Prototyping to elicit user requirements for product development: Using head-mounted augmented reality when designing interactive devices

Bo Kang, Nathan Crilly, Weining Ning and *Per Ola Kristensson*, Department of Engineering, University of Cambridge, UK

Designers of interactive devices are challenged by the need to accurately elicit user requirements from low-cost prototypes at the early stages of the design process. Head-mounted augmented reality (AR) can potentially assist in this process by economically representing physical-digital blended features with relatively high-fidelity prototypes. To explore this potential, we present and evaluate a head-mounted AR-enhanced hybrid prototyping system created in the context of a fan product development process. We conducted a mixed-methods study comparing the AR-enhanced prototyping method with a conventional prototyping method. The results reveal that the AR system can elicit similar user requirements as the conventional prototyping method with an improved overall experience.

Keywords: human–computer interaction, prototypes, product development, creative design, augmented reality

Conducting user studies with prototypes is a key step to realising the elicitation of user requirements in product development. Yet the accurate elicitation of user requirements can be extremely challenging in the specific domain of interactive devices, especially when such devices are at the early stage of the development, such as function identification or feature prioritization. The main reason is additional device interactivity and connectivity which increase the inherent complexity of the prototyping space where designers require a more holistic view of the system components, linked tasks, and related contexts (Eckert & Clarkson, 2002; Kim et al., 2016; Rowland et al., 2015). Moreover, the prevalence of high-tech products is accompanied by increasingly rapid development processes and shorter product iteration cycles (Rowland et al., 2015). As a consequence, it is often challenging and tedious to rapidly prototype interactive devices and accurately elicit user requirements using established prototyping methods (Corno et al., 2019; Mazzei et al., 2018; Taivalsaari & Mikkonen, 2018).

Corresponding author:
Bo Kang
bk410@cam.ac.uk

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New approaches, tools, and procedures are required to efficiently elicit user requirements in the development of interactive devices. One potential technology that has drawn attention from researchers is optical see-through augmented reality due to its flexibility and accuracy in 3D content representation and interaction realization with a relatively low cost (Zampelis et al., 2012). A multitude of research has explored the use of AR as a prototyping method (Fiorentino et al., 2002; Gasques et al., 2019; Hammady & Ma, 2019; Kent et al., 2021). However, the majority of these prior studies use AR conservatively using static features, such as appearance design (Park et al., 2015; Viyanon et al., 2017; Voit et al., 2019). The support for prototyping interactive features with AR has rarely been explored. Additionally, prior work mainly concerns the novelty of AR-integrated solutions in laboratory environments. In contrast, the potential use of AR prototyping to handle real-world environments and contexts has not yet been expounded with high granularity.

This paper addresses a clear gap in the literature: the lack of knowledge of the positive and negative qualities induced by prototyping interactive devices and eliciting user requirements therein with a more advanced, integrated, but inexpensive, AR-enhanced solution. To help explore this potential, we report the results of a study in a context derived from a real industrial case to test the efficacy of the AR-enhanced prototyping method in user requirement elicitation in the product development process of a domestic air fan. We built an AR-enhanced system to demonstrate a dynamic interactive feature that spans both physical and virtual domains. The system can help probe users' preferences for attributes related to the fan's oscillation feature in order to inform later design stages. To evaluate the efficacy of the system, we conduct a mixed-methods study with twelve participants and compare the performance of the AR system with three commonly used conventional prototyping media: paper, computer, and cell phone.

Our study enhances understanding of the positive and negative qualities emerging from the AR approach through diverse research lenses. The study involves three tasks intended to ascertain participants' preferences for the oscillation angle and speed of the fan, as well as user interface (UI) patterns. Overall, the results elicited with the AR system are similar to those collected with the conventional method. However, the user experience of the AR method surpasses the conventional one which indicates the latent potential of integrating AR into the development process of interactive products. In summary, the contribution of this research is that it reveals the AR system can elicit similar user requirements to a conventional prototyping method, but with improved overall experience. We further discuss the feasibility and economic benefits of the AR prototyping method in practice.

