Making despite Material Constraints with Augmented Reality-Mediated Prototyping

Sowmya Somanath
sowmyasomanath@uvic.ca
University of Victoria
Victoria, Canada

Lora Oehlberg
University of Calgary
Calgary, Canada
lora.oehlberg@ucalgary.ca

Ehud Sharlin
University of Calgary
Calgary, Canada
ehud@ucalgary.ca

ABSTRACT

We present a discussion on designing an Augmented Reality (AR)-based prototyping approach to help makers continue building low-fidelity physical computing projects despite material constraints and demonstrate an example, Polymorphic Cube (PMC). Lack of immediate or easy access to electronics is a roadblock to building physical computing projects. We present AR-mediated prototyping as an approach where mobile AR can be used to simulate missing I/O components in-situ during electronics prototyping. Using our suggested approach makers can build a circuit with available real-world materials, substitute the missing components using any augmented physical proxy, and continue implementation tinkering and interaction with the hybrid circuit. Evaluation of PMC demonstrated that users can leverage computing to overcome the lack of electronic components and build low-fidelity prototypes to support design thinking. Our study revealed the benefits and limitations of our current prototype system and encourages future explorations into an AR-mediated prototyping approach to making.

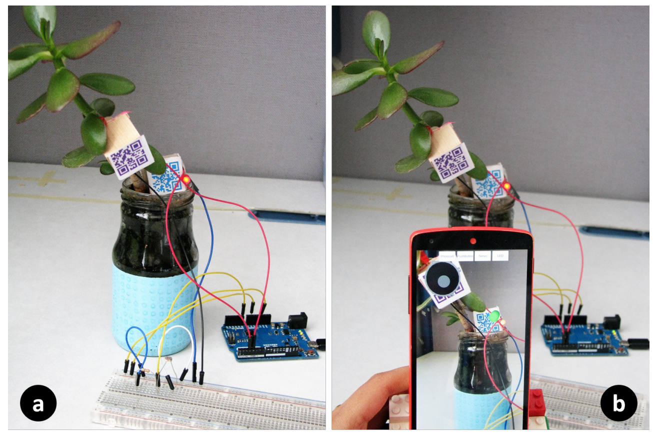

Figure 1: AR-Mediated Prototyping blends real and virtual components to create physical computing projects despite missing materials. Above, a plant monitoring system prototyped using our technology probe (Polymorphic Cube).

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

prototyping, material constraints, physical computing, maker

ACM Reference Format:
Sowmya Somanath, Lora Oehlberg, and Ehud Sharlin. 2020. Making despite Material Constraints with Augmented Reality-Mediated Prototyping. In *FabLearn 2020 - 9th Annual Conference on Maker Education (FabLearn '20), April 4–5, 2020, New York, NY, USA.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3386201.3386206

1 INTRODUCTION

Building physical computing projects such as toys, robots, and interactive textiles require access to low- and high-tech material resources such as craft supplies, electronics, and microcontrollers. However, makers may not always have immediate or easy access to all the required high-tech material resources for making [3]. Reasons such as material cost or the lack of immediate availability in impoverished communities present potential roadblocks [25, 26]. When electronic components are not available, makers may conduct iterative on-line or empirical research to find substitutes [25]. However, not all makers have access to learning resources (e.g., the Internet, textbooks) or the motivation to conduct such research [26], and thus become discouraged or discard their project ideas entirely [26]. This inequity compromises the democratic vision of the Maker Movement [29]; by helping people continue to make despite missing material resources, we can equitably extend the reach of the Maker Movement's vision.

One possible response to missing materials is to digitally create and simulate the circuit. Researchers have proposed electronics simulation software (e.g., Tinkercad) as a way for makers to virtually explore "what-if" scenarios easily and instantly when no electronic components are available. However, makers would eventually need to re-construct the circuit for real-world applications. A step forward would be to combine the real and virtual worlds for prototyping as people often have at least a few components to start with. Researchers have demonstrated the benefits of such hybrid prototyping techniques wherein circuits are built digitally and interaction is facilitated physically or virtually (e.g., [13, 32] and, have found them to be useful for design thinking [13] and to support individual and collaborative circuit testing scenarios [32].

While such projects offer promising alternatives, there are two main limitations with the current approaches to support prototyping physical computing projects despite material constraints. First, circuit building and design thinking primarily happens in the

FabLearn '20, April 4–5, 2020, New York, NY, USA

ACM ISBN 978-1-4503-7543-6/20/04...$15.00
https://doi.org/10.1145/3386201.3386206

virtual space [13, 32], which is counter to the concept of physical computing projects that require creating physical circuits. Second, access to specialized hardware (e.g, shields used by [32]) can be a constraint for a maker who did not have immediate or easy access to the required resources to start with. To address these challenges and support prototyping despite material constraints, we propose *Augmented Reality (AR)-mediated prototyping* – an approach that leverages mobile AR to simulate missing components to continue prototyping physical computing projects. With the growing availability of smartphones worldwide [27], mobile AR could provide a low-cost and accessible solution for continuing to prototype in varied contexts.

In this paper, we present our vision for AR-mediated prototyping as a solution for addressing material constraints. AR-mediated prototyping is an approach wherein makers can use a physical proxy (any found object) as a placeholder for missing electronic components, physically connect the proxy to the circuit being built, superimpose the proxy with interactive AR components using a smartphone, and program the integrated circuit (real world and AR components) using the microcontroller-based IDE. Informed by our vision, we demonstrate and evaluate a simple proof-of-concept technology probe, Polymorphic Cube (PMC, Figure 1), to learn about the strengths and limitations of such an approach to prototyping. Our studies indicate that PMC-like technology could help makers focus on prototyping project ideas despite the lack of materials and continue to take part in implementation tinkering and testing of multiple design ideas. One expected limitation of our AR-mediated prototyping approach is that because the missing components are simulated using AR they cannot physically affect the real-world components. For example, a VR motor cannot spin a real-world object. However, participants' responses highlight that this might be an acceptable limitation for quickly developed low-fidelity prototypes. We conclude the paper with a discussion on the strengths and limitations of AR-mediated prototyping, and point to some future directions to support makers in building low-fidelity physical computing projects despite material constraints.

