Augmented Reality in Physics education: Motion understanding using an Augmented Airtable

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Abstract. Education is a highly interesting field for Augmented Reality (AR) applications allowing for tangible experimentation and increased immersion. In this paper we present our efforts on adding an AR visualization on a physics airtable experiment used for the understanding of object motion and collisions on a nearly frictionless surface. Using AR, information such as the objects velocity, angular velocity and kinetic energy can be overlayed over the objects in real-time to give direct understanding of physics motion laws. We present the implementation of two versions of such an AR system, using an HMD and a projector respectively, and discuss the development challenges and advantages/disadvantages of each one.

Keywords: Augmented Reality · Education · Tracking.

1 Introduction

Augmented Reality (AR) is a quickly advancing technology with many diverse applications fields [5] such as entertainment [15], industrial maintenance and assembly [13], medicine and healthcare or communication.

Education and teaching is a very promising field for AR applications [7]. AR has the ability to increase immersion and provide comprehensive user interfaces that directly superimpose useful virtual content over the real-world. Furthermore, AR can provide gamification of hands-on learning processes such as practical experiments, thereby making learning a more pleasant experience [10].

The support of AR in education and teaching has been a topic of research for a long time. Bower et al.[6] described four learning categories in which AR can be useful: Constructive learning by encouraging students with deep engagement with tasks and concepts; situated learning by embedding the experiences in real-world; game-based learning with immersive game designs and narratives and; enquiry-based learning by electronically acquired data used for analysis and virtual models within a real world context.

Understanding the concepts of mathematics for young students is often cumbersome. AR as a tool can provide great advantages allowing students to directly see the effects of math-related concepts[9]. The usage of media in classrooms for reinforcing the learning experience is not uncommon. However, unlike AR, they are not immersive or interactive. AR can have direct influence on students learning styles, attitude and aptitude and it can also effect teacher's approach and style by blending ficitonal narratives with real world environments[8].

This work is part of the Be-Greifen research project [3] that aims to enhance practical physics experiments for students with technologies such as AR in order to make them more tangible and comprehensible with new forms of interaction. With the help of interactive experiments, physical connections are to be made easier to understand for learners of science, engineering and mathematics education. Physical principles of mechanics and thermodynamics, are made interactively researchable in real time [11].

In this paper, we present the work done within this project, revolving around a specific experiment that is designed for the understanding of the laws of classical mechanics related to velocity, energy and momentum during collisions. The goal of this work is to track objects on an airtable with a camera and display real-time visualizations in AR that assist the study and understanding of the laws that determine their motion.

Two AR setups were developed for this experiment, one designed for university students in a laboratory environment using a Head Mounted Display (HMD), and a second one using projection-based AR designed for an exhibition in a science museum addressed to a much broader user base. In the following we discuss the technical implications and challenges encountered in the development of these AR systems and present the final outcome and impressions from both versions.

2 Augmented Airtable Concept

The general experimental setup consists of an airtable, a camera, and cylindrical objects (pucks) that move on the airtable. The airtable creates a thin layer of air so that objects can float on its surface with minimum friction to reduce kinetic energy loss. The experimental concept is that users move these pucks and observe their motion during collisions with the boundaries of the tables or with other pucks.

In the original version of the physics laboratory experiment (see Figure 1), a camera placed over the airtable records the movement of pucks during the experiment. The resulting footage is then processed offline to compute data such as the velocity, angular velocity and kinetic energy of the pucks. This data is used for the experimental validation of laws of mechanics such as the preservation of momentum.

The work presented here focuses on the enhancement of this physics experiment using AR. The images from the camera placed on top of the airtable are used to perform live 6 Degree-of-Freedom (6DoF) pose tracking of the pucks and this pose is used to display live AR augmentations using another device such as an HMD or a projector. The use of AR allows to display live information to-

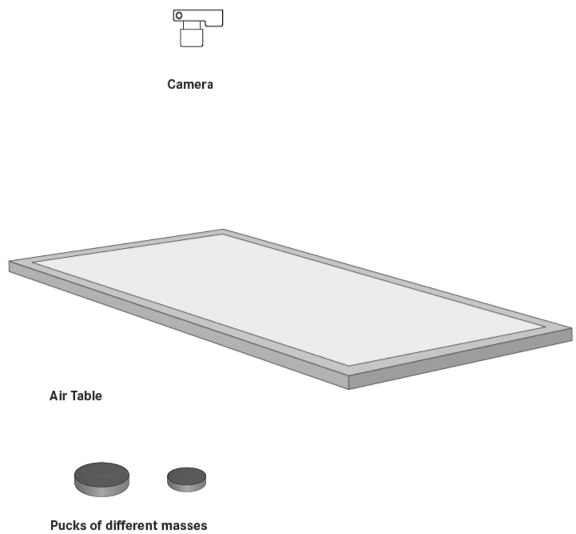

Fig. 1. The initial setup of the airtable experiment in the physics lab with a camera on top of the table recording the movement of the pucks.

gether with visualizations that can support the understanding of motion on the airtable.

