DVTS-Based Remote Laboratory Across the Pacific Over the Gigabit Network

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Abstract—**The objective of this study is to investigate a remote laboratory on electric motors using high-speed networks between Japan and the United States. The client, situated at Stanford University, Stanford, CA, accessed the remote laboratory system set up in Japan. Through this client, the remotely located user operated the motors and conducted experiments. The remote laboratory was conducted over a high-quality digital video conference system, making it possible for both sides to communicate smoothly with each other and for the remote user to observe close-up details of the laboratory, including the motor's fine movements. Using a network bandwidth of 15 Mb/s, the authors were able to demonstrate the validity of the remote laboratory experiment.**

Index Terms—**Digital video, Internet, mechatronics, practice, real-time, reality, remote laboratory.**

I. INTRODUCTION

THE COMBINATION of theory and practice in the learning of any engineering discipline is important. Since students are able to obtain a deeper understanding of a subject when they have practical workshop experience after learning the theoretical aspects, laboratory work forms an essential component of scientific, medical, and engineering training. Considerable effort has, thus, gone into investigating ways to incorporate practical workshops and laboratories into distance learning.

One way is video streaming, i.e., replaying recorded videos of the workshop or laboratory. While videos are useful in complementing textbook learning, the student is limited to a passive viewer's role and unable to interact actively. Thus, having distance learning systems that are in real-time, interactive, and operational is most desirable. Such a system, often called a "virtual laboratory," can consist of software or actual laboratory setups that can be accessed online.

The former software-based virtual laboratories (SVLs) employ virtual reality techniques and visual simulations. They have the advantages of realistic three-dimensional (3-D) graphics, interactiveness, real-time operation, safety (no injuries can occur in a SVL), accessibility by multiple users, and easy adaptability to the Internet [1], [2]. SVLs are also useful when simulating such situations as nuclear plant operations, explosives placement, surgery [3], or investigations of semiconductor properties [4], which are too costly or impractical to experiment with real systems. The shortcomings of SVLs, on the other hand, are that much time, effort, cost, and considerable expertise are required to develop such systems.

In the latter type of virtual laboratory, the remotely located student operates and conducts real experiments via the Internet. Jain has proposed the concept of "wiring the classroom" and "wiring the laboratory" [5]. In this paper, this type of virtual laboratory is called a "remote lab." A remote laboratory (lab) places emphasis on "real experience" as compared with an SVL. Although the interaction takes place via a computer display, the educational effect upon students gained through real experience is indisputable. Many lab experiments offered in the curricula of educational institutions involve electrically controlled equipment. By providing computer interfaces [e.g., digital input/output, analog-to-digital (A/D), digital-to-analog (D/A)] and a network interface to such experiments, the instructors allow students to conduct the lab remotely.

Using such existing lab setups, one develops remote labs operable via the Internet or campus network in a relatively short time and at a low cost. The authors (Kikuchi and Kenjo) developed such a prototype client-server system for remotely conducting a mechatronics workbench called Mechatro Lab 2 [6], which is used to demonstrate various types of electric motors and their electronic operations.

The system includes a video camera and related equipment to transmit video streaming of the motor lab to the client [7], [8]. The video display should have a high definition and a wide screen if it is to convey sufficiently the atmosphere and "reality" of the lab. Yet, high-quality video streaming takes up a very wide bandwidth of the network and can result in congestion. For instance, a fully digital video stream consumes more than 30 Mb/s with National Television Standards Committee (NTSC) standards quality video. To avoid congestion, therefore, most current systems employ a small video screen and low frame rate; as a result, the visual quality suffers, and the "reality" of the lab is greatly diminished.