2 RELATED WORK

2.1 Authoring Platforms

Researchers have demonstrated authoring platforms that support integrating physical and digital worlds of prototyping. For example, d.tools [13] is an integrated authoring environment for designing, analyzing, and testing early prototypes of physical user interfaces. Designers begin by plugging physical components into the d.tools hardware interface and then author interaction behavior digitally using a statechart-based visual programming interface. The designer triggers the interaction model by either interacting with the physical electronics or by simulating the virtual version of the plugged electronic component. Extending this idea, Proxino [32], addresses the issue of the lack of physical interactions with virtual components and offers three solutions. First, Proxino uses a proxy shield that enables virtual circuits to be tested in the real-world. Second, it allows makers to share resources, that is, a maker without components can use a remote person's real-world components to test a virtual circuit. Third, the maker can also leverage sensors available in technologies such as a tablet to interact with the virtual circuit.

Researchers have also proposed tabletop-based solutions to teach learners about physical computing concepts using both real-world materials and digital augmentations. For example, Conradi et al. [9] presented the Flow of Electrons, a tabletop system to help users learn about electronics. Users place various tagged electronics such as microcontrollers and electronic components on the tabletop, and using touch, virtually build the circuit. Animations of digital wires confirm correct wiring and as soon as the virtual circuit is closed, animated "electrons" start to flow. react3D [24] is also a tabletop system used to explore circuit building and uses abstract tangibles to serve as electronic components. However, to test interactions (e.g., turning an LED on/off) real electronic components must be attached to the representative tangible block.

Our vision for AR-mediated prototyping is inspired by these projects and extends them as follows: (1) unlike d.tools [13] and Proxino [32], we try to close the gap between the virtual and physical worlds by enabling people to physically build a hybrid circuit by leveraging mobile AR. The maker could benefit from constructing a physical hybrid circuit by focusing on several low-fidelity prototyping aspects such as the spatial arrangement of the circuit (e.g., where the electronics may be located), envisioning how the interaction would take place (e.g., how many components need to be interacted simultaneously), and building a close enough physical and functional system wherein the proxies can be replaced with real-world components relatively easily. (2) Unlike the tabletop systems [9, 24], our focus is not to teach the makers concepts related to circuit building, but instead to help them to make do with what they have and continue building prototypes to explore ideas.

2.2 Augmented Reality Toolkits

Several researchers have explored the use of Augmented Reality (AR) as a way to tightly couple the physical and digital worlds using rich and interactive 3D content [2, 5, 20]. Some examples in the context of physical computing include LightUp [1, 8], Conduct AR [21] and MixFab [30]. LightUp [1, 8] is a low-cost educational tool that recognizes the circuit behavior and gives live and interactive graphic feedback using AR technology. ConductAR [21] can recognize and analyze hand-drawn, printed, and hybrid conductive ink patterns. The augmentation helps users to understand and enhance circuit operation. MixFab [30] is a mixed-reality environment that helps users design objects in an immersive AR environment for 3D fabrication. The immersive AR environment enables creating objects, interacting with the virtual objects and the introduction of physical objects into the design of the object.

Our prototyping approach is inspired by these works but currently PMC does not use AR to superimpose additional information or feedback, and does not explicitly support educational activities such as circuit debugging. Instead we use mobile AR as a readily available solution to simulate missing I/O components so that makers can continue building low-fidelity physical interactive circuits.

3 AR-MEDIATED PROTOTYPING: VISION

AR-mediated prototyping lets makers' substitute AR stand-in components for missing electronics. Makers connect, interact with, and

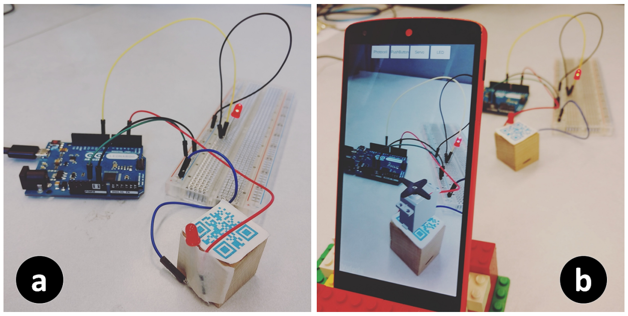

Figure 2: AR-mediated Prototyping: (a) trackable wooden cube proxy (b) companion AR application.

program a unified circuit that includes both real-world and virtual materials (Figure 2). Within this base vision for AR-mediated prototyping, there are several aspects to consider: (1) physical and virtual form of AR components, (2) circuitry and programming, and (3) physical interactions. In this section, we discuss these aspects and suggest three goals for designing technology for AR-mediated prototyping.

3.1 Physical and Virtual Form

AR components have both a physical and virtual presence. We envision that makers will select the dimensions and physical appearance of the placeholder object. For example, such an object could be a physical replica of the missing component made using art and craft materials, any readily-available found object, or even a QR code sticker (Figure 2a). Makers assign the placeholder object to a virtual electronic component, represented in virtual space by a 3D model. The AR component may simulate a single electronic component or a more complex subcircuit. The AR component can represent components that are analog or digital and input or output. Based on the physical and virtual aspects of an AR placeholder, we suggest that the first goal for an AR-mediated prototyping tool is to help makers easily construct and assign AR components (*Goal #1*).

