Mixed reality learning spaces for collaborative experimentation: A challenge for engineering education and training

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Abstract—**Although the vast majority of research in human-computer interaction involves only our senses of sight and hearing, with sporadic forays into touch, future laboratories used in engineering education will mostly benefit from developments beyond video and sound. Tangible and embedded interaction, augmented and mixed reality characterizes ultimate technologies for further applications in collaborative remote engineering and lab work. This paper presents our latest research to facilitate collaborative experimentation with such innovative technologies. Our vision is a collaborative learning space, which involves an amalgam of real, virtual and remote lab tools to support a wide spectrum of simple and complex, concrete and abstract, safe and dangerous experimentation settings. We will review related concepts and discuss lessons learned from our research and prototype development. Recent work involves the use of mixed reality (as opposed to 'pure' virtual reality) techniques to support seamless collaborative work between remote sites. We describe this and identify areas for future research.**

***Index Terms*—e-learning, remote experiments, virtual labs, hands-on labs, mixed reality.**

I. Introduction

Laboratories are fundamental educational tools in engineering education and vocational training. As new technologies are changing the character of laboratory-based courses, there is an intensive discussion about the pro and cons of physical versus computer-simulated laboratories. The increasing popularity of remote laboratories adds a further dimension to the debate. In addition, the debate turns more complex for another reason: almost all laboratories in science and engineering are mediated by computers. Accordingly, many lab devices are nowadays operated via a computer-based interface anyway. In such cases, the mode of accessing the lab equipment may not differ much, whether the student is collocated with the physical apparatus or is interacting remotely via a virtual interaction panel. Thus, in order to ascertain what is actually meant by the aforementioned types of labs, we will in the first step differentiate between hands-on and virtual (simulated), local and distributed, and mono-user or multi-user environments (Fig. 1).

The question, indeed, is to what extent virtual or remote laboratories can replace hands-on labs. There is no general answer to this broadly framed question [1]. For a methodologically careful discussion we examine the educational objectives in relation to each laboratory type.

nature of equipment \ user access	local	distant
physical (real)	**hands-on lab**	**remote lab**
virtual (modelled)	**virtual lab**	**distributed virtual lab**

Figure 1. Laboratory environments

Hands-on labs allow learners to operate a real plant or to manipulate tactile objects while being directly collocated with the tools and objects in the same place. This type of learning environment provides students with the hazards of the real world - the disparity between theory and practice. Learning experiences in real-life situations are not only a key prerequisite for learning psychomotor skills, but also relevant for understanding theoretical concepts. In addition, hands-on labs are important initially to establish the 'reality' of remote laboratories or the accuracy of simulations for later study.

Virtual laboratories are non-physical tools. Actually, they are simulated labs. Consequently, a virtual laboratory can be defined as a computer-based model of a real-life lab. It can be realized as a local or distributed application. An important educational value of virtual labs is the reduced risk associated with operator errors, and the opportunity to experiment and practice without being exposed to hazards. That is why the virtual lab very often acts as an antechamber (e.g. for pre-lab assignment) to the real-world experiment, allowing the application and testing of theoretical knowledge in a safe environment before trying out the same actions on real equipment. In other cases virtual lab equipment is useful to provide complex experiments without the need to purchase real equipment.

Remote labs are useful complementary educational resources, because they allow monitoring or supervising a running experiment from geographically dispersed places. Getting rid of geographic proximity restrictions has far reaching consequences for education. Students and teachers working from distant locations, 24 hours a day, can share networked remote lab facilities.

We can summarize that experiments in a hands-on laboratory impose a valuable and indispensable experience of physical phenomena and reality. Virtual laboratories provide a safe environment for experimentation with dangerous equipment. Remote labs (like virtual labs) have a significant advantage over real laboratories because of their flexible accessibility. In conclusion, there is no simple answer to the question, which laboratory is the best for engineering education or vocational training. All types of laboratories offer certain advantages. Anyhow the question arises, whether we are able to design a new kind of innovative learning environment that supports a balanced *mixture* of multiple real, virtual and remote labs.

In the following sections we will discuss these issues in depth. We will start with a short introduction to the topic of Mixed Reality (as opposed to 'pure' virtual reality). We will review related concepts and discuss lessons learned from our own research and prototype development. Before concluding, a case study will be presented. This recent work involves the use of mixed reality techniques to support seamless collaborative work between remote sites. Finally we identify areas for future research.

