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Enhancing 3D Modeling with Augmented Reality in an After-school Engineering Program (Work in Progress)

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Abstract

We report on a 3-week study which was part of a longer (16-week) after-school engineering program built around Unmanned Aerial Vehicles (UAVs/Drones). Participating youth are middle school students from low income families (n = 8). These youth are tasked with understanding the capabilities of UAVs and using them to address a societal need: delivering supplies via drone to a remote village impacted by a natural disaster. The UAV curriculum is developed around a realistic storyline in which youth consider the needs of a small town to monitor conditions of a nearby disaster. Throughout the lessons, conditions change resulting in youth needing to plan and implement survey and rescue activities using the UAVs. Embedded in this curriculum are several design challenges that youth must address in order to use their UAVs effectively to support the town's isolated residents. Here, we focus on a specific design challenge where youth augment their UAV with custom-built "skyhooks" for supply delivery. They start by sketching skyhooks in 2D and end with choosing 3D models of the skyhooks to complete the challenge of delivering supplies to the disaster area. In the intermediate design steps, youth use an AR application (3D AR Visualizer) to help them visualize the transition from 2D models to 3D models with the UAV augmented to the scene.

Our research examines how using 3D modeling with AR can enhance youth spatial reasoning skills. We collected both product and process data in the form of artifacts generated during design iterations, pre and post activity mental rotation tests, screen-recordings of youth using the 3D AR Visualizer, and youth design reflections. Our results indicate that youth were able to better understand the strengths and weaknesses of pre-designed 3D models with the help of the AR application, and they made better and more informed design decisions that resulted in successful delivery of supplies to the disaster area.

Introduction

As Osborn and Agogino [1] state, "*spatial reasoning is a mental process that involves thinking about relationships between three-dimensional (3D) objects.*" From the early 1990's researchers have been studying the importance of spatial reasoning skills. Most researchers who have studied spatial skills or their components state the fact that engineering, architecture, and most scientific jobs require people to have good spatial thinking skills [2]. People with high spatial ability benefit particularly as they have enough cognitive capacity for mental model construction. Researchers like Hsi et al. [3] have been recommending the need to introduce spatial skills in introductory engineering courses and emphasizing the need for including these skills throughout engineering curriculum.

An approach to enhance spatial thinking or spatial reasoning skills is learning three-dimensional (3D) modeling [4]. 3D modeling involves several steps and design decisions to make sure that a feasible design is made. Learning 3D modeling is supposed to not only enhance students' design decisions but also improve their spatial thinking ability. With the proliferation of consumer-level 3D printing, Virtual Reality (VR), and Augmented Reality (AR), there is a sparked interest among educators to teach 3D modeling using tools like Tinkercad in formal and informal settings [5], [6]. An additional benefit of 3D modeling knowledge is the career path it opens. Several companies and industries are in the need for 3D designers for a variety of projects including product design, VLSI design, 3D animation, or 3D graphic design and the demand is expected to continue growing.

Although beginner-friendly 3D modeling tools, instructional materials, and training programs are available to novice 3D modelers, learning 3D modeling can still be daunting [7], [8]. Prior work has documented a number of usability and learnability problems in using complex 3D modeling software, including dealing with confusing terminologies, creating complex shapes, and interacting with unfamiliar 3D geometry [9], [10], [11]. But, there is a challenge with only using 3D Computer Aided Design (CAD) tools. Recent studies with engineering students indicate that a 3D CAD experience alone provides limited real-time 3D interactions for students and thus does not seem to enhance students' visualization skills [12]. Even though powerful computers and softwares are available nowadays, developing visualization skills is necessary for imagining, specifying, and creating complex designs with functional features in the three spatial dimensions (X, Y, and Z). The enhancement of visualization skills of students is essential for their development of design skills in fields like engineering, architecture, graphic designing, and many more. Based on studies of visualization skills of students in engineering courses, students have difficulties in dealing with orthographic applications (projections, orthographic to isometric transformations, etc.). They seem to lack sufficient geometric and/or trigonometric relational skills, both of which are essential when modeling even simple geometric objects [13].

AR, an emerging technology could provide a solution to this problem. The potential benefits of AR are improvements in students' abilities with respect to spatial cognition, concept development, decision making as well as design modifications and refinements due to the support for viewing and 'touching' the design. Current AR technologies can help improve design and visualization skills, aid in scientific simulations, and serve as a tool for learning [2], [14], [18].