1 Obstacles to developing interactive devices

1.1 Complexity of prototyping interactive devices

Advanced sensor technologies and the proliferation of computing power have helped fuel the growth of interactive devices. Entailing the materiality of both tangible and intangible aspects, the design of these kinds of devices is becoming increasingly challenging (Berger et al., 2019). Designers developing the increasingly sophisticated interactive devices are now being exposed to design space with a more substantial level of complexity (Rowland et al., 2015), including internal complexity (e.g. additional features and usage modes embedded in a single product), external complexity (e.g. relationships between controls and states are becoming less invisible), interaction complexity (e.g. a user has to adapt to multiple ways of interacting), and contextual complexity (e.g. a task has to be completed across various platforms over time) (Huang & Stolterman, 2012; Janlert & Stolterman, 2008).

Interactive devices widen the scope of factors that need to be considered in the design process (Kim et al., 2016) and raises more challenges for existing ways of creating prototypes. First, flexible and cost-effective manufacturing methods are demanded to represent diverse forms and sizes of the physical hardware of embedded systems (Mazzei et al., 2018). Second, a uniquely broad spectrum of development technologies and skills is required for the implementation of embedded systems. For instance, various programming languages are playing increasingly critical roles in prototyping the backend software, connectivity, and user interfaces (Corno et al., 2019; Taivalsaari & Mikkonen, 2018). Moreover, compared with conventional prototypes, such as an appearance model for industrial design or an interface prototype for UI design, prototypes of interactive devices are more in line with the validation of the underlying logic of an intricate system which provides a dynamic experience influenced by variations of multiple contextual factors. Prototyping for this product category often emphasizes the experiential aspect of representations (in any medium) needed to successfully (re)live or convey an experience with a product, space, or system (Buchenau & Suri, 2000). Five intricate and dynamic dimensions are defined in the foundational work on prototyping and prototyping methods (Lim et al., 2008), that is, appearance, data, functionality, interactivity, and spatial structure, to cover the core aspects of a design idea in interactive systems design. These intertwined dimensions reveal the complexity of prototypes of interactive systems. The complexities and accompanied challenges prevalent in interactive devices and their development processes play an associative role in issues during prototype testing with users.

1.2 Difficulties of requirement elicitation with low-fidelity prototypes

Testing prototypes with users is an effective way to identify user requirements and further facilitate the decision-making of designers (Gervasi et al., 2013). There are different types of requirements that need to be elicited from the users through a wide spectrum of prototype utilizations (Jensen et al., 2017). For instance, designers may want to know users' preferences and understand how they prioritize them (Xu et al., 2009). While being involved in the design process, users may experience difficulties in articulating their views and needs that are tacit in nature (Gervasi et al., 2013; Schaffhausen & Kowalewski, 2016). The elicitation of users' views and knowledge can be further limited by the quality of prototypes (Bryan-Kinns & Hamilton, 2002). Therefore, many discussions on prototyping delve into the issue of the prototype's fidelity, as it is positively associated with value (Tiong et al., 2018). The value here refers to the design information gained through prototyping which will eventually contribute to the iteration of the design concepts and details.

Generally, high-fidelity prototypes are required to elicit more reliable opinions on the design. However, this calls for designers to make additional decisions that demand more supporting resources (Mathias et al., 2019). Based on the common industrial practice (Camburn et al., 2017), product teams normally choose among some widely used prototyping methods to help with the elicitation of user requirements at the early stage of the development, involving the use of multiple media and aiming at building prototypes in an efficient and convenient way. The benefits of using low-fidelity prototyping techniques have been emphasized in prior research (Lim et al., 2008). For example, paper is one of the most widely used "low-delity-materials" for prototyping, providing designers with a fast and easy way to design and refine user interfaces (Sefelin et al., 2003; Snyder, 2003). Rodriguez-Calero et al. (2020) demonstrated that the refinement of a prototype can be lessened through the use of a hand-drawn sketch to promote feedback from participants. Overall, paper-and-pencil prototypes are considered as a fun and low-commitment starting point for horizontal, task-based, decision-making, and scenario-based prototyping strategies (Beaudouin-Lafon & Mackay, 2009). Computer-based applications and mobile devices are also frequently used prototyping techniques in the industry due to their flexibility in providing prototypes with differing levels of fidelity and interactivity (Hardy et al., 2015; Lim et al., 2006; Long et al., 1996).

