Augmented Reality Sandboxes for Civil and Construction Engineering Education

Joseph Louis [a] and Jennifer Lather [b]

[a] School of Civil and Construction Engineering, Oregon State University, USA
[b] Durham School of Architectural Engineering and Construction, University of Nebraska – Lincoln, USA
E-mail: joseph.louis@oregonstate.edu, lather@unl.edu

Abstract –

Civil and Construction Engineering (CCE) is a discipline that seeks to engineer the physical world, yet students in classrooms are limited to studying and applying concepts predominantly on paper or computer screens. This paper proposes a framework for the use of augmented reality (AR) sandboxes to bring the vastness of the physical environment that characterizes the problem domains of civil and construction engineering and the students will eventually be working in, into the classroom. Because the surface of the sandbox can be intuitively fashioned to represent a scaled-down version of the wide range of terrain found in the physical world, this tool can demonstrate not just the application of classroom concepts, but even their development from first principles. A description of the AR Sandbox is provided along with the software architecture that is created to enable course delivery to meet the related learning objectives for earthwork planning. This paper presents learning CCE design and analysis concepts that are traditionally presented through diagrams to be delivered through an AR Sandbox. A framework for evaluating the effectiveness of this new mode of instruction is proposed which can inform guidelines on the implementation of novel visualization and interaction technologies in the CCE classroom. Implications of this work include use by earthwork construction teams and professional engineers where AR sandboxes can aid planning and managing large scale construction projects.

Keywords –

Augmented Reality; Sandbox; Heavy Civil; Construction Education; Mass Haul Diagram

1 Introduction

Civil and Construction Engineering (CCE) is a discipline that seeks to engineer and transform the physical world around us, yet students in classrooms are limited to studying and applying concepts predominantly on paper or computer screens. While the technology available in education have increased to many interactive media, CCE as well as many engineering disciplines are slow to implement new modes of learning into modern curricula [1]. The traditional modes and media of instruction, e.g., paper and screens, create a disconnect between the concepts learned in class and their application in the field, e.g., spatial reasoning and broad concept understanding, which is usually bridged only after considerable work-experience in industry. A similar disconnect exists between the designers and builders of civil infrastructure, who necessarily work in two different environments (the office vs. the field).

This paper seeks to bring the vastness of the physical environment that students will be working in, into the classroom, with a tangible interface known as an augmented reality (AR) sandbox. The AR sandbox will serve as an interactive media through which civil infrastructure design and construction concepts will be demonstrated in the classroom. This platform will augment traditional learning tools such as CAD and spreadsheet programs by providing a much needed and appropriate kinesthetic aspect to student learning and engagement. This paper focuses on the development of the physical sandbox and software applications that enable the teaching of various CCE concepts through the AR sandbox. The methodology that will be used to evaluate the effectiveness of the sandbox as a media for education is also discussed in this paper. The concept of mass haul diagraming for earthwork planning and analysis is used as a case study to explore the use of the sandbox in civil and construction education.

A literature review of existing implementations of AR sandboxes for education is first provided to set the context for this research, which is followed by a description of the hardware and software architecture necessary for the working of the sandbox. This is followed by a description of the experimental methods to evaluate the effectiveness of the sandbox for teaching and learning, followed by conclusions of the research.

2 Literature Review

A review of current literature in the field of mixed virtual reality and augmented reality sandboxes is provided to set the context for the research. Following that, a discussion of diverse learning styles is provided to highlight the need for incorporating spatial reasoning into the CCE curriculum, which is provided by the AR sandbox. This sets the stage for presenting the point of departure of this paper from the current state of CCE education and AR sandbox research.

2.1 Augmented and Virtual Reality

Within the commonly used Mixed Reality continuum (Fig. 1), there are two poles, the real world (reality) and the virtual world (virtual reality), where either can be augmented by the other [2]. The augmented reality (AR) is the part of the spectrum where virtual objects are augmented on reality. The augmented virtuality (AV) is the part of the spectrum where real objects are augmented on the virtual environment. In the AR Sandbox, both of these augmentations can occur, sometimes where the virtual representation of the sand is used to generate a virtual topographical map (AR) and sometimes where the sand is meant to augment the understanding of data through exploring how changes in the sand impact a simulation of roadway construction (AV), for example in a cut and fill diagram. These theoretical differences have implications for AR sandbox design and implementation in educational settings. Through understanding the types of tasks to be performed in the mixed reality sandbox environment, the software specifications for AR and AV tasks can be identified. These can aid identification of technology for investigation, design, and analysis tasks associated with spatial reasoning in the civil and construction engineering domain.

