AR Circuits

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Abstract—An electronic circuit simulator was developed to aid in the teaching of elementary electrical principles. It allows users to design and evaluate arbitrarily complex circuits constrained only by the space available. The circuit is analysed in real-time and the voltage and current levels are displayed dynamically and intuitively by the models representing the circuit components and their wiring.

1 INTRODUCTION

SOME topics in education contain inherently 3-dimensional and dynamic structures and processes, which are poorly dealt with by traditional teaching techniques, for example, chemistry [1]. Text and static 2D pictures and schematics do not intuitively demonstrate these difficult concepts, as the student must mentally translate, interpolate and extrapolate from these highly abstracted representations to a more realistic mental model. Concepts with time-varying aspects are especially difficult to represent with static images. Recently, technology has started to become more prevalent in education [2] [3], with computers able to display interactive projections of animated 3D scenes.

Augmented Reality (AR) is an emerging technology which allows users to view the real world augmented with digital content that in some way relates to the world. The most common form of AR involves viewing printed images with a webcam, which are known to the computer and are tracked using computer vision techniques. Digital content is then added to the video stream, typically in a manner which makes it appear that the content is physically attached to the printed image. In an education setting, the augmented content would relate to the concepts being taught, with the aim of improving the learning of the student.

AR offers some advantages for education that other technologies do not, especially for spatially complex topics [4]. The virtual environment is safe, and can be much more tightly controlled and monitored by educators, as well as providing content digitally, which can be inexpensive compared to physical teaching aids. Students who struggle with standard teaching techniques have also been shown to perform at a similar level to other students when using AR [5]. The importance of interaction has also been shown: Engineering students who took a special hands-on course over the course of their degree performed significantly better at the standardised spatial visualisation Mental Cutting Test than they had at the beginning of their degree, while other engineering students showed no improvement over the course of their degree [6]. Others [7] also showed benefits of using virtual reality, a closely related technology which also uses virtual environments, but does not contain the real-world aspects.

AR Circuits is a project aimed at providing a cheap, interactive and most of all, fun method of teaching basic electrical concepts such as electrical potential, current and resistance plus some more advanced topics.

The system implemented uses a marker based method of interaction with the user and electrical information is relayed back via dynamic 3D graphics.

2 Related Work

Four papers with similar goals or methods to AR Circuits were analysed before implementation. Their discussion and critique follows.

2.1 Augmented Reality for Teaching Spatial Relations

In this paper [8] the authors describe their tool Augmented Chemical Reactions, which is aimed at using AR to teach students about how the geometry of molecules effect reactions between them. Molecules are spatially registered to fiducial markers. Marker-cubes can be used to allow the user to view the molecule from any angle. When the markers of two molecules with the ability to bond to each other come into proximity to each other, possible bonds are shown as transparent tubes. The user can then bond the molecules if they wish.

Critique

This paper did not show complex examples or discuss in great depth the usage of their tool. This was partly due to the length of the submission, but also partly to a lack of conciseness in describing supporting topics such as the motivation and Augmented Reality, and partly to superficial explanations. The lack of detail was especially important as the tool's use for scientists designing molecules was emphasised. No mention was given to the underlying physics simulator, or the limitations of molecule numbers or complexity, which would be important information for an interested scientist. In addition, the usage in a classroom was not discussed.

An area for further work not mentioned in the paper could be integrating extra visualisations of the chemical reaction at the visible scale. A common problem with advanced concepts is the difficulty with bridging the gap between abstract concepts and real-world observations. This tool could allow a macroscopic view demonstrating the tangible outputs of a reaction alongside the individual molecule view. Extra data such as temperature and state-changes could be shown to give a more complete understanding of the reaction.

2.2 Construct3D

Construct3D is an AR educational tool described in the paper "Mathematics And Geometry Education With Collaborative Augmented Reality" [9]. Using one of a number of suggested hardware set-ups, users create geometric entities such as curves and spheres using a 6 degrees-of-freedom 'stylus' and the Personal Interaction Panel, an AR interaction system [10]. With their geometric entities they can then investigate concepts such as geometric sections and vectors. In the more ambitious hardware set-ups, users can walk around and through the geometry they create. The geometry exists on 3D layers, allowing different visibility modes for different users or teaching scenarios.