3.2 Circuitry and Programming

To support physical circuitry, we envision that makers should be able to connect the physical placeholder objects to the physical circuit. Upon connection, the circuit should recognize the physical proxies similar to real-world components. Connecting the components can be facilitated by connecting wires in a way that resemble the actual connections for real-world components or it may be a simplified connection that facilitates quicker low-fidelity prototyping [6]. For example, Figure 2a shows a simplified connection wherein all AR components can be connected to the circuit using only two wires. To support programming, we envision that makers will write code for AR components in the same programming language and code base that defines the behavior of real-world components. This would allow the hybrid ecosystem of real and virtual components to behave as a single system. Based on these considerations, we suggest that the technology for AR-mediated prototyping should enable coupling – via circuity and programming – the AR components and real-world prototyping materials to create a unified project (*Goal #2*).

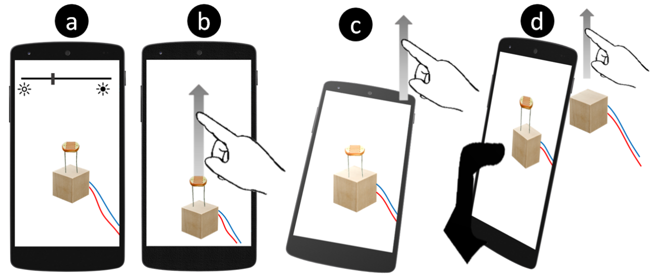

Figure 3: Interacting with AR light sensor component using (a) on-screen widget, (b) touch, (c) built-in phone sensors, and (d) physical placeholder object.

3.3 Physical Interactions

When working with hyrbid circuits, makers may need to simultaneously interact with AR and real-world components. Possible ways of interacting with AR components will depend on the AR technology being used. For example, for mobile devices such as smartphones or tablets, we identified four possible interaction styles (Figure 3) based on a continuum of AR interaction paradigms [11]. First, the maker could use an *on-screen widget* (Figure 3a), e.g., control the amount of light received by the light sensor using a slider widget. Second, the maker could use *touch interactions* (Figure 3b), e.g., covering the sensor by tapping the virtual representation on a capacitive touchscreen. Third, a maker could interact with *built-in phone sensors* (Figure 3c), e.g., amount of light received by the sensor can be controlled by interacting with the camera of the phone. Fourth, a maker could interact with the *physical placeholder object* (Figure 3d), e.g., control the sensor by physically interacting with the placeholder object. Alternative AR platforms (e.g., Hololens) may be able to use some of these interaction styles, but may also introduce additional ways of interacting with AR components such as full-body interactions. Based on these considerations, we suggest that the technology for AR-mediated prototyping should support appropriate interaction with AR components (*Goal #3*).

4 POLYMORPHIC CUBE

Informed by our vision, we implemented a technology probe [14], Polymorphic Cube (PMC). The goal of PMC is to elicit feedback from makers about AR-mediated prototyping. To that end, PMC is basic and currently supports simple ways to assign AR components, build and program circuits, and interact with the AR components.

4.1 Construct and Assign AR Components

In our PMC prototype, makers use a wooden cube with a QR code (Figure 2a) as a physical proxy for missing I/O components. We selected a one-inch cube as a placeholder because it is a stable object that can be connected to a circuit and was important for attaching a tag that could be consistently recognized. We developed a simple companion mobile application that allows the maker to assign the cube to a variety of components (Figure 2b). Currently, PMC can simulate four components (Figure 4): LED (digital output), servo (analog/digital output), pushbutton (digital input), and photocell

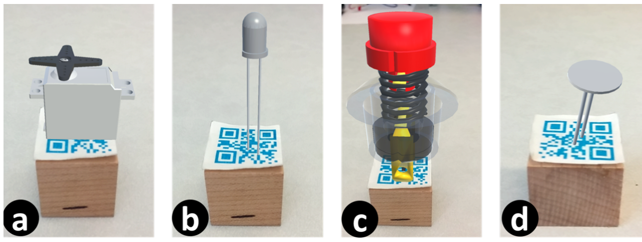

Figure 4: Example AR components: (a) servomotor, (b) LED, (c) pushbutton, and (d) photocell.

(analog input). The maker can select and assign the cube to different I/O components through a button-based menu positioned at the top of the mobile interface. Rather than having a large set of pre-assigned QR codes mapped to different I/O components, we use the concept of polymorphism [4] and let the maker assign a QR code to any I/O component they need. All of the AR electronic component models used we downloaded free from the 3D warehouse website [1]. We used the Vuforia Unity SDK [2] to create the Android AR application.

4.2 Circuit Building and Programming

The proxy object in our current prototype has an electronic footprint of an LED. We attach an LED with two soldered wires to one face of the cube using tape. The wires enable connecting the cube to an Arduino pin (Figure 2a) and also help recognize when an AR component is plugged into the circuit. The attached LED also serves as a feedback mechanism, indicating to the maker that the AR proxy object is recognized by the circuit i.e., if the wires are correctly connected to the Arduino, the LED turns on. In our current implementation, the maker can program the hybrid circuit using the Arduino IDE. The value sent to or received from the I/O component are transmitted to the AR components in the app via WiFi. For example, to move an AR servo, the variable position in the for-loop is sent to the AR app via WiFi.

