Magnetic Field Visualization in Augmented Reality and Serious Games

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To support the teaching of the physical concept of magnetic fields, we created a serious game that uses magnets as gameplay elements in augmented reality. In order to make this game accurate and helpful, it contains a simulation of magnetic fields in 3d and multiple methods of visualizing these fields. This simulation is extensible to different types of magnets and their interactions with electrical conductors. Finally, the application uses 3d object tracking to project the visualization onto actual magnets in physical experiments and include them into the gameplay.

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1 INTRODUCTION

Learning is an essential aspect of human life, but different people acquire knowledge in various ways. Some tend to learn better through visual means, while others prefer auditory means or more hands-on type of approaches. Often classes a taught in a conventional way, perhaps to the detriment of students who prefer other learning methods which may lead to loss of interest or difficulty understanding theoretical concepts [10].

Augmented Reality is a tool that allows us to enhance the way we interact with different concepts and has shown to improve performance of students in an educational setting, by making the concepts interact-able and reactive to students and their own actions. This way students are able to explore the concepts by asking themselves questions such as "What happens if I do this?" or "How does this change when I perform a certain action?", prompting a more intuitive learning experience and understanding of the underlying concepts.

In this project we focused on magnetic fields and aimed to develop a serious game that makes use of AR to visualize such fields in an interactable way, allowing for a more intuitive learning experience.

The project involved contribution from several individuals, including our supervisor Dr. David A. Plecher, a postdotoral reasearcher at the Interaction and Communication department of the School of Computation, Information and Technology at the Technische Universität München. Additionally, Max Warkentin, a Ph.D. student studying Theoretical Physics at the Faculty of Physics at the Ludwigs-Maximilians-Universität acted as our expert regarding the physically accurate computation of the magnetic field for our project, providing us with information about the necessary mathematical formulas.

2 RELATED WORK

2.1 Serious Games in Education

Serious Games have been proving themselves as an effective tool for learning in the recent years. Studies have shown that serious games can improve learning outcomes over traditional teaching methods. Bellotti et al. have concluded that game-based learning is effective for motivating students to achieve learning goals [4]. High school students have been observed to perform better when learning about a subject through a serious game than with traditional means [11]. Ullah et al. researched serious games in combination with AR to study aspects of serious games in science education. They have shown that serious games coupled with AR technology make it easier for students to understand concepts as well as having a positive effect on the mood of the students [12].

2.2 Augmented Reality

Augmented Reality (AR) is a technology that allows virtual content to be positioned in the real world, blending a virtual world with the real world. It has been used in a variety of fields including education and entertainment. In educational settings, AR has proven to be a useful tool to visualize complex concepts in an interactive setting. Cai et al. found that AR technology can improve the performance of high school students as it is able to turn abstract learning concepts about physics into perceivable dynamic content. AR applications can make phenomenon that can't be directly observed in reality visible in the classroom and in turn, the application helps the students to understand the concepts [5]. In 2012, Matsutomo et al. [7] already proposed using augmented reality for teaching about magnetic fields, although their system was limited to very simple setups. Radu and Schneider have also explored augmented reality as an educational medium by using it as a means to portray a magnetic field in AR for a performed experiment. Following the experiment, the students who were shown an AR representation of the field were significantly more effective in developing an understanding of the magnetic fields and how it responds to electrical currents [9].

3 PROJECT PLANNING

3.1 Idea Development

Our idea for this project developed over time. Initially, we knew we wanted to use Augmented Reality to interact and visualize a phenomenon. We met with David, our supervisor, on a weekly basis and decided to combine a physics concept with Augmented Reality to interact and visualize a physics phenomenon. Then we met with Max Warkentin, our physics expert, to discuss more concrete ideas. With further meetings with our supervisor and emails with our physics expert, we settled to our final idea: visualizing and interacting with Magnetic Fields using Augmented Reality. As the audience for our application, We targeted pupils at the 9th or 10th grade and students starting their studies. Now that the idea and audience are determined, we can clearly state our goal: Help pupils or new students have a better intuitive understanding of Magnets and Magnetic Fields by making a Serious Game that visualizes and provides ways to interact with these concepts using Augmented Reality.