2.1 Notation

We use the following notation for the description of poses in this work. A 6DoF camera pose is given by a transformation from a given world coordinate system W to the camera coordinate system C. This transformation consists of a rotation matrix $\mathbf{R}_{cw} \in SO(3)$ from world-to-camera coordinate system and a translation vector $\mathbf{W}_c \in \mathbb{R}^{3\times 1}$ denoting the position of the camera coordinate system origin in the world coordinate system. A 3D point $\mathbf{p}_w$ in world coordinates can be transformed to camera coordinates $\mathbf{p}_c$ by applying:

$$\mathbf{p}_c = \mathbf{R}_{cw}\mathbf{p}_w + \mathbf{W}_c. \tag{1}$$

By multiplying $\mathbf{p}_c$ by the camera intrinsics matrix $\mathbf{K}$ and normalizing by the depth, we can obtain the pixel coordinates of the projection of the point on the camera image.

2.2 Marker Tracker

For the 6DoF tracking of the pucks we use the marker tracking software of [12], an approach based on tracking by detection of circularly encoded markers (examples in Figure 3). Considering a coordinate system M with its origin at the center of a marker, the marker tracker provides for every frame an estimate of the camera pose consisting of a rotation $\mathbf{R}_{cm}$ and a translation vector of the position of the camera in the marker coordinate system $\mathbf{C}_m$. The circular marker patterns are printed on the pucks used in the airtable experiments.

2.3 Motion and Energy Computation

From the marker positions and orientation attributes such as the velocity, angular velocity and kinetic energy can be derived. To compute the velocity vector $\mathbf{v}_m$ of a marker, the positions from the tracker and the time interval are required. The time interval depends on the frame-rate of the camera, $\Delta\mathbf{t} = \frac{1}{fps}$. Using the marker positions in two consecutive frames $k, k-1$ the velocity is computed as:

$$\mathbf{v}_m = \frac{\mathbf{M}_c^k - \mathbf{M}_c^{k-1}}{\Delta\mathbf{t}} \tag{2}$$

Since the marker is always moving on the flat surface of the airtable, it can only rotate on one axis (z-axis in our implementation). This allows to compute the angular velocity a_m by using consecutive measurements of the x-axis angle θ_x:

$$a_m = \frac{\theta_x^k - \theta_x^{k-1}}{\Delta\mathbf{t}} \tag{3}$$

The kinetic energy computation requires the current velocity and the mass n_m of an object, $\mathcal{E}_{kin} = \frac{1}{2} n_m \mathbf{v}_m^2$.

3 Implementation for Laboratory - HMD Version

In this section we will describe the first version of the Augmented Airtable implementation that uses an HMD. This version was primarily designed for engineering students that perform the airtable experiment on their physics laboratory class. The idea is to show live data such as velocity, angular velocity and kinematic energy of the pucks overlaid on the HMD. This aims to assist the students in evaluating the outcome of their experiments directly instead of doing that in post processing of captured videos. It also provides a more tangible experience for the understanding of the laws that define the motion of the pucks.

3.1 Physics Laboratory Setup

The system follows the general principle previously described in Figure 1 consisting of the airtable, a camera positioned over the table, and different pucks with markers. Pucks have different sizes and weights in order to allow the study of the effects of mass on collisions. Also, pucks made of different materials are available for the study of elastic and unelastic collisions.

The added component is an HMD, in this case the Microsoft Hololens [1]. The user with the HMD is able to move freely around the table, therefore the device pose needs to be tracked as well. This is done using a combination of the internal SLAM tracking system of the Hololens and an additional marker placed on the table in order to establish a correspondence between the coordinate systems. The required calibrations and pose transformations are described in the following section. A server PC that tracks markers on the camera images and sends the tracked positions to the HMD through a wireless connection is also required in this setup.