4.3 Interactions with Components

PMC implements touch-based interaction with the virtual I/O components (Figure 3d). Touch-based interaction style mimics the interaction style that a maker uses to interact with the real-world components, thereby taking advantage of learned hands-on skills [15]. Each AR component model resembles a real-world component and affords similar interactions. For example, the maker can push the cap of the 3D button model using touch. To visualize a button press, the button spring is animated to compress and expand.

4.4 Example

Figure 5 demonstrates an example of using PMC to build a simple prototoype of a light controller system. In this example, PMC simulates a missing button. A maker completes four steps to prototype. First, the maker builds a light switch circuit by connecting the PMC cube to the breadboard and the microcontroller using the two wires attached to the cube (Figure 5a). Second, the maker assigns the PMC cube to a pushbutton by selecting from the menu on the phone app (Figure 5b). Third, the maker writes the Arduino code to control the real-world LED using a virtual button and uploads the Arduino program to the microcontroller (Figure 5c). Lastly, the maker interacts with the simulated button on the mobile screen by pressing and releasing the button to turn the real-world LED light on/off (Figure 5d).

[1]https://3dwarehouse.sketchup.com/?hl=en
[2]https://developer.vuforia.com/downloads/sdk

5 EVALUATION

Our evaluation goals are similar to past work on tools for makers (e.g., [7]): to understand the viability of our technique (e.g., can people build and program a hybrid circuit using PMC) and to gather participants' thoughts on the usefulness and limitations of the technique. We conducted a two-part study consisting of a **lab study** and **survey**. In the lab study, participants were introduced to PMC and they built multiple prototypes of a controllable lamp using real-world prototyping materials and an AR component. In the survey, we specifically focused on understanding how people envision interacting with AR components.

5.1 Participants

Twelve people between 20-44 years of age (3 females, 9 males) participated in our lab study. We recruited via notices posted to local makerspaces, emails sent to a university-wide mailing list, and word-of-mouth recruitment. We recruited participants who had prior experience using the Arduino as we were not testing for people's ability to learn circuitry and coding using PMC. We selected participants on a first-come-first-serve basis and the participants were remunerated with $20. Our participants self-identified as makers and came from different disciplines and professional backgrounds: energy teacher, IT/ electronics consultant, visual artist and science communicator, and graduate students (electrical engineering, computational media design and computer science). Participants had a range of self-rated expertise in physical computing: novice (1), beginner (5), competent (5) and expert (1). Participants also had a varied frequency of involvement with physical computing activities: rarely (4), occasionally (3) and frequently (5).

For our survey study, we reached out to all our previous participants i.e. 12 from the lab study and 4 from our pilot studies, who had experienced building projects using the PMC. From the total 16 participants we contacted, **13 participants** responded agreeing to complete the survey. This group constituted 3 people who had taken part in the pilot studies and 10 participants from the lab study.

5.2 Procedure

Our lab study lasting one hour each consisted of four phases. In the pre-study phase, participants completed a questionnaire that gathered information about demographics and prior experience, as well as, people's current strategies to address the challenge of missing electronic components when building physical computing projects. Next, in the familiarization phase, participants were shown a step-by-step technical introduction to PMC where the researcher build a circuit consisting of a real button and an AR servo. Then, in the building phase, participants built four different versions of a controllable lamp using PMC and some real-world electronics (LED, photocell, pushbutton and servo). To facilitate the circuit

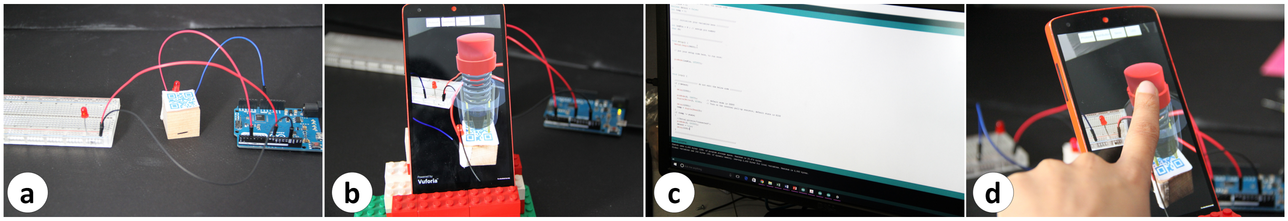

Figure 5: Example of a simple light controller built using PMC: (a) build a circuit, (b) assign the PMC cube to a pushbutton, (c) write code, and (d) interact with the AR pushbutton to test the system.

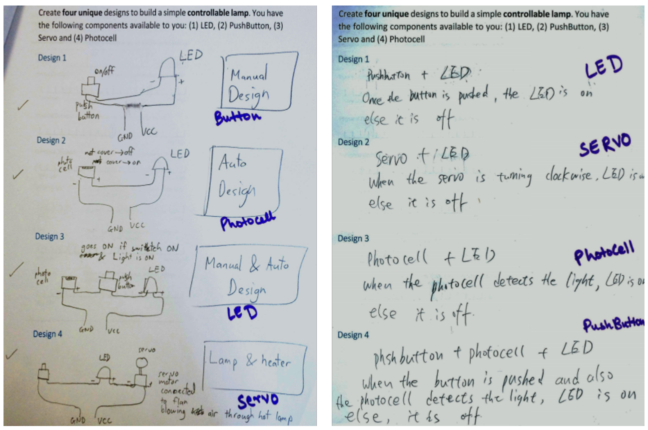

Figure 6: To create the scenario of "a missing component" we took each sketch and selected one component to be an AR component, indicated by the purple text. Above are two example sketches.

building phase, participants were asked to first sketch the four different variants of their controllable lamps (Figure 6. Each sketch implementation marked a trial and in each trial, we took away one of the required components and asked the participant to use a PMC instead. Based on the sketches we ensured that each participant would experience a lack of each type of component (actuator, sensor, and I/O). There was no time limit for the trials. When the prototype was working as proposed in the sketch, the participant did a quick demo of the system for the researcher and then moved to the next trial. Finally, in the last phase, we asked participants to fill out a post-study questionnaire about their overall thoughts on using the PMC. We asked them to rate PMC using a 5-point Likert-scale [19] (where 1 was much worse and 5 was much better) on questions related to ease of use and experience with different components. We also conducted a semi-structured interview to gain further insights. Each session was video recorded for posterior data analysis.

