Virtual Classroom Extension for Effective Distance Education

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Key requirements of effective distance learning are interactivity among participants and the student's sense of presence in the classroom. This system meets those requirements, letting the instructor perceive remote students' body language and facial expressions as they listen and speak, and letting remote students participate in the on-campus classroom.

A recent report from the National Center for Educational Statistics indicates that more than half of US higher-education institutions offer distance-education services, with enrollment doubling every three years.[1] However, current distance-education systems fail to match the effectiveness of conventional on-campus education because of several shortcomings.

First, students engaged in distance education (or *remote students*) feel isolated because they lack interactive communication with the instructor and on-campus students. Second, remote students don't have access to other helpful on-campus activities, such as instructors' office hours and study groups.

Finally, the availability of distance-education services is limited by a reliance on expensive, specialized infrastructure (such as teleconference-enabled classrooms with attached broadcasting rooms) requiring a large technical support staff. Moreover, the technology places a substantial burden on instructors, who must deviate considerably from their usual approach to course preparation and delivery. Surveys indicate that cost (for program development and equipment acquisition and maintenance), faculty workload, and course quality are the major factors that prevent higher-education institutions from starting or expanding distance-education course offerings.[1]

Research advances in computer networking, information security, computer graphics, and education science provide opportunities to reassess the role of technology in education and to develop a new approach to education in general. Almost vertical progress in the performance of commodity audio, video, general-computing, networking, and graphics hardware also encourages reassessment. A debate over abandoning the current attendance-based approach to education in favor of a radically new approach, although interesting, is beyond this article's scope. Our goal is to leverage technological and research advances to increase distance education's effectiveness to a level comparable to that of a conventional on-campus education. To that end, we have designed and implemented a new remote-lecture attendance system.

System overview

We have recently deployed our system in a classroom at Purdue University. The system displays remote students in a virtual extension of the classroom, which is projected on the classroom's back wall (see Figure 1a). A video available at http://www.cs.purdue.edu/cgvlab/dl illustrates the system's operation.

The system models a remote student with a real-time video sprite (a video in which the background pixels are set as transparent). The system then inserts the video sprite into a geometric model of the classroom extension. Although each remote student can be located at a different site, all the remote students are integrated in a unified virtual environment, which is displayed at a natural location within the classroom instructor's field of view. The instructor gets a sense of remote students' body language and facial expressions and sees them raising their hands in real time (Figures 1b-1d). The system continuously captures audio from each remote student and plays it back in the classroom, and each remote student continuously receives instructor audio and a classroom video feed.

The system enables interaction as follows:

- The instructor sees and hears the remote students.
- Local students hear the remote students and can see them by turning around and looking at the back-wall screen, just as they do when they want to see a classmate seated at the back of the classroom.

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Figure 1. (a) Distance-education system deployed in classroom. (b-d) Photographs of the back-wall screen show remote students integrated in a virtual extension of the classroom.

- Remote students hear the instructor and can see the instructor, the group of local students, or the group of remote students.

The current system implementation doesn't let the remote students hear the local students and doesn't send the local blackboard to the remote sites.

Figure 2 (next page) shows the hardware components used in the on-campus classroom (see the "Hardware Components" sidebar). The system relies exclusively on commodity components, and the only notable piece of additional equipment is the rear-facing projector. The system can be deployed at minimal cost to allow any course to offer distance-education seats. We target small to medium classrooms that seat 20 to 40 on-campus students, thus better enabling interactive lectures. Larger class sizes preclude interaction between instructor and students, so augmenting such a classroom with an interactive distance-education system would be futile.

The current first phase supports five remote students seated at various off-campus locations. Each student is connected through a two-way audio and video link to the local classroom, with a sustained frame rate of 5 Hz. This frame rate is sufficient to enable interactions between remote and local participants, and it implies bandwidth levels well within the limits of commodity connectivity such as DSL and cable modem.

Our system doesn't require substantial modifications to the way the instructor prepares and delivers the lecture, and the instructor needs little or no training to use the system effectively. We expect that our approach will lead schools to abandon their current approach of maintaining one or a few distance-education classrooms with specialized staff and specially trained instructors. Instead, they will merge support for distance education with general IT support.

We developed the system with the help of graduate and undergraduate students from computer science, computer graphics technology, and education science in a special multisemester course. This course proved to be a powerful educational experience for the students

Hardware Components

The hardware equipment at the classroom end of our system (see Figure 2) consists of

- a PC (3.2-GHz Intel Xeon with 3-Gbyte RAM and 512-Mbyte) with a graphics card (PCIe x16 nVidia Quadro FX 4400),
- a panoramic camera to capture the classroom and the instructor (PointGreyResearch Flea with fisheye lens),
- a lavaliere microphone to capture instructor audio (Azden 31 LT),
- a rear-facing projector for projecting the virtual classroom extension (Hitachi CP-X1250 XGA Multimedia), and
- a sound playback system (Panasonic SA-HE200K audio receiver, Panasonic SB-WA100 subwoofer, and four Panasonic SB-AFC10 speakers).

The classroom was already outfitted with the sound system and a PC for driving the usual front-facing projector. To avoid interfering with lectures, we didn't use that PC during our system's development phase.

