Remote Instrumentation

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The widespread use of the Internet has resulted in innovations in the field of science education. Increased availability of resources has allowed students in a variety of settings to perform research in many scientific fields. These resources span a wide range, from web-based course materials to instruments that are controlled remotely. Complex instrumentation that can be accessed remotely over the Internet introduces students to facilities that they otherwise would likely not be able to use. Such facilities are excellent training tools for the next generation of scientists and researchers. This chapter focuses on three examples of remote instruments and uses these cases for a broader discussion on the effectiveness of remote laboratories in STEM education.

What Is a Remote Instrument?

Professionals use remote instruments in many science and engineering fields as part of their research. We will discuss three representative examples drawn from the fields of astronomy, chemistry, and chemical engineering.

Astronomy has been a leader in this area because telescopes are often in remote locations such as Mauna Kea in Hawaii or even in space. The advances in modern computing techniques have made the operations of these telescopes quite hands-off and largely computer controlled. In many cases, astronomers hand the telescope operators the observing plans and then wait for the data. Although being onsite allows for changes to the observing plan while it is in operation, long-distance monitoring can be, and often is, substituted.

The remote or robotic nature of telescopes is now being used in the undergraduate classroom. These instruments serve as an important education tool for students who are in remote locations or in places with limited resources. Undergraduate students have hectic class schedules and traveling to use a distant telescope cannot usually be part of their classroom or laboratory experience. Even colleges or universities that might have an observatory facility as part of their campus often provide remote access to the telescopes. Some of these facilities are labeled as "robotic," since the students do not directly control the instrument. Rather, they provide an observing plan that gets executed for them by a telescope operator or another student trained in the use of the facility. Educationally, this is still a valuable resource, since in planning the experiment, the students have to familiarize themselves with the capabilities of the telescope and the night sky at the site.

Telescopes that are under complete remote control are more unusual. In an instrument where the user controls it remotely, safety becomes a major issue. In the case of remotely controlled telescopes, one has to assume that the users are not experienced enough to realize that they might be executing commands that might damage the instrument or they might simply make a mistake in the commands they input. For such instances, the telescope control software has to have the ability to disable the instrument if such commands are given. The other major issue in recent years has been the network security issues that can sometimes prevent students from unfettered access to the instrument control software.

With remote access to chemical instrumentation, the same general considerations of student skill/experience and inadvertent or malicious computer attacks also come into play. For example, single-crystal X-ray diffractometers are composed of several mechanical and/or electrical systems, including the X-ray generator, which uses a high voltage source and produces an intense X-ray beam; the low-temperature system, which uses liquid nitrogen; the goniometer, which has high precision and rather delicate mechanical gears; X-ray detectors, which can be mechanically damaged; and both embedded and free-standing computers. Each of these components is under software control and can be damaged either inadvertently or maliciously. Limits are typically included in the software that controls these systems to minimize accidental damage. However, if students are to carry out realistic experiments and/or collected publication quality data for teaching and research, they need sufficient instrument control so that they will inevitably be able to alter and/or bypass these limits. Thus, one can set up a system that has some balance between being relatively resistant to naive/malicious user damage and one that is more research-like, but there will always be a tradeoff between these two considerations.

Whereas proper experimental design is necessary to ensure that instruments are safely operated and not damaged, remote chemical experiments are actually safer to the remote user. This may be an important advantage to a remote laboratory, particularly when resources to staff a laboratory course with TAs are inadequate. Nevertheless, safety must remain a concern in the design of remote experiments to make up for the lack of continuous onsite, real-time human intervention.

Experience with novices using chemical instrumentation having various levels of sophistication has shown that, contrary to what one might initially expect, it is often easier to both collect the data and interpret them when "research-grade" rather than "teaching" instruments are used. This is a reflection of both the facts that research-grade instruments are typically newer than many teaching instruments and, more fundamentally, that more expensive components used in research instruments typically are both more automated (at least potentially) and produce data that are of higher resolution and have higher signal/noise ratios.

Examples of Remote Instruments

MIT Haystack Observatory 37-m radio telescope

The MIT Haystack Observatory has been involved in an NSF-funded initiative to bring radio astronomy to the undergraduate classroom. A small radio telescope kit has been developed and commercialized—teachers who want their students to get a hands-on experience can purchase this kit and build a radio telescope. However, this small telescope is not capable of performing any serious research. A research-grade 37-m radio telescope is available for students to perform research projects.

