Calibrating and Networking Inside-Out Tracked Mixed Reality Systems in Classroom Settings

A Thesis in the Field of Computer Science

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Abstract

Mixed reality allows us to do a wide range of activities in a virtual space that aligns with the real world. For example, we currently have software for 3D painting in mixed reality, a topic that students and teachers would be excited to explore in a mixed reality classroom setting, and we now have the low-cost mixed reality headsets available to make outfitting such a classroom practical. However, with the inside-out tracking systems used by these lower-cost mixed reality displays, there is not a consistent coordinate system shared between multiple headsets. This motivates the need for a fast and simple calibration procedure to align the individual coordinate systems of multiple headsets so that students can work collaboratively in a classroom setting. The accuracy must be sufficient to support collaborative tasks, but it does not need to be extremely accurate for this purpose. To combat this, our research team is developing a system for physical calibration with a calibration cube, which we call the SyncCube. The concept is that each user simply places one of their controllers into the SyncCube for a few seconds, and this provides the consistent six degree-of-freedom (position and rotation) physical reference needed to align their world origins. To ensure our system works, my honors thesis research focuses on designing and pilot testing a controlled experiment that mimics the way the calibration would be used in a classroom setting. This experiment uses a physical periodic table viewed through the headsets of students with MR. Their headsets are calibrated with our system and tested by pointing at various elements on a periodic table. We found that with this calibration technique, students did not always see the

teacher pointing at the correct element, but the element was only off by one element to the left. For further research, we plan to test the effect of the angle of users' on the accuracy of the calibration as well as the drift over time.

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Table of Contents

List of Tables

List of Figures

Introduction

Virtual reality (VR) and mixed reality (MR) have seen significant development in the last decade. Popular VR headsets include the Meta Quest and HTC Vive, among others. There are different methods for headset tracking, all of which work well in the headset's local space. However, when working with multiplayer games and software, it's difficult to synchronize users to move in the same virtual space with separate headsets. When working with VR calibration, there are two main classes of tracking technologies: Inside-out tracking and Room-fixed Outside-in tracking (Figure 1). The first kind is called Inside-out Based Tracking which is used by the Meta Quest and most modern VR devices. This sets the world origin, which is the key reference frame that determines the location of everything else in the virtual scene, relative to the VR headset, not a predefined point in the room. Opposite to this is Room-fixed Outside-in Based Tracking. This tracking requires various cameras in fixed locations in the room, and the VR headset registers these cameras to figure out where it is in the room space. The downside to this strategy is that the tracking system is limited to the room it is in. It is not portable and highly expensive to set up in multiple rooms. Because of this, most VR headsets have switched to the strategy of Inside-out tracking. This tracking strategy allows for a larger area of calibration and is less expensive, but it comes with the cost of movement drift. On the other hand, outside-in has less movement drift due to the fixed reference points, but the area of calibration is much smaller, and the system is very costly. The HTC Vive uses a mix of both Room-fixed Outside-in and Inside-out tracking. Two devices (called lighthouses) are set up in the room. These lighthouses provide a reference point for the

VR headset, but the headset uses cameras and sensors to track itself. This is cheaper and easier to setup than traditional Room-fixed Outside-in tracking, but it is still much more expensive than modern headsets. A good example of this is the Meta Quest which uses a cloud-based calibration, but this creates an issue with privacy concerns in addition to the issues from inside-out based tracking. In this paper, we create a solution for VR calibration that is cost-efficient and designed for a large classroom setting, called the SyncCube (Figure 2). We want to know if the SyncCube is precise enough to be a valid VR calibration technique for a classroom setting, and we define the requirements for this as follows:

1. Fast and simple for multiple students to perform quickly on their own.
2. Accurate enough to support collaborative, small-group activities and discussions that involve pointing at and/or interacting with shared physical and virtual content but, importantly, not as accurate as the use of MR in surgery, engineering, and other high-end applications.