At each remote-student site, the hardware includes a desktop computer, a webcam (Logitech QuickCam Pro 4000) to capture the student image, and a headset (Logitech Premium USB 350).

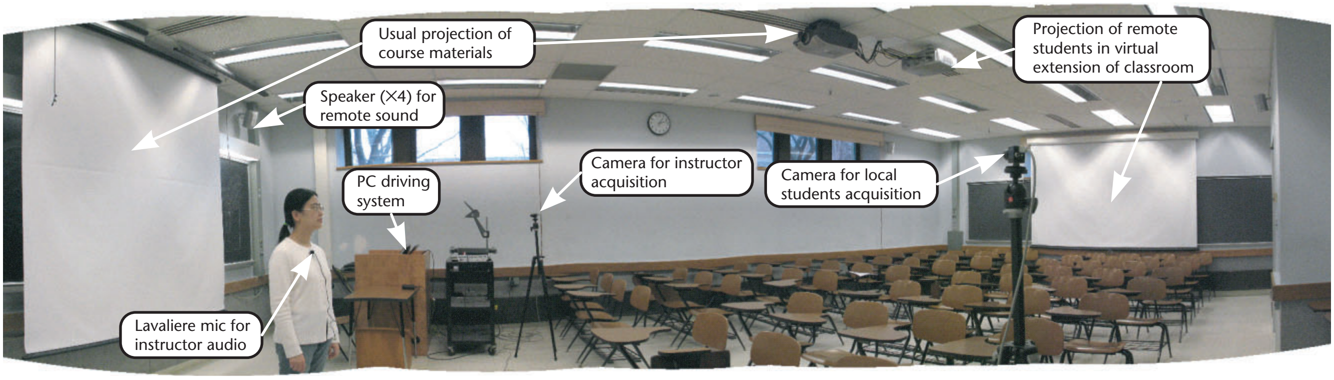

Figure 2. Hardware components of the classroom system.

involved. The course organization, goals, and achievements are described in a separate publication.[2]

Background

Several systems employing audio, video, and communication technology to deliver education remotely have preceded our system. However, education science research demonstrates that distance education is far from being a solved problem.

Prior systems

Several distance-education systems are in operation. One is a virtual-classroom multimedia distance-learning system that extends streaming and conferencing tools by supporting both unicast and multicast networks.[3] It uses a specialized compression algorithm for handwritten text and improved synchronization and resource allocation for media streaming. It provides the ability to record the live classroom sessions. One audio and video feed is transmitted at a time, originating either from the instructor or from a remote student. The instructor must grant permission for students to ask questions, strongly limiting interactivity and keeping the focus on the use of technology rather than on the educational activity.

The Smart Classroom system takes a step toward increased interactivity and realism.[4] It provides a face-to-face interactive classroom environment by projecting the images of the remote students on the wall of a real classroom and lets the instructor move freely in the room. The developers have proposed special network technologies for large-scale access and for heterogeneous network architectures for real-time data transmission between the instructor and the remote students, but they have given no results on the effectiveness of these technologies. Like the previous system, the Smart Classroom system achieves limited interactivity because only one student at a time can send audio and video and the instructor must grant permission. The system projects only the image of the remote student who has the token to speak, so the instructor cannot maintain contact with all remote students simultaneously in real time.

IRI-h is a system that sends audio and video feeds simultaneously from multiple sites.[5] The system's distinguishing feature is the "shared view," a window with reconfigurable content that all participants can view. The window simultaneously displays a dynamic subset of the participants. However, each participant is shown in a separate subwindow within the shared window, and the lack of a unified visualization reduces the effectiveness of visual communication. Moreover, the window displays participants at variable locations within the virtual environment, according to the current subset visualized in the shared view, eliminating seating consistency, which is known to be beneficial in conventional classrooms.

The Virtual Blackboard is a classroom learning environment that lets the instructor and the remote students manipulate video, audio, text, whiteboard images, and 3D graphics simultaneously.[6] The system aims to provide a wide range of modalities for interaction by letting the remote students and the instructor participate in an online lesson and at the same time exchange information and share applications. Nevertheless, interaction is unnatural in that the remote students and the instructor can communicate only via text, whiteboard, e-mail, and shared applications.

Responding to the increasing societal need for distance learning, several systems are available commercially (see "Commercially Available Systems" sidebar). In addition, several audio-video communication systems are available free of charge, such as Yahoo Messenger (http://messenger.yahoo.com) and Skype (http://www.skype.com). These systems have the merit of popularizing the Internet's capability to support live communication. However, they can't readily support distance learning because they are primarily one-to-one video communication systems. Even if the instructor could see each remote student's webcam in a separate window on a large display, such a visualization would be ineffectual. The instructor could not maintain visual contact with all remote students simultaneously and would be forced to scan each window sequentially, spending considerable effort to adapt cognitively to each of multiple contexts.

Finally, a look at university distance-education services reveals that remote course delivery is usually provided asynchronously through Web sites, disks (CD-ROMs and DVDs), and cable and standard television channels. For synchronous delivery, universities use expensive dedicated videoconferencing infrastructures (for example, see http://www.extension.harvard.edu/DistanceEd and http://www.icn.org/about_icn/icn_publications.html).