The follow-up survey asked participants to compare and rank in order of preference (where 1 was least preferred and 4 was most preferred) the four different interaction styles for AR-mediated prototyping we outlined in our vision (shown in Figure 3). We also asked participants to provide a rationale for their ranking order. The questionnaire consisted of eight categories of electronics as used by SparksFun website: (1) light sensors, (2) weather sensors, (3) flex, force and vibration sensor, (4) direction sensors, (5) distance sensors, (6) sound sensors, (7) biometric sensors and (8) encoders.

5.3 Data Analysis

We transcribed individual interviews and the responses were coded and categorized into higher-level themes (e.g., easy access and flexibility, interactivity supports sharing) as related to each of our design goals [28]. We quantitatively analyzed the Likert-scale questionnaire to compute the median values. We used the individual video recordings to identify and count the different interaction styles used by the participants when interacting with the AR object.

6 RESULTS

6.1 Responding to Lack of Materials

From our lab study questionnaire responses, we learned that 11 of 12 participants had previously encountered a situation when they had limited access to electronics. Overall, participants had three practical solutions to overcome the challenge of material unavailability. First, the majority of our participants (8 of 12) had placed an order online and waited while the electronics arrived: *Usually I stop what I am doing and order the component. This can be difficult as it can delay the project for weeks sometimes* [P8]. Second, a few participants (4 of 12) had attempted to re-use existing and readily available electronics as an alternative: *I missed some switches in my design which I ended up replacing with transistors and resistors combined* [P7]. Lastly, one participant mentioned that they had borrowed the missing electronic components from a friend. All participants agreed that using PMC-like technology could be a better solution compared to the identified strategies. For example, P1 said, *if I open my box at home I have all of these [button and LED], but I don't have a servo. So it was cool that we started with the servo, because I actually tried what I could not have done at home. Because I did not have a servo, I simulated it and it was really helpful.* Overall, all participants found that PMC is easy to understand (median=4, n=12) and was usable for the given task (median=4, n=12).

6.2 Building AR Components (Goal #1)

We envisioned that both physical and virtual forms of an AR component are important. One participant explicitly supported this idea and suggested that (*"it would be nice to have the cube comparable to the real component size"*[P12]). Some of our participants (4 of 12) suggested that physical form of an AR component is less important. Participant P4 argued that in AR-mediated prototyping, components do *"not need to have a lot of physical presence"*. Participant P4's rationale was that because AR components are virtual, we do not have to worry about the physical space they occupy – *"one does not have to worry about things like if a motor has place to spin"*. A similar

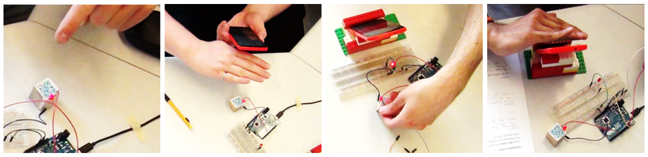

Figure 7: Participants attempting to interact with the physical placeholder object and built-in phone sensors.

opinion was expressed by participant P10, who mentioned that the placeholder object could *"even [be] integrated into the breadboard, so the breadboard would have specific pins that were cubes"*.

In our current implementation, makers assign the proxy objects to realistic 3D models of electronic components. Participants P6 and P9 specifically mentioned that the ability to have a 360 degree view of 3D models made the experience feel physical. In addition, currently, makers can map the proxy object to only one elctronic component. While 7 participants agreed with this option, 5 participants suggested assigning one placeholder object to multiple components or a sub circuit could be beneficial. Participants P11 and P13 mentioned that 1-to-many assignment could be beneficial when the placeholder object represents multiple instances of the same components (e.g., array of LEDs). P7 specifically mentioned that assigning one placeholder object to multiple components could also be useful to better facilitate interactions with the components: *Say we had a big circuit here and we had 5 cubes spread. Then maybe at some point I would like to turn on a switch and cover a photocell, and press another button. So I don't know how to deal with it.* Overall, all participants found PMC easy to assign and experiment with: *"I liked being able to change to anything very easily."* [P12]. All our participants also mentioned that they could imagine using a tool like PMC to test their design ideas if the tool included access to a large library of electronic components. Participant P13 specifically mentioned that such a library need not be limited to existing electronic components and should include end-user defined components.

6.3 Coupling Components (Goal #2)

All participants successfully built four unique prototypes of the controllable lamp using PMC during the lab study. Overall, from the lab study results we found that participants with varying expertise levels found it easy to build circuits using PMC (median=4, n=12). Interviews revealed that 4 of 12 participants liked the simplistic two-wire connection. Within the context of low-fidelity prototyping, participants P10 and P11 mentioned that the two-wire connection was easy and had an advantage over complex real components that require more effort when (re)building a circuit. Participant P9 mentioned that simple wiring also helps aesthetics – *"its kind of cleaner"*. Related to programming, we found that participants found it easy to program the AR components using the Arduino IDE (median=4, n=12). One participant suggested that it would be beneficial for PMC-like platforms to work with different programming approaches such as programming by demonstration as used in other projects (e.g., [12, 22]).