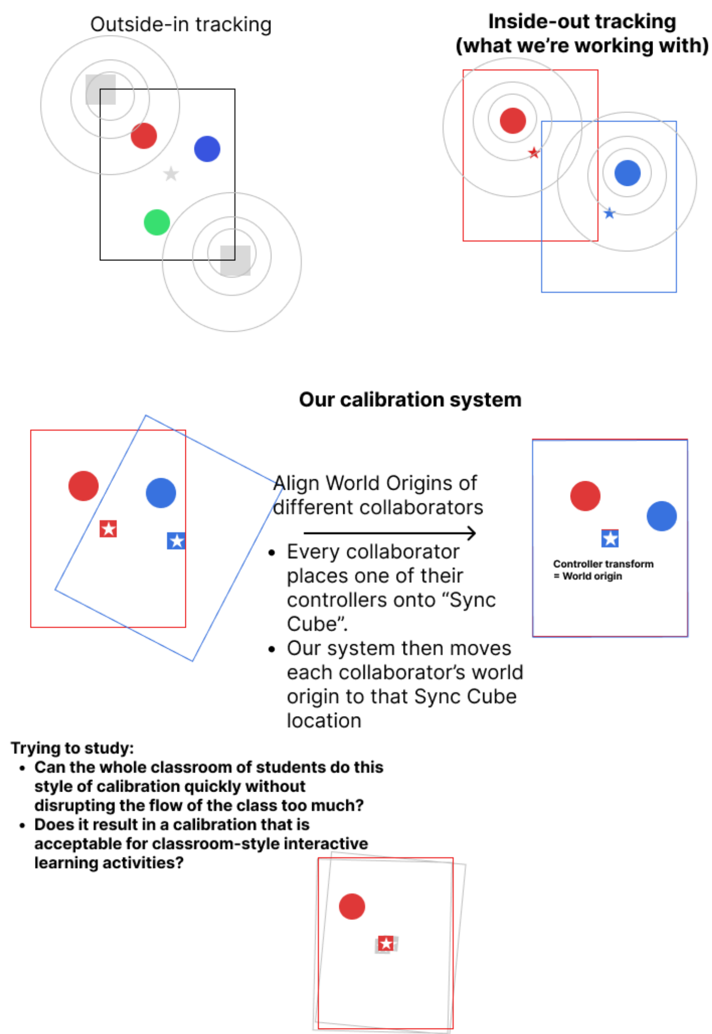

Figure 1. Outside-in Tracking vs. Inside-out Tracking

The stars represent individual headsets and the box is their own respective world space. The gray squares are lighthouses for inside-out tracking, while the gray circles represent where the tracking originates from.

We hypothesize that if six study participants in different areas of the same classroom use the SyncCube to align their headsets to be in the same virtual environment, then the calibration will be precise enough to determine which element the experimenter is pointing at on a periodic table in MR.