Commercially Available Systems

Distance education is an increasingly important societal need, for which many commercial solutions have been developed. A recent report by the eLearning Guild lists the following as the top 10 synchronous learning systems in terms of market share[1] (listed in order of most to least):

- Adobe Acrobat Connect (Adobe Systems, http://www.adobe.com/products/acrobatconnect)
- Elluminate Live! (Elluminate, http://www.elluminate.com)
- WebEx Training Center (Cisco Systems, http://www.webex.com)
- Microsoft Office Live Meeting (Microsoft, http://office.microsoft.com/livemeeting)
- Saba Centra Live (Saba, http://www.saba.com/products/centra)
- GoToMeeting (Citrix Online, https://www.gotomeeting.com)
- AT&T (formerly Interwise) Connect (AT&T, http://www.interwise.com)
- Desire2Learn Learning Environment (Desire2Learn, http://www.desire2learn.com)
- LearnLinc (iLinc Communications, http://www.ilinc.com)
- Second Life (Linden Research, http://secondlife.com)

These systems share a few core features: audio/video communication, instant messaging, and desktop, whiteboard, and application sharing. The systems have individual strengths. For example, Adobe Acrobat Connect can display rich multimedia content in various Internet browsers. Elluminate Live! optimizes available network bandwidth utilization. Microsoft Office Live Meeting has seamless integration. AT&T Connect supports a variety of mobile computing devices. GoToMeeting provides 128-bit AES encryption communication security. These features have clear relevance for distance learning, and we plan to adopt or replicate them in future versions of our system.

However, these systems are complementary to our system—they do not subsume it. Our system has the advantages of natural interaction between instructor and students (remote or local) and minimal interference with normal on-campus education. The commercial systems assume that distance learning is a separate, parallel campus activity. They burden the instructor and students with distance-learning-specific chores. For example, the instructor must play the role of a master of ceremonies, granting audio-sending privileges to remote students, and students must reply to real-time polling aimed at gauging their level of engagement and understanding. In contrast, our system keeps the audio channels of remote students open at all times, and the instructor can naturally monitor local and remote students alike.

Reference

1. S. Wexler, et al., "Synchronous Learning Systems (SLS): Benchmarks, Best Practices, and Real-Time Analysis about Real-Time Learning," *eLearning Guild 360 Report*, June 2007, http://www.elearningguild.com.

Distance-education research

As institutional participation and student enrollment in distance education have grown, education science research has aimed to assess current systems and draft guiding principles for making distance education's effectiveness equal to that of conventional on-campus education.

In distance education, remote students frequently have no opportunity to interact with other participants directly, or interaction occurs through delayed, asynchronous communication, which prevents in-depth, continuous discussions. Studies have shown that the lack of face-to face interaction and support from peers in these experiences leads to a feeling of alienation and isolation.[7] Research on communication, collaboration, participation, and peer feedback in distance-education systems has shown that the level of interactivity is a major factor for increasing learning in distance-education environments.[8]

Distance-education systems are deficient in both student-to-student and student-to-instructor interaction.[9] Many educators and students regard student-to-instructor interaction as essential. Studies on interactivity reveal that students have a real need to make genuine connections with their instructor. Interaction between students and the instructor helps ensure that the students and instructor develop a feeling of community and connectedness to the course.[8]

Distance-education systems currently fail to fully engage students because they don't provide a sense of cognitive, social, and physical presence. *Cognitive presence* is the focus of intellectual processes on a context or task(s). *Social presence* means that "being with someone virtually feels like being with [that person] physically."[10] *Physical presence* is a feeling of "being present in … the virtual or real environment: being there."[10] A major dimension of presence is interactivity—for example, increased interaction provides more stimuli, which in turn promotes a sense of presence.

From the research, we conclude that distance education systems can be more effective if they make the remote students and the instructor feel that the remote students are actually present in the classroom. Systems can achieve this through a high level of interactivity and visual realism of the virtual environment.

System architecture

Our system has two main components: the classroom system deployed in the on-campus classroom and the remote-student system deployed for each remotely located student (see Figure 3 on the next page).

The classroom system projects an image of a virtual 3D room on the back wall of the classroom to provide additional seats for remote students. The classroom system communicates with each remote-student site to send audio and video from the classroom and to receive audio