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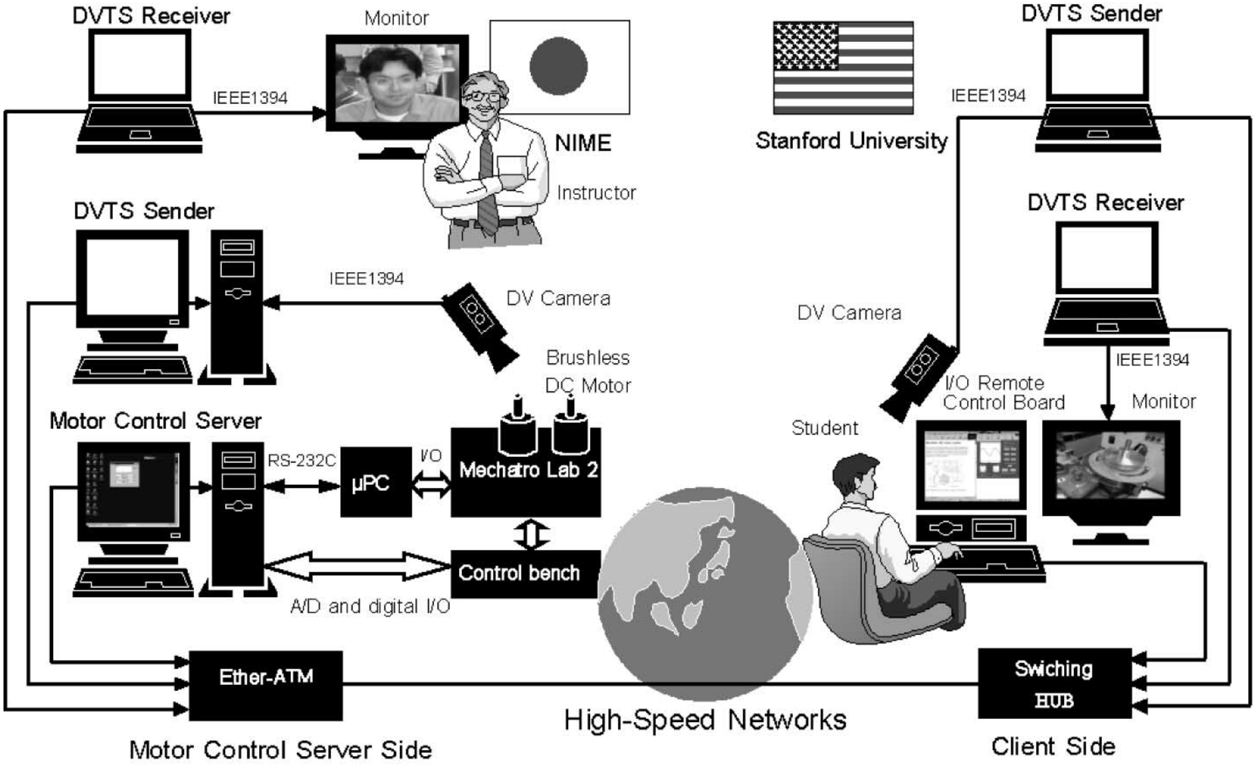


Fig. 1. Remote lab between NIME (Japan) and Stanford University (U.S.) using high-speed networks.

The demand for high-speed networks exists, not only with regard to remote labs, but also for a variety of purposes among universities, corporations, and national/local governments, which hope to make full use of advanced Internet capabilities [9]. In fact, high-speed networks of the gigabit class are currently being installed worldwide, although their present use is limited mostly to research and development and educational purposes. Foreseeing greatly extended distributions of such networks in the near future, the authors conducted a trial remote lab experiment between Japan and the United States using such a high-speed network. To improve the transmitted "reality" of the lab, a high-quality video conference system called DVTS (digital video transport system) [10], developed by the Communications Research Laboratory (CRL), Tokyo, Japan, and the Widely Integrated Distributed Environments (WIDE), were used.

The following section discusses the system configuration and course content of the remote laboratory. Section III presents the high-speed network topology between Japan and the U.S., and Section IV discusses the results of the trial experiment. Finally, the conclusions are presented in Section V.

II. OUTLINE OF REMOTE LABORATORY SYSTEM

As shown in Fig. 1, the remote laboratory system consists of a client-server computer architecture and software.

A. *Remote Laboratory Server*

The remote server, consisting of a motor control server and two DVTSs, is shown on the left-hand side (LHS) of Fig. 1. The motor control server consists of a Mechatro Lab 2 setup, a microcontroller (uPC), and a control bench. The role of the computer, which the authors call the *motor control server*, is to analyze the commands sent by the remote learner, control the test motor, and transfer measurement data on motor current and voltage to the client. The uPC drives the test motor at up to 1500 rpm.