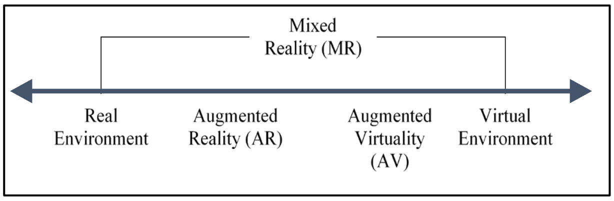

Figure 1. Mixed Reality Continuum

2.2 Augmented Reality Sandbox

The augmented reality (AR) sandbox is a device consisting of a depth sensor, projects, and a physical box filled with sand. It was initially developed at UC Davis to enable a tangible means of manipulating and visualizing spatial data [3]. This device represents a novel application of AR wherein the virtual information is dependent on the physical shape of the real-world sand. Its primary applications thus far have been in providing students with an intuitive understanding of geographic concepts [4] such as topographic maps, and hydrology [5]. Apart from concepts in these fields, other educational and visualization experiences have been created in the areas of natural sciences [6], mathematics [7], and disaster response [8]. The common theme regarding all of the AR experiences implemented in an AR sandbox thus far has been the presence of a strong spatial component relating to vast areas of physical terrain. Furthermore, all of the above experiences only allow one primary means of interacting with the underlying model and visualization, through physically manipulating the sand. For the above applications, the primary concepts under study is the natural terrain, which is can be represented and interacted with adequately by the sand alone.

However, civil and construction engineering concepts involve additional built infrastructure to be considered along with the surrounding terrain. Therefore, this paper builds upon the current capabilities of the AR sandbox interface to provide a more general platform for the sandbox that enables multiple modes of interactivity with the underlying terrain and physical infrastructure under consideration.

2.3 Engineering Education for Diversity

Many researchers have investigated how learning style impacts learning in the STEM fields [9], as well as gender differences in learning style for engineering students [10], suggesting that engineering education be approached with a mixed method approach to incorporate more Active, Sensing, Visual and Global components.

In addition, spatial reasoning has been shown to be a key indicator of engineering education success especially for female engineering students [11]. New trends in VR and AR have added new tools for educators across engineering topics and grade levels [12], [13]. With a large number of new tools, the need for evaluation is expanding into understanding specific interactions, including human-computer interaction (HCI), team interaction, and conventional communication. Previous work has begun to develop metrics to aid researchers in understanding different factors associated with interactive media and teams [14]. Additional tools are needed to understand how both media and interaction play a role in the use of mixed reality in engineering education and how they can assist different learners to succeed in their engineering education. To aid research in this area, research is needed in a new method of incorporating spatial reasoning for engineering education, particularly in the area of civil and construction engineering, where spatial concepts are of critical importance.

It is anticipated that the use of the AR sandbox will provide the spatial component to learning that will enable core concepts in civil and construction engineering to be appeal to a more diverse audience.

2.4 Point of Departure

The point of departure of this paper from current work lies at the intersection of current state of the art in AR sandboxes and the need for enhanced means of incorporating spatial reasoning in engineering educations, especially for civil and construction engineering. Current implementations of the AR sandbox do not consider the interaction of built infrastructure with the terrain, and rather focus on the terrain itself, thereby limiting its application to areas of study relating to geology and hydrology. Therefore the overarching goal of this paper enhance the capabilities to the AR sandbox to enable users to create, visualize, and interact with digital representations of the built environment and infrastructure in addition to the physical terrain that is represented by the sand. Towards this end, the paper describes the development of the sandbox and a case study of developing an application for a specific construction engineering concept taught in the classroom. Furthermore, a discussion of the experimental method for evaluating the effectiveness of the sandbox for education is also provided.