II. MIXED REALITY

Mixed reality comprises concepts and technologies to design innovative user interfaces where physical and digital artifacts co-exist in the same computer-based environment. Mixed Reality is focused on merging real and virtual worlds, combining a variety of techniques to mix and/or link real with virtual objects [2]. 3D modeling, tracking, haptic feedback, simulation, rendering and display techniques are core elements of Mixed Reality applications. Early developments were mostly based on blending computer generated virtual worlds or simulations with real-life video. Later on, interfaces where developed, which sense and generate real-life data being exchanged between virtual objects and their physical counterparts.

The term Mixed Reality is often used interchangeably with Augmented Reality (AR) or Augmented Virtuality (AV). But there is a difference between AR and AV, which can be explained by the so-called Reality-Virtuality (RV) Continuum. This concept was first introduced by Milgram [2], who generally defines a Mixed Reality environment as being "... anywhere between the extrema of the RV Continuum", where the Reality-Virtuality extends from the completely real to the completely virtual environment with AR and AV in between (Fig. 2).

Mixed Reality techniques have been first tested in single user applications. Billinghurst and Kato [3] demonstrated that Mixed Reality is also very useful for collaborative work environments. Also Benford et al. [4] demonstrated techniques of Mixed Reality as a way of joining real and virtual spaces for collaborative work.

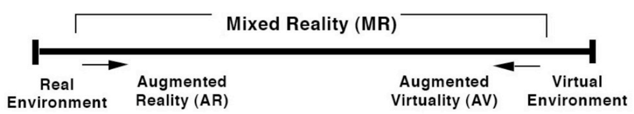

Figure 2. Reality-Virtuality (RV) Continuum [2]

The Mixed Reality approach brings the virtual world of computers into the physical world of ordinary human activity. This includes aspects of natural communication that serve as mediators for mutual understanding: physical object handling, eye contact, and facial play. Thus Mixed Reality supports users to continue using physical artifacts they encounter in their ordinary job and then to enhance them with the functionality of virtual models: Users can make use of computer generated data or simulation models while continuing their tasks, instead of constantly returning to a stationary computer or keyboard. Moreover, Mixed Reality also seems to be a promising concept to support social presence in collaborative remote environments, as it can enable co-located and distributed users to interact in distributed virtual spaces while viewing or even manipulating real world objects at the same time.

Mixed Reality interfaces can overlay graphics, video, and audio onto the real world. This allows the creation of shared workspaces that combine the advantages of both virtual environments and seamless collaboration with the real environment. Information overlay may be used by remote collaborators to annotate the user's view, or may enhance face-to-face conversation by producing shared interactive virtual models. In this way, Mixed Reality techniques can produce a shared sense of presence and reality [5]. Thus, Mixed Reality approaches are ideal for multi-user collaborative lab and work applications.

III. INTERFACING REAL AND VIRTUAL LAB WORLDS

Most existing experimentation tools strictly separate reality and virtuality. Accordingly it is not possible to establish mixed experimentation settings. The reason for this is manifold. First of all it is not easy to combine arbitrarily virtual lab equipment (simulated components) with real equipment to provide a running mixed experimentation environment, because a seamless connection between both worlds has to be implemented. In most cases such interfaces between virtual and physical lab components do not exists and there are no standards available, which describe the bidirectional information flow across real and virtual boundaries in a unified method. As reality may be the continuation of virtuality or vice versa a general dynamic system approach seems to be necessary.

Based on theoretical research and a series of case studies carried out at artecLab, we have developed an interface for mixed reality, supporting a unified view on the interaction between real and virtual spaces [6, 7]. All measurements of physical phenomena and all human perceptions are based on energy exchange. However, the level of involved energy might differ considerably. On a semiotic level, energy is the carrier of signs and signals, on an action level, energy is the driving force.