Mechatro Lab 2 (ML2) (Fig. 2) can be used with various kinds of electric motors and their electronic operations. The brushless dc motor is one of the motors provided with ML2. One of the three stators, located in the center, is a six-pole stator with concentrated windings. It is used to construct a three-phase dc brushless motor (hereafter, simply called brushless motor), using a permanent-magnet rotor and a Hall-element sensor board. The use of this motor type is growing at a spectacular pace in many areas, including PC peripherals (typically hard-disk drives), robots, numerically controlled machines, home appliances (e.g., air conditioners, refrigerators, and washing machines), and industrial applications (e.g., pumps and ventilators), supplanting conventional induction motors and brush-type dc motors. Another type of electronically driven motor is the stepping motor, and its drive technique in a brushless mode is advancing. Thus, mechatronics engineers need to possess a working knowledge of the brushless motor's construction and its electronic drive technique.

To be able to conduct Mechatro Lab 2 through the remote lab, a control bench and a microcontroller with an RS-232C transmission function were built and provided. With this setup, the motor's line-to-line voltage, neutral point voltage, and input current are transmitted via an insulated transformer and filter circuit to the A/D converter in the motor control server. A relay

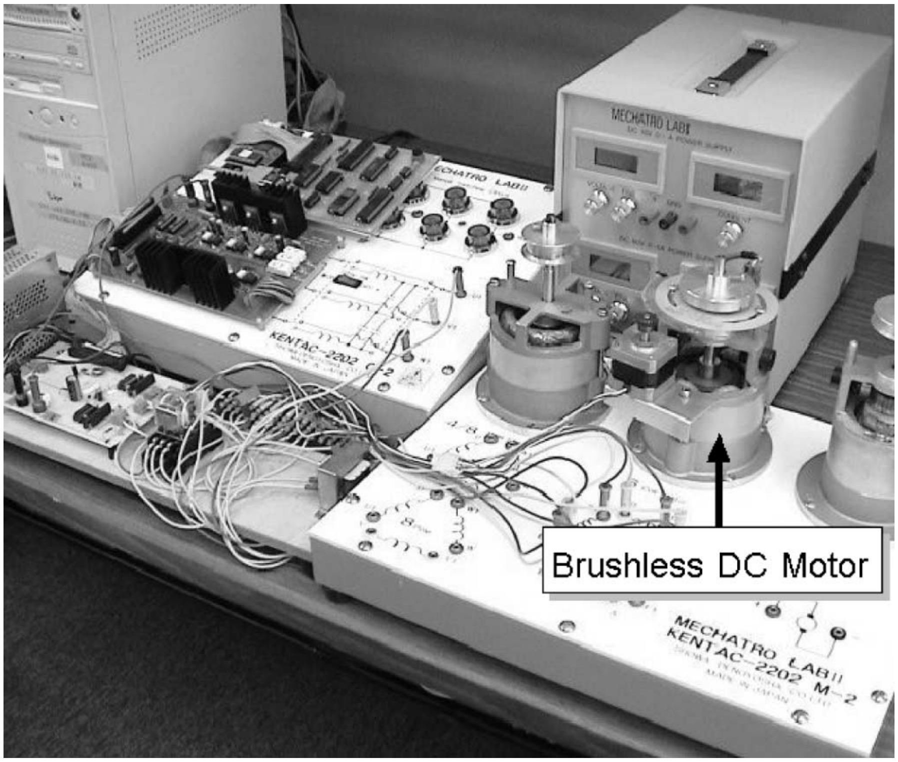
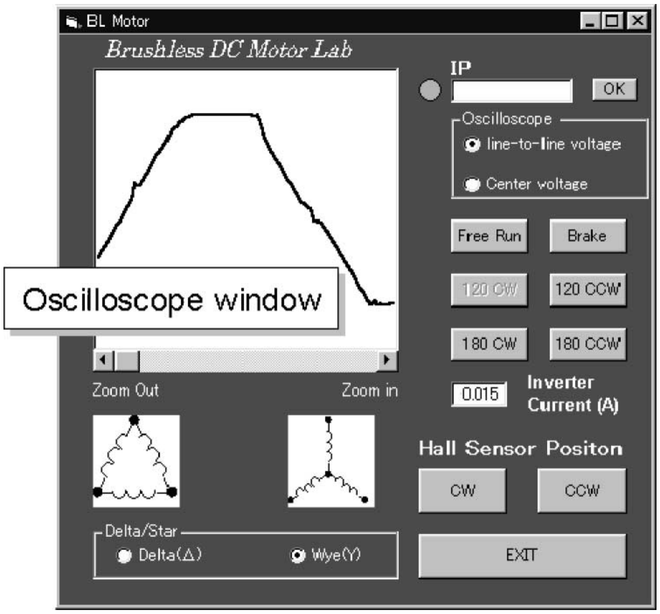