6.4 Interaction with AR components (Goal #3)

In our vision, we proposed four interaction styles. In PMC, we implemented touch-based interactions (Figure 3b). To understand how people generally prefer to interact with AR components we looked to our data from both the lab study and the survey. Responses to the the likert-questionnaire from the lab study revealed that participants found interacting with a virtual servo, photocell, and button using touch about the same as interacting with their real-world counterparts (median=3, n=12). Specifically for input components, post-study interviews revealed that all participants liked the simple touch-based interactions. Participant P9 explicitly mentioned that the animation of physical components provided useful feedback for interaction: *"With the physical one [button], it was like did I get it, did I press it on. With this [virtual button] I knew it was working, the feedback was really nice"* [P9].

This pattern was also observed in the responses to the survey, which included a wider variety of electronic components. The responses to the survey showed that in order of preference, the first preference for a majority of the participants was either touch-based interactions or interactions using widgets (median=2.5, n=13), a close second choice was built-in phone sensors (median=2.25, n=13), and direct physical interaction with the placeholder object was least preferred (median=1.94, n=13). Participants reasoned that they preferred touch-based interaction because it is intuitive, the interaction was collocated with the object, it facilitated more control, and that it could be consistently used with a variety of electronics. Interacting with widgets was preferred because participants had prior experience using widgets for controlling specific values.

While we received positive responses for touch-based interactions from the lab study and survey, during the lab study we had observed that 7 of 12 participants attempted to interact with the simulated I/O components using built-in phone sensors and direct interactions with the physical placeholder object (Figure 7). By checking some of their survey responses we found that they prefered touch-based interaction over the other options because they found them to be less consistent when applied to a larger range of electronics. One participant added: *"this [phone sensor-based] seems like a tricky option because it can create a disconnect between how users interact with components. If I'm acting within a virtual world for one component, say a button, it doesn't seem consistent that the phone acts as a sensor for another, why do I have to shake the phone for a vibration sensor/accelerometer?"* [P13]. Similarly, a reduced degree of coherence (i.e. the degree to which physical and digital might be perceived as the same thing) [17] was highlighted as a possible problem for interacting directly with the placeholder object: *"I feel like its more appropriate for a full virtual reality environment. In the current AR setting, it seems like it would divide your attention between two objects (the AR device, and the actual circuit). I prefer focusing on one thing at a time, so it makes sense to me to keep all interactions virtual"* [P13].

7 DISCUSSION AND FUTURE WORK

The primary goal of our AR-mediated prototyping approach is to help makers continue prototyping physical computing projects despite missing material resources. All our participants' could overcome the lack of a required I/O component and build several prototypes of the controllable lamp using PMC. Initial reactions of makers toward PMC have been encouraging. Participant statements not only reveal that our vision considerations were meaningful, but

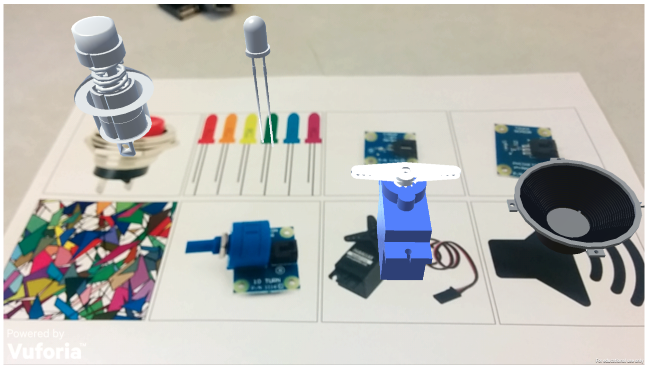

Figure 8: Detecting multiple AR components.

they also demonstrate a high level of excitement toward the use of PMC-like technology for making when challenged with material shortages. However, PMC, as the first exploration in this direction, also raises some questions to be explored in the future regarding the development of a prototyping tool for makers.

Physical Kinematics. While a few (4 of 12) participants suggested that the physical form factor of the proxy is less relevant, we think that in order to advance design thinking and to go beyond implementation tinkering use cases, it would be necessary to continue exploring the physicality and materiality aspects of the proxy object. In our current implementation of the PMC, the AR components cannot physically demonstrate material behaviours (e.g., a virtual servo cannot spin a real-world component) and makers would have to simulate those material behaviours themselves similar to wizard-of-oz techniques [10]. There are however some future directions that could be considered to improve this experience. For example, it might be interesting to explore the use of low-cost self-actuated flexible interfaces (e.g., [23]) to enable physical kinematics. Alternatively, makers with access to advanced technologies could also use 4D printing techniques [16] to print proxies that respond to external stimuli (e.g., interaction gestures) and transform into shapes that correspond to that of the missing real-world electronics.

Scalability. In our current study of PMC, we allowed participants to use one cube as a stand-in for one missing electronic component. Our findings indicate that participants could successfully work with one augmented cube when building physical circuits. However, in scenarios where a maker may not have immediate or easy access to many materials, scalability of the technology is important. From an implementation standpoint, we have successfully tested tracking multiple objects (Figure 8). However, as indicated by our participants, there are several aspects to consider to scale interaction when using multiple AR objects. For example, if two placeholder objects are placed far away from each other and the maker needs to interact with them simultaneously, then the maker would need a much larger display than a phone can offer. One obvious solution is to make use of larger displays such as a tablet. Alternatively, it would also be interesting to explore solutions similar to Surround-See [33] that enable peripheral vision around mobile devices. In addition to exploring how to scale AR-mediated prototyping, an important thread to explore in the future is understanding how many AR components can be used in circuit before AR-mediated prototyping begins to deviate away from physical making.