There exists an inevitable tension between the quality of the prototypes developed and the consumption of limited resources for that development (e.g., time, budget, and skills) (Hallgrimsson, 2012). When users interact with prototypes, their perception and understanding can be significantly influenced by the fidelity of functionality (Lim et al., 2006) and interactivity (Gill et al., 2008; McCurdy et al., 2006). Even when high levels of functionality and interactivity are realized, the inconsistency across different fidelity dimensions—including connected features, product behaviours, and visual appearances—can also confuse users and compromise effective requirement elicitation (Bryan-Kinns & Hamilton, 2002; Hare et al., 2013). Law et al. (2014) pointed out that one prototype or a single medium is usually not enough to elicit authentic user experiences in a user study.

In conclusion, it can be difficult for designers to properly present prototypes of interactive devices to participants for user studies due to the complexities inherent in both interactive products themselves and their development processes. On the other hand, it can also be hard for these participants to accurately perceive interactive devices and externalize their understanding and preferences toward the presented devices.

2 Product prototyping with augmented reality

2.1 Previous research on AR prototyping

Considering the benefits of combining and representing real-world data and corresponding interactive elements, AR has been recognized as a promising technique in developing products and facilitating communications amongst stakeholders (Li & Fessenden, 2016; Zampelis et al., 2012). One strand of relevant research explored the vast adaptability of AR in visualizing information and constructing virtual representations of products or features. These visualizations can then facilitate communication and improve the efficiency of the design process by eliminating the need for internal modification of a prototype (Zampelis et al., 2012; Zorriassatine et al., 2003). For example, Shen et al. (2010) demonstrated that the cost and time involved in the iterative design process can be reduced with the implementation of an AR-based co-modelling framework for collaborative product design. Gasques et al. (2019) developed the lightweight prototyping tool called 'PintAR' which facilitates users to express interactive experience through sketch creation and corresponding interactions within AR. With respect to products and scenarios where prototypes are difficult to build through conventional methods, AR can also serve as an effective alternative. For instance, Kim et al. (2016) established a projection-based AR design tool enabling prototyping for infrastructures, such as kiosks and large public displays, which can be expensive and time-consuming when prototyping with conventional methods.

The intuitiveness that AR in prototyping adds to the perception and interaction of users provides further motivation for its implementation in many elds. For example, Cianfanelli et al. (2017) employed AR to model navigable human airways for educational purposes and their study confirmed the positive impact of AR on users' analogical reasoning and mental simulation. Li &

Fessenden (2016) concluded that representing design through AR can decrease users' working memory load as a result of the improved intuitiveness and simplicity of use. Radu and Schneider (2019) investigated the benefits and drawbacks of AR for inquiry-based learning and found that educational AR representations increased participants' self-efficacy. AR has also proved its strength in promoting user engagement. Masclet et al. (2020) found out that spatial AR can affect socio-cognitive processes in groups involved in co-creative design sessions. By way of illustration, Pavlik and Bridges (2013) explored how digital storytelling of journalism content can be improved by AR. Their work indicates that AR can help provide readers with more contextualized information, leading to a more engaged citizenry. Further, it was recognized that the emotional impact of AR as a novel technology for users has also contributed to increased user participation (Faust et al., 2019; Kang et al., 2019).

Although there are many interesting applications of AR technology trying to explore the potential of AR, very few of them have convincingly embedded AR solutions in product development processes. The strengths of AR in enhancing people's perception and reasoning have rarely been probed in realistic, dynamic contexts. There is prior work exploring the relevance of Virtual Reality (VR) to communicate designs in product development processes (Berg & Vance, 2017; Laing & Apperley, 2020; Neroni et al., 2021; Thorsteinsson et al., 2010), yet users' lack of connections with the real world when wearing VR headsets makes VR prototyping fundamentally different from AR prototyping.

