A novel Approach to Engineering Education Laboratory Experiences through the Integration of Virtual Reality and Telerobotics

Preston Ward, Michael Hempel, Hamid Sharif
pward6@huskers.unl.edu, mhempel@unl.edu, hamidsharif@unl.edu
Department of Electrical and Computer Engineering, University of Nebraska-Lincoln

Abstract

Hands-on laboratory experiments are an essential part of engineering education at the undergraduate and graduate levels. However, establishing and maintaining these laboratory capabilities is expensive, time-consuming, and often requires significant building space. To address these challenges, we explore remote laboratories to provide similar student experiences in a more accessible, inclusive, and cost-effective way, enabled by the recent increases in the availability of low-cost virtual reality (VR) solutions and robotic arms. While VR is a widely used educational tool, this design approaches the necessity for high-resolution images, support for fine motor control, and low-latency operation, specifically for engineering classes. In this paper, we present our framework design that allows users to control a Baxter robot in the Advanced Telecommunications Engineering Lab (TEL) remotely, allowing students to conduct experiments involving lab equipment at any time, from virtually anywhere. This paper discusses the technical implementation of this project and its benefits to electrical and computer engineering education. It also provides a pathway to implementing this approach into other undergraduate engineering courses.

Keywords

Undergraduate student paper, telerobotics, virtual laboratory, virtual reality, engineering

Introduction

During the COVID-19 pandemic, universities around the world adapted by integrating asynchronous lectures into their curricula. While this allowed students to participate in their courses and proceed through their education requirements, a challenge emerged in how to adequately enable asynchronous or remote participation in laboratories that are designed around hands-on experimentation, for example, for electrical engineering classes. Although universities have largely reverted to typical courses after the pandemic, remote or asynchronous degree program opportunities remain attractive and of interest to students. Hence, the demand for transforming hands-on laboratories to remote formats remains, especially for creating more opportunities for non-traditional and disabled students. In this paper, we present our work on creating a near-presence VR-driven laboratory experience in the TEL lab. This approach is built around telerobotics and its integration into undergraduate Electrical Engineering education at the University of Nebraska-Lincoln.

Related Works

To accommodate non-traditional students, and in response to the COVID-19 pandemic, universities began exploring remote labs to enhance their learning. In reviewing the related literature, we found the following work. The most common implementation is through 2D computer-simulated laboratories. In 2010, Tüysüz discovered that these virtual labs benefitted students by giving them more time to work on the project [1]. Rather than rushing through the experiment, they carefully thought about the material. However, virtual labs still do not provide the full experience and educational value of hands-on labs. Integrating VR allows students to work in a 3D space, becoming more immersed in the project, thus enhancing their learning [2]. In fact, Whitney et al. showed that users preferred using a VR interface and finished their tasks quicker [3]. Zhou et al. used a Baxter robot with a Microsoft Kinect v2 camera mounted on the head of the robot for a civil engineering operation at the University of Florida [4]. These researchers captured point cloud data from the Kinect camera and published the scene into Unity, using an HTC Vive for VR control. Teleoperators were able, with some limitations, to remotely install a PVC pipe.

Approach and System Overview

To achieve teleoperation services for education, our system is designed around the Baxter robot platform in our TEL lab, and a VR system for the end user, as shown in Fig. 1.