3 Development of AR Sandbox

The AR sandbox used in this research was built from commonly available materials and implemented by the authors and a team of students at Oregon State University. This section describes the hardware and software architecture that comprises the AR sandbox.

3.1 Hardware Design of AR Sandbox

Figure 2 shows a schematic representation of the AR sandbox along with its three primary hardware components: depth sensor, projector, and computer terminal. As can be seen in the figure, the depth sensor and projector are mounted side-by-side on a metal bracket that extends over a box of sand. Both the depth sensor and the projector are connected to the computer terminal.

For portability, the sandbox was mounted on a wheeled double shelf cart, wherein the sand was placed on the top shelf along with the computer terminal. Half inch (1.27 cm) thick clear acrylic board walls were affixed to the sides of the top shelf to accommodate the volume of sand. The picture of the finished sandbox is shown in Figure 3.

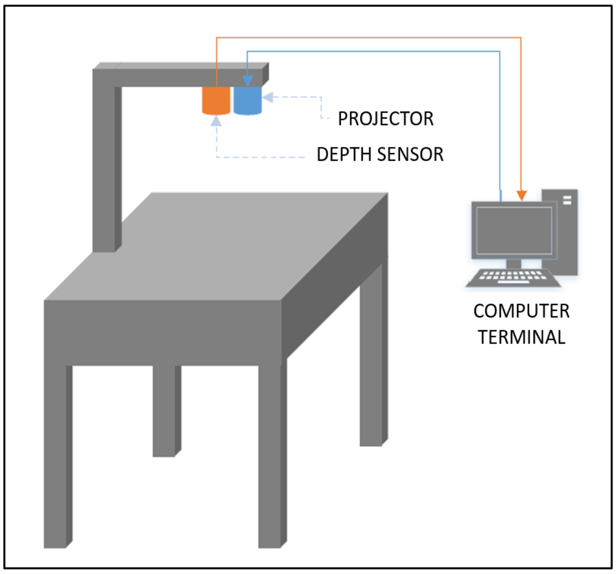

Figure 2. Schematic diagram of AR sandbox

Figure 3. AR sandbox mounted on wheeled cart

The role of the three primary components are the depth sensor, projector, and computer terminal, described below:

3.1.1 Depth Sensor

The depth sensor that was used is a Kinect Sensor by Microsoft. The Kinect is equipped with a 1280x960p full-color camera, and an infrared (IR) emitter and sensor along with an array of microphones and a tilt motor. For this project's purposes, the Kinect's IR sensor and emitter are primarily used and allow us to capture a depth image. This IR system offers a workable range of 0.8m to 3.5m from the target with a data precision of 1cm [15]. When choosing the Kinect, the most important factors for considerations were the accuracy the sensor and the usability of its application programming interface (API). The Kinect is one of the most accurate depth sensors on the common market and the API created by Microsoft has been created specifically for developers to use when utilizing the sensor for their applications.

3.1.2 Projector

The projector that was used for this sandbox is an AAXA M5 Mini Portable Business Projector. This projector occupies of a volume of 1.5cm x 1.5cm x 4.6cm (6in x 6in x 1.8in) and only weighs 0.86kg (1.9 pounds), while offering a 1280x800p picture at 900 lumens. Allowing for a screen up to 3.81m (150in), this projector allows for a very bright and clear image for its size. The most important factors of the projector are its size, weight, and brightness. Because of the way the projector is mounted above the box, a smaller and light projector was necessary to ensure its stability. With the majority of projectors at this size providing a brightness of 50-100 lumens, the 900 lumens make this projector highly suitable for its intended purpose.

3.1.3 Computer Terminal

To power the AR sandbox, a HP Z240 full tower desktop computer was used which had 16 GB of RAM, a 1TB spinning disk, and an Intel core i7 processor with a base speed of 4.2 GHz. Furthermore, a Nvidia GTX 10XX series graphics card was implemented in the terminal to handle rendering. In regard to the computer terminal, it is necessary to use a full tower desktop since a majority of graphics cards are too big to fit in a small form factor machine. Using a Nvidia GTX graphics card provides the best results for rendering real time graphics at the lowest cost when compared to a similar workstation graphics card. A mouse and keyboard are connected to the computer terminal to enable additional interaction capabilities to the AR sandbox. The output of the terminal is projected on to the sandbox and thus there is no additional monitor that is provided with the sandbox, although one can be easily added for development and debugging purposes.

