ElectroVR: An Electrostatic Playground for Collaborative, Simulation-Based Exploratory Learning in Immersive Virtual Reality

Scott W. Greenwald, Wiley Corning, Gavin McDowell, Pattie Maes, and John Belcher
scottgwald@media.mit.edu, wjlc@mit.edu, gavinmcd@mit.edu, pattie@media.mit.edu, jbelcher@mit.edu
Massachusetts Institute of Technology

Abstract: The ElectroVR interactive demonstration allows two participants to occupy a single physical and immersive virtual space with one another, in which they can learn through spatial interaction with an electrostatics simulation sandbox. Narrative sequences optionally offer exposition of key principles and suggestions of exploratory activities. The demo shows three key approaches operating in tandem: collocated, multi-user, positionally tracked Virtual Reality (VR); a spatial simulation-based exploratory learning environment; and a playback system that presents narrative sequences prepared by instructors in the virtual environment. As such, it offers a novel and powerful embodiment of the "4E learning" paradigm that is the theme of this conference.

Introduction

We explore a promising design space for constructivist learning at the intersection of three well-established approaches: (1) embodied learning in immersive six-degree-of-freedom (6DoF) VR, (2) simulation-based exploratory learning, and (3) collaborative learning. These have not been combined previously to our knowledge. This demo brings together all three of these in a novel learning experience in the domain of electricity and magnetism. This domain was chosen because it is known to be both challenging and highly spatial, and hence likely to benefit from the use of stereoscopic 3D presentation, 6DoF head movement, and hand-based embodied interaction.

Figure 1. Collocated use of positionally tracked VR.

One further key idea put forth in the demo is that of recording and playback. The demo makes most prominent use of this in a series of narrative sequences that are recorded in the environment by instructors. Learners hear instructors' explanations, accompanied by minimal avatars which move realistically, replicating the instructors' real movements from the time of recording. This creates a strong sense of copresence – that is, the learner feels they are sharing a space with a human (Greenwald et al., 2017b). In addition, these avatars interact with the same interactive affordances (objects and tools) that are available to learner. Whatever is demonstrated by the instructor can be directly accessed by the learner as well. This sets the stage for engaging exploratory activities that follow the narrative sequences.

Not only is the playback of recorded narrative sequences powerful pedagogically, it is also a key strategy that can make the production of substantial quantities of content (from tens of minutes to hours) tractable for a small team. Using typical approaches, where experiences make significant use of animated sequences that are produced using digital art and graphic design tools, authoring 20 to 30 minutes of VR content is a highly resource- and time-intensive process. Our approach is analogous to bringing a video camera into a physics lab in order to create content – the lab equipment can be used in many different ways to illustrate a variety of ideas and principles. It is the instructor that creates a narrative and guided activity to address a given topic area, and the content is produced in real-time (of course, subject to repeat takes and manual preparation time in the virtual environment).

Background and prior work

In the past five years, consumer VR devices have burst onto the market, and created new opportunities for the application of VR at scale. Although learning is thought to be one of the most promising areas, few attempts have been made at implementing it in formal learning settings. Among these, the most common approaches have been to expose learners to (1) the content that is available in online marketplaces in a very broad, nonpedagogical fashion, and (2) the process of making VR content using today's tools. In contrast, this demo represents an attempt to convey a specific set of ideas in electricity and magnetism (Coulomb's Law and Gauss' Law), which are challenging, and can benefit from an intuition-building approach that is complementary to algebraic approaches that are the usual focus of the corresponding coursework.

We briefly review prior work in the areas of (i) collocated 6DoF VR, (ii) science learning in VR, and (iii) non-VR collaborative science learning.