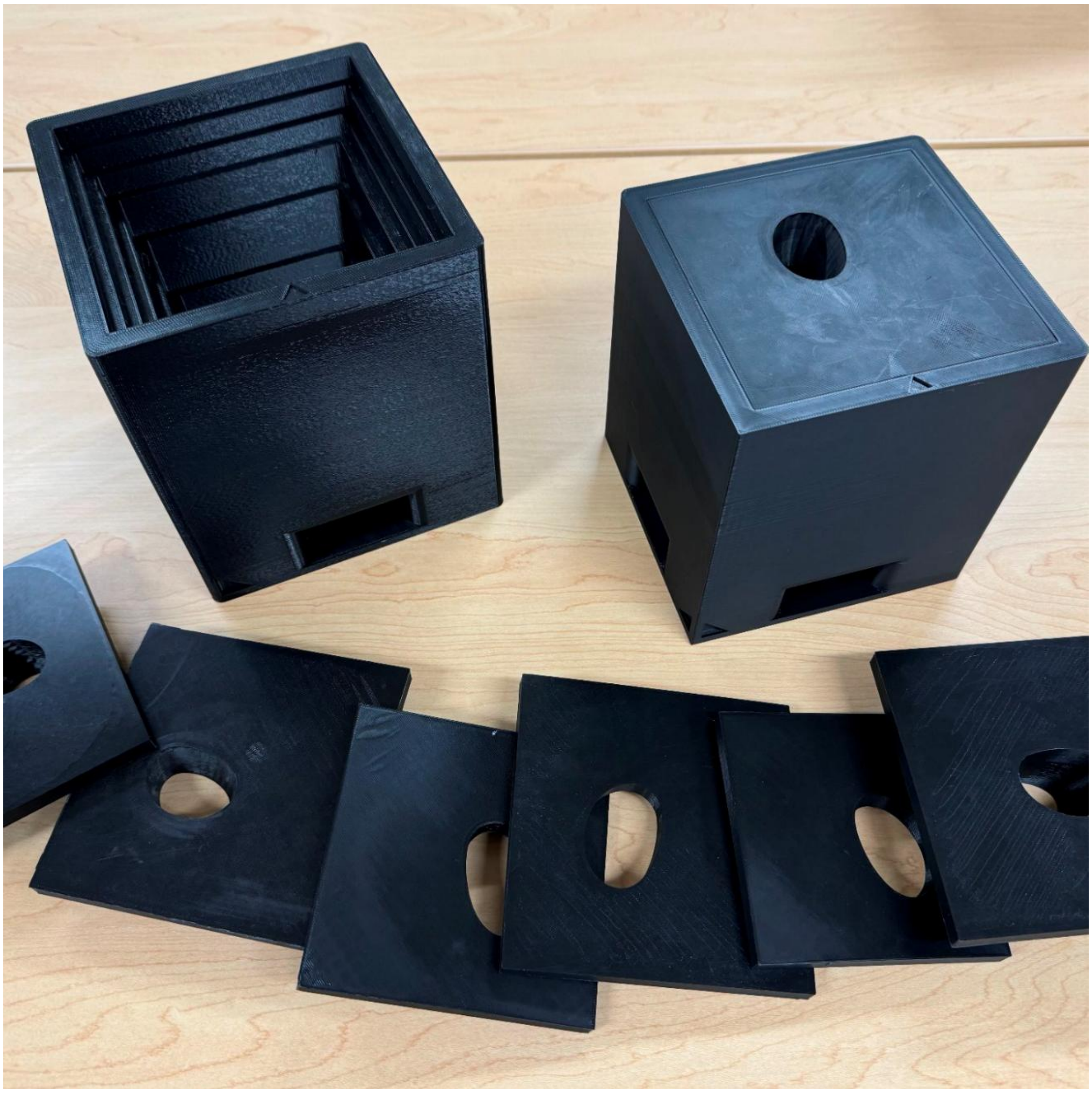

Figure 2. 3D printed SyncCube

The various lids of the SyncCube can be printed to fit different controller shapes for different headsets. Source: [1]

Related Work

A. VR Tracking and Calibration Techniques

There are various different techniques for VR tracking and calibration, each with their own benefits and drawbacks. While the accuracy of tracking technologies has been studied extensively in prior VR research, current techniques usually aim for ultra-high precision tracking which leads to complex calibration methods. One experiment tested the accuracy of the Oculus Quest 2 which found a mean of -0.001m as compared to the HTC Vive Tracker which had a mean accuracy of 0.007m [2]. These existing tracking methods are both accurate, but the internal hardware requires the headset to continuously update based on the point(s) of alignment, which involves a large computational complexity. In addition, the HTC Vive Tracker takes extra time to set up the lighthouses, and it confines the user to a small tracking area. While traditional room-fixed large-scale systems allow for high accuracy, precision, and reliability, "setup and operation is know-how intense and time-consuming, [and] their acquisition cost is high" [2, p. 42].

Another common technique for VR calibration is Simultaneous Localization and Mapping (SLAM) which uses fixed points to create a point cloud map of the world and detect where the user is in relation to these points and continuously update the user's position. Users pick one or two points that correspond with features in the point cloud to serve as the origin and specify the orientation. However, the position and rotation of these points can cause the accuracy to decrease, especially if there is only one point. When the Oculus Quest was tested with two-point alignment, SLAM tracking resulted in a mean of ±0.02m for precision and ±0.04m for accuracy [3]. Similar to the HTC Vive and Oculus Quest 2, this calibration technique also uses continuous updating and has the drawback of time consumption. Additionally, there is an implementation of SLAM-Share tracking that uses a drone to take images of the surrounding area and continuously merge the results with a synchronized map of the landscape. This tracking works in under 200ms and can reach 30 FPS [4]. This is not that fast for tracking methods, and this work focuses on virtual holograms which may not translate to a large tracking area. A different approach to VR calibration is to use a camera as an anchor point for alignment, one of the most basic methods of Inside-out tracking. This idea was tested with the Oculus Quest 2 and found a mean translational error of 5.012mm (0.005m) [5]. However, working with cameras raises privacy concerns, and this doesn't work with cross-platform. Instead of using continuous mapping for tracking, Hu et al. designed a method that uses a QR code for connecting devices which then synchronizes the timestamps of multiple devices in relation to the host device in order to find its location [6]. This method made setup quicker and easier, but it is still computationally complex and driven by the goal of high precision which has not yet been tested. SynchronizAR is another tracking method which takes the distance between headsets to calculate the relative coordinates in world space. This design achieved a mean translational accuracy of 0.15m [7], but it still relies on continuous updates. In contrast, our implementation aims to be accurate and precise while only requiring an initial update to the coordinate system in order to reduce lag and server overload, which increases when more headsets are synchronized with one another. Since the SyncCube aligns the user's coordinate system so that all users have the same world origin, this calibration only needs to happen once before networking the headsets together. However, an issue that can occur with this is drift over time, but this can be fixed by recalibrating the coordinate system with the SyncCube. The SyncCube is not restricted to a specific area size, and it is relatively quick to set up.