One of the challenging problems to implement energy-based interfaces is that physical phenomena are modeled in various domains in different notations — e.g. mechanical domain, electric domain, and hydraulic domain. Bond graphs are suited to overcome this manifold. They give effective insights in how to design a mixed reality system as a whole, reusable, and easily extendible model. A concept to design and implement a universal energy interface between real and virtual objects was developed and is called Hyper-Bond [6]. The name Hyper-Bond has been chosen because of its relation to the description of dynamic systems with bond graphs, first introduced by Paynter [8]. The concept of Hyper-Bond can be summarized as follows:

In a dynamic system links between various sub-systems can be described as energy- (or power-) connections, which preserve the behavior of the overall system. Power is a product of effort (e) and flow (f). Effort e stands for force, pressure, voltage, etc., and flow f stands for velocity, flow of a fluid, current, etc. If an appropriate interface is provided to sense effort and flow at one side of the intersection and generate effort and flow at the other side and vice versa, two subsystems (real or virtual) can be connected in a way, which preserves the behavior of a comparable connected real system. Hyper-Bonds represent a hardware- and software implementation of this mechanism to sense and generate physical phenomena at the leading edge of an energy-connection of two subsystems. Power (effort × flow) can be bi-directionally transferred from a real energy-level into a virtual signal/information-level and vice versa. Real systems, virtual systems and Hyper-Bonds can be described by bond graphs and analyzed according to classical control theory [8]. The concept allows the splitting of dynamic systems into "pieces" as long as effort and flow are preserved at either side of the intersection to maintain a dynamic equilibrium.

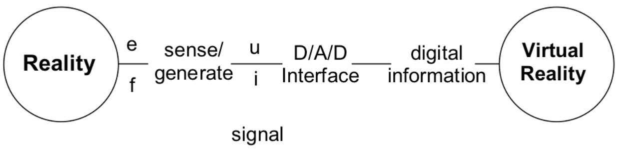

Figure 3. Interface between real and virtual object

Fig. 3 describes in general the interface between the real world and the virtual world: Effort and flow are sensed (or generated) providing voltage and current (or effort and flow in the opposite), an analog-digital converter provides digital information for the software (or an digital-analog converter converts digital information in analog signals to drive a generating mechanism for effort and flow to the real world). This interface generates or dissipates energy (or power). The power, provided through the real system, has to be dissipated, because the virtual continuation with software needs nearly negligible power. In the opposite direction, the digital information provided through the software, has to generate the power necessary to connect the real system.

This concept may be useful not only to couple real and virtual objects of a single physical phenomenon, but also together with distributed real and virtual systems. The process, as a flow of energy - controlled by signals and information - is either real or completely modeled in virtuality and simulated. In distributed environments information flow can cross the border between reality and virtuality in an arbitrary bidirectional way. Reality may be the continuation of virtuality or vice versa. That provides a seamless connection between both worlds. The bridging or mixing of reality and virtuality opens up some new perspectives not only for work environments but also for learning or training environments [9]. The next section describes two prototypes of this approach for collaborative experimentation.

IV. CASE STUDIES

A. *Collaborative task solving between remote sites*

In a first case study we implemented a shared virtual and remote laboratory for electro-pneumatics based on Hyper-Bond technology [10]. The environment allows working collaboratively with real and virtual systems, consisting of parts, which may be remotely distributed. Accordingly a remote laboratory workbench can be coupled with a local virtual workbench and vice versa. The system supports full hardware-in-the-loop functionality allowing to build up complete electro-pneumatic circuits, which may consist of distributed mixed physical and virtual electro-pneumatics (Fig. 4 & 5). The virtual and real workbenches can either be located at remote sites connected via the Internet or the virtual workbenches may be distributed at different sites connected via the Internet to the (only one) real workbench. The software of the virtual workbench allows the access of many users at the same time. Therefore students or workers distributed at different locations can together solve tasks at their virtual workbenches and export the results to the real workbench for testing their common solution in reality.