2.2 *Sprinting interactive devices with AR*

The recent growth of rapid prototyping tools for digital products, such as Flinto (Flinto, 2022) and Sketch (Sketch, 2022), makes low-cost, high-fidelity application prototyping feasible. Software product development methods attempting to shorten the developing cycles are also springing up. For example, *Sprint* (Knapp et al., 2016) was invented for software development which attempts to compress months of work into one week through yielding clear data from user testing with realistic prototypes. However, the prototyping of physical products, especially the ones comprising electronic components, remains expensive and complex, despite the advent of related techniques such as 3D printing and microcontrollers. Consequently, there is a gap in the fidelity space between software and hardware forms, as illustrated in Figure 1. From this we can observe that *sprinting* interactive devices containing both physical and digital modules with conventional methods can be challenging due to the difficulties encountered in maintaining a synchronized prototyping cycle for hardware and software.

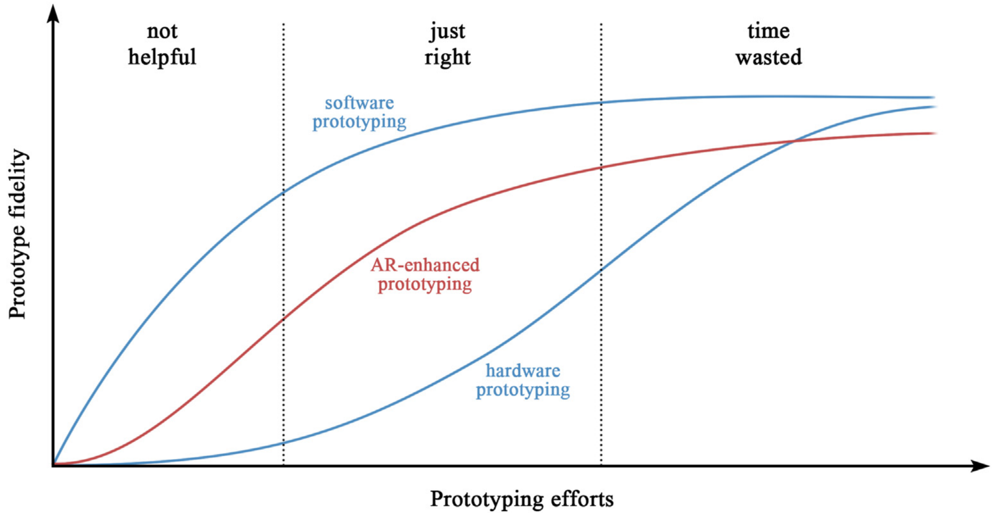

Figure 1 The prototyping efforts–fidelity relationship of hardware, software, and AR prototyping. The middle area denotes the stage whereby AR-enhanced prototyping is suitable to replace or complement the conventional prototyping methods. AR prototyping eliminates the discrepancy regarding fidelity between hardware and software prototyping for a single interactive device

There is a just right amount of effort to be expended on the prototyping during the product development to achieve optimal impact (McElroy, 2016). Less or more than that would be considered as not being helpful or even redundant. However, without heavy investment in hardware prototyping, the product team might have to risk losing the authenticity of feedback they have collected from user studies, especially when planning to purposefully test details, answer specific questions or resolve unique opportunities instead of comprehending core concepts or big ideas (Tiong et al., 2018).

Tiong et al. (2018) found that most designers indicate that their decision-making process regarding prototyping normally arose from simply repeating previous procedures as opposed to seeking new approaches to enhance the prototyping process. On the other hand, the majority of AR research typically highlights the novelty of interaction techniques and relies on carefully designed environments and tedious setups before the start of user studies, such as the integration of AR with a robotic 3D printer (Peng et al., 2018). The gap between the providers of AR tools and the users of those tools is very large and understudied. We take the stance that sustainable development of the AR community requires academics to delve into feasible and robust solutions that can reduce friction in introducing AR technology and thereby bring economic returns in the short term to stimulate continuous growth of the AR market.

Therefore, we would like to specify the benefits of leveraging AR in helping designers and researchers to acquire insights from an economic perspective.