3.2 Software Architecture of the AR Sandbox

The software architecture of the AR sandbox was developed to provide future developers the opportunity to develop applications relating to core concepts in CCE that could be deployed through the AR sandbox interface without the need to interface with low-level details of the hardware components. Thus, the fundamental functionality that was enabled involved obtaining a depth image information from the depth sensor using Kinect's API and storing that as a heightmap to provides heights on the sandbox at any given x and y location in the sensor region. Also, a geometry interpreter was implemented to convert heightmap data from the depth sensor into a three-dimensional mesh. Apart from dealing with the depth sensor, calibration is required to ensure that the sensor and projector are correctly aligned with each other as well as with the surface of the sand. These settings include adjustments to the area exposed to the depth sensor and to the area covered by the projection. This module continually interacts with the user interface (UI) as it prompts the user with the setting to be adjusted and then stores these settings in the Calibration Settings.

In order to ensure satisfactory graphical performance of the system, this architecture utilizes two pairs of vertex and fragment shaders written in the OpenGL Shader Language (GLSL). The first is responsible for coloring the terrain mesh in order to visually represent height information. The second is used to color road segments to represent cut and fill data. The visual appearance of these shaders will change depending on the current display mode. The rendering subsystem is handled by the Unity game engine and is accessed indirectly through shaders and Unity's UI system.

Finally, a basic application that is enabled to ensure that the system is working correctly is the display of real-time depth information. Display depth is used to visualize the height or altitude of an area. If a part of the sand is above a certain height, then it's displayed using a shade of red. If the sand is below a certain height, then is displayed using a shade of blue. The intensity of the color depends on how far the height of the sand is from a predetermined height. A close up of this display of depth is shown in Figure 4 along with contour lines along sections of equal height.

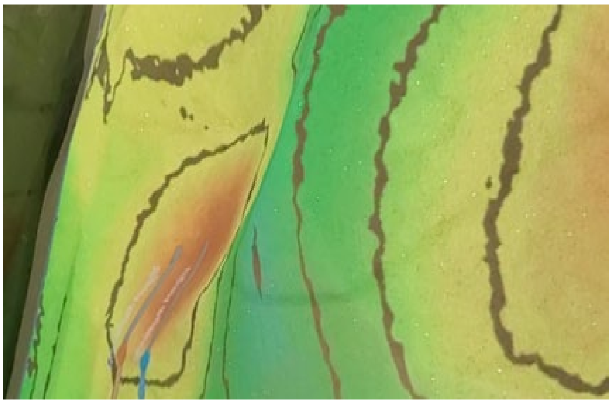

Figure 4. Height map display with contour lines

4 Case Study for Mass Haul Diagrams

Mass haul diagrams are an analytical tool that is used in the planning of horizontal construction projects like the building of roadways and trenching for pipelines [16]. Mass haul diagrams provide a visualization of the quantities of earth that need to be cut, filled, and moved, along the centerline of the horizontal project. This information is used by project managers to plan for earthmoving equipment fleets and enables them to determine the schedule and cost of the project. Traditional mass haul diagrams are taught to students using a spreadsheet interface which takes as input the elevation profile of the existing ground and proposed pavement and the cross sections of the roadway (or trench) to be built. The output of the analysis is a two-dimensional visualization of cut and fill volumes on the y-axis plotted against the distance along centerline on the x-axis. An example mass haul diagram is shown in Figure 5.

As can be observed from the figure, the information in the mass haul diagram is not intuitive to grasp, especially given its similarity to the input elevation profiles. Another key aspect of the earthmoving that is missing in the current visualization is that it does not show indicate the three-dimensional nature of the volume of soil to be moved. Furthermore, there is no indication of the surrounding terrain as the information is only plotted along a one-dimensional centerline of the road. This can lead to potential misunderstanding of the entire concept.

