

## ***Remote Laboratory Research: Evidence for Effectiveness***

Laboratory experiences have long been considered a core component of technical degree programs – particularly in engineering and the applied sciences. Despite this, there has been surprisingly little consideration given to why laboratories are utilised and what are the intended learning outcomes for students. An ABET Colloquy in 2002 [1,2] described a core set of thirteen objectives for Engineering laboratories. These relate to the development of abilities such as applying appropriate instrumentation and tools, identifying the strengths and limitations of theoretical models, and the ability to collect, analyse and interpret data, as well as many others.

While not addressed explicitly, an implicit theme amongst a number of these objectives is the development of an understanding of either real-world engineering, or the way in which specific skills and knowledge relates to professional practice. These essential requirements had already been well articulated in earlier work. Consider, for example, the following quote from [3] (underlining is ours):

*“The undergraduate student should become an experimenter in the laboratory, which should provide him with the basic tools for experimentation, just as the engineering sciences provide him with the basic tools for analysis ... It is a place to learn new and developing subject matter as well as insight and understanding of the real world of the engineer. Such insights include model identification, validation and limitations of assumptions, prediction of the performance of complex systems, testing and compliance with specifications, and an exploration for new fundamental information.”*

Of particular significance is the articulated need to support students in gaining insight into the “real world” – presumably meaning the domain of professional practice within which the students are likely to be applying their skills. Once again, there has been remarkably little consideration given within the literature to how laboratories support this engagement with the realities of professional practice. Anecdotally, this will often have occurred through:

- Exposure to tools, equipment, instrumentation, etc. which is either used in professional contexts, or which is indicative of commercial equipment;
- Utilisation of skills (both technical and process management-oriented) which are explicitly relevant within real-world settings;
- Laboratory exercises which are representative of realistic problems and behaviours or which highlight relevant elements of these problems.

In response to an increasing consideration of the role of laboratories, and the emergence of sophisticated, networked ICT infrastructure, consideration was given to the possibility of remote access to physical laboratory apparatus. The earliest examples of this date back more than a decade, though the development of robust, enterprise-wide solutions is more recent. The last decade has seen a growing body of research into remote laboratories. The annual conference series *REV: Remote Instrumentation and Virtual Engineering*, which was first held in 2004, predominantly focuses on remote laboratories. Significant journal publications are regularly appearing in both specialised journals (e.g. *The International Journal of Online Engineering*) and mainstream Engineering Educational journals (*The IEEE Transactions on Engineering Education*, *The European Journal of Engineering Education*, etc.). Over the last decade there have been over 400 peer refereed publications that address remote laboratory issues.

The earliest era of remote laboratory research saw most effort being directed at technical evolution – preoccupations included experimenting with technologies for real-time audio and video streaming in an effort to overcome bandwidth limitations whilst ensuring service quality, and dealing successfully with the arbitration of multiple simultaneous connections to shared online laboratory apparatus and equipment [4,5]. To a significant extent, many of these issues have been successfully overcome. Continuous, reliable and high quality services have been maintained for much of the past decade.

In parallel with the progressive improvements in the technical systems has been an increasing interest in considering the pedagogic elements of remote laboratories. Early work in this area tended to focus on comparing different lab modalities – particularly hands-on (sometimes also called *proximal*) laboratories, remote laboratories, and simulations. The results of this early research were somewhat mixed. On the one hand, aggregated evaluations of student learning seemed to imply that there is no significant difference between the educational outcomes from students who performed an experiment remotely, versus those who carried out a hands-on experiment [6]. Such findings are similar in orientation to the majority of research in web-based learning (WBL) which has focused on WBL effectiveness compared with traditional classroom learning [7,8]. According to a number of these studies, there is no difference effect in performance between students enrolled in the two environments [9,10]. However, more detailed studies have shown that, whilst overall learning is still achieved, students' performances on different criteria can vary depending upon the form of access used and that indeed some outcomes appear to be enhanced by non-hands-on access modes, whilst others seem to be degraded [6,11,12].

For example, [13] considered the extent to which remote laboratories can provide the same educational benefits achievable in hands-on laboratories. A greater degree of analysis is reported in [11], where a very detailed experimental analysis on student learning outcomes is reported. The research provided clear evidence, based on statistically significant student sample sizes, that:

- The access mode affects some (though not all) learning outcomes. In particular, there were some learning outcomes that were achieved more effectively through hands-on experimentation (e.g. identification of assumptions) and others that were achieved more effectively through remote access (e.g. processing of data).
- The access mode affects the student perceptions of the laboratory objectives. Surprisingly, remote access increased the students' perceptions that the laboratory was focused on the importance of hardware, over the perceptions of students with hands-on access.
- Students engage quite differently with different access modes. Whilst there was not a statistically significant difference in their level of engagement (or intellectual stimulation) with the different laboratories, this stimulation arose from quite different sources. In hands-on laboratories the stimulation arose from being exposed to new experimental apparatus. With remotely accessed laboratories the stimulation arose more directly from the opportunity to connect theory to practice.

The overall conclusions from this research indicate that remote laboratories, if used appropriately in a way that is cognizant of the intended educational outcomes of the laboratory experience, can provide significant benefits [14]. Similar findings to these have subsequently been reported by numerous other studies, including [2,4,11]. Other research [16] has explicitly addressed the loss of the hands-on experience in remote laboratories,

with findings that confirm that there is no loss in the educational outcomes – provided the laboratories relate to the relevant learning objectives.

Having recognised that hands-on and remote laboratories do indeed provide *different* benefits in supporting *educational objectives* and hence can be used very effectively together, consideration can shift to how best to then enhance those educational benefits. Recent attention has been given to aspects such as support for multiple students collaborating in a remote laboratory (e.g. [17,18,19]), communication when using remote laboratories (e.g. [20]), and integration of remote laboratories into learning management systems (e.g. [21]). Perhaps more interesting is the ability of remote laboratories to provide experiences that cannot be easily created (or possibly cannot be created at all) in a hands-on laboratory. Examples of these include:

- The ability to augment the laboratory experience in some way, such as overlaying a live video feed of the experimental apparatus with a representation of some physical but non-visible phenomena (e.g. [22,23]);
- Embedding the laboratory into a real-world context, such as allowing students to collect data from load sensors and cameras attached to a physical road bridge as traffic crosses the bridge (e.g. [15]);
- Providing access to experimental situations that are not feasible in conventional hands-on labs, for reasons of safety, security or access (e.g. experimentation using radiation or dangerous chemicals).

Whilst there has been significant research into the pedagogic foundations of remote labs and how they can be used to complement hands-on laboratory experiences, there has been limited consideration of their ability to provide logistical or resourcing benefits, despite this often being used as a key argument in support of their use. Early discussions considered aspects such as cost, security, reliability and convenience [24]. This looked at the extent to which operating costs can be reduced through savings in both physical space requirements and reductions in maintenance costs. There has also been considerable interest in the opportunities created for the sharing of laboratory infrastructure [25,26,27], though rigorous studies on this have yet to appear.

## References

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