In this paper, we explore the opportunities that 3D modeling and AR provide in enhancing spatial reasoning skills of youth. We present a brief overview of the after-school engineering curriculum where this 3-week long study was implemented. We describe the design of our AR app and how it was used and evaluated in the study. We discuss our initial findings from this work-in-progress and share our ideas for future implementations.

Related work

We have built our design framework for this project off of two key past observations. The first observation being that 3D modeling has a positive impact on enhancing spatial skills. Second, that 3D modeling coupled with AR leads to enhanced spatial understanding of virtual objects.

3D Modeling helps enhance spatial skills

Factors like age and experience matter in the improvement of spatial skills but it has been found in prior research that this skill can be enhanced with the help of 3D modeling. Researchers like Devon et. al. (1994) [27] have found that 3D solid modeling systems help enhance spatial visualization skills in engineering graphics students. Other research involving youth aged 11 to 15 has shown that the process of 3D modeling helps develop spatial awareness skills [4]. The spatial abilities include perception of objects from different angles, mental construction and maintenance of visuals, and rotation and changing of shapes in the mind [15], [16]. Many of the most powerful 3D modeling tools are difficult for new learners to approach due to issues like confusing terminology and having to deal with complex geometries. Tools like Tinkercad provide a much low barrier to entry with fewer unfamiliar words and simpler geometry [5], [6]. This in turn makes it easier for youth in middle or high school to learn 3D modeling conveniently. In our design for the 3D AR Visualizer application we focus on keeping a simple 3D modeling interface, while promoting the kinds of interactions that help develop spatial reasoning.

Need for AR in enhancing spatial reasoning

Emerging computer technologies like simulation, animation, Virtual Reality (VR), Augmented Reality (AR), and rapid prototyping have proved to be a possible means for enhancing spatial ability/skills and spatial thinking [17]. While, 3D modeling alone has not shown to help develop spatial reasoning skills [12] AR provides an avenue to give the concepts introduced with 3D modeling real world grounding. Tools like Construct3D that use AR to teach 3D geometric construction in mathematics and geometry education have proven to be successful in helping improve youth spatial skills [18]. Recent studies by Tang et. al. [29] have used an AR to help create 3D models and they found that using AR provides a more “natural” interface for 3D modeling than traditional desktop 3D modeling applications.

AR is being used widely in various fields. In the classroom, AR has shown to contribute to help motivate youth and increase their academic achievement [19]. Research into the properties of AR revealed that it allows for intuitive spatial representations of complex mathematical and engineering concepts that assist in student understanding [14], [18], [20]. Though researchers are studying and exploring benefits of AR in educational settings to help improve spatial skills not much has been done in informal settings. In our work we try to address this gap. Considering the prior findings, we have chosen AR as the complement to the 3D modeling aspect of our application. The AR element aims to provide additional context for the 3D models selected by the youth and help develop their spatial understanding of the models in real world.

Context of implementation

Our study was part of a 16-week long engineering curriculum outlined in Figure 1, designed around the use of Unmanned Aerial Vehicles (UAVs) for social good. This curriculum was designed and implemented by an interdisciplinary partnership that includes scientists from University Corporation for Atmospheric Research(UCAR), learning scientists and STEM education researchers from the University of Colorado, and the *I Have A Dream Foundation*(IHAD). IHAD is a national program, organized into local chapters, that supports low-income youth through long-term educational and cultural enrichment programs (www.ihaveadreamfoundation.org.)

Youth who were part of the program were asked to develop a solution to a problem: how to survey and provide relief to a town that has been damaged and isolated due to a natural disaster. We outlined the engineering practices that youth needed to engage in during each session in order to make progress on the driving questions for each session. Engineering practices [21] that we emphasized included asking questions and defining problems, planning and carrying out investigations, analyzing and interpreting data, designing solutions, and engaging in argument from evidence. In Figure 1, the applicable engineering practices are shown in gray. The goal was for youth to be immersed in using those practices to figure out how to design, test, and iterate on their designs for using UAVs to provide relief to a town during a natural disaster.

