Mathland: Playful Mathematical Learning in Mixed Reality

Microsoft Hololens

Object Controller

Arm Controller

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Abstract
Mathematical experiences are intrinsic to our everyday lives, yet mathematics education is mostly confined to textbooks. Seymour Papert used the term 'Mathland' to propose a world where one would learn mathematics as naturally as one learns French while growing up in France. We demonstrate a Mixed Reality application that augments the physical world with interactive mathematical concepts to enable constructionist mathematical learning in the real world. Using Mathland, people can collaboratively explore, experience and experiment with mathematical phenomena in playful, applied and exploratory ways. We implemented Mathland using the Microsoft Hololens and two custom controllers to afford complete immersion through tangible interactions, embodiment and situated learning.

Author Keywords
Virtual/Augmented Reality; Education/Learning; Play; Tangible; Wearable Computers; Embodied Interaction; Situated Learning

ACM Classification Keywords
H.5.1. Information interfaces and presentation (e.g., HCI): Multimedia Information Systems: Artificial, augmented, and virtual realities

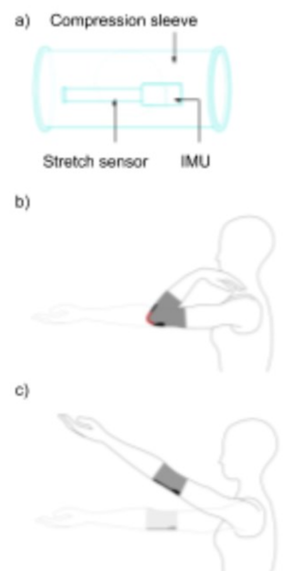

Figure 1: Arm controller

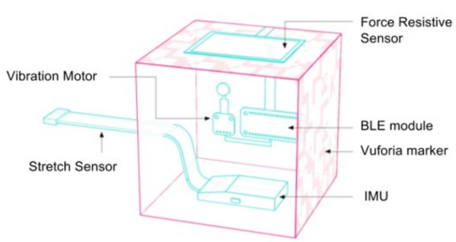

Figure 2: Object controller

Introduction

Mathematics is the language of our universe, yet we feel disconnected from it. Mathematical anxiety is a common problem, but it is not one's actual but perceived ability that hinders one from excelling in mathematics [1]. The lack of interest in mathematics leads to a high dropout rates in science, technology, engineering and mathematics (STEM) fields, especially for women [5]. Mathematical anxiety can be attributed to the way math is taught using abstract symbols that have no meaning for students, in punitive ways such that math becomes a punishment, and as a set of rules to be memorized rather than understood [1,4].

We seek to replace the abstract symbols in math with mathematical applications, the punitive teaching methods with playful experiences, and the rote-learning of concepts with exploratory mathematical learning. We create an immersive and constructionist world for learners to learn mathematics through explorations in the real world. Mathland is like a mathematical lens through which the users can explore the hidden mathematical realities of the world, and also a mathematical playground where users can experiment with mathematical phenomena.

Background & Related Work

There has been a slow shift from education to learning, which places more emphasis on the learner compared to education. Constructivist learning theory [10] states that learners construct knowledge by making observations. Seymour Papert built onto constructivist learning to propose constructionist learning, in which learners construct their own knowledge while building projects. His Logo programming language [9] allowed people to learn geometry in constructionist ways.

Computer simulations have been popular in education, especially science education as many science concepts are difficult for students to understand because of the lack of real-life visuals [2]. Computer games can also enhance math learning [3], and Virtual Reality (VR) has also been explored for immersive science education, e.g Project Science Space [11].

Mathland allows for constructionist, simulation-based and playful learning in the real world, instead of computer screens or virtual reality. There are some MR applications, like Construct3D [6], for learning in the real world. However, instead of facilitating constructionist learning and connecting the content to user's physical environment, these applications simply overlay content on top of the physical world.

Mathland

Mathland supports immersive and constructionist mathematical learning in the real world using Mixed Reality (MR). MR allows us to overlay the physical world with virtual annotations so that the users can collaboratively learn in the real world. We wanted the users to not only visualize mathematical phenomena, but also use it in constructionist ways. In this version, we focus on Newtonian physics, which is an application of mathematics, and people often experience it in their everyday lives, e.g. when we throw a ball.

We used the Microsoft Hololens for our MR experience as the Hololens offers 3D visualizations on an untethered, wearable form factor so that the user can freely walk around in their environment. Also, user interactions, like gaze input, voice commands, and hand gestures, are supported on the Hololens, which has a shared coordinate system to allow for shared virtual experiences among several users.

Designing an immersive MR experience

Immersion involves giving the "illusion of reality" to human senses [12]. We annotate virtual objects and give them physical perception so they 'feel' real, i.e. 'physical perception'. We define 'physical perception' using the following characteristics:

a. Interaction with the physical world, e.g. virtual

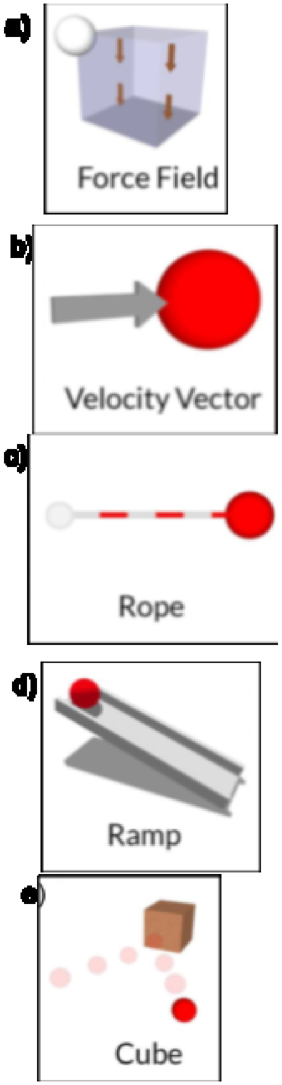

Figure 3: Virtual objects

objects can bounce off a physical wall, b. Interaction with people's physical bodies, e.g. people can throw a virtual ball using natural arm gestures
c. Physical manipulability, e.g. virtual objects can be felt, moved and rotated like physical objects.