The radio telescope is completely remotely accessible. Students are given access to the telescope control computer with some initial training. Then, they perform their experiments with limited guidance from the observatory staff. Project ideas and teaching materials for the faculty are available on the Haystack Observatory website (http://www.haystack.mit.edu). The website also provides suggestions for several modes of classroom use—demonstrations run by the teacher, laboratory units, and long-term student research projects. A list of publications resulting from the program can be found at http://web.haystack.mit.edu/urei/bibliography.html.

To equip the telescope for remote operations, several hardware upgrades were made. The software was also updated, and online monitoring facilities were added. Over the last several years, the remote system has been performing well—over 150 students per year from over 20 colleges nationwide use the telescope. The program has been very successful and has opened a research-grade instrument for undergraduate education and research.

Single crystal X-ray diffraction

A single crystal X-ray diffractometer suitable for both student teaching and research costs several hundred thousand dollars to purchase and 5–10% of this amount to operate each year. The Youngstown State University (YSU)–Predominantly Undergraduate Institution Undergraduate Diffraction Consortium (YSU-PUI UDC) has several dozen members, and its current instruments are housed at Youngstown State University in northeast Ohio. The YSU lab has four diffractometers that were partially funded by four NSF grants: three research and teaching instrumentation grants (which are functionally indistinguishable at predominantly undergraduate institutions [PUIs]) and an educational materials development grant that interacted in a synergic fashion with one another. The instruments housed at YSU are two Bruker P4 single crystal systems that are a decade old, a Bruker APEX charge coupled device–equipped single crystal diffractometer that is 3 years old, and a Bruker D8 powder diffractometer that is 2 years old. The APEX system was purchased with remote access as its central goal and is now fully controllable from remote locations, whereas the other instruments are currently being brought online after our successes with the APEX system. We are also in the process of installing a complete interactive audio and visual web-cam system in the lab to allow video conferencing with remote users and remote viewing of the physical hardware in operation.

These instruments are being used for a range of purposes, from student research projects involving the determination of previously unknown structures through quite elementary exercises that are included in our freshman chemistry program taught at local high schools. After trying several approaches, we have settled on using the pcAnywhere software for remote access to our systems. It is quite inexpensive and versions are available for all Microsoft operating systems. The user logs onto the instrument host at YSU using pcAnywhere, which opens a window on the remote computer. This window is an image of the host screen at YSU that can be controlled using the mouse and keyboard at the remote site. The remote user has the same instrument control as one at YSU with two exceptions. The crystals must be physically mounted and centered on the goniometer at YSU after they have been mailed from the remote site and, if the system crashes, it must be restarted locally. These tasks are either carried out by the YSU faculty and staff or by a YSU student who does this as part of his or her regular teaching duties.

Adiabatic flame temperature experiment

In contrast to the above examples, remote instruments may also be of a more modest nature, with the primary purpose of introducing students to experimental design or to reinforce concepts in a lecture course.

We have developed an experiment for measurement of the temperature of a flame at different locations in and near the flame as a function of the fuel/air ratio. The experiment is used in an introductory chemical engineering course, Material and Energy Balances, at Columbia University. The experiments are closely related to theoretical calculations of an adiabatic flame temperature, which is a common and laborious example that is typically used in such courses.

The experiment is very simple, allowing the students to rapidly learn the nuts and bolts of the operation, so that the time required for the experiment is on the order of a couple of hours. The students are asked to measure temperature by placing a Pt-Rh thermocouple at various locations in and near the flame. Safety valves are included in the experimental design to shut off the fuel flow in the event of an interruption in the flame. The thermocouple is mounted on an XY-positioning table, and the students choose the positions to take the measurement. Students are also able to control the fuel and airflow rates. On the computer monitor of the remote user, a video of the flame and experimental equipment, along with the experimental data, are displayed.

Students are required to run the experiment and to prepare a short report, comparing experiment with theory. Groups may elect to repeat the experiments on several occasions, as they compare results with calculations. This type of an iterative approach is not always possible with traditional laboratories, in which laboratory access is limited by course scheduling, but may be instructive because it more closely simulates one aspect of "real-world" experimental studies.