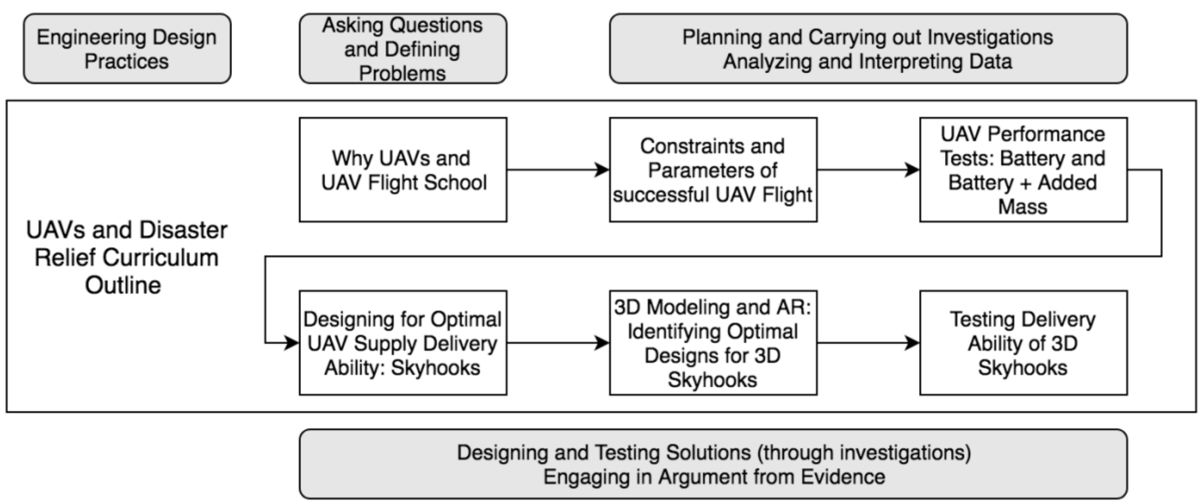

Figure 1. Engineering Design practices meet 3D modeling and Augmented Reality(AR)

Participating youth were organized into small groups with clearly assigned roles for operating UAVs, such as drone pilot, safety officer, and spotter. Each group was supported by a dedicated STEM coach and another adult volunteer. Two undergraduates and one graduate from the engineering program at the University of Colorado were recruited and trained to serve as STEM coaches. They were responsible for facilitating the curriculum each week.

Youth met in their school premises once-per-week for 1.5-hour sessions. In these sessions, they: (1) learned to fly UAVs, (2) used engineering practices to design and conduct experiments to understand UAV performance characteristics (weight, battery life, and flight time trade-offs), (3) modified their UAV to conduct experiments and aerial surveys, (4) planned and conducted aerial surveys of the town of “Disasterville”, and (5) raced their UAV to deliver maximum amount of supplies using 3D printed skyhooks. Mock-ups of the “Disasterville” town, including building, trees, cars, and people, were built in the school cafeteria where youth conducted their aerial surveys. To complete the aerial surveys, youth needed to modify their drones to carry cameras, sensors, and tools. One of the towns had been hit by a tornado; another was in the path of an erupting volcano. Deciphering the nature of the disaster to befall each town was part of the challenge. There were several engineering design challenges that were introduced in the curriculum. Identifying several parameters when adding capacity to UAVs was one of the main challenges. Youth had to perform science investigations and use mathematics to analyze the capacity of the UAVs. One of the engineering design problem required using the UAVs to retrieve a payload from the far side of the school cafeteria and return it to a target landing zone. Youth designed skyhooks to attach to the UAVs in order to “grab” the payload, using their choice of rubber bands, pipe cleaners, paper clips, tape, etc. It is exceptionally challenging to grab a payload with a simple mechanical hook, such as a bent paper clip. Thus, these lessons provided good opportunity for youth to engage in rich engineering practices, by testing and modifying their skyhook designs in an iterative fashion. The findings from this 16-week long study has been reported elsewhere [28].

Drawing from prior research on the benefits of 3D modeling and AR in enhancing youth spatial reasoning skills and design skills, we included a 3-week study where youth had the opportunity to use some of the engineering practices to identify skyhook designs that would best deliver supplies to a disaster site. The study was designed to have youth use their experiences with skyhooks and AR tools to choose pre-designed 3D printed skyhooks for supply delivery. The reason for specifically choosing 3D models of skyhooks was to help youth make a connection with the skyhooks they had designed before (using craft materials) and choose from 3D model designs based on their prior experience.