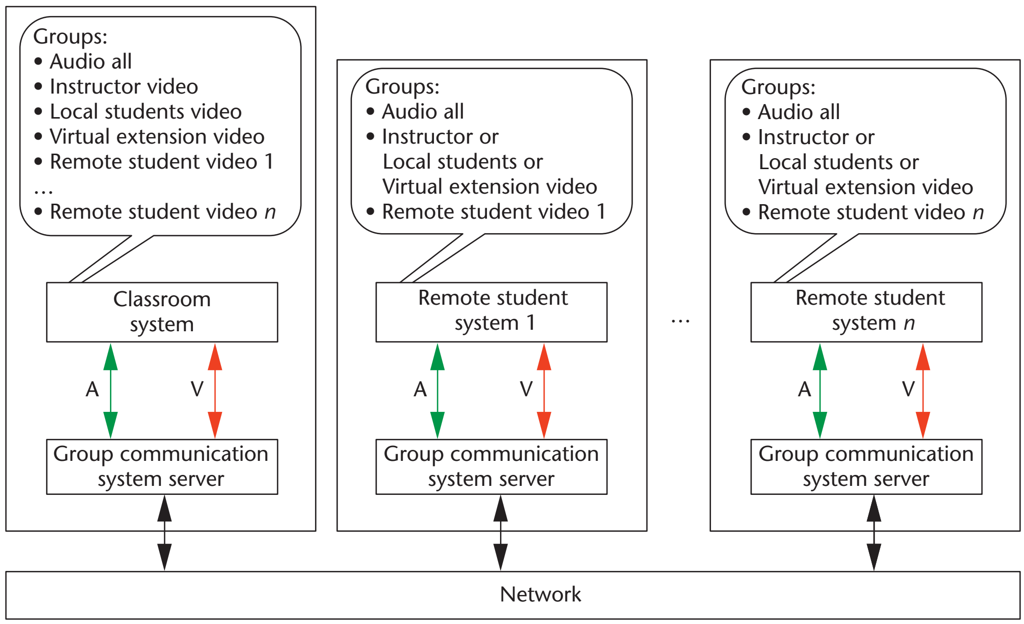

Figure 3. Our distance-learning system architecture features the classroom system and remote-student systems.

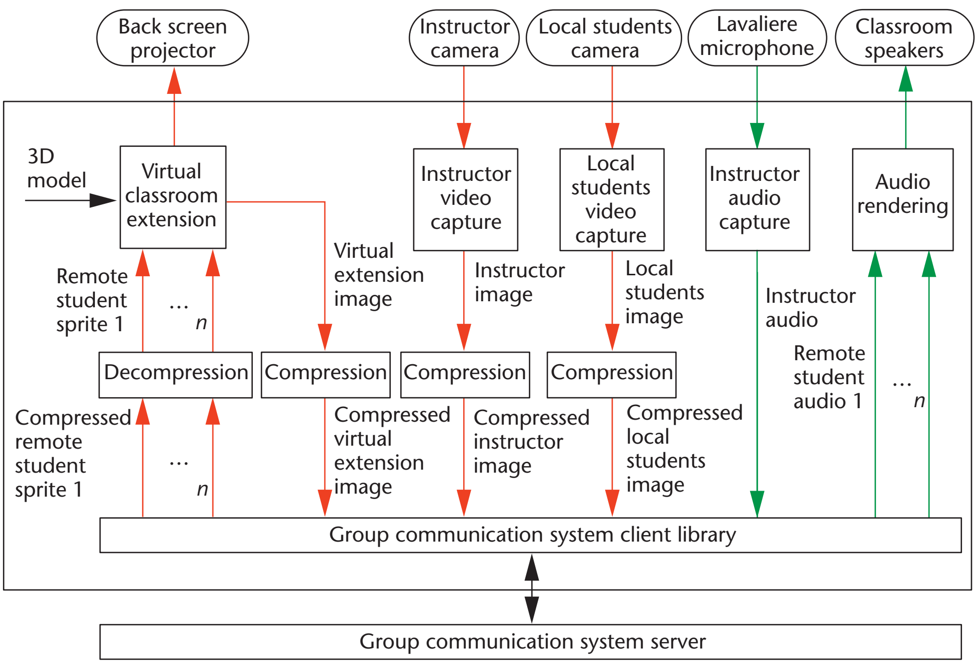

Figure 4. The classroom system.

and video from each remote site. Three video feeds are captured at the classroom: the instructor, the local students, and the virtual-extension feeds. Only one of these feeds is sent to a remote-student site at any given time.

The remote-student system displays the selected classroom video feed and renders audio from the classroom and the other remote students in real time. The remote-student system captures the student as a video sprite, which it sends to the classroom in real time. The remote-student system also captures the student audio, which it sends to each of the other remote students and to the classroom in real time. Audio communication between remote students and the instructor is always on.

The classroom and remote-student systems use a common communication infrastructure for audio and video transmission based on a group communication system (GCS). A GCS enables efficient communication between a set of applications logically organized in groups. Services a GCS provides include group membership as well as reliable and ordered message delivery. Thus, applications need not provide these services on their own and can simply send to and receive data from groups. An application can be a member of many groups.

A typical GCS follows an architecture whose major functionality is provided by a set of GCS servers. Appli-

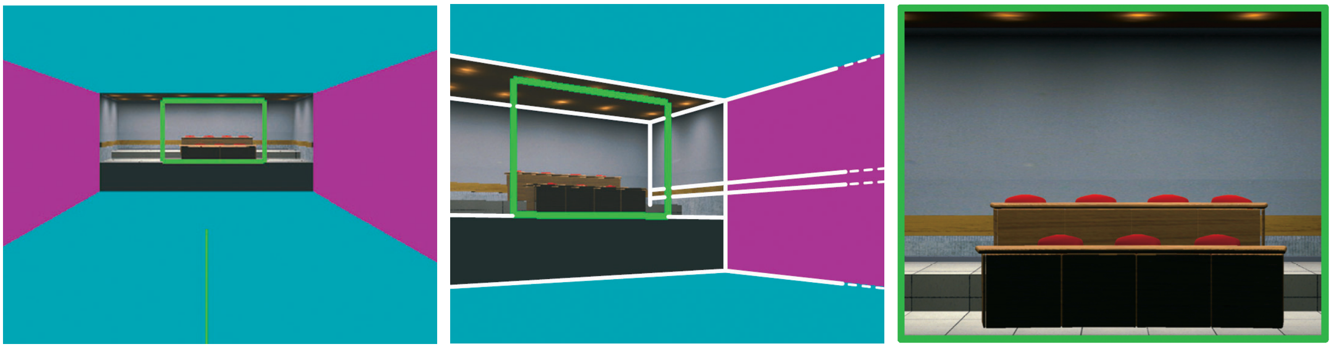

Figure 5. Visualizations of classroom extension (left and middle) and back-wall projector image.