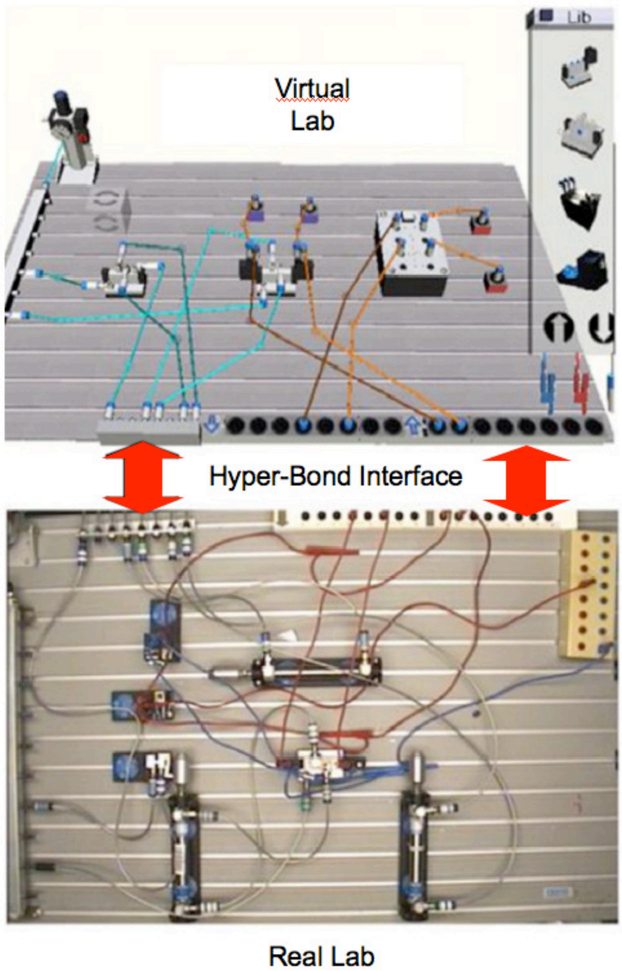

Figure 4. Mixed Reality Lab for e-pneumtics [11]

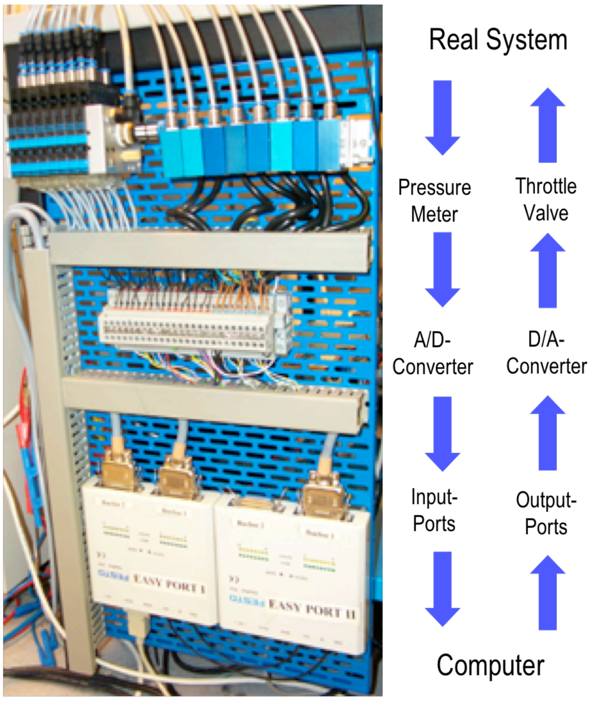

Figure 5. Hyper-Bond interface hardware (for electro-pneumatics)

The real and virtual workbenches were implemented as a Web Service to take advantage of web technology (e.g. easy accessibility, platform independence) [11]. A central module is the Mixed Reality (MR) Server, which realizes this Web Service. The Web Service itself processes HTTP requests and also manages the sessions of all remote users. Relevant data belonging to a certain work session is stored on the server, such as virtual model data, support material and background information. The WWW front end consists of a HTML page including a Virtual Construction Kit (VCK) and a video stream window. The VCK itself is a VRML based tool for assembling virtual worlds: by dragging and dropping objects from a library onto the virtual workbench new objects (e.g. cylinders, valves, and switches) can be added. Each of these objects has connectors which can be linked to other ones. Links can either be tubes (air pressure) or wires (electricity). Connections between real and virtual workbench elements were realized by the aforementioned Hyper-Bond technology.