3.2 AR Libraries

To enable the use of Augmented Reality (AR) features in our project, we decided to use an AR library to implement tracking of markers and objects.

We have tested several different libraries including ARFoundation/ARKit, VisionLib and Vuforia, and compared the results to find the library most appropriate for our project. When comparing these libraries we were mostly interested in the performance and accuracy of the object tracking as our goal was to be able to reliably track a physical magnet. Initially, we considered ARKit, but as it requires an Apple device for object tracking and we were not able to to test the application with this library so we explored other approaches.

Our testing reavealed that VisionLib and Vuforia had similar performance in terms of object tracking. However, with Vuforia it was also possible to start tracking the object from any angle using it's Model Target Generator (MTG) as well as testing and debugging the application in the Unity Editor.

3.3 Tools Used

After consideration the following tools were used to develop our serious game:

- **Unity:** Cross-platform Game Engine.

- **Vuforia Engine:** Software Development Kit (SDK) for creating Augmented Reality apps with support for the Unity Engine. This AR library contains functionality for recognizing images, objects, and spaces as well as the ability to augment the real world with virtual objects.
- **Blender:** To create a 3D model that resembles our real magnet
- **Substance Painter:** Used for designing the textures containing patterns to improve tracking performance of Vuforia's Model Targets.

4 GAME DESIGN

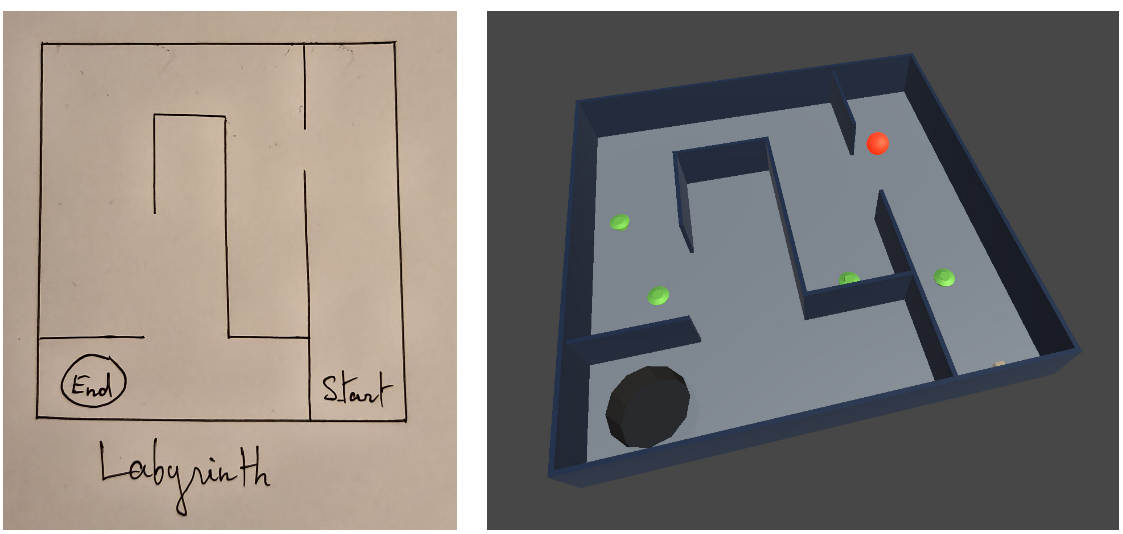
One good thing about computer science is that technology is always improving which allows us to perform actions that were previously thought to be difficult or even impossible. This means that we are given a chance to experiment with new types of gameplay [6], and in our case this meant combining augmented reality with a physics concept to design our game. The final application contains both physically accurate simulations and visualizations as well as two simple games that allow the user to accustom themselves with the properties of magnetic fields and their interactions.

4.1 Sandbox

The first scene of the application is a physical sandbox. It contains a simulated magnet, a few small objects that interact with it, and an electric conductor. Furthermore, the different visualizers are selectable to display the magnetic field and its interactions. These elements are important to show the simulated properties, and can be used in further scientific applications beyond the scope of a simple game.

4.2 Labyrinth

The first game-related scene is the labyrinth. In this mini-game the player must figure out how to correctly move the physical magnet in space to interact with the ball and lead it to the end point. This serves as an introductions to some of the features of the second game, and allows the player to get to know the magnet simulation.



