Recent Advances in Remote Experimentation

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Abstract. *This short paper discusses challenges in meeting Quality of Service (QoS) requirements for the specific case of hands-on sessions in a flexible learning context where students carry out remote experiments on a physical system via the Internet. Novel solutions are developed to overcome the current lack of predictability of the Internet so that QoS can be improved via content adaptation to the available bandwidth. In addition, an augmented-reality approach is used to enhance the user perception of the remote system, and a unique simulation-based scheme is proposed to recover from packet losses. The proposed approach is illustrated through the remote control of an inverted pendulum.*

Introduction

The world-wide spread of the Internet and its general acceptance have brought new opportunities in distance learning and in traditional education because it provides more flexibility for the students to learn in different places and at different times [1]. In particular, the so-called *flexible learning* approach promotes on-line accesses to Asynchronous Learning Networks (ALN) and Real-Time Services (RTS). The ALN provides instructional documents, video-taped lectures, electronic messaging, and a discussion forum while the RTS facilities supports video-conferencing with teachers and broadcasting of live lectures.

A typical on-line offering includes expositive material and other classical collaboration means which often are not sufficient to support the complete learning experience required by disciplines where the student must also develop hands-on practical experience. In particular, experimental work is essential to the development of an effective professional in engineering. To address this need, new real-time services specialized in control-engineering education have been developed enabling students to gain access to remote laboratory facilities located in various geographical locations ([2], [3], and [4]). Such distributed laboratory resources may be used by teachers to present live in-class demonstrations in a regular lecture hall located away from the laboratory facilities that house the physical experiments. In addition, the resources are used by students to carry out experimental studies via the Internet accessing equipment that may be available elsewhere at the local campus or at a very distant site.

Implementation

Figure 1 shows the implemented client-server architecture [5] that serves as the basis for the distributed laboratory where the users conduct control experiments on a physical set up consisting of an inverted pendulum mounted on a cart. The remote users (clients) are provided with multiplatform freeware to observe and to pilot the physical setup using the Internet as the communication channel. The server is the computer that controls in real-time the laboratory equipment through adequate I/O peripherals, and also manages all communications with the users. Access via an Internet service provider or a direct on-campus connection is required to enable the link between the clients and the server.

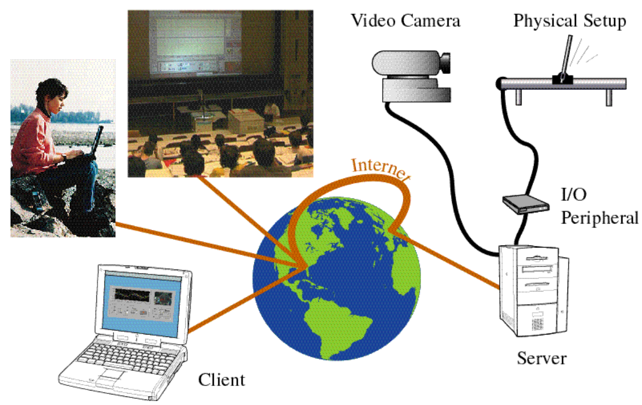

Fig. 1. Client-server Architecture.

For control experiments, the user interface at the client side typically features an area showing a scope that displays all the relevant signals (see label 1 in Fig. 2), and also includes areas with dialog boxes that permit setting the controller parameters and specifying the access rights of the users (labels 2 and 3 in Fig. 2). In more advanced implementations the control algorithm may also be presented as a user option [6].

Real-time audio and video feedback are also integrated in the user interface to provide additional dimensions of sensorial perception. In particular, digital cameras are used to send to the user essential views of key parts of the physical setup (label 4 in Fig. 2).

Challenges

The Internet has been chosen as a communication channel to provide easy access to almost anyone at a reasonable cost. There are however some drawbacks compared to advanced proprietary or expensive solutions such as dedicated digital phone lines or ATM connections. The main constraints when using the Internet are *limited bandwidth availability* and *bandwidth variations*. Despite these limitations, a high level of Quality of Service (QoS) has to be provided to the user to ensure a successful execution of the on-line experiment.