Open-source 3D models. Our participants appreciated the flexibility of AR-mediated prototyping. All participants mentioned that having a comprehensive list of virtual components would improve the usefulness of PMC-like tools – *"I see myself using it [PMC] if you had a library of models"* [P5]. In our current PMC prototype, we used freely available online 3D models of electronics. Digital easy-to-use maker tools for creating models of electronic components could help expand the ecology of virtual materials that makers can use within their hybrid AR-mediated physical computing projects. For example, participant P13 suggested that support for design iteration could be further improved by allowing participants to use both physical and virtual components (e.g., virtual knobs, screens, and UI components). In addition, makers could share their digital design files along with software code on online communities such as Thingiverse [3] or Instructables [31] to help others explore ideas by tinkering code and material functionality.

Interactions with Virtual Components. While our participant responses indicates that touch-based interaction is perhaps an userful interaction style to incorporate in future AR-mediated prototyping tools, there were also some concerns raised by the participants. For example, upon trying PMC, 5 of 12 participants found touch-based interaction less satisfying for sensors such as the photocell. In the future, to gather more generalizable interaction style results, it would be interesting to use the touch-based interaction style as a baseline and compare it to other interaction styles for a wide variety of components (sensors, actuators, and encoders).

Transferability of Skills. Since PMC was not designed to be an educational tool, we did not gather data on whether it helped develop coding ability and circuit understanding. However, several participants expressed that PMC could be useful for learning and some mentioned that the introduction of such relatively low-cost and readily available technology could be beneficial for classroom activities. Within that context, one participant mentioned that the simplistic two-wire connection could be misleading and it might be initially difficult to understand the abstraction of the cube. To enable transferability of skills, PMC-like tools can draw from existing AR-based educational tools such as LightUp [8] and ConductAR [21], helping makers replace the surrogate AR component with a real component by overlaying circuit connection diagrams. This could help makers overcome both material challenges as well as conceptual difficulties involved in technology-based DIY.

8 LIMITATIONS

Our work demonstrated that the introduction of new tools for making can help people engage in prototyping-related tasks despite constraints that may limit participation, such as the lack of immediate or easy access to material resources. However, our work is an early effort in the exploration of tools for making that address specific real-world constraints faced by makers, and therefore has limitations. Our evaluation study was conducted with adult makers in North America who had prior experience with physical computing. Perhaps due to their location and expertise, they had devised

[3]http://www.thingiverse.com/

strategies to overcome issues related to unavailability of material resources. We posit that a different context and demographic (e.g., primary school students in rural India [26]) will affect future design considerations for such prototyping support tools for makers. Our participants only built variations for one example project (lamp) using the PMC. We think that testing the use of PMC for building a number of different projects can reveal further strengths and limitations. Lastly, our evaluation of PMC focused more explicitly on assessing how PMC supports prototyping-related tasks (corresponding to the "create" dimension of Bloom's taxonomy [18]). Although other outcomes (such as remembering, understanding, applying, analyzing and evaluating [18]) are part of the cognitive process, we did not explicitly measure for them. We think that knowing more about how PMC-like tools can support those dimensions can help further advance the development of tools for makers.

9 CONCLUSION

We presented our vision and a proof-of-concept prototype for AR-mediated prototyping that can help makers to create physical computing projects despite the lack of easy or immediate access to material resources. We conducted a preliminary usability study to understand the strengths and limitations of AR-mediated prototyping using our prototype system, Polymorphic Cubes (PMC). Our results indicate early success for such hybrid forms of low-fidelity prototyping to address material constraints and show that makers can use PMC-like tools to construct circuits and engage in implementation tinkering and design thinking.

ACKNOWLEDGMENTS

We would like to thank our participants for their valuable feedback. This work is supported by NSERC grants RGPIN-2018-05950, RGPIN-2016-04540, RGPAS-2019-00077 and RGPIN-2013-312218.