The remote laboratory has been used twice at Columbia. Students have been questioned about their experiences, and they indicated that they found the experience useful. The students indicated that the ability to work at their own pace and according to their preferred schedule (they had 24/7 access) was an attractive feature of remote experimentation. Furthermore, they indicated that they did not feel that their experience would have been better if they had performed the experiment in the laboratory.

Remote Instrumentation for STEM Education

Several recent studies have indicated the importance of research- and inquiry-based education at all levels (1–3). The NSF study (3) concluded that, "All students have access to supportive, excellent undergraduate education in science, mathematics, engineering, and technology, and all students learn these subjects by direct experience with the methods and processes of inquiry." Translating the faculty research into the classroom may require a drastic overhaul of the course curriculum but can result in a rewarding experience both for the teacher and the student. Providing teachers with the means and materials that facilitate the incorporation of research into their teaching is an important goal of a remote instrument facility.

Whereas the research experience has been proven to be an important addition to the educational process, do remote instruments meet the same goals of a hands-on instrument? It turns out that modern instrumentation has become so complex that computer control has become necessary. Most of the interaction that the student has with the instrument is with the computer, not necessarily the instrument itself. The student still has to plan and execute the experiment, troubleshoot any potential problems, and analyze and interpret the data. This results in a relevant and educational research experience.

For many subjects, the actual experience of being in the laboratory, handling, for example, potentially dangerous chemicals, is part of the learning experience, even if all of the instrumentation is computerized and can be operated remotely. For such disciplines, remote experimentation can serve to supplement traditional hands-on laboratories, effectively increasing the quantity of experimental work to which a student is exposed. Remote instruments need not be viewed as a threat to traditional laboratory learning experiences. This is particularly true for more expensive instrumentation that would not typically be located at most PUIs.

Another aspect of professional research is collaboration. This collaboration might be with colleagues within the same institution, but is often with colleagues in different, and distant, institutions. The Internet has made such collaboration much easier in the professional science and engineering fields. Translating such collaborative experiences into the undergraduate classroom does take more effort on the part of the teachers. However, having a remote instrument can facilitate such interactions. Students can share data and results on websites set up for such purposes. Astronomical observations that require long-term study for meaningful results lend themselves to collaborations between students and interested faculty. Similarly, the students at one site might be primarily responsible for the synthesis of a new compound, at a second for its spectroscopic and computational characterization, and at a third for its single crystal X-ray diffraction analysis. Such interactions are routine for most academic chemists, and remote instrumentation access provides a way to give collaborating students a fuller understanding of what their remote collaborators are doing. They also allow students to carry out and publish research using instruments for which their local faculty mentors have the expertise but not research-grade instrumentation. This is an especially important issue at PUIs, which typically have only a limited range of research-grade instruments needed to carry out publishable research.

Cross-disciplinary collaborations are also possible. In radio astronomy, observations of emission from molecular transitions have applications in physics and chemistry. The instrument and its systems are of interest to electrical, mechanical, and computer engineers. Similarly, a geologist might collaborate with a crystallographer to more characterize the nature of the compositional disorder in a mineral sample collected from a particular location. Projects can be performed that span these fields.

The use of remote instrumentation also facilitates the building of learning communities involving faculty from multiple institutions. In particular, because they are all using the same instruments, the integration of a lecture or laboratory experiment from another site is much easier.

Barriers to Wide Use of Remote Instrumentation

There are several potential barriers to the widespread use of remote instrumentation. The institution that owns the remote instrument and wants to make it more widely available will need to invest the time and money into making the facility robust and easy to use. They also need to provide training materials, project suggestions, and faculty training. Fortunately, both NSF and private foundations provide educational materials development and dissemination grants that can be used for these purposes.

It is also very important to advertise the availability of the remote instrument to the relevant audiences. In the case of the Haystack radio telescope, the staff and students have presented posters on the capabilities of the project and the results from the research. Most of these presentations have occurred at meetings of the American Astronomical Society, where the attendees are involved in the field. To make the telescope attractive to faculty in other disciplines, more diverse venues have been tried, such as meetings of the American Association of Physics Teachers and the Council for Undergraduate Research. The most successful generator of new users has been an NSF Chautauqua short course that the Haystack Observatory staff has taught onsite, which brings the college teachers to the Observatory, gives them hands-on training on the telescope, and introduces the available teaching materials.