(a) Sketch of the Labyrinth mini-game (b) Labyrinth final result

4.3 Magnetic Pinball

The pinball table is the main, more complex game. Similar to the first mini-game, this one increases the difficulty by having the player move a magnet in space to control the ball in order to play a pinball mini-game. The pinball mini-game is composed of multiple components that influence the behavior of the ball:

- Rollover: successfully making a ball roll on top of this component awards points multiplier and gives the ball a speed boost.
- Bumper: successfully making a ball bump into this component awards points and bounces the ball away.
- Gate: successfully making a ball go through a gate awards points and changes the ball's polarity.
- Plunger: successfully placing a ball into this component charges the ball making it easier to be influenced by the magnet.
- Hole: successfully making a ball fall into this component makes the ball disappear and awards points. Holes in the middle award less points than holes at the extremities.

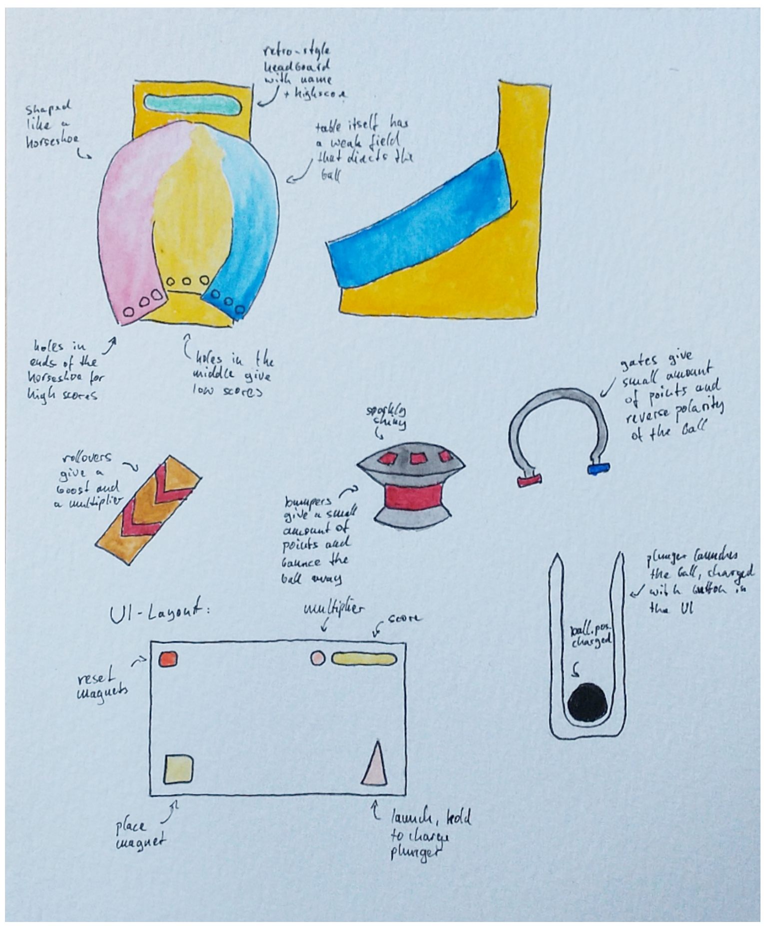
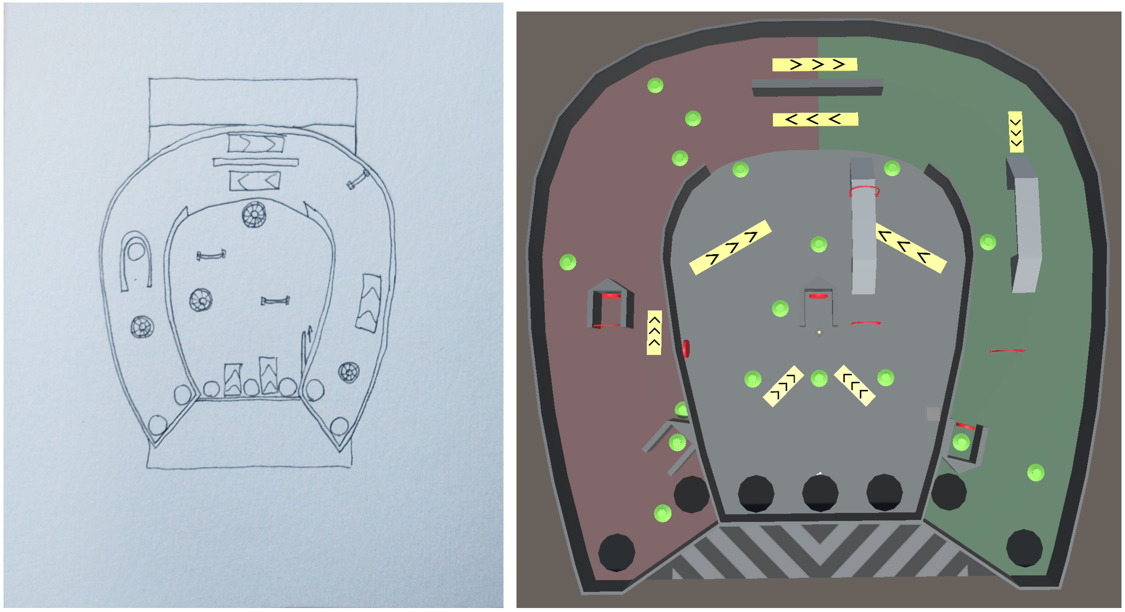