Prototyping to elicit user requirements for product development

We adapt and simplify the economic model (Van Wijk, 2005) originally used to illustrate the profitability of visualization. In a user study, the particular properties of the perception and cognition of a participant is denoted as P. $K(t)$ represents the knowledge obtained by a user over time when interacting with a prototype $R(t)$:

$$K(t) = K(t_0) + \int_0^t P(R, K, t)dt$$

For each participant interacting with the prototype R for the duration, we can acquire $\Delta K = K(t) - K(t_0)$. We assume that there are n users recruited to evaluate the proposed feature. Then the overall return of investment, denoted as F, equals to the collective ΔK from all participants, less the different kinds of costs required by the user studies C_X. The total prototyping profit is:

$$F = n\Delta K - C_x$$

There are three fundamental ways of increasing profits according to this equation: decreasing C_X or increasing n or ΔK. First, we can reduce prototyping costs, C_X, by, for example, reducing the initial investment in hardware and development. Second, we can improve the knowledge gained, ΔK, during each user study session, such as by using a prototype with higher fidelity, embedding more contextual information in the test space, or increasing the duration of each session so that participants can thoroughly explore the proposed feature. Third, we can recruit more participants in user studies to achieve a higher n. In other words, to make more profit out of a prototype, we can try to collect as much knowledge as possible with the lowest investment. Note that increasing n will lead to a higher C_X . However, the gained ΔK is likely to outweigh the increased C_X in contributing to a higher F. We discuss how the proposed AR solution can potentially increase the profit in Section 6.4.

3 Developing the AR-enhanced prototype

To test the capability of AR in easing the complexity of prototyping interactive devices and eliciting user requirements, we describe a specific scenario as the study context in this research.[1] By introducing the challenges in this scenario, we aim to articulate the intricately dynamic relationship between considerations involved in the prototyping process. In this way, we can provide a relatively accurate sense of the complexity hidden behind some seemingly simple design decisions. We introduce a conventional prototyping method that would normally be used by practitioners to manage the given context in practice. The analysis of this specific case and the conventional prototyping methods that might typically be used serves as a starting point to compile characteristics and events that influence the design process with the AR prototyping system.

In the end, we develop a bespoke AR system based on the task specification and the design questions that are tackled in the given context.

3.1 Scenario

A product team is attempting to upgrade a fan product from version 1 to version 2 by adding an oscillation feature. The oscillation feature will be operated through a bespoke smartphone application. Once in the oscillation mode, users can change angles in Pan directions (left/right), Tilt directions (up/down), or both directions in two orthogonal planes simultaneously (3D oscillation) at the same time to generate better airflows around the whole room. Design attributes related to the oscillation feature are maximum Pan/Tilt angle and speed, pre-set angles, and pre-set sinusoidal patterns for 3D oscillation. Examples can be seen in Figure 2. The evolution of the product involves several major changes in the hardware, software, and cloud services. Therefore, the research team would like to gain a preliminary understanding of potential users' preferences regarding key attributes of the proposed feature, which will inform the next iteration of the product. In the context of this study, we primarily analyse three attributes: oscillation angle, oscillation speed, and parameter adjustment interfaces.

3.2 Task analysis

Figure 3 illustrates a representative workflow for the feature development in the given context, where ideas from designers are manifested through prototypes of different fidelities and are later used in user studies for insights collection. In this process, the performance of the prototype would have a significant influence on the quality of the insights gained through use studies and, consequently, the decision-making in the device production and launch.