3.2 Implementation

Since no software for tracking the circular markers using the Hololens was available and porting the marker tracking software would induce frame-rate limitations and a siginificant overhead to the HMD processor, an additional marker tracking software was required. A Vuforia marker tracker was used for this purpose [2]. This additional marker is rigidly attached to the table surface to establish a correspondence between the airtable and the HMD. The marker has to be constantly visible by the airtable camera and visible by the Hololens only when starting the tracker to perform initialization by localizing the vuforia marker in the world coordinate system of the Hololens.

In order to describe the necessary pose transformations we define additionally the coordinate system V of the Vuforia marker and the coordinate system H of the Hololens tracker. The circular marker tracker output can provide the marker's position $\mathbf{M}_c$ and rotation $\mathbf{R}_{mc}$. The Vuforia tracker outputs the Vuforia marker's postion in the camera coordinate system $\mathbf{V}_c$ and rotation $\mathbf{R}_{vc}$ and the marker's position in the Hololens coordinate system $\mathbf{V}_h$ and rotation $\mathbf{R}_{vh}$. The relation between the marker tracker and Vuforia tracker is as follows:

$$\mathbf{M}_v = \mathbf{R}_{vc}\mathbf{M}_c \tag{4a}$$

$$\mathbf{R}_{vm} = \mathbf{R}_{vc}\mathbf{R}_{cm} \tag{4b}$$

The position and rotation of the marker computed by a server PC are then transferred to Hololens via wireless network connection. The use of a server allows to run the tracking software on a high frequency (60fps supported by the camera used here) to follow fast marker motion without burdening the HMD processor. On Hololens, the Vuforia marker's position $\mathbf{V}_h$ and rotation $\mathbf{R}_{vh}$ are initialized in relation to the registered position and rotation of the device itself in the 3D space (the origin of the world coordinate system of the Hololens SLAM tracker). Therefore, the orientation of the circular marker around the Vuforia marker, must be according to this registered origin:

$$\mathbf{M}_h = \mathbf{R}_{vh}\mathbf{M}_v \tag{5a}$$

$$\mathbf{R}_{mh} = \mathbf{R}_{mv}\mathbf{R}_{vh} \tag{5b}$$

The combination of the transformations from Equations 4 and 5 allows to transform the marker poses to Hololens coordinate system in order to display augmentations over the markers. An example of the visualizations in this version of the system can be seen in Figure 2

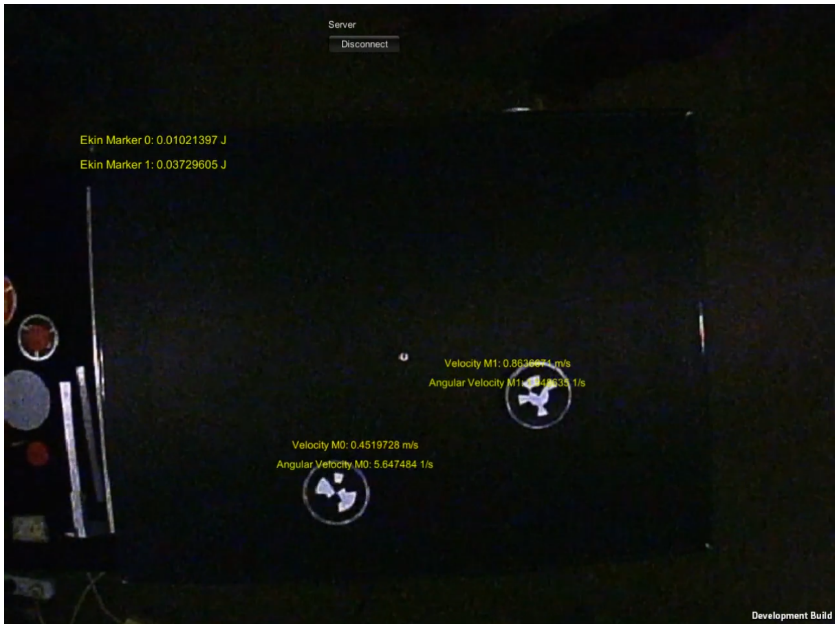

Fig. 2. Example of the visualization for the physics lab experiments. Live values of velocity, angular velocity and kinetic energy of markers are shown

3.3 Discussion/Limitations

Although the pose of the circular marker was registered and tracked correctly on the Hololens, the application itself still has some limitations that make its deployment problematic. These issues are mainly caused by hardware limitations, especially the limited field of view of the HMD. This makes it difficult for the user to follow the markers especially at high velocity and also to maintain an overview of augmentations on the entire airtable surface. Secondly, the wireless network connection for the transmission of marker poses to the Hololens can occasionally be a source of delays for the system. A delay in the pose in such an AR system can create a lot of discomfort for the user especially during fast motion of the pucks. Finally, the pose from the Vuforia on the Hololens was sometimes unreliable, leading to a wrong initialization of the system. To summarize, the use of an HMD for AR can be a viable option in more static experiments such as [14], however for this particular experiment of fast motion the existing hardware technology is not yet sufficient. Therefore, a different direction for the deployment of the system using projector based AR was also adopted and is described in the following section.