Fig. 2. Concept sketch of the different components in our Pinball mini-game



(a) Sketch of the table in our Pinball mini-game (b) Pinball final result

5 SIMULATING MAGNETS

5.1 General Idea

Using sensors to measure and display the real magnetic fields in an experimental setup exceeds the capabilities of a smartphone, which the application was developed for. Therefore, simulating the behaviour of magnets is foundational to visualizing it correctly. From a most simplistic point of view, magnets exude a force on magnetic objects in the space around them, that gets weaker with increasing distance to the magnet. Starting from this simple assumption, one can use a spatial kernel function to approximate the magnetic influence at any position in space (alg. 1).

Algorithm 1 Linear Monopole Function

function POLE.GETMAGNETISM(*position*)
  $dist \leftarrow ||position - pole||$
  if $dist > maxDist$ **then**
    return $(0, 0, 0)$
  end if
  $dir \leftarrow (position - pole).normalized$
  $force \leftarrow dir * \frac{maxStrength*(maxDist-dist)}{maxDist}$
  return $force$
end function

5.2 Magnetic Components

In reality, magnets take more complex forms than one-dimensional mono-poles, and require more sophisticated models to accurately represent them. A very useful component in this case is a polyline that represents one pole of a magnet (e.g. one "arm" of a horseshoe magnet). Such a polyline consists of multiple points in space, connected by straight lines. Without great loss of generality, we can assume that the magnetic force at any position is dominated by the force exuded by the closest point on the polyline[1]. Using this assumption, a kernel function can be applied once more (alg. 2).

Another helpful component, especially in the case of horseshoe magnets, is the homogenous field. Simulating it on its

Algorithm 2 Magnetic Polyline Function

```
function POLYLINE.GETMAGNETISM(position)
    closest ← ClosestPoint(polyline, position)
    dist ← ||(position − closest)||
    if dist > maxDist then
        return (0, 0, 0)
    end if
    dir ← (position − closest).normalized
    force ← dir * (maxStrength*(maxDist−dist)) / maxDist
    return force
end function
function CLOSESTPOINT(polyline, position)
    closest ← (∞, ∞, ∞)
    for i ← 1, i < polyline.length, i++ do                ▷ Line Projection
        A ← polyline.points[i]
        B ← polyline.points[i − 1]
        P ← position − A
        AB ← B − A
        C ← AB.normalized
        C ← (C*P)/(C*C) * C
        if ||C|| < ||AB|| then                            ▷ Check Boundaries
            if ||A + C − B|| < ||AB|| then
                point ← A + C
            else
                point ← A
            end if
        else
            point ← B
        end if
        if ||(closest − position)|| > ||(point − position|| then
            closest ← point
        end if
    end for
    return closest
end function
```

own instead of trying to create a homogenous field between two polylines ensures true homogenity, which is usually desirable. A homogenous field needs only a direction, a strength, and a volume in which it acts, which can be provided by a collider. Within the field, the force is equal at any point (alg. 3).