Relevance

Collaboration is emphasised, with the tool featuring shared scene-graphs and AR applications between hardware systems. This advanced form of collaboration with multiple communicating systems is not within the scope of our project, however the simpler collaboration which a single system can support is. While the educational content is not as closely related to our project, the design considerations regarding educational use are highly relevant.

Critique

The contexts in which Construct3D would be likely used for were well considered, including the possible participants and the available resources. This means that collaboration at different scales and usage through different mediums such as HMDs and monitors were designed for. An initial trial study showed that students found the tool very useful, and the tool was improved based on feedback. Large-scale studies on the educational benefits were carried out, and are summarised in a paper from 2007 [11]. Many improvements were made based on the results of these studies.

2.3 Understanding Ohm's law - Enlightenment Through Augmented Reality

In this paper [12], authors Peng and Müller-Wittig discuss a system that allows a user to interactively build circuits via the placement of fiducial markers. The markers represent resistors, which are displayed with their colour coded stripes showing.

The surface onto which the markers are placed has a fixed set of component slots. The user needs to place enough markers into these slots to make a complete circuit. At this point the user sees a wire rendered around the circuit, the software calculates the total resistance of the circuit and consequently the current which must be flowing through a bulb which is connected in series with a virtual DC power supply.

The bulb is a real light source, driven by a DC supply and interfaced to the computer via an Arduino development board. It is the only source of feedback provided to the user barring the textual information presented to the user in a dialogue box.

Peng and Müller-Wittig's paper also provides some insight into the relevance and efficacy of augmented reality applications as teaching tools and the cost benefits of doing so.

Relevance

This project's goals are very similar to our own, if somewhat limited in their scope. As such this project makes an excellent starting point for us and its method and results are worthy of note.

Similarities:

- A single web camera is all that is required for input into the system, although there is no reason either system may not be improved with a more complicated set up, such as a head mounted display.
- Fiducial markers are used to represent the location of the components they represent. Those components are displayed above the marker.

- OpenSceneGraph is used to build the virtual part of the scene.

We do, however, plan to expand on the number of different components available, their use of static models for components and their lack of feedback through augmented reality.

Criticism

The system appeared to be very simple to use and may be an effective teaching tool. It was limited, however, in the following areas.

- The user receives feedback from the circuit only through the bulb. The system could be expanded to show the effects of voltage division.
- Their use of fixed slots limits the user to a few simple circuits. This feature does make it easier to calculate voltages and allows the user to more easily distinguish between components which are in the circuit and which are out.
- The results of the simulation's calculations are displayed in a dialogue box on screen, they could have attempted to display information over the component it pertains to.

2.4 Motion in Augmented Reality Games: An Engine for Creating Plausible Physical Interactions in Augmented Reality Games

Namee et al [13] have developed a game engine for interactive augmented reality gaming. The engine is modular in design, it contains a World Model, an AR Registration Engine, a Physics Engine and a Renderer.

They implemented the Registration module with the ARToolkit API, the Physics module with the Open Dynamics Engine and Havok, and the renderer with OpenGL. As they point out though, MARG is technology agnostic and the implementations is not that important; the paper's focus is on software abstraction, design and the two proof of concept applications.

Objects in the Motion in Augmented Reality Games (MARG) engine can be virtual, physical or a combination and they always have an associated physics model.

Two concept games were developed by the team to demonstrate the engine's ability to handle interactions between physical and virtual objects. To show how well the user's expectations of the outcomes of these interactions are met, the team timed participants completing simple challenges using both the AR games and matching games made of entirely physical components. Although the completion times were greater and had more spread for the AR versions the times were still comparable showing that MARG can integrate virtual objects with physical ones believably.

2.5 Relevance

The top level design of MARG is very similar to the design of our software, if the mechanical physics engine is replaced with an electrical physics engine/simulator then the software meets our needs completely. That is to say in both our project and theirs the user controls physical and virtual objects in 3D space and those objects are modelled by a physics engine.

2.6 Critique

MARG's well thought out design allows quite a bit of flexibility in terms of what may be implemented. Their two example games demonstrate the full power of MARG.

The results of their user tests appear to show MARG being slightly more difficult to use than an equivalent physical system yet they do not explore the cause of this.