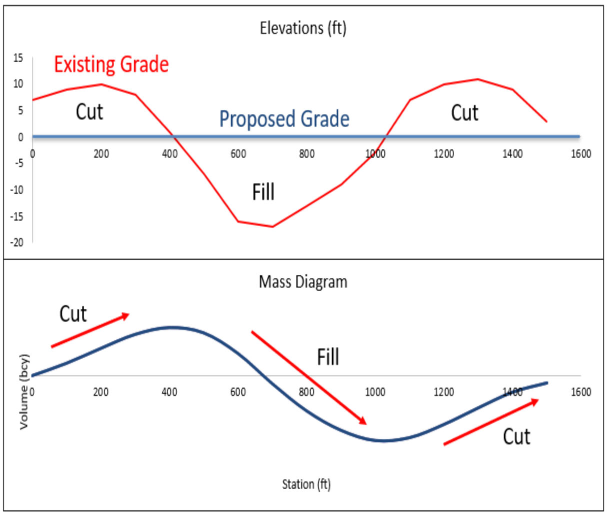

Figure 5. Mass haul diagram for earthmoving

These limitations of the traditional method of instruction of mass haul diagrams present a barrier to the understanding of the core concepts of the method, which essentially relate to the volumes of earth to be moved. Thus, an application was created upon the foundational AR sandbox software architecture described previously for visualizing an interactive mass haul diagram. This application could be run in two modes: Design and Cut & Fill modes.

4.1.1 Design Mode

In the design mode, the user designs the road segment location. The design mode is used to enable the user to create the shape of the roadway segment for mass haul analysis. Specifically, the user can design the horizontal and vertical alignment of the roadway using Bezier control points that provide smooth curves to the shape of the roadways segment. Figure 6 shows an example of the control points (represented as yellow squares) on the alignment of the roadway. This figure also shows the cut and fill representation which will be explained in the following subsection.

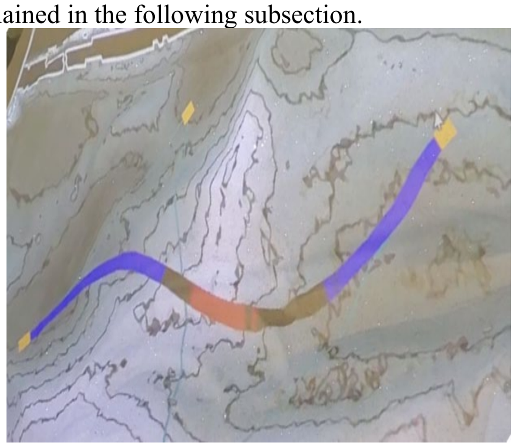

Figure 6. Control points on virtual roadway projected on the sandbox

The user can edit the horizontal alignment of the road by using a mouse to select and move a specific control point. The user can change the vertical alignment of the roadway by selecting and moving a control point and pressing down on the shift key on the provided keyboard. The user can also add and delete control points using UI buttons that are available. Adding a control point enables the user to greater length and curvature to the road segment.

4.1.2 Cut & Fill Mode

Cut and Fill mode is used to visualize the volumes of material that must be added or removed in order to achieve the desired road path. This mode is the default mode and differs from the design mode only in terms of not showing the control points that determine the alignment of the roadway. The cut or fill of a road will be calculated by determining the height of a part of the sand where the road should be, then displaying a colored view of the road. As can be observed in Figure 6, the cut and fill of soil that is required to bring the existing grade of the terrain to the proposed grade of the roadway is displayed visually along the roadway.

Specifically, cut is represented in red and fill in blue. If the elevation of the terrain along the roadway of the proposed roadway, that portion is represented in black color. Apart from providing students with the spatial context of where the cut and fill areas on the roadway are, moving sand out of cut and into fill portions along the roadway enables them to obtain tactile sensory feedback in obtaining an understanding of the quantity of soil needed to be moved to build a roadway.

Also, the effect of change in terrain on cut-fill sections of the roadway are represented immediately to due to the real-time nature of the depth sensor. This provides students with immediate visual feedback on the effect of physically moving soil from one part of the roadway to another. Quantities are also presented along with the visualization.