In the 3-week study, youth first made sketches of skyhooks they would like to design (see Figure 2), they were introduced to 3D modeling and printing, and they brainstormed the advantages and challenges of using 3D printed skyhooks versus skyhooks built out of craft materials. In the second week, the STEM coaches introduced the 3D AR Visualizer app to youth and asked them to evaluate seven different 3D models of skyhooks (described in Design of 3D AR Visualizer). Using the AR option youth augmented their 3D model selections onto their UAVs (used the AR tool to visualize the skyhook attached to the UAV). Based on the feasibility and their knowledge of design constraints (e.g., weight of skyhook and shape of the hook) for delivering supplies youth made their top two choices of skyhooks. Research team took notes of the skyhooks they had to 3D print. In the final week, youth were given the 3D models they had selected, and they tested them in a race. In the race, youth attached their skyhooks to the UAVs and carried supplies (tiny buckets) from one end of the school cafeteria to another, in the target landing zone (Figure 5). The whole idea of the race was to be consistent with the problem that youth were trying to solve and help deliver supplies to a disaster struck area. The youth who were able to successfully deliver maximum supplies in shortest time won the race.

Figure 2. Youth drawing sketch of the skyhook he would want to 3D print

Design of 3D AR Visualizer

3D AR Visualizer allows youth to view 3D models of skyhooks in a virtual environment and in the real world using marker-based AR. We chose this specific type of marker (Figure 3(a)) because it allows for the most precise placement of the model in the augmented context (Figure 3(b)). There is only one type of marker used for this since the selection of the 3D model to display is done by the user in the application menus.

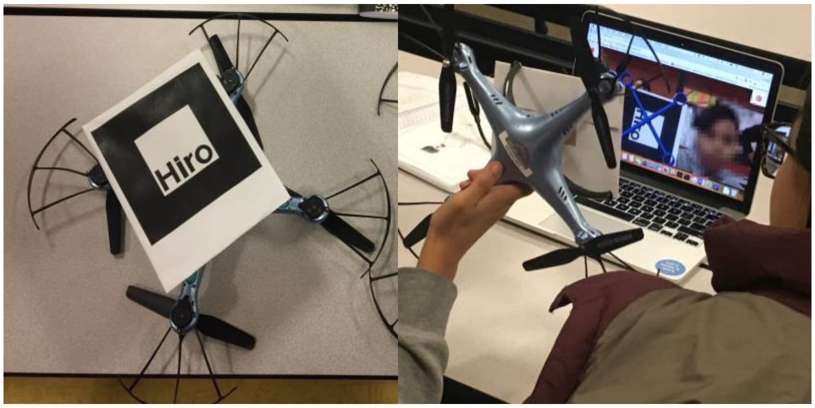

Figure 3(a) UAV with maker attached, (b) youth using the AR app with maker

The first view (screen) of the application gives the user an option of two different model categories to choose from: bar and mesh. The total number of models that the user can choose from is seven (4 bar, 3 mesh) (Figure 4). For this first iteration of the study, we developed the 3D skyhook model options ahead of time. When the user selects a category of model they are taken to the "Edit" screen which allows them to cycle through the various models in that category and spin them around in a 3D environment. At any time while on the "Edit" screen the user can select the camera button which will take them to the "AR" screen. The "AR" screen shows a video stream that comes from a connected web cam which is detected by the application. Upon detection of the marker that the program is trained to recognize, the selected 3D model is displayed on that part of the video.