B. Using VR and MR in Classroom Settings

As technology improves, new devices grow more widespread, and their benefits can be useful in many different sectors. VR usage is not common in education, but it can prove useful for creating an engaging environment and allowing for safe demonstrations and simulations for students to learn from. Some examples of this include eliminating commute time to campus by using a virtual classroom and creating demonstrations to visualize "transmissions of wireless signals in 3D space" [8, p. 39]. One study developed by Young et al. found that students "felt directly involved in the class" and that "it was fun and learning at the same time is innovative" [9, p. 4]. However, despite the increase in engagement and entertainment, the Virtual Learning Environments' (VLE) usability was below average [9]. A separate study found that students gained significant knowledge from an AR chemistry demonstration, but a physical chemistry experiment was still more effective [10]. Regardless of this, it was found that "VR [enhanced] learning outcomes by improving learners' motivation, cognitive processes, active involvement, spatial ability, and reflective thinking" [11, p. 64]. It is also important to note that most VR applications to education and learning focus on single-user environments. It is only in recent years that it became practical to use head-tracked MR technologies to create an environment where students can interact with each other and the virtual and physical content. Ha developed a VR system using Unity to test the usability and effectiveness of a multi-user environment [11]. This system had an average usability score of 88.2 [11], much higher than previous usability scores in single-user environments. Not only are current technologies increasingly easier to use, they are also becoming affordable. One of the main reasons that headsets are more affordable is due to their inside-out tracking which tends to be geared toward single-user environments. This is why our research is aimed at synchronizing multiple headsets for a multi-user environment while retaining precision and usability.

Methodology

A. Background

In order to align the coordinate systems of multiple headsets, we developed a device called the SyncCube (Figure 2). This work was done by members of our multi-year project prior to my research. This device holds the left VR controller in a rigid position that is consistent for each user. The controller's position and rotation in a headset's local coordinate system specifies a transformation between the headset coordinate system and a room-specified coordinate system, indicated by the placement of the SyncCube in the room, and this transformation is sent to the headset. When multiple players align their world origin to the SyncCube, all users should be in the same coordinate space. This is particularly useful in a classroom so that when a teacher points at something in virtual reality, all of the students should see the teacher pointing at the same location. The SyncCube should also be placed against a wall, because the program sets one axis of the world coordinate system to the plane of the wall. The teacher has a virtual laser pointer to aim at the elements on the real life periodic table, so the plane is used to stop the laser pointer from continuing infinitely. With this, our goal is to test the feasibility of this calibration technique in a classroom scenario by evaluating the precision and ease of setup.

B. Mock Classroom Scenario and Technical Implementation

We designed the study around a MR classroom scenario where one teacher and multiple students come together to work collaboratively with MR and a physical item in the classroom (i.e. still life, data chart). To create a mock version of this classroom, we decided to use a virtual and physical periodic table to represent the physical classroom item (Figure 3).