Fig. 2. Photo of Mechatro Lab 2.

is used to change the motor's winding connection between wye (star) and delta. Furthermore, a normal small stepping motor and a gear mechanism were mounted to adjust the Hall-element sensor board from a distance.

The video-based remote laboratory employs DVTS, which is an application for sending and receiving real-time, high-quality, high-bandwidth (30-Mb/s) digital video (DV) streams over the Internet. The DVTS is set at National Television Standards Committee (NTSC) standard quality video: 525 lines and 29.97 picture frames/s. DVTS employs DV format for video and audio media. DV is of a popular consumer video format, using the IEEE Standard 1394 (IEEE1394) interface for exchanging digital video stream. IEEE1394 is a high-performance serial bus standard for peer-to-peer communications at speeds of 100, 200, or 400 Mb/s [11].

In Fig. 1, DVTS employs a sending PC and a receiving PC. As shown on the LHS of Fig. 1, the camcorder connected to the sender PC creates an IEEE1394-encapsulated DV packet stream. The sender PC receives the DV stream via the IEEE1394 interface, encapsulates the DV packet of IEEE1394 into real-time transportation protocol (RTP) [10] [an Internet protocol (IP) for transmitting real-time data, such as audio and video] and transmits to the client's DVTS receiver PC via IP networks. The receiver PC obtains the IEEE1394 DV packets by reconstructing the DV data received using RTP. The packets are transferred to the monitor display via the IEEE1394 interface. DVTS specifications require the use of PCs with Pentium 600 MHz and over to maintain the quality of video streaming without packet loss.



Inverter Current (A): 0.015

Fig. 3. I/O remote-control board.

B. Client for Learner

The client system consists of three PCs, as shown on the right-hand side (RHS) of Fig. 1. One PC is for the learner and the others are for DVTS. The I/O remote-control board supports the remote laboratory, as illustrated in Fig. 3. On this window, one can start the brushless motor (Fig. 4) after selecting the following items: 120° or 180° operation [12], delta or wye

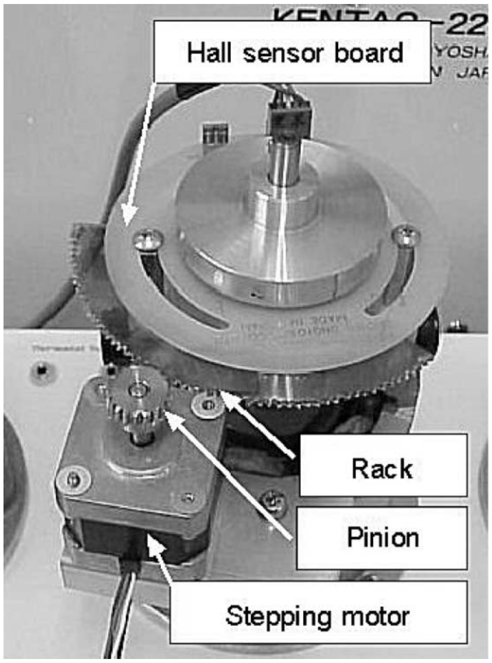


Fig. 4. Rack-and-pinion mechanism driven by a stepping motor fore adjusting Hall-sensor board of brushless motor.