[1]There is only case in which this assumption creates results that are noticeably different from the behaviour of a real magnetic field: If the polyline is concave and the measurement is taken within an "opening". This case can, if necessary, be mitigated by additional components as discussed later.

Algorithm 3 Homogenous Field Algorithm

```
function homField.GetMagnetism(position)
    if homField.collider.Contains(position) then
        return homField.direction * homField.power
    else
        return (0, 0, 0)
    end if
end function
```

5.3 Creating Specific Magnets

Using the established components and ideas, it is possible to simulate complex and diverse magnets. The most important magnet for this project was the horseshoe magnet. A sufficiently accurate horseshoe magnet can be created by combining two polylines with opposing charges (for the "arms") and a homogenous field (for the field between the arms, useful to mitigate the slight inaccuracy of the polylines in enclosed spaces). This model (figure 4) provides accurate approximations for both inner and outer field of the horseshoe magnet (figure 5). To calculate the magnetic force at any given position, the components are evaluated individually and only the final result is returned. This prevents overlaps of inner and outer field (alg. 4).

As the simulation includes the calculation of the Lorentz-force, it is necessary to also simulate the behaviour of an

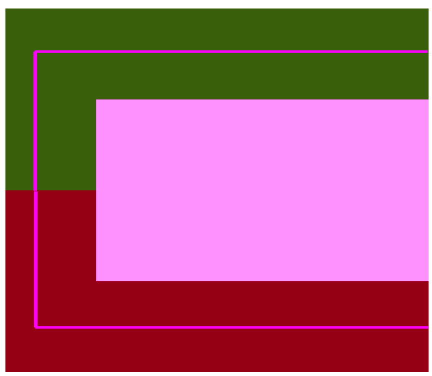


Fig. 4. Structure of a simulated horseshoe magnet, magnetic components shown in magenta

Algorithm 4 Horseshoe Magnet Algorithm

```
function horsehoe.GetMagnetism(position)
    force ← horseshoe.homField.GetMagnetism(position)
    if force ≠ (0, 0, 0) then                          ▷ Is the position within the homogenous field?
        return force
    end if
    force ← force + horseshoe.north.GetMagnetism(position)
    force ← force + horseshoe.south.GetMagnetism(position)
    return force
end function
```

electric conductor. The magnetic field of an electric conductor is circular and perpendicular to the direction of the conductor. Simulating this field can, again, be done using polylines (alg. 5).

This system of simulating magnets is extensible to support various forms of magnets. In this case, we limited the supported models to the kinds of magnet we would be using in the game and the simulations, but in the future it would be perfectly easy to construct further magnets from the components we have created.

Algorithm 5 Conductor Field Algorithm

```
function conductor.GetMagnetism(position)
    closest ← ClosestPoint(conductor, position)            ▷ equivalent to polylines
    dist ← ||(position − closest)||
    if dist > maxDist then
        return (0, 0, 0)
    end if
    dir ← (conductor.direction × (position − closest)).normalized    ▷ perpendicular to normal
    force ← dir ∗ maxStrength∗(maxDist−dist) / maxDist
    return force
end function
```

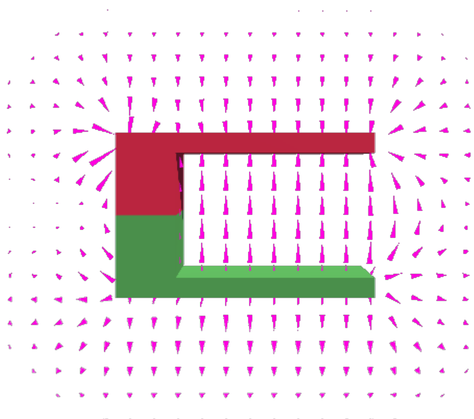
6 VISUALIZATION

Given the previously explained simulation of magnetic fields, it is now possible to visualize them. Magnetic fields ultimately are vector fields, and can be visualized as such. Using augmented reality for this visualization provides a fundamental advantage over traditional methods: it allows a user to look at and apply the visualization from any direction in space, providing more comprehensive insight. For different purposes, it is useful to have different visualizations. This project contains two essential methods of field visualization, plus one method of visualizing the Lorentz-force resulting from an electric conductor being introduced into the field.