4 Implementation for Science Museum - Projection AR

A second version of the Augmented Airtable was developed for the exhibition of the Dynamikum Science Center [4]. Since this exhibition is visited by people of all ages and technological expertise levels, the focus here was on learning through entertainment. Therefore, a more suitable visualization for this purpose was developed. Additionally, this version is meant to be a group experience rather than an individual one, therefore projective AR is used instead of HMDs. This choice is also of importance for the robustness and lifetime of the setup considering the state of current HMDs for AR.

4.1 Science Museum Setup

Apart from the main components described previously, a projector is introduced in this version (Figure 3). The projector is placed in close proximity to the camera, also over the airtable, with the purpose to project AR visualizations on the moving pucks. The camera images are processed by a server PC which is also responsible for generating the augmentation images for the projector. No HMD is used in this version. Instead a multi-person experience is created through the projection of AR visualizations directly on the airtable.

Fig. 3. Left: Setup in Dynamikum Science Center. Right: Markers

4.2 Implementation

The setup in this scenario is static. The camera never moves and is always in a fixed distance from the projector. As mentioned in 2.1, the final projection is obtained by multiplying the intrinsics matrix $\mathbf{K}$ by camera coordinates $\mathbf{p}_c$. However, this is the projection onto the camera image and not on projector image. An additional transformation from camera to projector is therefore required. A homography calibration matrix $\mathbf{H}$ which maps the center points of the marker in the image to its counterpart in the real world is computed offline. The final projected point in image space is multiplied by the homography matrix in order to compute the point in the projector space.

4.3 Visualization

In this version a different visualization is used, focusing primarily on conceptual understanding rather than exact measurements. Therefore, velocity and angular velocity were used to create a trail of two color-coded lines in the position of the marker every frame(Figure 4). For visualizing velocity, the value from the marker tracker was mapped to a color in the range of blue and red, with red being a high and blue a low velocity. This color was rendered on the line strip and interpolated to the next value. For the angular velocity, a thinner line strip was rendered in the middle of the bigger strip with colors light blue and yellow representing low and high velocity respectively(Figure 5). The lines are always visible on the table unless the user picks up or covers the marker in which case the trail will be cleared.

Fig. 4. A color-coded line for visualizing the velocity and angular velocity. The inner line strip is used for angular velocity and the outer strip for velocity.

4.4 Discussion

The initial evaluation in the museum showed that this application of AR was well received, is entertaining, and can be useful in reinforcing the concepts of movement and velocity in physics. Further investigation is currently being conducted by collecting data from the visitors. At the moment the entire paths that markers have travelled are being visualized which is useful for understanding the change of velocity on the path. However, when several markers are moving on the table, after some time, it becomes difficult to distinguish the paths. One option to deal with this would be to use different color-codings for each marker rather than red(yellow)-blue(light blue) for all. Another option would be to use directional arrows for visualizing the path of the markers with the colors rendered only inside the arrows. An updated version of the visualization will be designed after the initial evaluation round has finished.