cations interact with a server through a GCS client library. The GCS abstraction provides a modular design and a communication organization based on topics of interest to the participants in the system. Groups are simply predefined names, not reserved IP addresses as in IP multicast. Our system uses a single group, *Audio All*, for all audio communication, since all participants must receive all audio. All participants subscribe to this group. A participant sends the audio it captures and receives the audio captured by all other participants.

Video communication is handled using $n + 1$ groups, where n is the number of remote students. We assign one group for each of the three video feeds captured from the classroom. The classroom system is a member of each of the three groups, whereas a remote-student system is a member only of the classroom video group it is currently interested in. Finally, one group is assigned for the video captured from each remote student site. The members of the group called *Remote-Student Video i* are the remote-student system *i* and the classroom system, which send and receive the remote-student *i* video.

Classroom system

The classroom system's primary task is to host remote students in a campus classroom, causing minimal interference with normal lecture activities. The classroom system implements the interface between the instructor and remote students. Providing the remote students with instructor audio and video doesn't pose unusual challenges. However, the fact that each remote student can be located at a different site complicates the simulation of the remote students' presence for the instructor. Mixing and rendering real-time audio feeds enables straightforward audio contact, but enabling visual contact is more challenging.

We have developed a method that lets the instructor naturally monitor all remote students in parallel. The system extracts student sprites from individual video feeds and inserts them into a unified virtual environment, which is displayed at a natural location in the instructor's field of view (see Figure 1). For the instructor, the penalty of hosting the remote students is limited to the inherent disadvantage of a slightly larger class.

Figure 4 shows the classroom system, which consists of five main modules: virtual classroom extension, instructor video capture, local students video capture, instructor audio capture, and audio rendering.

Virtual classroom extension

To provide a believable virtual environment for hosting remote students, we created a realistic 3D digital model of a classroom that matches the geometry of the real-world classroom. Figure 5 shows visualizations of the virtual extension. The extension's seating capacity and configuration are tailored to the number of remote students it hosts.

We modeled the classroom using an animation system. We placed the remote-student sprites at predetermined locations in the geometric model to match the seats. The sprite size approximately matches the size of a student actually seated at that respective location. The system updates the remote students every time it receives a complete remote-student image. Although the scene's geometric complexity doesn't pose problems for modern graphics cards, we had to precompute high-quality lighting effects and encode them into texture maps to enable interactive rendering.

In the current version of the system, the virtual extension is rendered with the same view, so that users can simply update the video sprites over a constant background. Interactive 3D rendering will become important in future versions of the system that will track the instructor.

Distance-education systems typically customize methods and interaction techniques developed in the context of generic teleconferencing. Our system is no different. Several teleconferencing systems, including Teleport, integrate multiple remote participants modeled as live video sprites into a common virtual space.[11]

Instructor and local students video capture

The instructor video capture module acquires the view of the classroom that includes the instructor and sends it to the remote student sites. This module uses a camera with a fisheye lens because its large field of view keeps the instructor in the frame without tracking the instructor or moving the camera (see Figure 6a on the next page). During a dialogue between the instructor and a remote student, the instructor can achieve the illusion of eye contact with the student by facing both the fisheye and the back screen.

The local students video capture module also relies on a fisheye camera, which faces the back of the classroom (see Figure 6b). Figure 6c shows video feedback from the classroom to remote students, created by the module for virtual extension.

Figure 6. Three classroom video feeds are available to the remote student, who selects one of them: (a) instructor, (b) local students, and (c) virtual classroom extension.

Audio capture and rendering

The audio capture module acquires audio at the classroom and remote sites. The module acquires instructor audio with a wireless lavaliere microphone and sends it to the remote student sites. The audio-rendering module receives and mixes audio from each remote student and renders the mixed sound on the classroom speakers. The same software module renders audio for the classroom and the remote students. The software at location *L* discards audio packets received from the group that originated from location *L*.

Remote-student system

Figure 7 diagrams a remote-student system. Remote-student system *i* has two tasks. The first is to simulate the classroom environment for remote student *i* by receiving and rendering video of the classroom and by receiving and rendering audio of the classroom and the other remote students. The second task is to capture audio and video of remote student *i* and to send them to the classroom for integration into the virtual extension. The remote-student system has several modules.

Remote-student capture

The remote-student capture module provides the instructor with a quality visual depiction of the remote student in real time. Acquiring a 3D model of the student in real time remains a challenge. However, we obtain a good approximation of the appearance of the remote student by modeling the student as a real-time video sprite. The video sprite is a good approximation in our context because the remote student is displayed far from the instructor (beyond the back wall of the classroom), so the sprite's flatness is not a concern.