Building a functional prototype that clearly demonstrates the oscillation feature described above can be resource-consuming. The completion of the feature involves successive steps in hardware and software prototyping in parallel. As illustrated in the shaded portion of Figure 3, hardware prototyping of this feature may include steps such as motor selection, PCB customization,

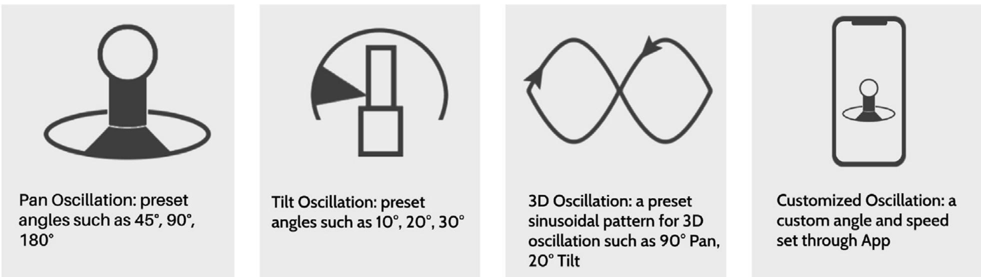

Figure 2 Suggested oscillation patterns and parameter settings from the research team that were to be evaluated in user study

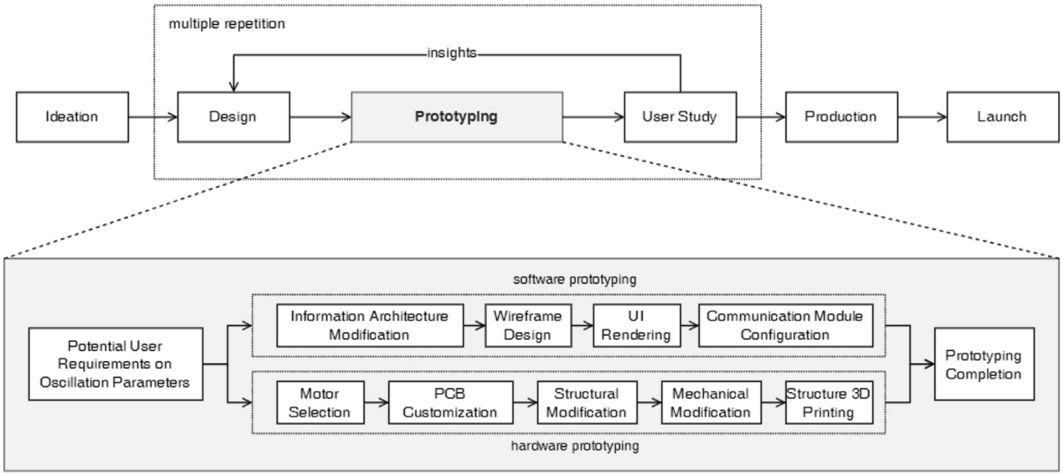

Figure 3 The workflow of the oscillation feature development. The task scenario we look into sits in the dashed frame. Multiple iterations are required for decision-making in design attributes. The hardware and software need to be prototyped in parallel for a high-fidelity model

structural modification, mechanical modification, and 3D printing of the structure; while software prototyping of it concerns information architecture, wire-frame output, user interface (UI) rendering, and the communication between modules. Compared to physical modules, digital materials involved in this process have few intrinsic limitations, which lead to a larger design space with more flexible, open-ended, and resource-saving solutions. Therefore, the completion of physical modules of the prototype will be slower and more costly than that of digital modules for the proposed feature.

We adopt the prototype's anatomy concluded by Lim et al. (2008), as introduced in Section 1.1, to analyse the relationships and interconnections between tangible and intangible components of the prototype of this oscillation feature (Table 1). Variables in different dimensions of the prototype may interfere and constrain with each other. For example, the potential users would like to have a 3D oscillation (as illustrated in Figure 2) with a large coverage area so that the airflow can be blown through every corner of the room. The requirement can be satisfied in the *data* and *spatial structure* dimension by software architects and UI designers. However, corresponding changes are relatively difficult to achieve in the *hardware appearance* dimension due to structural interference, which may ultimately lead to the termination of this proposal. The high dependence and intertwinement between these variables make it impossible to treat them separately, which is the root cause of the complexity in prototyping this oscillation feature and eliciting reliable requirements with a low fidelity prototype. Therefore, balancing the resources invested in prototyping with the credibility of the results of user studies becomes a challenge for designers (of the oscillation features) in current practice.