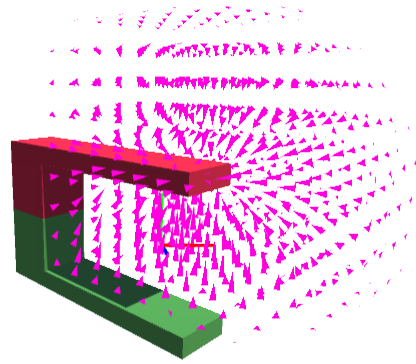
6.1 Field Vectors

One very typical way to visualize magnetic fields is the usage of a regular grid of vectors that align with the field once a magnet is close enough [3]. This method is even used in analog experiments and in teaching, with arrays of compass needles on a board. In this case, it is limited to displaying a 2d slice of the field. Extending this method into 3d in augmented reality is simple. Additionally, the vectors can be of adaptive length, therefore also displaying the relative strength of the field at their location. The direction of the field can be indicated by the shape of the lines (see fig. 5).

This type of visualization is well suited to gain a spatial overview over a scene. While a big 3d cluster of vector lines can get obscure in detail quickly, it works well to give an impression of the general structure and possibly the movement or change of magnetic fields. It can be beneficial to move the field-visualization independently from the magnet, allowing it to capture influences and interactions of multiple different fields freely.



(a) In 2d



(b) In 3d

Fig. 5. Field vector visualization on the example of a horseshoe magnet

6.2 Field Lines

Continuous field lines are another very common way to visualize magnetic fields. They visualize the "flow" within the field, giving a clear impression of the direction and the convergence in the respective area. Unlike field vectors, it is very difficult to use them to visualize a whole scene, but provide very good insights into subareas. Their calculation is slightly more complex; the trajectory of a each individual field line is calculated by numerical integration (in this case using Runge-Kutta) in space (see fig. 6), outgoing from a seed point [8].

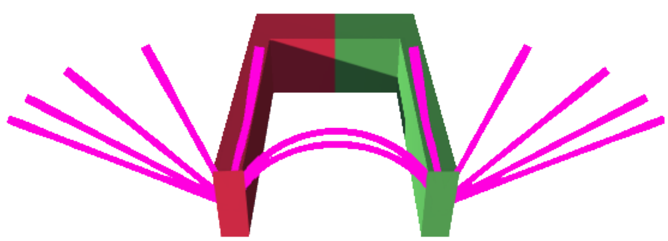


Fig. 6. Field line visualization detail of a horseshoe magnet

6.3 Right-Hand-Rule

The Lorentz-force is the combination of magnetic and electric force that acts on a moving charge in a magnetic field. In teaching, it is usually visualized using the shorthand of the right-hand-rule: thumb, index- and middle-finger of the right hand represent the three axes of magnetic force, electric force, and the resulting Lorentz-force. This visualization

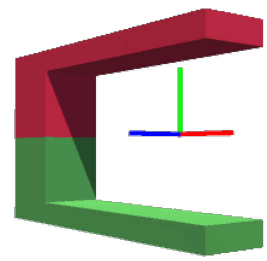


Fig. 7. Visualization of the right-hand-rule

is as simple as effective, and can be simply recreated in AR using three differently colored axes (see fig. 7). The direction of the Lorentz-force itself is calculated by taking the cross-product of the magnetic and electric force at the sample location.

7 AUGMENTED REALITY

7.1 Vuforia

Considering the advantages discussed in Section 3.2, we decided that the Vuforia SDK [1] would be the best fit for our project. It provides us with implementations to use different types of tracking in AR:

- **Image Targets:** Tracking of images/markers
- **Ground Plane Detection:** Detection of a flat surface to act as stage for virtual objects
- **Model Target:** Tracking of real 3D objects

The Model Targets are used to track our physical magnet. To create these Model Targets we were required to make use of Vuforia's Model Target Generator (MTG) [2], which takes in a 3D model that represents the object we want to track, and allows us to configure it for use with Vuforia's object tracking. To be able to detect the object at any angle without having to use preset guide views, we made use of Vuforia's advanced guide views, which required using the MTG to apply a deep learning training process. After this process the MTG's provides us a file containing the processed Model Target and this file can then be imported into Unity, ready to be used in the application for detection and tracking of the object.