3 Project Goals

This goals of this project were to use AR to provide a novel electricity education tool. Users build virtual electronic circuits and the states of the electrical components are visually represented. To achieve this, the following general goals were set:

- Represent various electrical components with some real-world object, each corresponding to a single marker.
- Allow users to create and destroy connections between components using some intuitive interaction.
- Visualise this connection.
- Simulate the current through and voltage drop of each component.
- Visualise this data.

Once the approach for solving these goals had been planned, a set of more specific goals for producing incrementally more challenging interactions and physical modelling were created:

- To test connection interactions, demonstrate a battery and lamp circuit.
- To test logical circuitry modelling and extended interactions, demonstrate a logic circuit where the user can change input states.
- To test the completed physics simulator and the current and voltage visualisations, demonstrate an AC circuit with the current and voltage represented as a pipe above the circuit.

4 System Description

The entire system was comprised of software running on a pc, a single camera which was fixed or free at the user's discretion, and a set of markers representing the circuit components which could be laid out on any flat surface.

4.1 Software

The application was developed using the the OpenSceneGraph library (which uses OpenGL) for 3D graphics, AR Toolkit for marker tracking, and the libconfig library to simplify settings and allowing the user to change soft parameters. Gnucap, a commandline, open-source circuit simulator was modified into a library an integrated into the project as well.

The software structure, starting at the top, can be simplified into the following hierarchichal model.

```
Circuit
   -- Scene (resistor)
      -- Fiducial marker identifier
      -- OSG 3D model
      -- Gnucap component
      -- Wire models
         -- 3D model
         -- 2 scene references
   -- Scene (supply)
      -- Same as above...
   -- etc.
```

Hence each scene is responsible for maintaining the electrical, graphical and spatial states of a single component. Each scene also owns a set of wires of a variable size. During each iteration components check for proximity between their leads and the leads of other component, adding and removing wires as necessary. The circuit object which requests these proximity checks enforces that each combination of scenes is only checked once

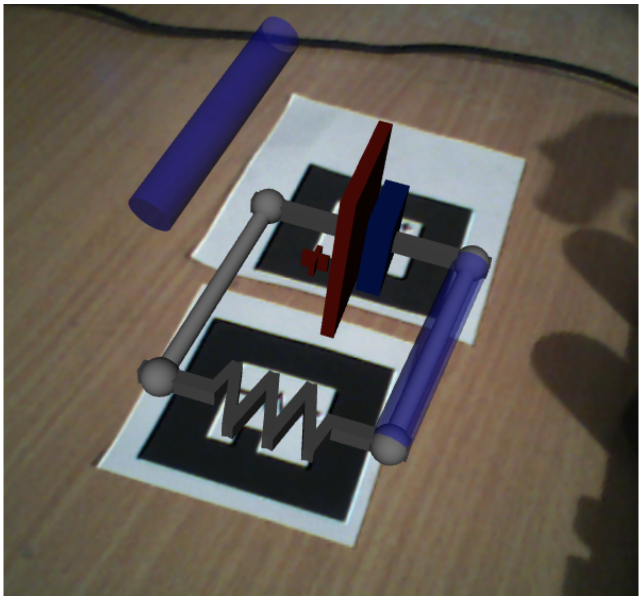

Fig. 1. The voltage level display

(e.g. ab == ba) to avoid duplicate wires being instantiated.

OpenSceneGraph

OpenSceneGraph provides am application programming interface to a powerful, OpenGL backed, 3D graphics engine. As the graphics requirements of the AR Circuits application were not very large, our interactions with this library were limited to importing models created in the Maya 3D modelling suite, generating simple geometric shapes programmatically (for wires and leads), and transforming all of these models according to marker location found using AR Toolkit.

An example of the programmatic generation and manipulation of an OSG model is the cylinders displayed above wires representing the potential difference between that node and ground as shown in figure1.

Libconfig

Libconfig is a simple and efficient C/C++ library for reading structured configuration files. It aided the development of AR Circuits and simplifies its use by allowing the user to specify the models, patterns, numbers and initial values of circuit components.