Table 1 Example variables of each prototyping dimension for the oscillation feature

Dimension	*Example Variables*	*Considerations for the Oscillation Feature*
Appearance	Size; shape; form; weight; proportion	What changes should be made to the physical components? Is the size of the device going to increase? How much information will be added to the app? Does the app need to be re-designed?
Data	Data size; data type; data use; hierarchy; organization	How do we edit the current semantic data model? How do we label or name the new data? What data relating to the feature will be shown on screen?
Functionality	System; function; users' functionality needs	What scenarios are associated with the usage of this feature? Will the user's requirement be satisfied by this feature? To what extent?
Interactivity	Input; behaviour; out-put behaviour; feedback; behaviour; information behaviour	How to trigger the oscillation in the app or on the remote controller? How to change the settings of this feature? How does the device behave if anything is obstructing the movement?
Spatial Structure	Arrangement of and relationship among physical and digital components	Do the current electronic components meet the requirements? Is there going to be any structural interference inside the device? Can the control of the new feature be added to the existing app screens? Or new screens are needed?

3.3 Task specification

Most teams would choose to advance feature development with minimal expenditure of time and cost, relying on designers to reduce participants' biases resulting from the low fidelity of the test prototype. Instead of building a functional rig to demonstrate the proposed feature and elicit user requirements, they would use simplified prototypes in ordinary user studies for this reason. Motivated by their popularity and suitability for the early design explorations, we adopt paper, computer, and cell phone prototyping introduced in Section 1.2, as the *conventional method* that the product team would use to elicit user preferences for the oscillation feature. These media were seen as representative of conventional prototyping methods, which can truly reflect the diversity of prototyping tools as a salient feature of user studies in product development processes. The planning and preparation of the conventional prototype took two mid-level designers approximately a week to complete.

3.3.1 Task 1: preferred oscillation angle determination

This task elicited participants' preferences for the oscillation angle. Here, participants were asked about the oscillation angle of the fan that they felt was sufficient for their daily use. For the conventional method, participants were asked to estimate and draw a preferred angle on the paper, as shown in Figure 4(a).

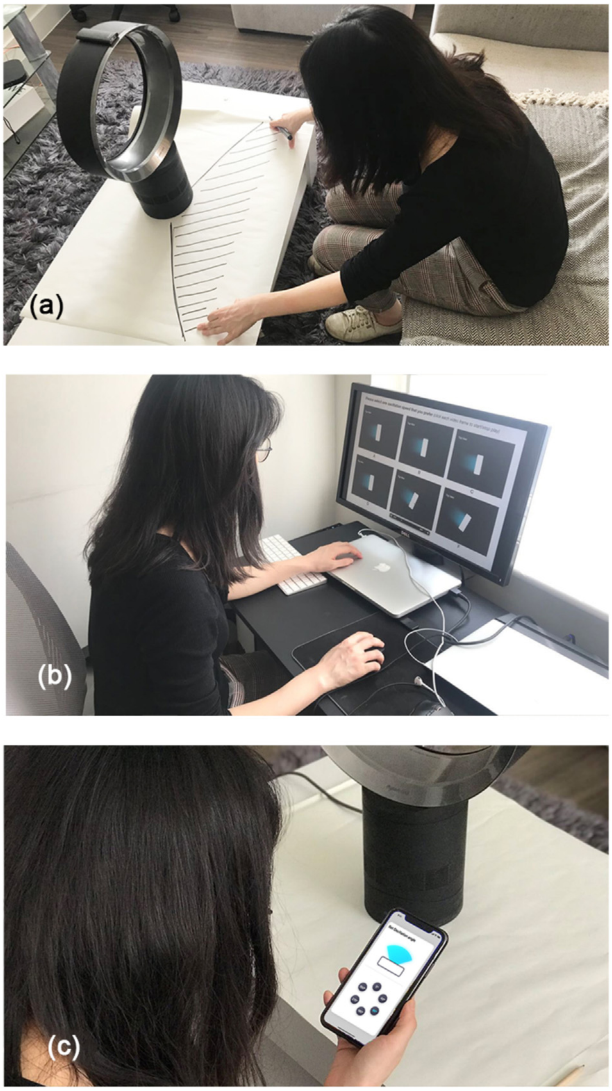

Figure 4 The conventional method of low fidelity prototyping is used to efficiently probe users' preference for attributes related to the fan oscillation feature. (a) The participant is drawing and estimating a preferred oscillation angle on the paper. (b) The participant is choosing a preferred oscillation speed from multiple animations on the computer. (c) The participant is comparing UI patterns, i.e., buttons with pre-set values and sliders with continuous values, on the phone