B. *CAVE as a workspace of real and virtual workbenches*

In a current case study we are upgrading our previous prototype and combining it with a Computer Automatic Virtual Environment (CAVE)[1]. We are using two CAVE-like constructions, because we want to test how remote and local users can immerse into a common workspace for solving a joined task, such as collaborative tele-design or tele-maintenance. Every CAVE consists of a room-sized cube covered with canvases. The different images of other workspaces with the participants working in them are projected onto the canvas walls. The common virtual workbench and the real physical workbench are accessible via the Internet and also visualized in each CAVE. Client computers connected to a central media server control the projections. Because available CAVEs are very expensive, we developed a low budget solution, which consists of wooden scaffoldings, ordinary video projectors and PC's. In comparison to commercial CAVEs our system offers nearly the same performance and provides a sufficient solution for research. The following figures show the arrangements used for the test cases. The basic architecture of the distributed CAVEs is illustrated in Fig. 8.

First experience gained in this case study has already illuminated how future engineering workspaces and laboratories could be structured [13]. Several key features of tomorrow's remote laboratories can be identified, including support for freely exploring a phenomenon and its appearance in various applications and contexts, means for a universal mixing of real and virtual objects, and distributed work on tasks in a multi-modal and multi-user way.

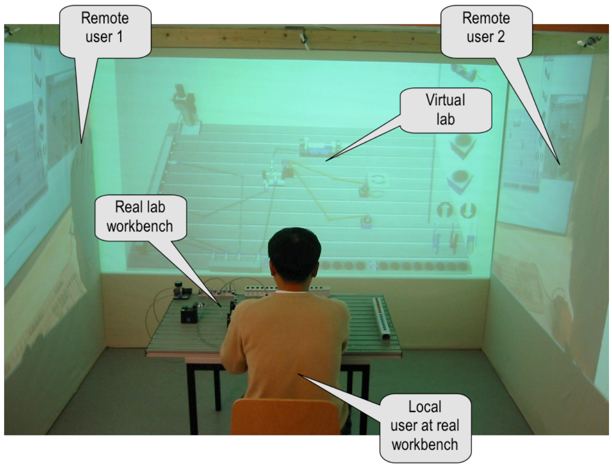

Figure 6. Workspace at the real workbench in a CAVE

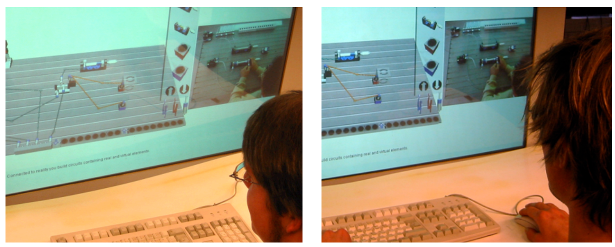

Figure 7. Two distributed users connected to the real workbench from remote

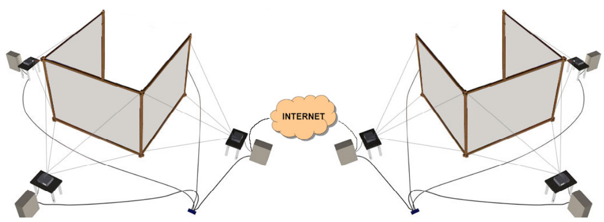

Figure 8. Distributed CAVE-based workspaces

[1] A CAVE is a 3-D immersive virtual reality environment where projectors are directed to the walls of a room-sized cube [12].

V. Conclusions

Presently some research effort is being done to foster collaborative engineering between remote sites. One of the problems is to seamlessly connect the real to the virtual world. As an example the paper described the connection of a real workbench with the remote located virtual ones.

Our vision is a collaborative learning space, which involves an amalgam of real, virtual and remote lab tools, as they represent a wide spectrum of relevant settings in lab learning. Learners should be able to use multiple senses (e.g. visual, auditory, tangible, haptic and olfactory stimuli), when interacting with remote lab devices. To share the tangibility of hands-on labs wherever they are in the world is the ultimate goal. The laboratories envisaged should support users to work with real and virtual, complex and simple systems, isolated or embedded parts, local or distributed components, thus allowing a continuous shift between various degrees of abstraction and various levels of distributed collaboration. Networked laboratory hardware equipment is linkable to virtual learning environments by means of special bidirectional sensor-actuator coupling interfaces. At the moment this seems to be a quite visionary approach. But future laboratories will benefit from further developments in computer simulation technology, mobile computing, sensor/actuator devices, integrated equipment supporting hardware-in-the-loop functionality, and enabling connections to be made between real-life phenomena and their virtual representation or continuation.

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