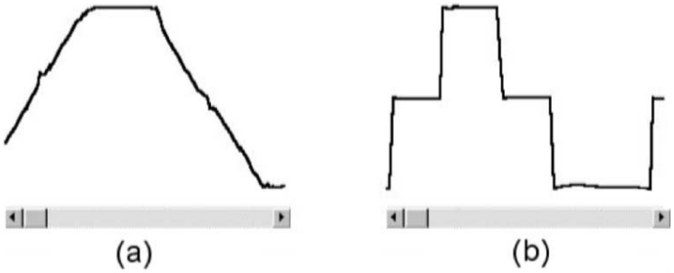


Fig. 5. Line-to-line voltage as viewed in remote oscilloscope window (120° switching). (a) Hall sensors are positioned optimally. (b) Hall sensors inappropriately positioned.

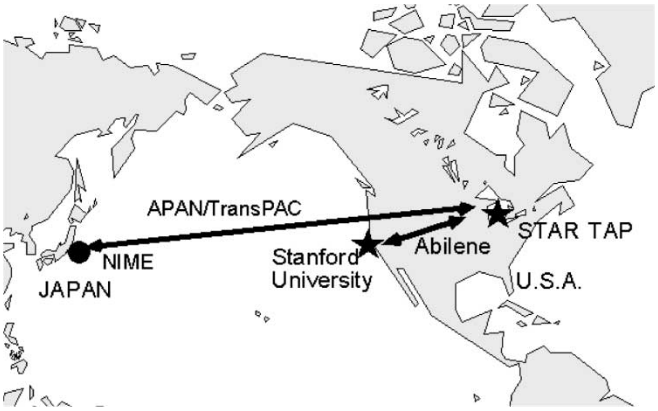


Fig. 6. Network route between NIME and Stanford University.

connection, and CW (clockwise) or counterclockwise (CCW) rotation. In Fig. 3, an oscilloscope window is provided to observe the line-to-line voltage and neutral position voltage. By observing this data, the user can study how the driving mode and winding connection affect the motor's characteristics.

For example, if the Hall sensors (for detecting the rotor's position) are positioned correctly inside the motor, the line-to-line voltage waveform is trapezoidal-shaped, as in Fig. 5(a). If the sensor position is shifted to either direction, the voltage will be as shown in Fig. 5(b), and there will be a noticeable speed difference when the direction of rotation is reversed.

The Hall sensors are mounted on the Hall-sensor board, which the user can rotate through the I/O remote-control board by pressing the mouse at the CW or CCW button for "Hall Sensor Position." He or she can then observe the results on the video and oscilloscope window in real time. When the mouse button is released, the sensor board will stop and hold its position. In the actual setup, a small stepping motor provides the driving force for sensor adjustment via a rack-and-pinion mechanism (Fig. 4). The I/O remote-control board was constructed using Microsoft Visual Basic (VB). Here, the authors adopted Microsoft ActiveX to make these programs usable as Internet applications.

III. GIGABIT NETWORK BETWEEN JAPAN AND THE UNITED STATES

The trial experiment for the web-based Remote Mechatro Lab was carried out between two locations: the National Institute of Multimedia Education (NIME) located in Makuhari, Japan, and Stanford University, Palo Alto, CA. The network topology between NIME and Stanford University is shown in Fig. 6.

In Japan, the Telecommunications Advancement Organization of Japan has developed a very high-speed backbone—the Japan Gigabit Network (JGN) [13], which links up major cities in Japan at 2.4 Gb/s (OC48) over asynchronous transfer mode (ATM). NIME reaches the Science, Technology, and Research Transit Access Point (STAR TAP) [14], an exchange point in Chicago, via a Tokyo exchange point.

This node is called APAN/TransPAC [15], [16], which employs high-speed ATM technology at 123 Mb/s (as of July 2001, when the experiment took place). The next nodes from STAR TAP to Stanford University are "Abilene" [17] and California Research and Education Network (CalREN2) [18]. These nodes employ Gigabit Ethernet technology and have a maximum network speed of 2.4 Gb/s.