Several projects have implemented systems to explore collocated, 6DoF VR. One system for group-togroup telepresence created a shared immersive virtual reality for local and remote groups of participants, using projection-based multi-user 3D displays (Beck et al., 2013). The “Holojam” system used head-mounted displays to allow many users to share a physical and virtual space. Use cases in data visualization and creative expression were demonstrated (Royston et al., 2016; Masson et al., 2017). “CocoVerse” is a shared collocated immersive virtual environment utilizing multiple head-mounted displays (HMD’s), and including several different multiuser co-creation interactions through hand-bound tools, including 2D and 3D painting, import and placement of arbitrary 2D images and 3D models, and a virtual camera tool (Greenwald et al., 2017a). A later version of this environment also included a software framework for recording and replaying users’ actions and their effects on the virtual environment. Users are represented using minimal avatars. In subsequent work building on this system, the authors explore the quality of non-verbal communication afforded by this form of avatar representation. Using subjective and objective measures, they find that the movement realism of embodied minimal avatars yields a strong sense social presence and an effective medium for gestural communication (Greenwald et al., 2017b). In our demo, we build on the same technology and avatar representation as CocoVerse, with the goal of leveraging the demonstrated communicative benefits into an environment containing rich science-oriented content.

In the area of spatial learning, *ScienceSpace* (Dede et al., 1996) was a pioneering work, implementing science-oriented educational content in 6DoF VR, including *MaxwellWorld* focused on electrostatics using interactive visualizations of charge, electric field, and electric flux. A refined model was developed for understanding the impact of the various affordances of immersive virtual reality on conceptual learning (Salzman et al., 1999). The much newer, more performant VR technology we use improves significantly on the user experience of ScienceSpace. A recent paper makes a direct comparison between learning on a 2D screen and learning in VR using electrostatics activities. Learners reported deeper spatial insights when using the VR version (Greenwald et al., 2018). Both of these prior works indicate that science-oriented spatial learning in VR is highly promising. Our demo goes further than both by incorporating collaboration, recorded in-world instruction, and an extensive set of affordances for exploration.

Finally, some notable prior works explored the area of non-immersive, simulation-based computer supported collaborative learning (CSCL). One of these used a system for co-located collaborative learning, particularly of topics in physics, through a 2D (traditional screen) web interface, leveraging spatial arrangement of information, interactions such as drawing, graphing, and text input (Coopey et al., 2013). This system enabled classroom-scale collaboration leveraging 2D representations. Our demo does not support a large number of users in this fashion, and it is oriented towards deep spatial insight, rather than algebraic and quantitative analytical skills. Other authors explore the use of 3D virtual environments using non-immersive technology in collaborative learning, through the design of a problem-based physics learning activity in Second Life, finding that such a virtual collaborative learning activity can be engaging and effective (Vrellis et al., 2010). In contrast, the direct spatial manipulation affordance of 6DoF immersive VR offers a more learnable, natural interface than the keyboard and mouse, in addition to the forms of non-verbal communication mentioned above.

This brief survey of prior work has shown how each of the approaches we leverage in our demo has been explored to some extent, but they have not been brought together in one system before.

User experience

The interactive content in the demo targets learning goals related to Coulomb’s Law and Gauss’s Law at the undergraduate level. Participants enter VR together, and are given the option to either explore the affordances of the toolbox, or view immersive narrative sequences, in which recorded avatars operate the various tools and explain principles of physics (Figure 2). In the case that they view narrative sequences, they are at first somewhat passive, gradually learning to interact with the simulation system as they see demonstrations from the recorded instructors. In the case that they opt to explore using the toolbox, they use the graphical and text elements to infer what is possible, and proceed to experiment. They can opt at any time to switch between the exploratory toolbox-oriented mode and the explanatory narrative-sequence-oriented mode of interaction.

The toolbox contains three kinds of items: charge distributions, visualization objects, and hand-based tools. Charge distributions create the electric field that permeates the 3D space (Figure 3). Visualization objects allow participants to visualize the field in different ways that are spatially local, and they can choose to place or move these objects (Figure 4). Hand-based tools determine the functions of the handheld controllers (Figure 5). Considering each of these from the perspective of collaboration: when one participant spawns a new charge distribution, it affects the field everywhere in space. This means that each participant can drastically affect the visual and interactive experience of the other participant, regardless where they are standing or whether they are attending to one another. Visualization objects, on the other hand, are local and will only be observed by the other participant if they look in the relevant direction – choosing to explore visually and perhaps interact with the other participant. Finally, the hand-based tools are controlled exclusively by one user, as they are bound to the controllers. Each can be independently assigned– there is no mutual exclusion when instantiating handheld tools.