Background subtraction

The challenge is to find the foreground pixels in each frame in real time. We took the approach of background subtraction. First, the remote student moves outside the webcam's field of view, and the webcam acquires a background frame. Then, the background frame is used to determine which pixels changed; these are labeled as foreground. Since the camera adjusts exposure in real time, background pixels don't exactly match the prerecorded background frame.

Background subtraction has been studied extensively in image and video processing. Piccardi presents a good overview of background subtraction techniques.[12] Although robust, efficient techniques exist for friendly backgrounds, some cases are challenging to the most sophisticated offline algorithms.

We have developed a simple background subtraction algorithm that assumes the background is static and sufficiently contrasts with the image's remote-student region. The assumption can be easily satisfied by a student joining the lecture from a private room. However, joining from a large, active environment requires the student to find a location with a static background, such as a wall. The algorithm is robust and efficient, enabling a sustained frame rate of 5 frames per second (fps) in parallel with the other remote-student workstation tasks (video and audio compression and decompression).

Remote-student interface

Figure 8 shows a remote student using the system. Through a simple interface, the remote student can reacquire background when needed. Background subtraction quality is monitored in two additional windows showing the video feed and the video sprite sent to the classroom. In our experiments, a remote student typically acquired background only once during a session. Events that could require reacquiring background are moving the webcam or permanent changes to the background.

The remote student uses class material (for example, a presentation slide as in Figure 8), which the student downloaded before the lecture. The remote student is responsible for advancing the presentation in synch with the local classroom.

Implementation

As mentioned earlier, we built the system from commodity components listed in the "Hardware Components" sidebar.

We developed the system software on the Microsoft Windows platform. Windows has the advantage of directly supporting any camera, headset, projector, graphics card, microphone, or sound console on the market now and likely in the future, a requirement for large-scale adoption of our system.

We implemented video and audio processing with Microsoft DirectShow filters, using threads for concurrency. Video processing in the classroom system is organized in three concurrent threads. The first thread captures and sends the instructor, local students, or remote students feed. The second thread receives the sprite messages from the remote students, and the third renders the virtual classroom into which the remote-student sprites are integrated. The video filter in the remote-student system also uses three concurrent threads. The first thread acquires and sends the remote student's sprite, the second receives the video feed from the classroom, and the third displays the classroom. For both systems, we set the receiving thread as the highest priority to guarantee a timely update of visual feedback.

The audio mixer is a filter that runs concurrently with video processing as a separate software application. Three concurrent threads capture and send, receive, and play back the audio feeds between remote students and the classroom. We use the DirectSound API for mixing and playing back audio.

We chose the Spread group communication system as our communication infrastructure because it provides an easy way to deploy the system while meeting performance requirements, and because it is publicly available.[13] Spread is a general-purpose GCS for wide- and local-area networks, using customized protocols that rely on unicast UDP (User Datagram Protocol) on wide-area networks and multicast in LANs when available. Like any GCS, Spread provides reliable and ordered message delivery, as well as a group membership service.

Our system consists of a Spread server and a Spread client library. It achieves interaction between an application and Spread through the Spread client library, which provides an easy-to-use interface. The interface allows an application to connect to a Spread server, join groups, and send and receive data to and from different groups.

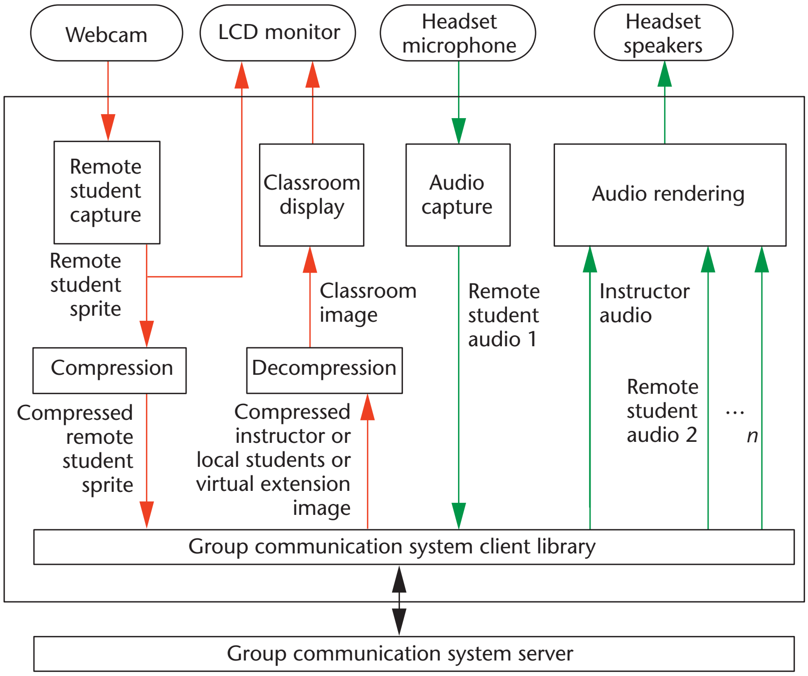

Figure 7. A remote-student system comprises several modules.