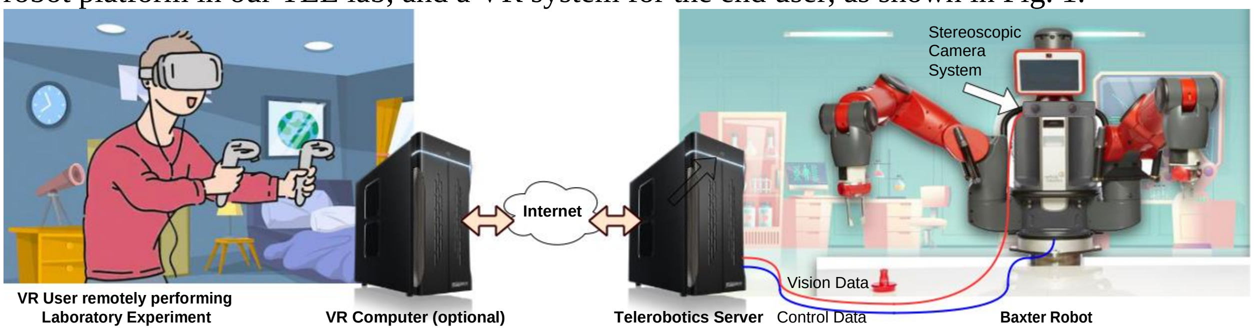

Figure 1. End-to-End System Architecture Overview

A Baxter robot from Rethink Robotics [5] and a stereoscopic camera system were installed in our lab. Baxter was chosen due to its availability, advanced human-machine interaction features, and ease of integration. Its command-and-control system was realized via a Linux server running Ubuntu 14.04 and Robot Operating System (ROS) Indigo. The server captures the vision feed and communicates with the robot. Via a ROS TCP connector, it will publish the camera stream and subscribe to control messages from the remote user's side. Additionally, the Linux machine will run an Inverse Kinematics (IK) solver to move the robot's actuators when it receives input.

The user-side functionality is implemented using the Unity 3D engine [6] for VR visualization and VR controller position capture. Our current implementation—shown in Figure 2—is based on a Meta Quest 2, but can easily be adapted to other VR headsets, e.g. HTC Vive, Valve Index, or Microsoft Hololens. When the student runs the Unity scene, their computer will connect to the lab through the ROS TCP connector. This allows us to receive and display the stereoscopic camera stream in VR and to publish the user's actions via the internet back to the lab and the Baxter control server.

System Capabilities and Considerations

Our system is designed to enable a near-presence experience for the end user – the user's perception of being physically present at the experiment, being able to naturally experience the environment and interact with it by closely mirroring the hands-on experience through VR and telerobotics. This is facilitated through the use of a stereoscopic camera system, with the feeds projected into the VR headset, which essentially allows the user to experience the environment in front of the robot as if they were physically present, including a sense of depth for accurate movement and interactions. The utilized robot, Baxter, is a dual 7-degree-of-freedom (DOF) robot with accurate movement, including gripper rotations and high-resolution positioning of all joints. It can grip and lift a variety of objects through the use of different end effector attachments. It also features advanced safety features to avoid injuring people within its operating area, and collision detection to avoid damaging the robot itself. Lab testing of the robotic teleoperation setup performed in our laboratory is shown in Figure 2 below.

When implementing this system, we need to consider two principal factors that can negatively impact the overall user experience: latency and robotic capabilities. End-to-end latency in this system is comprised of the video pipeline delays, control communication latency, the IK solver delay, and the actuator control latency. If latency is too large, the user is forced to endure long delays between performing an action and observing the result. Hence, latency reduction is at the core of our ongoing research efforts. This can be exacerbated by robotic limitations, most notably in the grippers. The Baxter robot can lift larger objects far easier than smaller ones such as wires, as a result of the small surface area, low friction, and flexibility. We are conducting research to optimize gripper designs for various different labs and anticipated exercised and target objects. This will be discussed more in the next section.

Figure 2. Telerobotic Experiment Depiction

Laboratory Exercise Implementation

Adapting this teleoperation setup to different classroom laboratories requires some amount of customization. These range from simple modifications to complex additional feature implementations. For example, in electronics labs, one of the easiest experiments to adapt is related to conducting measurements. For this task, multimeter probes can either be attached to the gripper, replace a gripper, or be dynamically picked up by a gripper. The student can then remotely move the probe from point to point and conduct measurements, while the camera view will show the measurement results. Alternatively, networked multimeters can be used that allow our GUI to visualize the multimeter readings directly in the VR headset view.

Other activities, like working with a breadboard, are more challenging to implement. Not only does this require precision, but also improved grippers or breadboard wire designs, to reliably grip and place wire ends. By adding high-friction rubberized sleeves to the wire ends in our setup, we could consistently place and remove wires from the breadboard. We are currently exploring additional approaches for other laboratory requirements, for example, by replacing wire ends with magnetic ends to ease placement and removal complexity.