I. Spatial mapping for interactions with physical world
We used the spatial mapping capability of the Hololens to scan the 3D physical environment and integrated it in the MR world. Integrating user's physical world into the MR world allows virtual objects to interact with the physical environment like physical objects do, e.g. a virtual ball can bounce off a physical wall.

II. Arm Controller for interactions with the human body
We developed a custom wearable Arm Controller to integrate the user's physical arm movements in MR. It allows the user to use their natural physical arm movements to interact with virtual objects in the same way they interact with physical objects. For example, users can play catch by catching and throwing the virtual ball in the same way they would play catch/throw with a physical ball. We used the Figur8 [13] sensor, which consists of an IMU and a stretch sensor (Figure 1) to implement the Arm Controller. Using inverse kinematics, we calculate the the user's physical arm position with respect to the user's head. Hololens already tracks the user's head position so we can use the relative position of the arm to calculate the global position of the arm.

III. Object controller for physical manipulability
The Object Controller (Figure 2) serves as a tangible placeholder or proxy for virtual objects in MR so users can reposition, rotate and resize virtual objects in the same way as they reposition, rotate and stretch physical objects. The user can gaze and tap on any of the virtual objects to connect the Object Controller to that virtual object. Any subsequent motion, i.e. a change in position and/or rotation, of the Object Controller is reflected in the position and rotation of the virtual object. The Object Controller has a stretchable tape that the user can pull to resize the object. The Object Controller uses Vuforia markers for tracking position, Figur8's IMU for tracking rotation, and Figur8's stretch sensor for resizing with haptic feedback.

Designing a MR world for constructionist learning
Mathland not only shows people the mathematics of their everyday Newtonian physics experiences, but also allow them to modify the physical laws and explore different Newtonian physics possibilities in MR. We were inspired by the Rube Goldberg machine [7], which demonstrates how relatively simple objects can be used to create relatively sophisticated systems. Tangible Rube Goldberg machines have been shown to enable constructionist learning of Newtonian Physics [8].

We have a menu of virtual items in Mathland, and we added three items to facilitate Newtonian concepts: 'Force Field' for creating a constant linear force, 'Velocity Vector' object for momentary force, and 'Rope' for force towards a point. We also have a 'Ramp' for objects to roll down on, and a 'Cube' that objects can bounce off of. Users can create multiple instances of the five virtual objects (Figure 3), and all the instances can be repositioned, resized and rotated. Users can use the virtual items to create new MR worlds. There is also a Puzzle mode in which the user can place a series of ring-shaped virtual Checkpoints, and the ball must pass through them in the right order to solve the puzzle. Figure 4 shows example of Newtonian puzzles.

Mathland's MR starts with a virtual ball. The application has two modes — Launch and Edit — and the user can switch between the two modes using voice commands. In the Edit mode, the ball is a static object, and does not react to any forces, collisions, etc. In the Launch mode, the ball is a dynamic object and responds to the force fields, velocity vectors, etc.

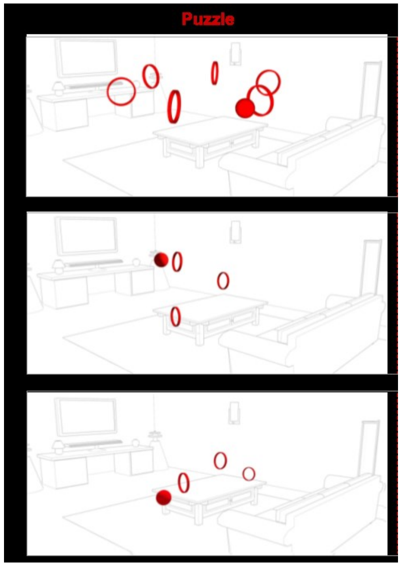

Figure 4: Puzzles for a) circular motion, b) linear motion, and c) projectile motion

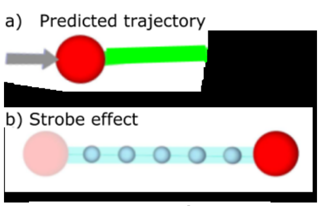

Figure 5: Visualizations

We provide two visualization for the ball's physics:
a. Predicted trajectory (Edit mode): Predicted trajectory (Figure 5a) visualization helps the user observe the expected trajectory of the ball before it is launched. The predicted trajectory is based on the MR world, i.e. the physical surrounding, virtual force fields, etc.
b. Trail and strobe effect (Launch mode): As the ball moves in the Launch mode, it leaves a trajectory (blue line/trail) behind to allow the users to see the path that the ball has traveled through (Figure 5b). As the ball moves after it is launched, we create virtual snapshots of the ball at fixed intervals of time, i.e. 'strobe effect'. Using the strobe effect, the users can compare the distance traveled by the ball between fixed time intervals and get an intuition for the velocity (the faster the ball, the more the distance between the snapshots).

Conclusion

We live in a mathematical universe and Mathland aims to unveil the hidden mathematical realities of nature. In Mathland, learners not only visualize mathematics in immersive ways, but also use it to construct new projects, i.e. constructionist learning. We use MR to situate learning in the user's real world context. Unlike existing MR applications, which simply overlay virtual content on the real world, we merge the real and virtual worlds through real-life like interactions with virtual objects. We envision a world where people can interactively and seamlessly experience and play with mathematical phenomena in their real world.

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