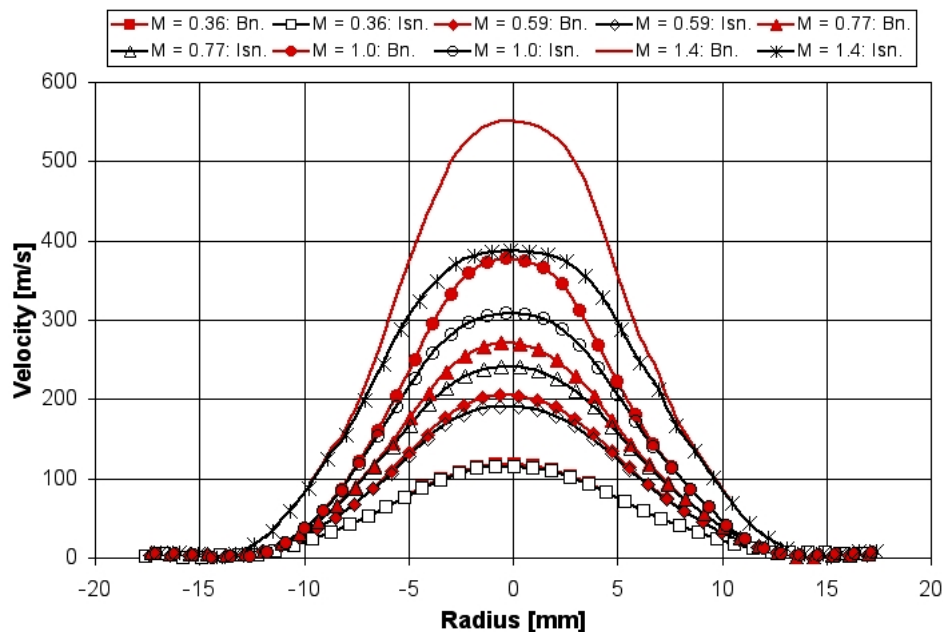


Figure 8. Velocity profile measured from the pitot profile using the Bernoulli equation and inviscid analysis for a range of equivalent Mach numbers.

## 5.0 Evaluation

How effective are remote-controlled laboratories? Do they provide the same ‘hands-on’ learning outcomes similar to performing the experiment in-person? The literature is rich on studies conducted to evaluate the educational outcomes for on-line courses that evolved either from lecture style courses<sup>20-26</sup>, or laboratory courses that are now purely simulation<sup>1,5,6,27</sup>. Due to the infancy of remote-controlled experimentation in the undergraduate curriculum, very few studies have been done to assess educational outcomes of remote-controlled laboratories. This paper presents preliminary results of formative evaluations on the remote-controlled Jet Thrust Laboratory that was run by students at Rutgers University in Fall 2001.

Two sets of student groups were run through the lab. Each set had six groups with group sizes ranging from 2-3 students. The first set (Set 1) performed an ‘in-person’ version of the laboratory and the second set (Set 2) conducted the remote-controlled laboratory of the same experiment. It should be noted that a teaching assistant was present in the room during ‘in-person’ laboratories, while the remote laboratory groups conducted the experiments alone in the department computer lab. The remote groups were videotaped to record any problems that arose during the experiment.

The evaluation compared the learning outcomes of the two sets of students and compiled statistics on their opinions about the experiment. The students conducting the remote controlled experiment were further divided into two subsets of three groups each. Students in subset 2a were given approximately an hour in the computer lab to individually go through the prelab (which describes the experiment, relevant analysis and general information about jet thrust) before performing the experiment in their groups. The second subset (Subset 2b) individually

went through the prelab at their convenience and only came to the computer lab to conduct the experiment in their groups. These groupings are summarized in Table 1.

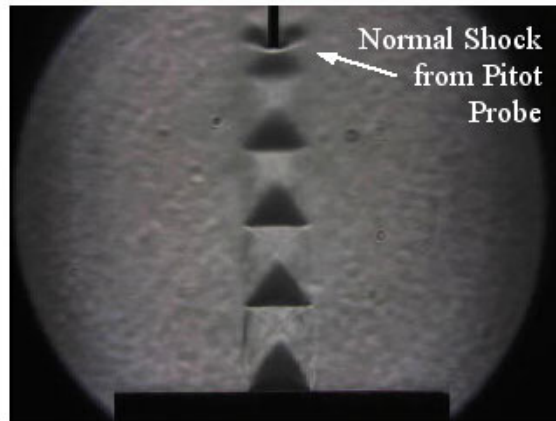


Figure 9. Schlieren image of jet with an equivalent Mach number of 1.4 with the pitot probe positioned in the core of the jet.

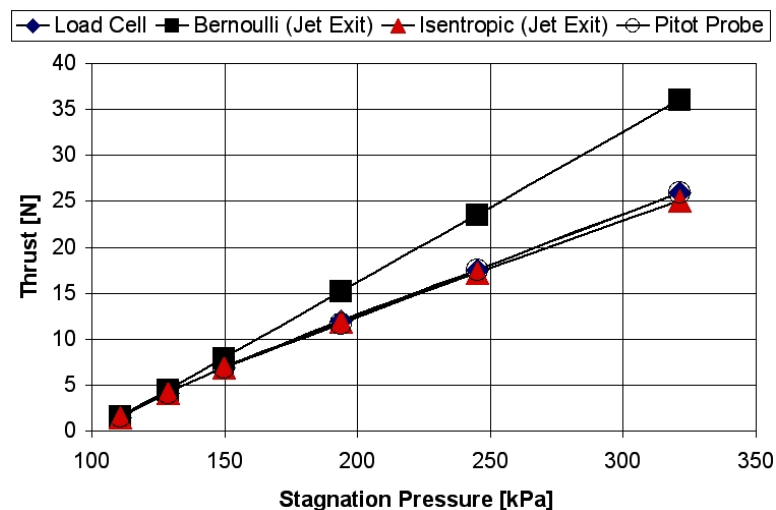


Figure 10. Thrust calculated from various measurement techniques over a range of jet stagnation pressures.