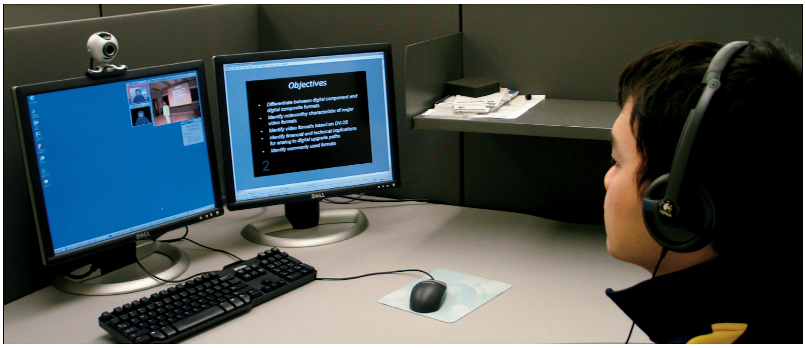
Figure 8. Remote-student site. Here the student views the instructor's presentation slide in the monitor at right and his own sprite and the instructor in the monitor at left.

Evaluation

We evaluated our system quantitatively and qualitatively, using formal performance measurements, informal assessment, and a pilot study.

Performance

The remote-student system's main computational tasks are the decompression of the 400- × 300-pixel classroom frame and the acquisition, construction, and compression of the 160- × 120-pixel remote-student sprite. The system performs each of these tasks at a sustained frame rate of 5 fps, leveraging efficient MPEG-4 compression and decompression implementations provided by the XviD library and leveraging the assumption of a static background for sprite construction.

The classroom system compresses the classroom image, decompresses the remote-student sprites, and updates their respective textures in the 3D virtual classroom extension. A single classroom workstation comfortably handles five remote students at 5 fps. In fact, simulations show that decompression performance and bandwidth to the graphics card are sufficient for up to 50 remote students (modeled with 5-fps 160- × 120-pixel sprites).

The average bit rate for sending and receiving a 160- × 120-pixel remote-student video sprite at 5 fps is approximately 35 Kbits per second (Kbps); the classroom video's average bit rate is approximately 355 Kbps for 400- × 300-pixel images at 5 fps. The audio bandwidth requirement is negligible by comparison. This implies upload and download bandwidth requirements of 35 and 355 Kbps, respectively, at each remote-student site, which are within the limits of commodity broadband networking (such as DSL or cable modem). For the classroom system, the upload and download requirements are 355 and 175 Kbps, within the limits of the connectivity available at most educational institutions.

Our prototype deployment conservatively meets the five-student, 5 fps performance target. Future larger-scale deployments will give us the opportunity to experiment with higher frame rates by pushing the system closer to the limits of the available bandwidth, as well as to evaluate the educational impact of such increased performance.

Informal assessment

During several demonstration sessions, we informally assessed the system, using our education science and technological expertise.

The system's sound quality is excellent, allowing users to detect vocal intonations and nuances. This facilitates a sense of rapport among the remote students and the instructor. The current implementation of the audio modules doesn't filter audio in any way. In our experiments, the microphones attached to the headsets did a good job of capturing only the remote student's voice. Noisier environments might require further audio processing to avoid noise accumulation.

The instructor interacts naturally with both local and remote students. The remote students effect on the local students is similar to that of an additional five students seated at the back of the classroom. Local students can easily see the remote students by turning around and looking at the back-wall screen, much as they would to see an actual student seated at the back of the classroom.

Of the three live video feeds the remote students can select, the instructor feed is most frequently used. A remote student who hears another remote student ask or answer a question switches to the virtual-extension view, which shows the active remote student. This mode also lets remote students see themselves as part of the virtual classroom extension. This view, along with the instructor's acknowledgment of visual signals such as hand raising, solidifies the remote students' perception that they are heard and seen by the local participants. When the instructor gives a local student permission to talk, the remote student switches to the third classroom video feed, which gives a good panoramic view of the local students and classroom.

Overall, the system showed great potential for supporting quality interactions between local and remote participants. Even during the short demonstration sessions (approximately 30 minutes each), participants engaged in vivid, spontaneous conversations, which are not typical for teleconferencing systems.

Pilot study

To further assess the distance-learning system's effectiveness, we conducted a pilot study involving 15 local and 5 remote students. One of the remote students was involved in developing the system. None of the other 19 students had been involved in a distance-learning class before this pilot study. The pilot study used an earlier version of the system, which provided only one local-classroom video feed to the remote students—the instructor video feed.

The students attended four one-hour lecture sessions. The lecture topics were introduction to digital video, camera operations, video formats, and video delivery. Before the first session, we briefed the remote students on how to use the system: each window's meaning, how to switch from one classroom video feed to another, and how to acquire the background for constructing their sprites.

Relying on our knowledge of the intended characteristics of the distance-learning system and on extensive research of relevant educational science literature, we identified two variables of interest: the *presence* of remote students in the local educational setting, as perceived by the local and remote participants, and *interactivity* between participants.

We measured three types of presence:

- *social*—the degree to which participants perceived other participants' sociability, warmth, sensitivity, personality, or closeness;
- *cognitive*—the degree to which participants felt connected to the system, so that any content presented was receivable, a feeling involving perception, attention, and reasoning; and
- *physical*—the degree to which remote and local participants perceived remote participants as actually present in the classroom.