4.2 Evaluation of Tasks in AR Sandbox

There has not been a substantial amount of research on the effectiveness of learning using AR sandboxes for CCE. Most evaluation has been on the use of AR Sandboxes in understanding hydrology and topography concepts in Environmental Engineering, with mixed results [4], [17], [18]. The main findings from these studies have found that user experience was positive while statistical differences between learning pre- and post- task have been minimal [19]. Rigorous evaluation of user learning and experience are needed in a variety of task types to understand the value of AR Sandboxes in education. Since previous studies have focused on learning concepts, we propose expanding evaluation to include both unstructured and structured tasks to help understand the use of this technology in both broad understanding of CEE and learning spatial concepts.

The two tasks of the AR Sandbox for CEE, design and cut & fill modes, represent the key tasks for evaluation. As mentioned earlier, spatial understanding has been identified as an indicator for engineering success [4], and this concept is especially important for people with a variety of cognitive styles. In order to understand the benefit of AR Sandboxes in CEE, we propose the collection of data across different task types (design and analysis type tasks), the collection of data on cognitive style, understanding of broad concepts through pre and post-tests, class performance, measures of user perception of the media interaction and potential team interaction during the activity, and comparison with traditional teaching and learning methodologies. For evaluation of AR sandboxes in the CCE education to be valuable, many more studies are needed with enough sample size to produce enough power to have statistical evidence of the value of these systems. Value can be in many forms, including performance, future success, confidence in abilities as an engineer, and enjoyment in education. Additional valuable parameters are expected to arise as researchers evaluate more types of tasks beyond concept understanding, such as unstructured design tasks and cut and fill analysis tasks.

5 Conclusions and Future Work

There exists an inherent dichotomy between the education and practice of civil and construction engineering because the former necessarily happens inside the classroom while the latter is mostly performed out in the real and physical world. This disconnect is usually bridged only after the student has spent sufficient time out in the field and is struck by the inevitable, but much delayed "a-ha" moment - a congruence achieved when abstract concepts are finally placed within their rightful physical context. The AR sandbox, through its seamless blending of virtual content within a tangible interface, has immense potential to deliver concepts to students in an intuitive and engaging manner to assist in alleviating that disconnect. Because the surface of the sandbox can be intuitively fashioned to represent a scaled-down version of the wide range of terrain found in the physical world, this tool can demonstrate not just the application of classroom concepts, but even their development from first principles, through interaction with design and analysis tasks in earthwork planning.

This project specifically provides an alternative means of teaching mass haul diagrams for earthwork planning. Whereas current lessons utilize static two-dimensional profile and plan views of three-dimensional terrain and roadways, this tool enables students to use their own hands to both construct roadways and modify surrounding terrain. The tool then displays the results of the mass haul analysis directly on the physical roadway itself in real-time, to provide an intuitive, interactive, and ultimately effective learning experience for students. The following specific advancements in interactive learning are enabled by the tool. The use of actual sand in the sandbox is anticipated to increase student learning and retention of concepts such as bank, loose, and compacted volumes; and which volumes are to be used during quantity calculations. The provision of a physical terrain and roadway model combined with a dynamically updated mass haul diagram in this project can demonstrate the utility of abovementioned tools for earthwork volumes calculation. The sandbox will serve as a physical medium to aid students in interpreting the design drawings that are provided from an authentic real-world project. The real-time nature of the proposed tool will also enable students to experiment with the terrain to see how it changes the cost and schedule of the operation. The provision of a modifiable scale model of the terrain will enable the testing of different alternatives and scenarios at no expense to the students or instructors.

While the effectiveness of the tools in imparting the lesson has not been evaluated yet, this paper details the experimental process that will be followed for assessment across a series of novel AR sandbox task types: design and analysis tasks. The results of this assessment can inform educators on the utility of the sandbox and other such novel methods of teaching and guide their plan for implementation.

Future work can also focus on integrating the presented approach of visualizing heavy civil operations with existing means of using virtual reality [20] and augmented reality [21] for visualizing simulated construction operations.

References

[1] M. Borrego, J. E. Froyd, and T. S. Hall, "Diffusion of engineering education innovations: A survey of awareness and adoption rates in US engineering departments," *J. Eng. Educ.*, vol. 99, no. 3, pp. 185–207, 2010.

[2] P. Milgram and F. Kishino, "A taxonomy of mixed reality visual displays," *IEICE Trans. Inf. Syst.*, vol. 77, no. 12, pp. 1321–1329, 1994.