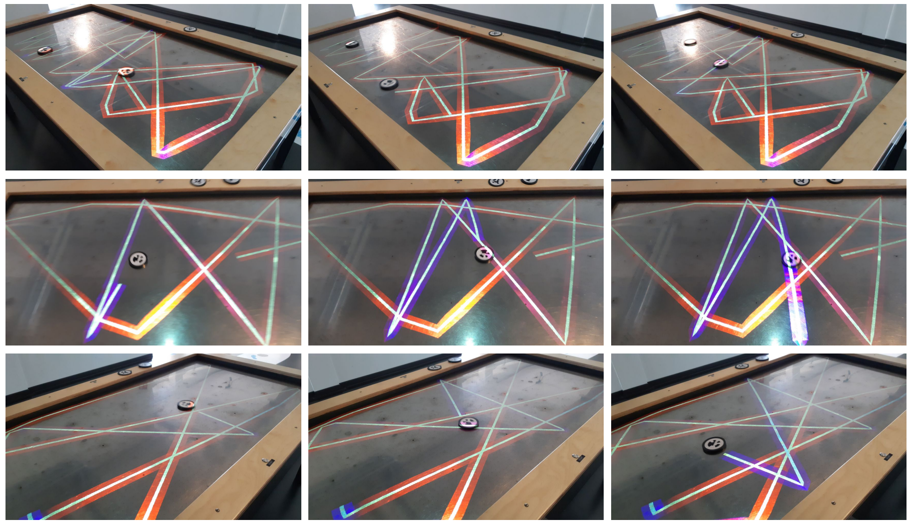

Fig. 5. Visualization of the markers movement on the air table. High velocity(angular velocity) is mapped to red(yellow) and low velocity(angular velocity) to blue(light blue)

5 Conclusion

In this paper we described our efforts in enriching a traditional physics experiment using AR. An airtable experiment used for the understanding of laws behind object motion and collisions was the target of our work. Two different AR implementations were presented, one intended for single user experimentation with an HMD, and a second one using projective AR targeting multi-user shared experiences. We discussed the details of these implementations and their limitations. In the projective AR version a much more satisfying end result was accomplished compared to the HMD version which suffered from limitations caused mainly by hardware issues such as the field of view of the device. In the future, these approaches will be evaluated at their locations of deployment (university and technology museum) in order to quantify the user experience, the interaction aspects and educational value of these systems.

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References

1. Microsoft hololens, https://www.microsoft.com/en-us/hololens (2018), https://www.microsoft.com/en-us/hololens
2. Ptc vuforia, https://www.ptc.com/en/products/augmented-reality (2018), https://www.ptc.com/en/products/augmented-reality
3. Be-greifen project, http://www.begreifen-projekt.de/ (2019), http://www.begreifen-projekt.de/
4. Dynamikum science center, https://dynamikum.de/ (2019), https://dynamikum.de/
5. Billinghurst, M., Clark, A., Lee, G., et al.: A survey of augmented reality. Foundations and Trends® in Human–Computer Interaction **8**(2-3), 73–272 (2015)
6. Bower, M., Howe, C., McCredie, N., Robinson, A., Grover, D.: Augmented reality in education – cases, places and potentials. Educational Media International **51**(1), 1–15 (jan 2014). https://doi.org/10.1080/09523987.2014.889400
7. Dunleavy, M., Dede, C.: Augmented reality teaching and learning. In: Handbook of research on educational communications and technology, pp. 735–745. Springer (2014)
8. Dunleavy, M., Dede, C., Mitchell, R.: Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning. Journal of Science Education and Technology **18**(1), 7–22 (sep 2008). https://doi.org/10.1007/s10956-008-9119-1
9. Kaufmann, H., Schmalstieg, D.: Mathematics and geometry education with collaborative augmented reality. Computers & Graphics **27**(3), 339–345 (jun 2003). https://doi.org/10.1016/s0097-8493(03)00028-1
10. Klopfer, E., Squire, K.: Environmental detectives—the development of an augmented reality platform for environmental simulations. Educational Technology Research and Development **56**(2), 203–228 (apr 2007). https://doi.org/10.1007/s11423-007-9037-6
11. Knierim, P., Kiss, F., Schmidt, A.: Look inside: Understanding thermal flux through augmented reality. In: 2018 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct). pp. 170–171. IEEE (2018)
12. Pagani, A., Koehler, J., Stricker, D.: Circular markers for camera pose estimation (2011)
13. Rambach, J., Pagani, A., Schneider, M., Artemenko, O., Stricker, D.: 6DoF Object Tracking based on 3D Scans for Augmented Reality Remote Live Support. Computers **7**(1), 6 (2018)
14. Strzys, M., Kapp, S., Thees, M., Klein, P., Lukowicz, P., Knierim, P., Schmidt, A., Kuhn, J.: Physics holo. lab learning experience: Using smartglasses for augmented reality labwork to foster the concepts of heat conduction. European Journal of Physics **39**(3), 035703 (2018)
15. Von Itzstein, G.S., Billinghurst, M., Smith, R.T., Thomas, B.H.: Augmented Reality Entertainment: Taking Gaming Out of the Box. In: Encyclopedia of Computer Graphics and Games, pp. 1–9. Springer (2017)