In the context of motion-control experiments where fast dynamics are expected, good QoS means a high level of interactivity. More specifically, when the user makes changes to the controller parameters or other experimental settings, it is important that the effect of these actions be posted quickly on the user interface. The absence of significant posting delays is necessary because otherwise the outdated information displayed by the interface may lead the user to erroneously interpret the effect of the changes made, and worse yet, lead him/her to make further adjustments based on incomplete information about the system response. Such quick posting of information is possible only if (*i*) the transmission delay over the net is minimized, and (*ii*) the update of the user interface is optimized to capture the dynamics of the specify equipment in use for the experiment.

It is important to emphasize that the performance specifications for remote experimentation differ greatly from those of other Internet real-time services, such as video conferencing or video broadcasting. For example, in remote experimentation the presence of jitter in the image update rate is typically not as critical as the reception of good sound quality. In contrast, in video conferencing the image rendering can be delayed as long as necessary to smooth the video sequence.

Advanced Solutions

The content of the data packets transmitted using the UDP protocol can be adapted to the available Internet bandwidth in order to keep the QoS at an acceptable level. This level reflects a trade-off between video image quality and frame rate (see the QoS slider bar in Fig. 2). A QoS control scheme is implemented on the server sing an estimate of the packet losses as the feedback signal. Hence, the video image resolution can be modified accordingly by changing the JPEG compression level using a nonlinear optimization technique. In this way the transmission content is automatically adapted to the available bandwidth.

To enhance the user perception, a virtual representation of key parts of the physical equipment is superposed on the video image (see the dotted lines in area 4 if Fig. 2). Such a composite view is called *augmented reality.* Useful information can be added, such as the reference signal for the controller (triangle drawn on the target track position), the force applied on the cart (length of the horizontal line drawn at the base of the cart), or even a virtual hand used to apply a disturbances on the pendulum (see button 5 and the hand displayed in area 4 which appears when the button is pressed). Different views of the laboratory equipment can be selected. When the available bandwidth is not large enough to ensure a sufficiently high video throughput, the display is limited to the virtual representation which in turn can be animated using real data or, in the worst case, using samples generated by a real-time simulator. In the pendulum example the animation of the virtual image can be done from knowledge of only two variables, namely, the angular and longitudinal positions of the pendulum.

The implementation of a real-time simulator in the client software permits the user to carry out off-line simulation for pedagogical purposes. The simulated responses can then be compared to a real experiment to evaluate the merits of the model. In addition, the simulator can be used to provide synthetic data that can be posted on the user interface when there are packet losses in the network connection. This gives continuity to the display, and provides the user with a sense of real time behavior. In such cases it is important to post an indicator that announces that the data shown is provided by a model due to the absence of reliable network data.

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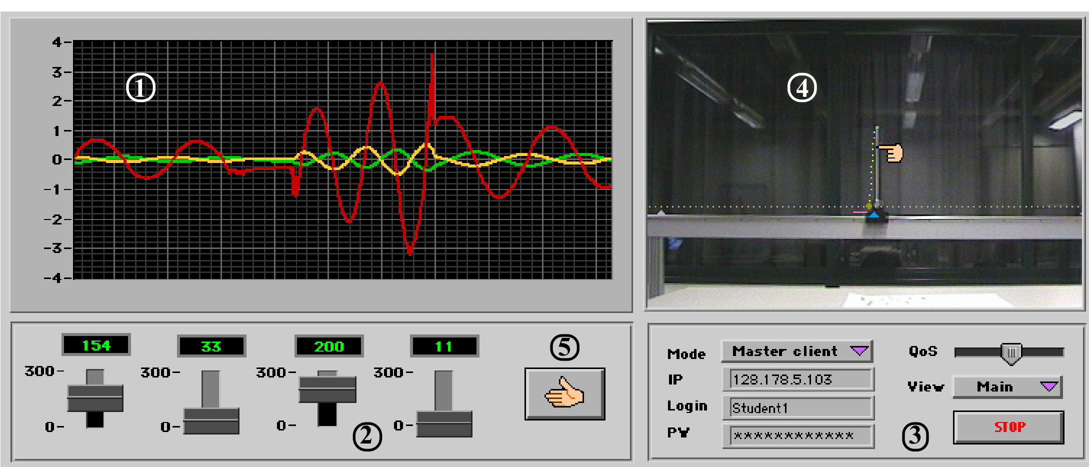

Fig. 2. User Interface of the remote client software.