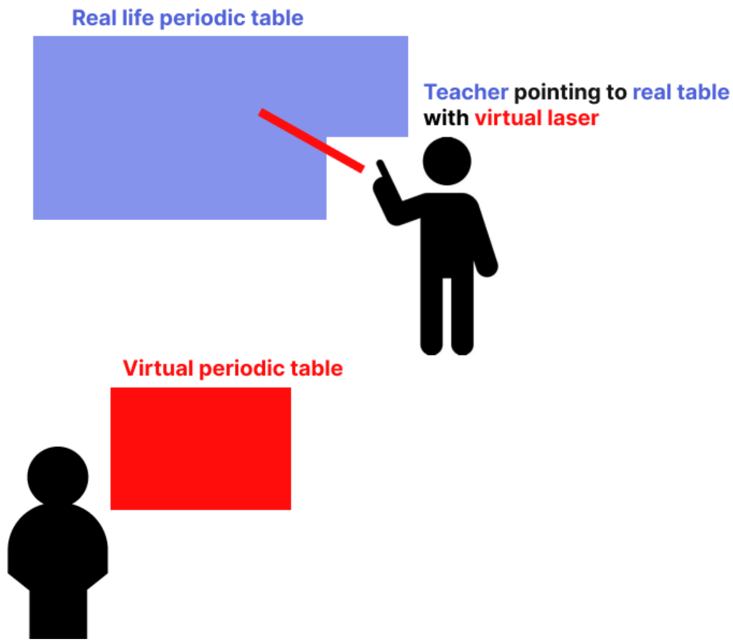

Figure 3. Experimental Setup

Blue objects represent things in real life while red objects represent things in virtual reality.

The goal is not complete accuracy, but enough accuracy that a student could tell which element a teacher is pointing at on a periodic table, so that this can be applied to an interactive 3D drawing class. To test this, I implemented a virtual periodic table in Unity. When any element is clicked, Unity saves the element name, timestamp, and trial number to a file. Once the program is terminated, the headset will have a file with the names and timestamps of all the elements that were clicked as well as the trial number for each element. I also implemented a basic unity relay and lobby networking system. One user clicks on a button to create a lobby. When the other users click the button to join, the headset will find the open lobby that was created and join it. Users with the teacher role have their own virtual laser which cuts off at the wall, so each headset will make a copy of that so they can all see where the teacher is pointing.

C. Study Design

To test the accuracy of the SyncCube's calibration, we design an experiment in which the experimenter acts as the teacher and the participants act as students in order to test this design in a classroom setting. We also test the speed in which the software can be set up in order to determine how easy this can be implemented in a classroom. The experiment is repeated across twenty classroom sessions in order to determine the average accuracy. The specific instructions given to the participants is located in Appendix 1. Before the experiment begins, the experimenter places fourteen numbers on the floor with tape, spaced out in the shape of a semicircle. The teacher also places tape on the floor to the right of the periodic table as a marker for themselves. The angle and distance of the markers to the periodic table should all be recorded, as well as the size of the periodic table and each individual element. The students should be between 2-4m away from the periodic table at angles between 50 degrees on either side. The teacher should be 1.4m away, angled 30 degrees to the right. Before giving the students their headsets, the teacher has them fill out a form of their personal information including age, gender, and race, along with written consent to participate in the study. The students begin by using the SyncCube to calibrate their headsets and then join the lobby created by the teacher. Before each student calibrates, the teacher will start a stopwatch to record the time it takes each student to calibrate their headset. The students calibrate their headsets in the order of the numbers on the floor and return to their number after. They are not allowed to move from this spot. The teacher calibrates their headset last and then returns to their marker which they must not move from. The experimenter acts as the teacher and will guide them through the basic controls of the Meta Quest in order to perform the experiment. The teacher presses the Y button on their left controller to broadcast a signal to all the headsets which will increase the trial number from zero to one. This indicates the start of the experiment, so any elements recorded with trial number 0 will be discarded. The teacher then uses this website [12] to randomly generate an element on the periodic table. They write down the element on a piece of paper to record the correct answers. The teacher then points at the element on the real-life periodic table with their laser pointer for ten seconds. Students click on the element that they see the teacher pointing to on their own virtual version of the periodic table (Figure 1). Students can ask for any instructions to be repeated, but they may not ask the teacher to point at the element again, nor may they say the names of any elements out loud to ensure there is no bias. After the first element has been pointed at for ten seconds, the teacher uses the same website to generate another element. Before pointing at the new element, the teacher presses the Y button again to increase the trial number to two. The teacher repeats this process for a total of twenty trials. To control for any accidental errors, students must let the teacher know if they misclicked and that trial number will be recorded for that student, so that the element during that trial number with the most recent timestamp will be used for data collection. This setup is repeated across twenty different mock classroom sessions in order to minimize error. After each classroom session, the headset will save a file with the elements clicked by that user along with corresponding timestamps and trial numbers. The experimenter downloads this file from each student's headset. The experimenter creates a table with the correct answers which they recorded and the answers of each student, disregarding any misclicks that were noted during the experiment and any elements with the trial number 0. Once all of this information has been gathered, the experimenter repeats this process for a total of twenty mock classroom scenarios.