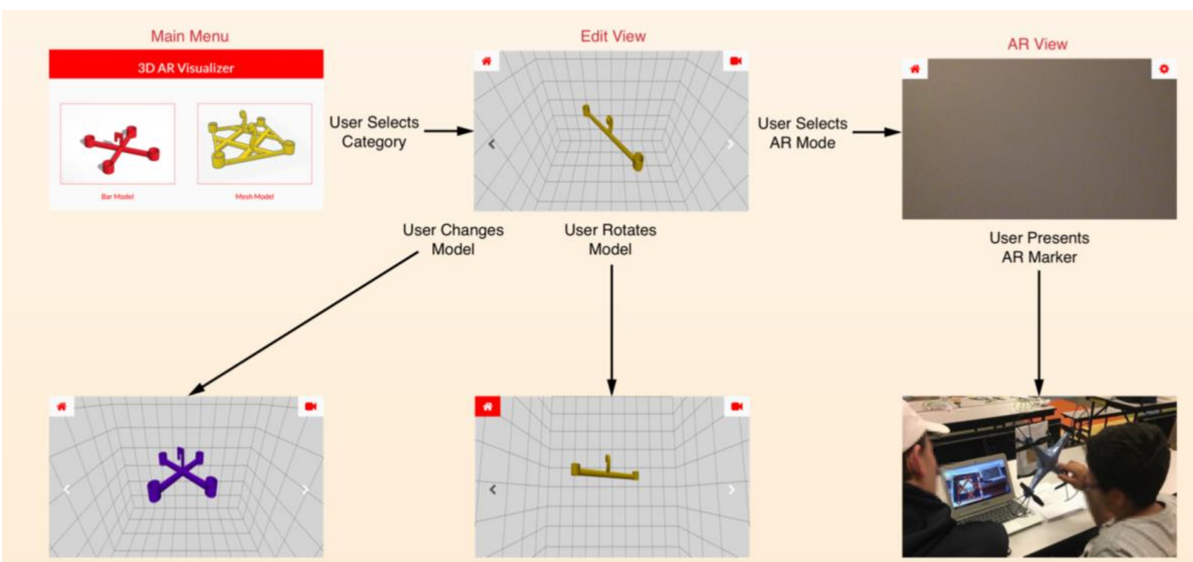

Figure 4. User flow diagram of the 3D AR Visualizer app

We chose web as the platform for this iteration of the application for three reasons:
i. **Ease of Distribution**: Using a website means that as long as a compatible browser (Google Chrome) is installed on the user's device, then there is no other installation requirement.
ii. **Rapid Development Cycle**: Updates to the application can be delivered rapidly through changing the relevant files on the server and having users reload the browser page. This leads to very quick iteration cycles due to there being no need to locally install any updates on the user's machine.
iii. **Many libraries to support the various functions**: The Javascript package ecosystem has many packages that support the various features we required including: 3D rendering, AR marker recognition, and webcam video streaming.

The core library used to render the models for this application was the open source library Three.js [25]. To support AR functionality, we used AR.js, which is built using a javascript port of ARtoolkit [26] as an extension of Three.js.

We tested the app with nine graduate students from our research lab and walked them through it in the similar way we would test with the middle school students. This helped us get feedback on the feasibility of the app and the usability of the interface.
Research methodology

Our study examined the degree to which 3D modeling and AR can help enhance engineering design skills in youth, ways AR can be integrated into an after-school engineering curriculum, and possible ways to enhance and analyze spatial reasoning skills in youth.

Participation
Eight middle school (6 male, 2 female) youth from a PK-8 School in Colorado participated in the program. At the school, 84% of the students are Hispanic, 12% are Caucasian, and 83% qualify for free-and-reduced lunch. In our program 7 of the youth were Hispanic and 1 was Caucasian. All the youth who participated in the program were in 7th grade at the time of the study and were enrolled in the IHAD after-school program that took place on the school's premises. Participation in the UAV program was voluntary, youth had self-selected themselves into the program instead of participating in the existing IHAD activities on campus that day of the week.

Data collection and analysis
We collected qualitative and quantitative data using surveys, artifacts, observations, screen recordings, and youth design reflections. We used journaling notebooks for gathering evidence about youths' interests, engagement, and knowledge. A research team member had electronically recorded all data anonymously and stored them in a secure location. The notebook prompts that look at youth interests, engagement, and knowledge are discussed in another paper [28] where we detail the curriculum and its findings.

On the first week, youth were given a pre-survey task that asked them questions from four categories: mental rotation, spatial visualization, 2D to 3D translation, and cross sectioning. There were two questions from each of these categories and the questions were selected from a set of well-tested instruments designed by the Spatial Intelligence and Learning Center [22], [23], [24]. A similar survey was administered at the end of week 3, this time the difficulty of the questions was the same but with a small variation in the figures.

Our session observation protocol focused on observing the degree to which youth were engaged in engineering design activities and decision making throughout the study. This included: the degree to which youth were enacting various engineering design practices, how youth were using 3D AR Visualizer, how they were perceiving the 3D models, and the rationale they were providing to the STEM coaches for choosing the 3D models. Members of the research team observed every session. At least two researchers observed several sessions to ensure that we were consistent in our observation foci.