REFERENCES

[1] Zain Asgar, Joshua Chan, Chang Liu, and Paulo Blikstein. 2011. LightUp: a Low-Cost, Multi-Age Toolkit for Learning and Prototyping Electronics. In *Proceedings of the 10th International Conference on Interaction Design and Children*. ACM, 225–226.
[2] Ronald T Azuma. 1997. A survey of augmented reality. *Presence: Teleoperators and virtual environments* 6, 4 (1997), 355–385.
[3] Jonathan Bean and Daniela Rosner. 2014. Making: movement or brand? *interactions* 21, 1 (2014), 26–27.
[4] Michel Beaudouin-Lafon and Wendy E Mackay. 2000. Reification, Polymorphism and Reuse: Three Principles for Designing Visual Interfaces. In *Proceedings of the working conference on Advanced visual interfaces*. ACM, 102–109.
[5] Mark Billinghurst, Raphael Grasset, and Julian Looser. 2005. Designing augmented reality interfaces. *ACM Siggraph Computer Graphics* 39, 1 (2005), 17–22.
[6] Paulo Blikstein. 2013. Gears of Our Childhood: Constructionist Toolkits, Robotics, and Physical Computing, Past and Future. In *Proceedings of the 12th international conference on interaction design and children*. ACM, 173–182.
[7] Leah Buechley, Mike Eisenberg, Jaime Catchen, and Ali Crockett. 2008. The LilyPad Arduino: Using Computational Textiles to Investigate Engagement, Aesthetics, and Diversity in Computer Science Education. In *Proceedings of CHI*. ACM, 423–432.
[8] Joshua Chan, Tarun Pondicherry, and Paulo Blikstein. 2013. LightUp: an Augmented, Learning Platform for Electronics. In *Proceedings of the 12th International Conference on Interaction Design and Children*. ACM, 491–494.
[9] Bettina Conradi, Verena Lerch, Martin Hommer, Robert Kowalski, Ioanna Vletsou, and Heinrich Hussmann. 2011. Flow of Electrons: an Augmented Workspace for Learning Physical Computing Experientially. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*. ACM, 182–191.
[10] Nils Dahlbäck, Arne Jönsson, and Lars Ahrenberg. 1993. Wizard of Oz studies: why and how. In *Proceedings of the 1st international conference on Intelligent user interfaces*. 193–200.
[11] Emmanuel Dubois, Laurence Nigay, Jocelyne Troccaz, Olivier Chavanon, and Lionel Carrat. 1999. Classification Space for Augmented Surgery: an Augmented Reality Case Study. In *13th International Conference on Human-Computer Interaction, INTERACT*, Vol. 1. 353.
[12] Phil Frei, Victor Su, Bakhtiar Mikhak, and Hiroshi Ishii. 2000. Curlybot: Designing a New Class of Computational Toys. In *Proceedings of CHI*. ACM, 129–136.
[13] Björn Hartmann, Scott R Klemmer, Michael Bernstein, Leith Abdulla, Brandon Burr, Avi Robinson-Mosher, and Jennifer Gee. 2006. Reflective Physical Prototyping through Integrated Design, Test, and Analysis. In *Proceedings of the 19th annual ACM symposium on User interface software and technology*. ACM, 299–308.
[14] Hilary Hutchinson et al. 2003. Technology Probes: Inspiring Design For and With Families. In *Proceedings of CHI*. ACM, 17–24.
[15] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible Bits: Towards Seamless Interfaces Between People, Bits and Atoms. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*. ACM, 234–241.
[16] Zhong Xun Khoo, Joanne Ee Mei Teoh, Yong Liu, Chee Kai Chua, Shoufeng Yang, Jia An, Kah Fai Leong, and Wai Yee Yeong. 2015. 3D printing of smart materials: A review on recent progresses in 4D printing. *Virtual and Physical Prototyping* 10, 3 (2015), 103–122.
[17] Boriana Koleva, Steve Benford, Kher Hui Ng, and Tom Rodden. 2003. A Framework for Tangible User Interfaces. In *Physical Interaction (PI03) Workshop on Real World User Interfaces*. 46–50.
[18] David R Krathwohl. 2002. A revision of Bloom's taxonomy: An overview. *Theory into practice* 41, 4 (2002), 212–218.
[19] Rensis Likert. 1932. A Technique for the Measurement of Attitudes. *Archives of psychology* (1932).
[20] Paul Milgram, Haruo Takemura, Akira Utsumi, and Fumio Kishino. 1995. Augmented Reality: A class of Displays on the Reality-Virtuality Continuum. In *Photonics for industrial applications*. International Society for Optics and Photonics, 282–292.
[21] Koya Narumi, Steve Hodges, and Yoshihiro Kawahara. 2015. ConductAR: an Augmented Reality Based Tool for Iterative Design of Conductive Ink Circuits. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. ACM, 791–800.
[22] Hayes Solos Raffle, Amanda J Parkes, and Hiroshi Ishii. 2004. Topobo: A Constructive Assembly System with Kinetic Memory. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM, 647–654.
[23] Anne Roudaut, Abhijit Karnik, Markus Löchtefeld, and Sriram Subramanian. 2013. Morphees: Toward High Shape Resolution in Self-Actuated Flexible Mobile Devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 593–602.
[24] Randall Shumaker and Lackey Stephanie. 2014. *Virtual, Augmented and Mixed Reality: Applications of Virtual and Augmented Reality: 6th International Conference, VAMR 2014, Held as Part of HCI International 2014, Heraklion, Crete, Greece, June 22-27, 2014, Proceedings*. Vol. 8526. Springer.
[25] Arnan Sipitakiat, Paulo Blikstein, and David P Cavallo. 2004. GoGo Board: Augmenting Programmable Bricks for Economically Challenged Audiences. In *Proceedings of the 6th international conference on Learning sciences*. International Society of the Learning Sciences, 481–488.
[26] Sowmya Somanath, Lora Oehlberg, Janette Hughes, Ehud Sharlin, and Mario Costa Sousa. 2017. 'Maker' within Constraints: Exploratory Study of Young Learners using Arduino at a High School in India. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 96–108.
[27] Statista. 2019. Number of smartphone users worldwide from 2016 to 2021. https://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/. [Online; accessed 2020].
[28] Anselm Strauss and Juliet M Corbin. 1990. *Basics of Qualitative Research: Grounded Theory Procedures and Techniques*. Sage Publications, Inc.
[29] Joshua G Tanenbaum, Amanda M Williams, Audrey Desjardins, and Karen Tanenbaum. 2013. Democratizing Technology: Pleasure, Utility and Expressiveness in DIY and Maker Practice. In *Proc. of the SIGCHI*. ACM, 2603–2612.
[30] Christian Weichel, Manfred Lau, David Kim, Nicolas Villar, and Hans W Gellersen. 2014. MixFab: a Mixed-Reality Environment for Personal Fabrication. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*. ACM, 3855–3864.
[31] Eric Wilhelm and Saul Griffith. 2020. Instructables - DIY How To Make Instructions. http://www.instructables.com/. [Online; accessed 2020].
[32] Te-Yen Wu, Jun Gong, Teddy Seyed, and Xing-Dong Yang. 2019. Proxino: Enabling Prototyping of Virtual Circuits with Physical Proxies. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. ACM, 121–132.
[33] Xing-Dong Yang, Khalad Hasan, Neil Bruce, and Pourang Irani. 2013. Surround-See: Enabling Peripheral Vision on Smartphones during Active Use. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*. ACM, 291–300.