IV. TRIAL OF REMOTE LAB OVER THE GIGABIT NETWORK

A. Conducting the Remote Lab

The remote lab began by communication taking place via DVTS between an instructor at NIME and a group of students/observers at Stanford University. Client windows were viewed at the Stanford Learning Laboratory (Fig. 7). The DVTS transmission rate (picture frames per second) has a setting range of 1–30 fps. The two DVTSs (at NIME and Stanford University) were first set at 30 fps, the equivalent rate for the NTSC, but connection errors of unknown origins occurred frequently. Since a 30-fps setting occupies a bandwidth of about 30 Mb/s, the authors assumed there were congestions

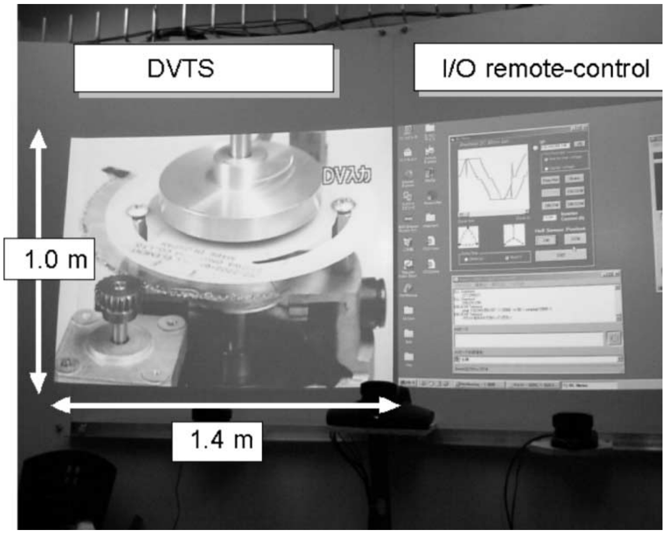


Fig. 7. Client windows (DVTS window of motor lab and I/O remote-control board) viewed at the Stanford Learning Laboratory using liquid-crystal projectors.

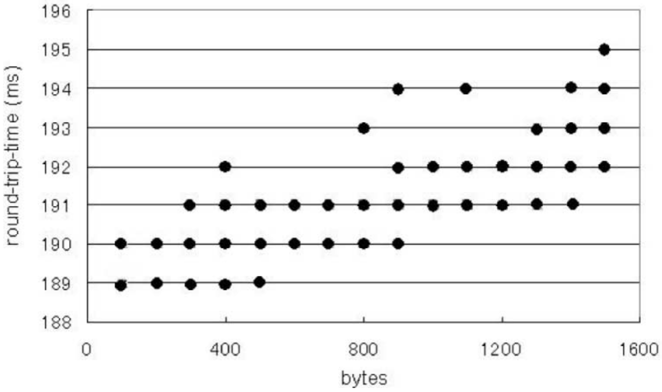


Fig. 8. Scatterplot of RTT versus packet size (measurements made in increments of 100 packets @ 50 probes each).

somewhere in the high-speed network nodes at the time and adjusted the picture frame rate downward to 15 fps, after which the DVTSs stabilized. In this condition, four brushless motor experiments were tested.

1) Delta and wye connection;
2) CW and CCW rotation;
3) Hall-sensor position corrections;
4) line-to-line voltage measurements.

All experiments went satisfactorily. The following comments by students and observers at Stanford University were noted:

- "I was impressed by the fact we were driving a motor in real time across 8300 km of the Pacific."
- "An actual laboratory is better (than simulation)."
- "With clear video streaming with near TV quality, we could observe the fine movements involved when the running motor was reversed or braked."

Other comments were also approving of the remote lab operation and its perceived "reality" using high-speed networks and DVTS. Round-trip transmission between NIME and Stanford University via the Chicago exchange point covers close to 20 000 km, resulting in a signal time delay. There were comments about this time lag.

> "The time delay was not great between initiating an operation and when the corresponding video image came back; and so it did not feel awkward."
>
> "The time lag is small enough that it does not interfere with the carrying out of normal conversations or conducting experiments."

B. Measurement of the Latency of the Gigabit Network

Because of the long distance that must be covered across the Pacific, a certain round-trip time (RTT) exists when transmitting over the high-speed network between Japan and the U.S. Operations of the remote laboratory will clearly be affected by this latency. It is difficult to determine the exact distance covered by optical fiber between NIME and Stanford University. A rough estimate for the round-trip distance would be 24 000 km, based on the network route map and geographical distance calculations. Assuming that the speed of light traveling through optical fiber is 180 000 km/s, one can calculate the RTT to be approximately 133 ms. In this experiment, the shortest observed RTT was measured at 189 ms, using a Microsoft "ping" command (Fig. 8).