Contributions to Education

A virtual laboratory reduces the amount of time and space required by physical labs, as well as increases accessibility. For large engineering programs, labs have limited test equipment and space. They also require students to attend labs during designated times, and require Teaching Assistants to conduct and oversee lab activities. Because of this and other accessibility challenges, not all students are able to attend labs as traditionally designed, missing out on essential learning. On the other hand, a remote laboratory reduces the need for space on different campuses as well as reduces the amount of needed test equipment. This allows students to work on the experiments at their own pace at a time of their choosing, and from anywhere. At the same time, remote labs also enable more ad-hoc interactions with lab technicians and teaching assistants, resulting in more efficient resource usage of space, materials, and personnel. Remote labs can be remotely monitored, and sessions can easily be recorded for grading, instructor feedback, and supervision.

This research benefits education by making labs significantly more accessible to non-traditional students, disabled students, as well as students who cannot fit a lab into a fixed schedule. It also enables online education institutions and hybrid degree programs to integrate laboratory experiences that would otherwise not be possible. This enables students of such programs to be far better prepared for their future careers and supports inclusion efforts by enabling and promoting lab access for students with disabilities. For example, since such labs are no longer a space with significant distractions, students with ADHD or who are on the autism spectrum will find a far more suitable and adapted experience through VR teleoperated labs.

Conclusions and Future Work

In this paper, we are presenting our design and implementation of our VR-driven telerobotics platform for enabling near-presence experiences for hands-on engineering laboratories that require higher visual fidelity and more accurate control than current VR integrations. We highlighted some of the research challenges and outcomes.

In our future work, we are going to examine ways to address some of the system challenges, such as reducing the end-to-end latency of the system to improve user experience, improving and adapting the robot gripper design to better adapt to different use cases, and working on UI capabilities for advanced measurement and device integration directly into the VR UI for optimized command and control. This includes the use of various manufacturer APIs for device control. It also includes latency reduction through AI-driven movement prediction to reduce the latency impact of the IK solver and actuator movement delays, and GPU-accelerated IK solvers.

Additionally, we will conduct user experience (UX) testing by having current electrical and computer engineering students at the University of Nebraska campuses conduct a series of typical hands-on electrical engineering experiments through traditional lab setups and through the VR platform, for in-depth qualitative and quantitative assessments of the benefits and remaining challenges of this novel approach.

References

[1] C. Tüysüz, "The Effect of the Virtual Laboratory on Students' Achievement and Attitude in Chemistry," International Online Journal of Educational Sciences, vol. 2, January 2010.

[2] H. Horner, "The Benefits and Challenges of Remote Labs for Engineering Students - Engineering Institute of Technology" [Online]. https://www.eit.edu.au/the-benefits-and-challenges-of-remote-labs-for-engineering-students/. (accessed Jul. 17, 2023).

[3] D. Whitney, E. Rosen, E. J. Phillips, G. Konidaris, and S. Tellex, “Comparing Robot Grasping Teleoperation Across Desktop and Virtual Reality with ROS Reality,” 18th International Symposium on Robotics Research, pp. 335–350, Nov. 2019.

[4] T. Zhou, Q. Zhu, J. Du, “Intuitive Robot Teleoperation for Civil Engineering Operations with Virtual Reality and Deep Learning Scene Reconstruction,” Advanced Engineering Informatics, vol. 46, October 2020.

[5] Rethink Robotics. (2012). Baxter: Collaborative Robot. [Online]. https://www.rethinkrobotics.com/baxter/.

[6] Unity Real-Time-Development Platform. [Online]. https://unity.com/

Preston Ward

Preston Ward is a sophomore Computer Engineering student at the University of Nebraska-Lincoln (UNL), and will graduate in 2026. His current research interests include robotics and telecommunications.

Michael Hempel

Michael Hempel (Senior Member, IEEE) is a Research Assistant Professor in the Department of Electrical and Computer Engineering at UNL. He is currently pursuing research at the nexus of cybersecurity, machine learning, and operational technology. He has authored or co-authored more than 170 publications in major international journals and conferences, and served as a TPC member on numerous international conferences.

Hamid Sharif

Hamid Sharif (Fellow, IEEE) is a Professor in the Department of Electrical and Computer Engineering at UNL. He has published about 400 research articles in international journals and conferences and has been serving on many IEEE and other international journals' editorial boards. He has received a number of research and best paper awards. He is currently a Distinguished Lecturer for the IEEE Vehicular Technology Society.