Gnucap

Gnucap is an open-source circuit analysis package. It has a command-line interface which accepts a SPICE styled netlist as input. This meant that some calculations were necessary before analysis as the netlist needed to be generated from a set of components. To simplify use the program was modified into a library so that voltage and current information could be accessed via function calls rather than interpreting the command-line version's formatted output. This necessitated a small rewrite of some portions of the POSIX styled IO code so that the library would compile with the Visual C++ compiler.

All extensions and modifications to this code were encapsulated by two simple wrapper classes representing the circuit analyser and electrical components.

5 User Interaction

The main focus during the development of this project was into two modes of user interaction. The first was user control over the circuit via placement of the markers. The second is the visual feedback the user receives in real-time showing the voltages and currents returned by the circuit analysis.

5.1 Control

User control over the circuit layout is effected by the user's placement of component markers. Toggling connections between components is achieved as shown pictorially in figure 2. The steps are as follows.

1) Two resistors are to be connected serially.
2) The leads to be connected are brought within a proximity threshold and the leads change colour to indicate this.
3) After a one second delay, a wire is created between the nodes.
4) This wire will maintain a direct line segment between the two nodes (connections are always one-to-one).
5) To disconnect, the same procedure is followed.
6) The resistors are now disconnected, to reconnect they will first have to be moved back out of proximity (to avoid continuous toggling).

5.2 Feedback

Voltage and current are displayed by cylinders running parallel to and above the wires. The height of the tube represents the electric potential between the node the wire is on and ground and the radius of the tube represents the current flowing through the wire. This is illustrated in figure 1. This representation was chosen as a realisation of the common electronic-hydraulic analogy, where the electron flow is compared to water flow in pipes. The height of water corresponds to electrical potential (voltage) as the water has gravitational potential energy, and the diameter of the pipes corresponds to the electrical current.

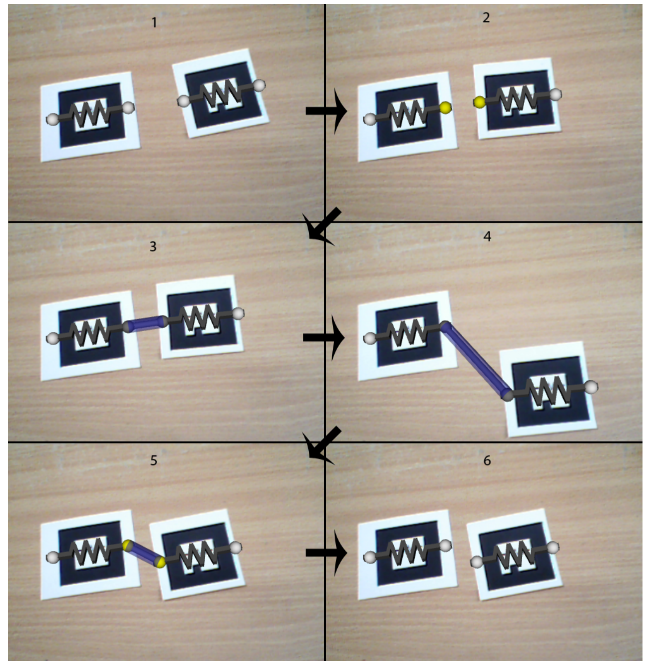

Fig. 2. The connection toggling process

5.3 Unconstrained View

Another important, but implicit, aspect to the user's experience with AR Circuits is the ability to view the scene from any angle or location they choose, so long as the relevant markers are not occluded or too distant.

6 Discussion

When the user is building the circuit and a marker is lost, if that marker is attached to another then the component of the lost marker does not disappear. Instead it maintains its position relative to the camera until the lost marker is reacquired. This helps the user to keep track of the circuit, but with many components could lead to clutter. It could also be confusing as it might appear that a marker is being tracked when actually it is not. Thus the user should be able to change this setting for personal preference, and possibly toggle the setting from within the program.

As with most interactive AR systems, incorrect occlusion of the real world by the digital content is an issue. When a user moves their hand to a position which should be in front of the 3D content (without blocking the marker) the content is drawn in front, as the graphics system does not have any depth information aside from the relative position of the marker. This reduces the believability of the system and can be confusing to view. Various methods of depth detection, are available which can be used to provide roughly correct occlusion. However they require extra hardware and the results are often noisy, so that the digital content appears to have frayed edges where it meets with the real-world object. For these reasons, it was decided not to use occlusion.