[3] "Augmented Reality Sandbox." https://arsandbox.ucdavis.edu/ (accessed Jun. 14, 2020).

[4] T. L. Woods, S. Reed, S. Hsi, J. A. Woods, and M. R. Woods, "Pilot study using the augmented reality sandbox to teach topographic maps and surficial processes in introductory geology labs," *J. Geosci. Educ.*, vol. 64, no. 3, pp. 199–214, 2016.

[5] G. Zhang *et al.*, "An efficient flood dynamic visualization approach based on 3D printing and augmented reality," *Int. J. Digit. Earth*, pp. 1–19, 2020.

[6] A. Ables, "Augmented and virtual reality: Discovering their uses in natural science classrooms and beyond," in *Proceedings of the 2017 ACM SIGUCCS Annual Conference*, 2017, pp. 61–65.

[7] S. Á. Sánchez, L. D. Martín, M. Á. Gimeno-González, T. Martín-Garcia, F. Almaraz-Menéndez, and C. Ruiz, "Augmented reality sandbox: a platform for educative experiences," in *Proceedings of the Fourth International Conference on Technological Ecosystems for Enhancing Multiculturality*, 2016, pp. 599–602.

[8] D. Savova, "AR Sandbox In Educational Programs For Disaster," in *6th International Conference on Cartography and GIS*, 2016, p. 847.

[9] P. Pallapu, "Effects of visual and verbal learning styles on learning," *Inst. Learn. Styles J.*, vol. 1, no. 1, pp. 34–41, 2007.

[10] P. A. Rosati, "Gender differences in the learning preferences of engineering students," *age*, vol. 2, p. 1, 1997.

[11] S. Hsi, M. C. Linn, and J. E. Bell, "The role of spatial reasoning in engineering and the design of spatial instruction," *J. Eng. Educ.*, vol. 86, no. 2, pp. 151–158, 1997.

[12] A.-H. G. Abulrub, A. N. Attridge, and M. A. Williams, "Virtual reality in engineering education: The future of creative learning," in *2011 IEEE global engineering education conference (EDUCON)*, 2011, pp. 751–757.

[13] F. Castronovo, D. Nikolic, S. E. Zappe, R. M. Leicht, and J. I. Messner, "Enhancement of learning objectives in construction engineering education: a step toward simulation assessment," in *Construction Research Congress 2014: Construction in a Global Network*, 2014, pp. 339–348.

[14] J. I. Lather, G. A. Macht, R. M. Leicht, and J. I. Messner, "Development of indices for user perceptions of interactive technologies in construction engineering," in *Proceedings of the 33rd International Conference of CIB W78*, 2016, pp. 1–10.

[15] M. R. Andersen *et al.*, "Kinect depth sensor evaluation for computer vision applications," *Aarhus Univ.*, pp. 1–37, 2012.

[16] R. L. Peurifoy and W. B. Ledbetter, "Construction planning, equipment, and methods," 1985.

[17] S. Giorgis, N. Mahlen, and K. Anne, "Instructor-led approach to integrating an augmented reality sandbox into a large-enrollment introductory geoscience course for nonmajors produces no gains," *J. Geosci. Educ.*, vol. 65, no. 3, pp. 283–291, 2017.

[18] N. Theodossiou, D. Karakatsanis, and E. Fotopoulou, "The Augmented Reality Sandbox as a tool for the education of Hydrology to Civil Engineering students."

[19] S. K. Kim, S.-J. Kang, Y.-J. Choi, M.-H. Choi, and M. Hong, "Augmented-Reality Survey: from Concept to Application.," *KSII Trans. Internet Inf. Syst.*, vol. 11, no. 2, 2017.

[20] J. Louis, P. Dunston, and J. Martinez, "Simulating and visualizing construction operations using robot simulators and discrete event simulation," in *Computing in Civil and Building Engineering (2014)*, 2014, pp. 355–363.

[21] J. Louis and J. Martinez, "Rendering stereoscopic augmented reality scenes with occlusions using depth from stereo and texture mapping," in *Construction Research Congress 2012: Construction Challenges in a Flat World*, 2012, pp. 1370–1380.