Although the observers have stated that they did not notice any appreciable time delay, the authors took actual measurements (Fig. 9). Thus, a 1-kHz signal was transmitted from NIME and, after being looped back at Stanford, returned to NIME. The time taken for the signal to make this round trip was measured with a digital storage oscilloscope. Results of time measurements using various DVTS picture frame rates are shown in Table I. The time lag was about 800–900 ms and was not affected greatly by the picture frame rate (f/s).

Furthermore, the RTT of the DVTS itself was measured with a 5-m-long 100 BASE-TX cable, with a configuration similar to that in Fig. 9. The latency was about 600 ms at a picture frame rate of 15 f/s. Ignoring the effect of the short cable, the measured time was used for digitizing the video at the camcorders, encapsulating and reconstructing the video packets at the PCs, and converting DV packets to video signals at the displays. Because the total latency between Japan and the U.S. was 900 ms, the latency of the high-speed network itself is about 300 ms at RTP. This computation includes the latency caused by the long distances of the optical fiber cables and the task time at the ATM routers.

The latency observed above does not present a major problem in the remote laboratory, where the user clicks (or presses) buttons on the I/O remote-control board using a mouse. If the interactive lab involves a continuous operation, however, such as a master/slave-type manipulation device like a surgery medical robot [19] and surgical training applications [20], a latency of 900 ms would be too large for the operator.

Note that the I/O motor control command packet (i.e., commands made on the I/O remote-control board of Fig. 3) is formatted as user datagram protocol (UDP), with no encapsulating and reconstructing of video packets; therefore, the latency is shorter than that for the DVTS.

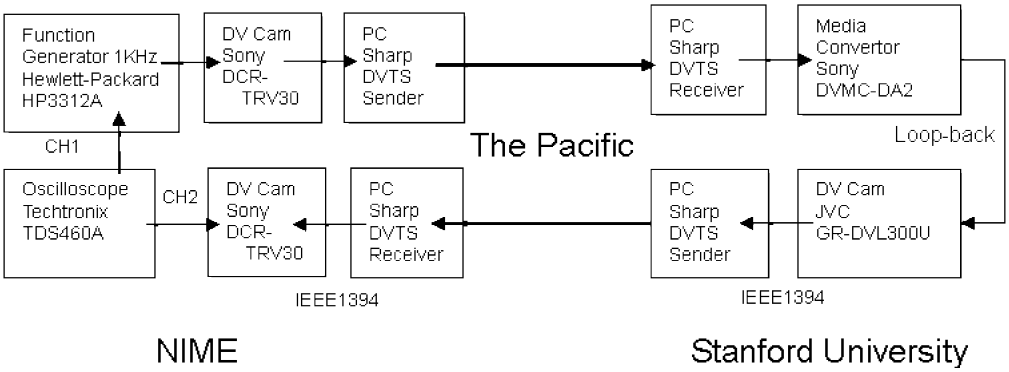


Fig. 9. Block diagram showing measurement of latency using DVTS.

TABLE I
MEASUREMENT OF RTT BETWEEN NIME AND STANFORD UNIVERSITY

No.	NIME (f/s)	Stanford Univ. (f/s)	Round Trip Time (ms)
1	15	15	900
2	10	10	830
3	5	5	840
4	1	1	828
5	1	15	828

V. CONCLUSION

A remote lab was conducted between Japan and the U.S. by taking advantage of high-speed networks and DVTS (a high-quality video conference system). Remote learners located at Stanford University accessed the DVTS-based remote laboratory at NIME interactively and in real time. The high-quality digital video conference system made it possible for the two connecting parties to communicate smoothly with each other and for the remote user to observe close-up details of the lab, including the motor's fine movements. Using a network bandwidth of 15 Mb/s, the authors were able to demonstrate that the remote laboratory can be conducted successfully over the gigabit network. In RTP, the RTT is approximately 900 ms, but this latency presented no problem for the remote laboratory, which is based on mouse operations.

In the near future, the authors expect to see expanding worldwide sharing of educational resources and lab facilities among universities and other educational institutions. In order for remote systems such as the remote lab presented here to contribute to this sharing, they must be able to overcome cultural and language differences by transmitting a high degree of "reality."

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