Results

This experiment was conducted as a pilot study in order to test the software and the experimental design so that it can be improved for the full study. I acted as the teacher while my three research collaborators acted as the students. Student #1 got 20/20 of the elements correct, while Student #2 and Student #3 got 8/20 and 11/20 respectively. The

Correct Element	Student #1	Student #2	Student #3
Cu	Cu	Cu	Cu
Cr	Cr	Cr	Cr
V	V	V	V
Bi	Bi	Pb	Pb
Ts	Ts	Lv	Lv
Sg	Sg	Sg	Sg
Xe	Xe	I	I
Ho	Ho	Dy	Dy
Lv	Lv	Mc	Mc
S	S	P	P
Pb	Pb	Tl	Tl
Ag	Ag	Pd	Ag
P	P	Si	Si
Li	Li	Li	Li
Cd	Cd	Ag	Cd
Ir	Ir	Ir	Ir
Mo	Mo	Mo	Mo
Mt	Mt	Hs	Mt
Zn	Zn	Zn	Zn
Cl	Cl	S	S

Table 1. Recorded Elements By Student
The red elements indicate the incorrect elements chosen by the students.

teacher was standing to the right of the periodic table, pointing at an angle of 30 degrees, while the three students were arranged at different angles. Student #1 had the smallest offset of 20 degrees to the left, while Student #2 and Student #3 were angled 30 degrees and 50 degrees to the left respectively. In order, the students were at a distance of 3.07m, 2.72m, and 1.96m away from the periodic table. The periodic table elements were each 6cm by 6cm. The incorrect elements were all one element to the left of the correct element. If we allow for the accuracy of the element to be one element away from the correct one, then all three students had 100% accuracy (modified score in Table 2). The time taken to calibrate the devices is not applicable to the experiment, because the three students were all collaborators on the software, so they knew how to calibrate the device already.

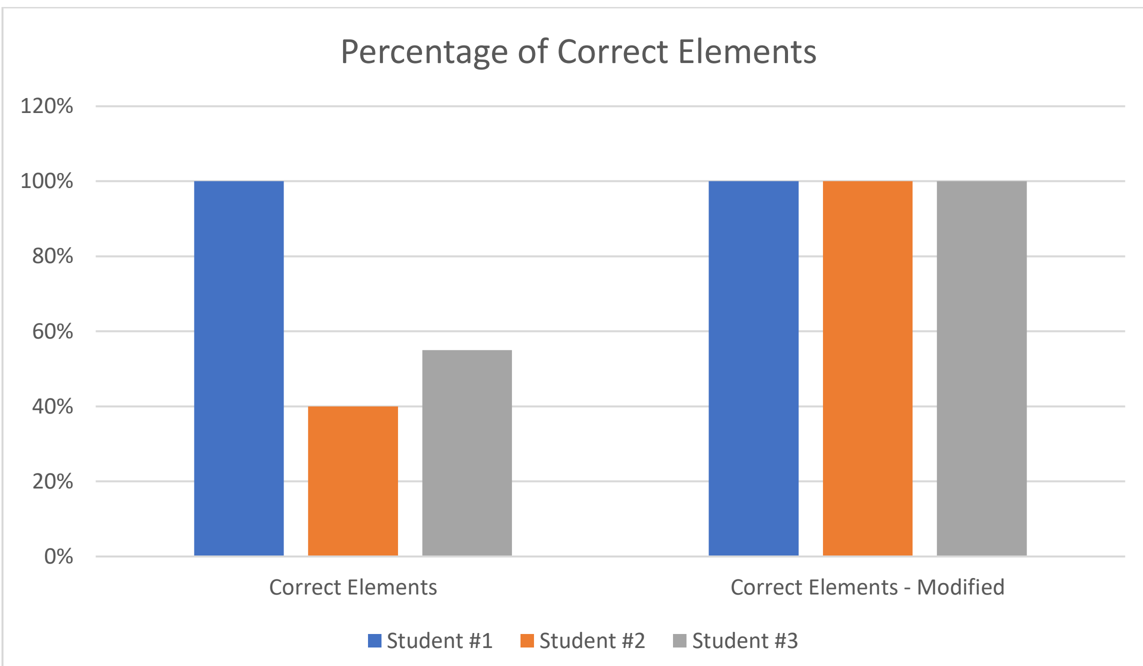

Table 2. Percentage of Correct Elements Per Student

Interpretation

We designed the study with the idea that an acceptable level of accuracy would be achieved if students standing 2-4 meters away could correctly observe the teacher pointing to an element on the periodic table that is drawn as a 6 cm square. As shown in Table 2, the pilot results show that we did not quite achieve this level of accuracy, but if we relax the acceptable level of accuracy to count answers that are within one element as correct, all three pilot participants would have achieved 100% accuracy in the task. So, although it is not quite there yet, we believe the technique is quite close to achieving our original goal.