Table 1. Division of Student groups

Set 1: 'In-person' Labs	Set 2: 'Remote-Controlled' Lab	
	Subset 2a: In-class prelab	Subset 2b: Prelab at own convenience
Student groups 1-6	Student groups 7-9	Student groups 10-12

## 5.1 Learning Outcomes

As mentioned earlier it is desired that the learning outcomes of the remote-controlled experiments should be as good or better than the in-person experiments. The learning outcomes were assessed by comparing the grades of the laboratory reports between the two sets of students. The reports were graded on criteria associated with the inclusion of various report components (abstract, introduction, experimental arrangement, results, discussion, sample calculations and derivations etc.), presentation of the information (spelling, appropriate graphs and their presentation, tables, etc.), and correctness of the analysis. A third party who had no knowledge or association with this study graded the laboratory reports. With reference to Figure 11 the average grade of the reports from students who conducted the remote-control laboratory were essentially the same as the students who conducted the laboratory in-person. Table 2 gives the values for an *unpaired t-test* which indicates that the difference between the scores of students who conducted the laboratory remotely and in-person were not significant (the calculated value of *t* is less than the critical value required for a level of significance  $\alpha = 0.05$ ).

A comparison of report scores was also made between students in subsets 2a and 2b; their lab report scores are summarized in Figure 12. As can be observed, the mean value score was 11.6% higher for students in subset 2a, i.e. those who performed the prelab in class. Using the unpaired *t-test* (with the values given in Table 2) the difference was found to be significant. Why the large difference between the two groups? Using the tracking data from the gatekeeper server, we found that students in subset 2b spent significantly less time on average reading prelab material than students in subset 2a who spent an hour going through the material in class. Although this is a somewhat discouraging statement of our students, it does point out that a multimedia prelab is an effective method to disseminate information needed to conduct the laboratory and write the report. The challenge, therefore, is to develop methodologies that ensure students completely go through the prelab exercises. Possible solutions include detailed online quizzing or not allowing the experiment to be run unless the students have spent sufficient time going through the prelab material. The latter could be enforced through tracking software already in place in the gateway server.

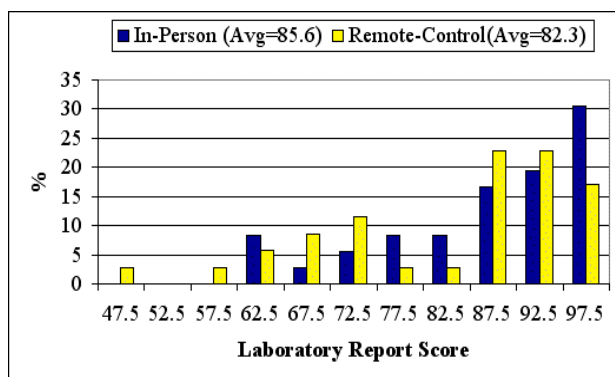


Figure 11. Comparison of Laboratory report score between the 'In-person' and 'Remote-Control' student groups.

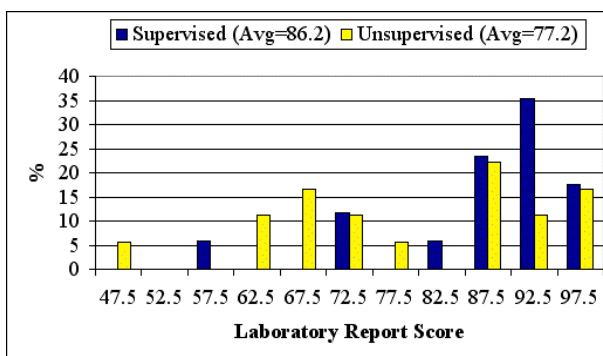


Figure 12. Comparison of scores between web-groups who had supervised 'pre-lab' session and groups who were unsupervised.



Table 2. Scores of students conducting in-person and remote laboratory and values needed for unpaired t-Test.

	Mean	Std. Dev.	Number	Calculated value of t	Degrees of Freedom	Critical value of t
Set 1	85.6	11.6	35	1.165	66.50	1.295
Set 2	82.1	13.5	35			
Subset 2a	86.2	11.1	17	2.042	31.43	1.309
Subset 2b	77.2	14.8	18			

## 6.0 Concluding Remarks

The advent of new internet technologies over the last few years have opened up a new medium to increase 'hands-on' laboratory experiences within engineering curriculums, despite declining instructional laboratory budgets. The Jet-thrust lab developed jointly by Rutgers University and the University of Illinois paves the way for a new era of co-operation between universities, pooling their resources in the area of remote-controlled instructional laboratories and providing their students and others with a rich, educational experience. We have shown that this can be achieved without compromising on educational outcomes. We believe that as more labs are brought on line, the departments will begin to see significant cost savings versus the sole development of 'in-person' laboratories.

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