Screen recordings were used to keep track of the moves that youth make when interacting with the 3D AR Visualizer app and the 3D models of the skyhooks. This helped us recognize youth understanding of 3D perspectives and their spatial visualization skills. Additionally, it was used to record the rationale that youth provided when choosing the 3D models, when looking at the 3D models only (Figure 6(a)) and when using the AR screen to justify their selection (Figure 6(b)).

Findings

We report on initial findings in this work-in-progress paper. Our findings are categorized into three main sections: benefits of integrating 3D modeling and AR into after-school engineering curriculum, ways to analyze spatial reasoning skill in youth, and the value of engineering design in after-school curriculum.

Integrating 3D AR Visualizer into after-school engineering curriculum

Youth designs of skyhooks and attachments and our observations suggest the value of integrating 3D modeling and AR into a curricular experience/storyline for youth to have experiences they can bring to the tools. For example, they made their own sketches and design work with craft supplies and figured out the most effective 3D model designs for delivering supplies. They were able to use that prior knowledge as they interacted with the 3D models through AR and choose which ones would be the best. Youth mentioned one of the main constraints to choose the best skyhook design is considering lighter 3D printed skyhooks, like one youth said "*make it very light*" [P1]. Another important factor for youth selection of the 3D skyhooks was the shape of the hook, like youth mentioned "*hook has to be curved*" [P2]. Based on their prior knowledge in designing skyhooks with craft materials youth were able to decide which shapes would make it easier to drop off the supplies (tiny buckets) (Figure 5).

Figure 5. Youth testing 3D printed skyhooks with the supplies attached

Analysis of spatial reasoning

The pre and post survey on spatial skills did not provide us enough insights into youth spatial reasoning skills. We did not find any reportable changes in youth spatial reasoning skills. A possible reason for it could be the short time period that we had (3-weeks) and also the fact that the youth did not want to answer surveys or tests at the end of their school time. We observed them answering questions looking at the images without reading the prompts or randomly selecting options. However, from our observations and screen recordings we found that youth had trouble with the different 3D perspectives and views, like top, front, bottom, left, and right view. They did not intuitively rotate and look at the 3D models from different angles. But, when asked to use the AR screen where they could visualize the 3D models of skyhooks augmented to the UAVs, youth were able to better understand the shape and design of the skyhooks. They even rotated the UAVs to look at the skyhooks from different angles and understand its fit and shape. Youth mentioned that the 3D AR Visualizer app helped them visualize the skyhooks "*better*" (Figure 6(b)). For example, using the app they were able to understand if a skyhook would fit diagonally on the UAVs legs (see Figure 6(a)) or on one side of it. From their experience designing skyhooks youth knew if the skyhooks were attached on one side of the UAVs legs then that side would have more weight and the UAV would be difficult to maneuver. This finding helped us understand the benefits of including AR with 3D modeling.

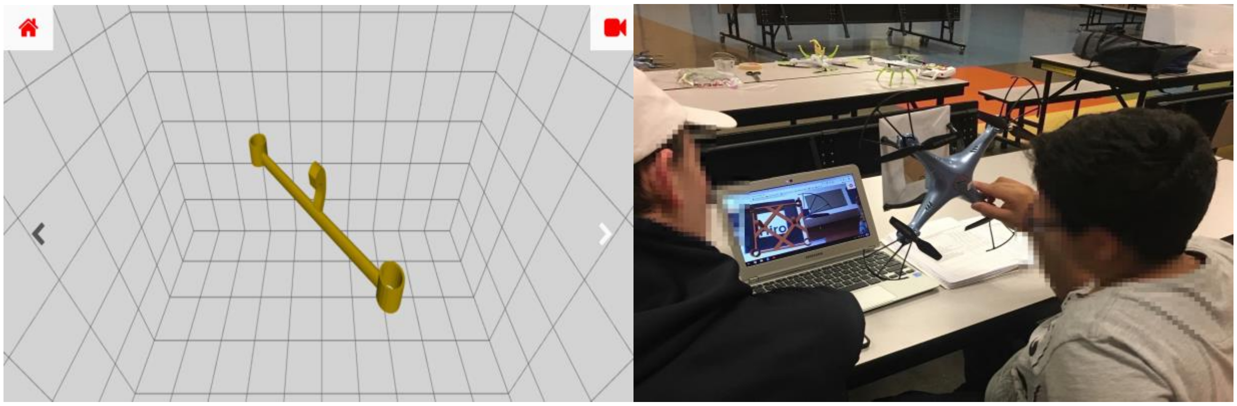

Figure 6(a) 3D AR Visualizer screen with bar model that fits diagonally on two legs of the UAV, 6(b) Youth using the 3D AR Visualizer to test the 3D designs