We measured interactivity as levels of student-to-student, student-to-instructor, student-to-content, and human-to-technology interaction.

We used four tools to measure these variables:

- tests that quantified the students' knowledge of the subject matter before and after the pilot,
- a comprehensive 93-question survey,
- focus group discussions, and
- an instructor interview.

Here, we briefly review the results from each tool. A detailed educational-science analysis of the results is forthcoming in a separate publication.

The tests given before and after the four lectures showed no significant difference in pretest scores between local and remote students, indicating that the two groups were roughly equivalent in the knowledge they brought to the study. Although the student group sizes were small, there were no outliers, strengthening our confidence in this conclusion. The posttest scores for each group were higher than their pretest scores, showing that both groups learned. The posttest scores also showed no significant difference between the two groups, suggesting that both groups learned the same amount. These tests indicate that the system provided sufficient levels of interactivity and cognitive presence so as not to obstruct learning.

The student survey and the focus group discussions revealed that the remote students perceived themselves as cognitively, physically, and socially present in the classroom—to a higher degree than the local students perceived them as present. We attribute this to the fact that remote student presence is of unequal importance to the two groups. That is, the remote students depend on the virtual connection to the local classroom, but local students are better served if they forget that the remote students are present.

The survey and discussions also showed that the system affords good interaction levels between remote students but low interaction levels between local and remote students. In the version of the system used in the pilot, the local students could hear and see remote students but couldn't be heard and seen by them.

Third, in the survey and discussions, the remote students suggested ways to improve the human-to-technology interaction. Suggestions included allowing remote students to hear and see local students, removing the limitation on range of motion for the remote student, and improving the remote-student video capture to render subtle natural movements such as head nodding, which had to be exaggerated to be effective.

The instructor who delivered the lectures in the pilot has extensive experience with synchronous and asynchronous distance-learning systems. In an interview after the pilot, he indicated that our distance-learning system provided a closer connection with the remote students than prior systems had. He noted that he could talk to the remote students frequently and casually, and that, overall, the lectures "did not feel like distance learning."

We have begun addressing some of the limitations of the system revealed by the pilot study, which serves as a formative evaluation tool. With the addition of the two classroom video feeds, we expect to strengthen remote students' sense of presence without increasing their conspicuousness to the local students.

The class taught during the pilot study relied mainly on instructor-to-student interaction and involved little student-to-student interaction. For classes where interaction between students is more important, we must improve local-to-remote student interaction. We have already taken the first step in this direction by providing the local-student video feed to the remote students. Rather than requiring local students to pass around a handheld wireless microphone to ask questions, we will use environment microphones to capture local-student audio. This will prevent affecting interaction between students and instructor. The additional audio feed will be mixed with the instructor feed and transmitted to the remote locations without additional bandwidth cost.

To give the remote student a greater range of motion, we are considering employing high-resolution webcams with larger fields of view, enabling the remote-student video sprite to be tracked and cropped out. We are investigating the reported head-nodding problem. Frame rate, resolution, and compression rate are possible causes. Another cause could be the remote students' incorrect perception of the distance to the instructor, which translates into motions of too little amplitude to be detected in similar real-world scenarios.

For the pilot study, the remote students were distributed throughout the building of the local classroom, and the remote student workstations were connected to the local classroom through a 100-Mbps LAN. Although the bandwidth requirement during the pilot never exceeded what can be reasonably expected from commodity broadband, the LAN pilot doesn't prove and wasn't intended to prove the success of a truly distributed deployment. However, the experiment is an important first step in the assessment of the setup, in the absence of confounding factors such as occasional networking bottlenecks. Once the LAN version of the system provides a flawless educational experience to remote students, we will move on to experiments involving a truly distributed deployment.

Conclusion

Although more advanced options exist for some parts of the system (for example, background subtraction), we have opted for simple, proven solutions that provide a sizable performance safety margin. In addition to the immediate enhancements just described, we plan to augment the system with capabilities such as instructor tracking, morphing the classroom extension to smoothly adjust to the number of students, exaggerated visualization of remote students for improved interaction efficiency, electronic whiteboard support, and distributed class materials.

The deployment of the first prototype is an important milestone that enables future work in several major directions. One direction is to use the system in actual courses for a rigorous evaluation of its educational impact. A second direction is to deploy the system over the Internet, which brings new challenges such as addressing security and privacy issues.

Finally, we will develop system support for other on-campus interactive educational activities such as attending office hours and study groups. Supporting study groups effectively requires arranging the remote-student avatars for roundtable-like discussions, adding the capability to freely exchange handwritten notes, and creating a comfortable virtual setting conducive to productive collaboration. An important subproblem is producing highly realistic digital 3D models of coffee shops, student union lounges, and other favorite campus venues. ■

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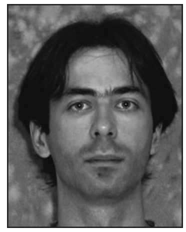

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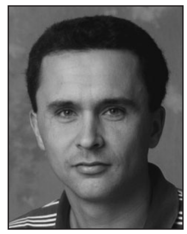

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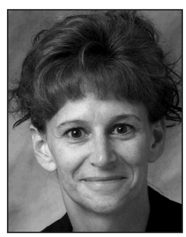

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