Each marker corresponds to a single component, and the expected use is for the marker image to be representative of the component. This limits the number of markers, and hence components, which can be viewed at once. An alternative to this paradigm is demonstrated by the Augmented Chemistry project [14], which uses AR to teach organic chemistry. One marker represents the molecule under construction and another is used to bring in new atoms to be added to the molecule. A book of markers, each representing an atom, is used to select which atom is being added. Using this interaction paradigm the number of components would not be constrained by the number of markers. However, in electronics only the connections are important, not the layout, whereas in chemistry the layout is fixed. A useful ability for understanding electronic circuits is being able to rearrange the layout of components, which the Augmented Chemistry paradigm does not easily allow.

6.1 Limitations

Challenges common to many visualisation systems are dealing with different data ranges, outliers and large data volume. Currently, no automatic scaling of voltage and current values is implemented. This means that the user must choose component values which result in values in a certain range, or the voltage-current visualisation might be so far from the markers (due to high voltage) as to be out of view, or so thin (due to low current) as to be invisible. However, if scaling was implemented, then outliers could force a scaling which results in other values appearing uniform. The problem of data volume is minimal here, as the circuit is aimed at electrical teaching, which typically does not involve circuits with a large number of components.

In addition to these implementation limitations, the system is limited by a number of technological factors. The number of markers which can be viewed at once is limited by the resolution of the camera. This could be improved by improving the camera resolution, but this would also impact performance, as the tracker would then have to process more pixels per frame. This processing is CPU intensive, so the frame-rate is limited by the computer's abilities. The graphics processing is GPU intensive, so if the computer has no graphics card or a poor one, the frame-rate will again be limited.

7 Further Work

A common approach to real circuit analysis is to use a test probe to measure electrical information at various points around a circuit. To emulate this interaction, a tangible probing prop could be tracked which shows electrical information about a component's lead, when brought into proximity of that lead. The information could be displayed in a separate window on the computer (when the main output is not full screen) or could be integrated into the main view, with waves being displayed above the wires, or even as the wires.

The voltage-current visualisation could be improved. One possibility is integrating it with the wires that connect components. This might be more intuitive, as the relationship between current, voltage and the wire is more explicit, but it also might be confusing to view, especially with AC flows, as the heights of the components would all be changing constantly. For some viewers this might enhance the experience, while for others it might confuse it, so allowing the user to choose from both visualisations might be preferable.

Gestures could be added to improve interaction. Shaking a marker could toggle the component into and out of edit mode. 'Shaking' would be defined as fast movement from side to side relative to other markers, rather than relative to the camera. This prevents camera shaking from falsely causing interaction. This would require three markers to be visible to determine the which marker was moving, unless some form of optical flow was added to detect background movement. In edit mode moving a marker vertically could cause its component to grow and shrink, and moving it horizontally could cause its primary parameter to change. An alternative could be using a special marker to alter the parameters or marker size.

To improve the scalability of the system, a circuit block element could be added. The user could build up a circuit and then assign it to a special marker as a single item. When the special marker is brought close to a component, instead of connecting to the component it would 'absorb' all connected components. Since the resulting composite component might contain many connectable nodes and these nodes will be closely packed, the connecting process should use a "connect to closest" rule to avoid making multiple connections at once. To edit the composite component, the user would shake the marker, at which point all other components disappear and the original markers used to make the composite component would be used to make changes.

To validate the concept and implementation, user studies should be carried out. A metric of performance as an educational tool might be the learning rate compared to using traditional techniques. A metric as an AR application might be time for the user to become familiar with a certain task.

8 Conclusion

AR Circuits is a prototype educational AR system. To become useful for teaching it requires refinement and expansion, but it demonstrates the concept of a circuit building tool. In particular, the visualisation metaphor for displaying voltage and current should be experimented with.

The use of technologies such as Augmented Reality in education is developing and becoming more accepted. AR Circuits was developed to demonstrate how some elements of AR can be harnessed to provide a novel learning experience.

The prototype allows the user to interactively build an arbitrary electronic circuit from a set of electronic components and visualise the current and voltage which result. Being able to explore building circuits and getting instant dynamic feedback on the effects of various circuit configurations could greatly improve student learning and motivation.

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