Looking at the results, the software is mostly accurate, but it has some limitations. If either user is at too much of angle, the software will not be as accurate. Feedback from participants suggested that for the elements they got wrong, the laser pointer seemed in between two elements rather than in the center of one.

Another important observation is that the SyncCube was placed on the left of the periodic table, so the plane for the wall was created to the left as well. Since all the incorrect elements were to the left, it would make sense if this was impacted by the position of the SyncCube. The elements that all students got correct were all in the middle section of the periodic table, aside from Lithium. As the elements got closer to the sides, the students at an angle were more likely to observe the element as one to the left of the correct element.

From this data, the software correctly calibrates the headsets to be in the same coordinate space, but it is not as accurate as expected. For the intent of a 3D drawing class, this accuracy is close and could likely be improved upon. If some minor corrections are made to improve the accuracy of the calibration at an angle, then this software could be very effective for a general classroom setting.

Future Work and Conclusion

In conducting the pilot study for this experiment, we were able to get feedback on what to improve for a future experiment. Since the virtual laser pointer was shaky, this could be made more stable in the software. The SyncCube could also be clamped down, and its calibration could be slightly more precise, since the outline of the virtual sync cube did not match up perfectly. The controllers also had to be placed firmly in the SyncCube for it to align properly, so this 3D design could be improved so that the controller has a more firm and stable base for calibration. As far as experimental design goes, I would repeat this test with several students spread out at different angles. I would also repeat it with the teacher at different angles to the periodic table, since the teacher's position seemed to be just as influential on the results as the students' position. I would also like to have students move around between sessions to see how much drift there is with the calibration. Another thing to study is the impact of the SyncCube's location on the offset of the elements. I think that if the SyncCube were placed directly underneath the periodic table, the accuracy would improve. I also want to collect more data on the specific distance and angle of each student to the periodic table as well as the dimensions of the periodic table and each individual element.

Overall, the SyncCube's calibration proved effective for Inside-out Tracking. The software can still be improved, but it is much cheaper and easier to use than current calibration techniques. It also requires less computational power by using only an initial calibration. The calibration was not as accurate as expected, but the overall technique of aligning the coordinate space of various headsets proved to be effective.

Appendix 1. Experimental Study Instructions

"Welcome to the Interactive Visualization Lab, and thank you for participating in our experiment. Before we begin, you will be given a Meta Quest 3 which will be used for the study. When you put it on, the Quest should open up the testing software and you should be able to see a virtual representation of the controllers in your hand. Then, I'll give you some basic instructions for how to use this software. If any of these instructions are unclear, please ask for assistance. On the right controller, there is a trigger that you should be able to press with your right index finger. Use the right controller to aim, and press the right trigger to click."

"Please walk up to the SyncCube at the front of the room. I will call you each one by one, and I will start the stopwatch once you begin walking. Once you're in front of the SyncCube, hold up your left hand so that the side of your left controller is facing you. You should see a menu pop up on your hand. Please use your right hand to click on the top button which says experimental setup. Place your left controller in the SyncCube and push down firmly to make sure it is seated properly. Click on the top button in the setup menu that you just pulled up to calibrate the room space. Check that the blue virtual outline of the SyncCube overlays the physical cube. If not, reposition the controller and try again. When you are done, click on the X to close the menu, and return to your spot. Once you have returned to your spot, I will stop the stopwatch and record the time taken for calibration. I will now create the lobby. Please reopen the setup menu on your left hand and press the button on the bottom of the menu to join the lobby. I will use a website to randomly generate 20 elements on the periodic table. I will point to each element for ten seconds, and you will have that time to click the element you see me pointing to on your own periodic table. If you make a mistake, please let me know, and I will record that information. You may then click on the element you meant to choose. If you have any questions at any time, please raise your hand. Do not say the names of any elements out loud to ensure there is no bias in the chosen answers. Once all thirty trials have finished, you will give your headset back to me who will exit the software for you. Thank you again for your participation."

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