Similarly, participants in the YSU-PUI UDC have presented talks and posters at regional and national meetings of the American Crystallographic Society, the American Chemical

Society, and the Biennial Conference on Chemical Education and have submitted the first of several papers on this topic to the *Journal of Chemical Education,* with future papers going to the *Journal of Chemical Crystallography* and the *Journal of Science Education.* Such methods are excellent for persuading "early adopters" to try remote access to instrumentation. Persuading most faculty, however, is a much greater challenge. Here, two strategies seem to be particularly important. The first is having available a wide range of lecture and laboratory materials along with formal and informal methods to familiarize new users with them. The second is to develop a "buzz" among the larger community that remote access is now past its many early trials and disappointments and can now be easily and routinely integrated into the courses of even nonspecialists.

Long-Term Sustainability of Remote Technology

In examining the long-term sustainability of the remote instrument, several factors have to be considered. The instrumentation requires maintenance, there needs to be appropriate levels of staffing, the program constantly needs to be advertised, the results of the research have to be disseminated, and new projects have to be developed. These activities require constant attention and funds.

Another factor to consider is the technology itself. Instrumentation undergoes constant refinement and, in the professional research fields, scientists have to keep up with modern equipment. In addition, one does not want to be training students on obsolete equipment, since that training will not really serve them in graduate school or the workplace. In the radio astronomy regime, the instrumentation is much larger and hence remains research-grade for a longer time. Also, the basic principle of detecting radiowaves does not change, and so the telescope is always valuable as a teaching tool. However, in other fields, this may not be the case. In the area of chemical instrumentation, an instrument remains on the cutting edge for only a few years, but publishable quality data can be collected for several decades if the instrument is regularly upgraded.

The need for access to research instruments will not go away. In fact, in the modern era of high technology, it is more crucial than ever to train students to be able to use instrumentation.

Assessment

Finally, we can discuss the effectiveness of the remote instrument. Are the students reaching the educational goals set by the teachers or are they merely being exposed to an expensive toy?

In the experience of the Haystack program, we find that students who visit the site are awed by the size of the antenna and the fact that they are controlling this enormous telescope. But in terms of the research experience, they get the same exposure as the students who do not visit, except their experience is more real. In most cases, if the distant students are well prepared and the access issues are straightened out, their frustration level is not very high. According to surveys of the students' experiences, most of them found the experience to be rewarding though somewhat confusing, since they were unable to interact directly with the staff to clarify the better approaches. The faculty, however, did not think that the difficulties with the equipment failures that they sometimes encountered and the difficulties with the data analysis were necessarily detrimental. They felt that the students had a better feeling for the "real world" when things did not work as well as they expected.

At YSU and its partners, the use of remote diffraction has been very positive. Informal surveys and comments have shown that our early adopters and their students get very excited by using this cutting-edge instrumentation. In measurable terms, it has allowed new topics to be integrated into the curricula of remote sites, it has dramatically increased the publication frequencies of several participants by adding the "final touch" to longstanding projects, and it has led to new collaborations between institutions. On the other hand, we are only now carrying out rigorous assessments of student learning, as opposed to attitudinal, outcomes. These are very time-consuming and require expertise that was not available to most faculty in graduate school. In particular, such chemical/science education research requires collaborations with colleagues rigorously trained in evaluation and assessment methods—something in short supply in the laboratory sciences. We are currently pursuing such studies via several master's students in chemical education, but this is one area where more support from NSF and other foundations/agencies would be very valuable. One suggestion would be a bridge program to extend the training and facilitate the integration of social science faculty into such projects.

In the experience of the Columbia University adiabatic flame temperature experiment, student responses were positive. The scope of this experiment is rather modest, and students spent roughly 1–2 hours working on it. Students felt the lab was more valuable than a traditional homework assignment (the course is otherwise a traditional lecture course, with biweekly homework assignments). They also indicated that they would not have learned more if they had performed the experiments in a traditional hands-on setting. The majority of the students reported also that they repeated the experiments after some initial analysis of the data. Students felt that having the ability to work on a remote experiment at their own pace and at their preferred time of the day was a very positive attribute.

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