7.2 Object Tracking

Our focus when it comes to object tracking was to find a way to make the tracking as reliable as possible, as the magnet is the main method of interaction with the game. We first tried to create a Model Target that resembles the magnet without making use of any patterns but we quickly noticed very poor performance regarding the tracking of the magnet. For reliable tracking, Vuforia's Model Targets requires an object with a good amount of features, but our horseshoe magnet consists of mostly flat surfaces and the only features of it are the few corner points.
To circumvent this issue, we have designed several iterations of textures with patterns for our 3D model, which gave Vuforia more features on the Model Target to work with. These patterns can then be printed on paper and glued to the

physical magnet and allowing for more reliable tracking with a feature rich target.
Each pattern was tested in the same lighting conditions and performing similar movements, including rotating the magnet around all three axis as well as moving the magnet at different rotations and varying distances from the camera.

Through this process determined that the pattern design shown in figure 8 to be the best performing pattern in terms of accuracy and reliability out of all the patterns we have considered.

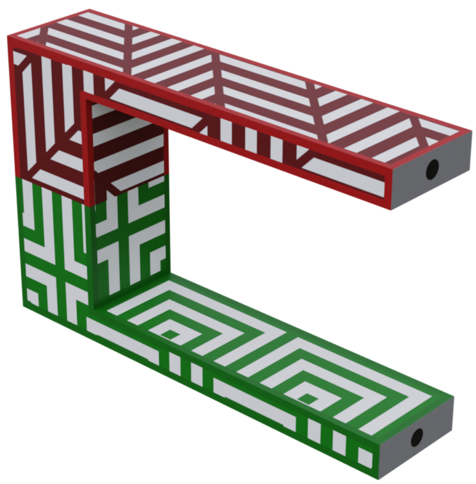


Fig. 8. Best performing pattern design

With this pattern we were able to track out physical magnet with good reliability, allowing for smooth undisturbed gameplay, even when the magnet is at a considerate distance from the camera. This made it possible to use the magnet as the main form of interaction with the game, using it to influence the ball with it's magnetic field.

8 FUTURE WORK

8.1 Study with target audience

As our game is a serious game, it would be of great importance to see if the game is able to transfer knowledge about magnetic fields. This could be achieved by performing a study with the target audience where they play the game followed by some follow up questions about the magnetic field and it's behaviour in different situations. By analyzing the results we could gather data about concepts that aren't transferred well to the target audience, and in turn change some aspects of our game to improve the understanding of them.

8.2 Game

There are several aspects of the game that could be improved. We could support the tracking of multiple different types of magnets, so it would be possible to switch magnets, and have a different behaviour of the magnetic field which would directly impact how the game is played. A lot more levels could be added to the game to have multiple different playing fields with distinct level design to change up the gameplay. In addition the game can be improved by adding more animations and sound effects to make the game more enjoyable.

8.3 Magnet Simulation

The usage of polylines for magnetic components is simplifying the actual behaviour of magnets. The current implementation delivers a good visual approximation, but becomes less accurate the bigger or more complex the magnet gets. A possible, although expensive, upgrade would be the usage of volumes instead of polylines. If the algorithm could find the closest point to the current location on the surface of a volume instead of a polyline, the simulated field would get more accurate when viewed up close. Still, another improvement could be made: Consider not only the closest point on the volume, but all contributing points in a certain radius. This, again, makes the computation significantly more expensive and difficult (therefore less suitable for real-time simulations in augmented reality), and has therefore been omitted in this project.

8.4 Field Visualization

The magnetic field visualizations also have room for improvement. Instead of using Unity's Line Renderers, we could use dynamic 3d meshes to visualize the field which could help give the field more perspective. Customization of the field visualization could also have a great benefit when there are cases where the color of the lines blend with the background or to change the density of the arrows during runtime. It would also be of great benefit to improve performance of the magnetic field so a large field containing many arrows can be shown on mobile devices without a significant performance impact.

9 ACKNOWLEDGEMENTS

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