System

ElectroVR creates a shared physical and virtual space among multiple users with HMD's and handheld controllers. This section describes three aspects of the system: the physical and network architecture; the simulation engine; and the recording and playback system.

Each user requires a dedicated computer to run their HMD (our system uses the HTC Vive). Each computer runs an instance of the interactive environment, and the instances are synchronized across the network. This is accomplished through a client-server architecture, in which one of the connected machines acts as both a client and as the authoritative server. Each client represents its user with an avatar, which shows the user's headset and controllers on all connected machines. Each client instances also runs its own copy of the simulation. Because some aspects of the input to the simulation are non-deterministic, some simulated elements such as the positions of point charges are periodically synchronized with the server.

The simulation engine computes the electric field analytically using superposition of the charge distribution primitives. The field due to each of these primitives is given by a simple expression – for example for point charges, the contribution to the field is inversely proportional to the inverse square of the distance from a given point to the location of the point charge. The dynamics of the system of point charges is computed with a fourth-order Runge-Kutta algorithm.

The recording and playback system allows for the capture and reproduction of the actions of users in the environment. During recording, ElectroVR captures users' microphone audio, the movement of their avatars, and the evolving state of the virtual environment. In particular, the system logs each state change and high-level command that is executed on the server, along with an associated time stamp.

Project history and outlook

Begun in the summer of 2016, this project has proceeded through an iterative design process involving exploratory prototyping, a focus group of physics instructors, co-design with physics instructors, and piloting with students and instructors. In the spring of 2018, it was piloted with roughly 50 students, who each spent between 45 minutes and two hours, either solo or together with one or more partners, immersed and interacting with the system. The system successfully achieved its design goals, with very positive feedback from students. An analysis of collaborative behavior during the said pilots is ongoing work, and future applications of this system will enable the effectiveness of collaborative learning in VR to be rigorously tested and characterized.

Figure 2. Toolbox (left) and narrative sequence with instructor avator (right).

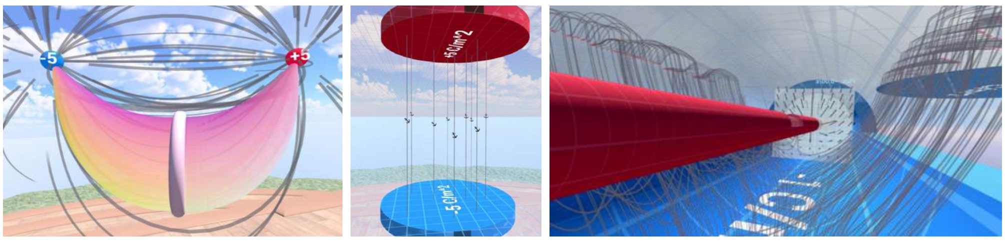

Figure 3. Example charge distributions (left to right): point charges, infinite slabs, and infinite cylinders.

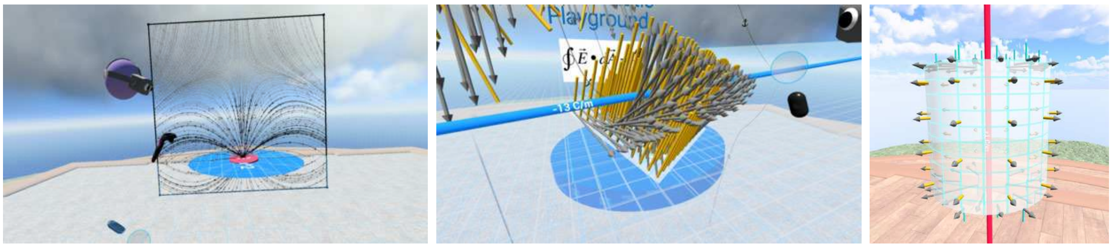

Figure 4. Visualization objects (left to right): 2D field line plane, flux plane, flux cylinder.