Value of engineering design in after-school curriculum

Our session observations provided a significant source of data since the protocol we used focused on youth engagement with engineering design practices. Overall, youth were engaged for long period of time and exhibited a deep level of engagement with engineering design practices. Their engagement was particularly notable whenever they had the opportunity to design/choose attachments for the UAVs. Specifically, youth were engaging in testing of specific designs, iterations of their designs, and ultimately creating or choosing sophisticated designs. We found youth actively engaging in adding new constraints to their designs after testing them out and changing their designs to optimize them. Like when choosing 3D printed skyhooks youth looked at all the seven 3D models and opted for the ones that would best hold the buckets when the UAV was in air and be able to carry maximum buckets. But when testing them out youth found the UAVs with the skyhooks and buckets attached would not take off. So they optimized their choice of skyhook and used ones with lighter weight. This finding was supported by youth design reflections, for example one youth mentioned, "*The weight, changed it and made it a little less*" [P3].

Discussion and future work

Integrating 3D modeling and AR into the UAV curriculum provided middle school youth from both low income and diverse populations with opportunities to use digital tools to support their engineering design processes and decision making. With under 6 hours of time with students, we utilized this study as a proof of concepts to try out some initial ideas about integrating 3D modeling and AR. We focused on what we could do with students in that short amount of time and are planning a follow up study where we expand what students do with 3D modeling and AR. For this work-in-progress paper, we focus on the lessons learned from adding new technology to an existing UAV curriculum. In addition, we ask our audience for feedback related to supporting students in using novel tools for engineering design and for ideas for how to best capture students' skill development over a relatively short period of time.

We learned that the addition of technologies, like AR, to students' learning experiences, the technology needs to serve a purpose that helps students see the value in a new tool to help address the challenge they are working on. This gives students a coherent experience even in a weekly after-school program. For example, we saw youth use their ideas about designing skyhooks from craft materials to help them decide which 3D printed hook would best suit their needs. That said, in our future work, we plan to make this adaptable so that it is a valuable tool for a range of design challenges. The second lesson learned is that new tools require a sufficient amount of time for students to use, learn, and manipulate. Doing some work ahead of time for students might save time but could diminish the value of the tool in their eyes. For example, we provided youth with 3D models to manipulate in AR instead of giving them 3D modeling tools to design their own. In the future, we would like to expand the tool use to include youth using 3D modeling software to design skyhooks and to test out their designs in the AR tool before 3D printing.

Next, we seek feedback on two aspects of our future work. First, what successes or design principles do you focus on when integrating new and innovative tools into after-school programs? Also, in what ways do you address the tension between students engaging engineering design practices and spending time reflecting on the practices and naming them for students? Second, what research methods would you consider for measuring and observing students' use of tools and their spatial reasoning skills? With limited time to use the tools, what do you recommend asking students to talk through as they work with tools? Finally, what instruments might better measure change in spatial reasoning in this study?

Limitations

This study occurred in the context of an after-school program where day to day challenges made it difficult to consistently implement the curriculum, 3D modeling, and AR, as well as collect data from all student. There were multiple competing demands in the after-school program, including the time it takes to learn to fly UAVs, the varying expectations of documentation of investigations, data, and specifications between adults and youth, and undergraduate facilitators who were new to the curriculum, and to working with middle school students. With the small but diverse participant population, we present this paper with acknowledgements of the pilot nature of the study. We lack knowledge of the generalizability across curriculum but plan to continue to pilot this app with larger groups of students. In addition, the app was developed to be specific to the curriculum and to the UAVs, however, we see potential in the available tools for expanding its capabilities. Finally, we acknowledge the need to find and tailor instruments to measure pre and post changes in spatial skills over a longer period of time with middle school aged students.

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