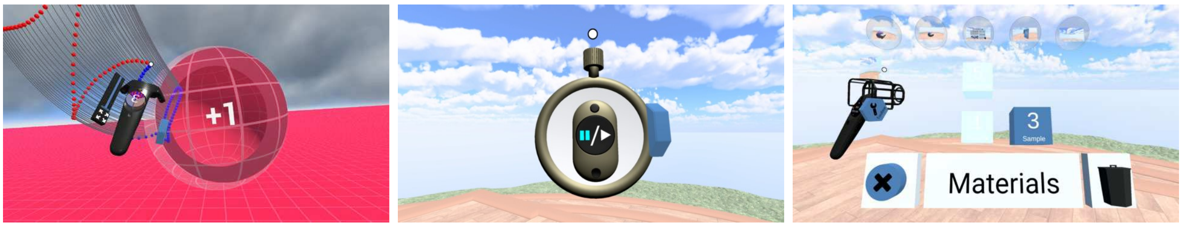

Figure 5. Hand-based tools (left to right): field line generator, simulator, camera.

References

Beck, S., Kunert, A., Kulik, A., and Froehlich, B. (2013). Immersive group-to-group telepresence. *IEEE Transactions on Visualization and Computer Graphics*, 19(4):616–625.

Coopey, E., Danahy, E., and Schneider, L. (2013). Interlace: Interactive learning and collaboration environment. In *Proceedings of the 2013 Conference on Computer Supported Cooperative Work Companion*, CSCW '13, pages 11–14, New York, NY, USA. ACM.

Dede, C., Salzman, M. C., and Bowen Loftin, R. (1996). Sciencespace: virtual realities for learning complex and abstract scientific concepts. In *Proceedings of the IEEE 1996 Virtual Reality Annual International Symposium*, pages 246–252.

Greenwald, S. W., Corning, W., Funk, M., and Maes, P. (2018). Comparing learning in virtual reality with learning on a 2d screen using electrostatics activities. *Journal of Universal Computer Science*, 24(2):220– 245.

Greenwald, S. W., Corning, W., and Maes, P. (2017a). Multi-user framework for collaboration and co-creation in virtual reality. In *Making a Difference: Prioritizing Equity and Access in CSCL/Proceedings of the 12th International Conference on Computer Supported Collaborative Learning*, volume 2 of *CSCL'17*, pages 879–880. Internation Society of the Learning Sciences.

Greenwald, S. W., Wang, Z., Funk, M., and Maes, P. (2017b). Investigating social presence and communication with embodied avatars in room-scale virtual reality. In Beck, D., Allison, C., Morgado, L., Pirker, J., Khosmood, F., Richter, J., and Gütl, C., editors, *Immersive Learning Research Network*, pages 75–90, Cham. Springer International Publishing.

Masson, T., Daffy, and Perlin, K. (2017). Holo-doodle: An adaptation and expansion of collaborative holojam virtual reality. In *ACM SIGGRAPH 2017 VR Village*, SIGGRAPH '17, pages 9:1–9:2, NY, NY,. ACM.

Royston, S., DeFanti, C., and Perlin, K. (2016). A collaborative untethered virtual reality environment for interactive social network visualization. *CoRR*, abs/1604.08239.

Salzman, M. C., Dede, C., Loftin, R. B., and Chen, J. (1999). A model for understanding how virtual reality aids complex conceptual learning. *Presence: Teleoperators and Virtual Environments*, 8(3):293–316.

Vrellis, I., Papachristos, N. M., Bellou, J., Avouris, N., and Mikropoulos, T. A. (2010). Designing a collaborative learning activity in second life - an exploratory study in physics. In *2010 10th IEEE International Conference on Advanced Learning Technologies*, pages 210–214.