3.3.2 Task 2: preferred oscillation speed determination

The second task was similar to the first, but the observed variable was now oscillation speed. Normally, the speed of an air control product is divided into several levels. In this task, we set 6 levels and produced corresponding animations of an oscillating fan. After some tests and discussions in the team, we take the top view to demonstrate the oscillation due to the clarity of the movement of the fan from this perspective. The six animations were placed and played on a presentation slide with the conventional method: participants were asked to watch and choose one of the six options, as shown in Figure 4(b).

3.3.3 Task 3: preferred UI pattern determination

In this task we investigated the way in which most participants would like to change the settings of the oscillation feature. Two commonly used UI patterns are buttons with pre-set values for users to choose from and sliders with continuous values, which allow users to adjust parameters without any constraints (which we adopted in the previous tasks). The pre-set buttons represent an interaction pattern with less effort input ("lazy" mode) and the sliders focus more on free adjustment ("free" mode). Participants were required to experience two interaction patterns on the phone, as shown in Figure 4(c).

We reckon that AR would be valuable for the above tasks since the proposed device possesses the following characteristics which would be impossible or costly to develop using conventional prototyping methods: (1) abstract features that are invisible to users, such as airflow and speed; (2) connections between multiple units in the space, for example, the remote controller or control application and the functioning rig; and (3) hardware with moving parts, which consumes considerable amount of resources to customize. More uncertainties and unforeseeable details exist in the identification of user requirements for products with these characteristics (Jensen et al., 2017). These three tasks, on one hand, can truly reflect the real context in the development process of this specific product. On the other hand, they can help create a test environment to verify our assumption about AR in user requirements elicitation.

3.4 AR-enhanced system

As a popular choice for most users to place a fan product, we set up a living room as the environment to conduct the tasks and selected a Dyson desk fan (AM06 12″—Blue/Iron) for the study. We adopted a HoloLens 1 device to present the AR content and developed the AR application in Unity 2019.2.21. The planning and preparation of the AR-enhanced prototype took a mid-level engineer approximately a week to complete.

Our proposed prototyping system splits functions between two principal components: the physical part and the digital part. This is in lieu of building a fully functioning rig with power modules, sensor modules, processor modules, communication modules, action modules, user input/output modules (the remote controller and the app) that are ready to be used. The physical rig of our prototyping system is the legacy product, version 1, which does not implement an oscillation feature. It serves the purpose of an appearance model that gives users an opportunity to see, touch, and feel the product directly in the physical world (the black fan superimposed by AR projections in Figure 5).

The digital part presented in the AR device contains a virtual rig and corresponding control components. The main functions of this digital part are designed to (1) present a functioning virtual rig as the carrier of the oscillation feature; (2) visualize abstract information to strengthen participants' comprehension; (3) replace the real-world user interface (remote controller and app) with direct manipulation in AR to support temporary user interaction.

Through the application of this method, the functions that used to be carried mainly by the hardware are distributed. In this way, the evolution of the prototype cannot be temporarily constrained by the hardware, leading to a potentially larger design space that can be explored with increased flexibility. The AR interface (Figure 5) consists of the following four parts:

— **Training session panel:** The training panel contains interactive components that will be used in the task. Participants need to practice there in advance to attain familiarity with the interactions available.
— **Task information panel:** The study consists of three tasks. Information and requirements for each task are presented on the information panel, which is located at the right-hand side of the participants for their reference.
— **Digital rig:** The digital rig in the study is superimposed on the physical rig in the real world. Participants can choose to display/hide it or switch the airflow on and o by pressing the buttons on the top of it. There is the appearance of blue airflow blowing out of the rig, visualizing its working condition.

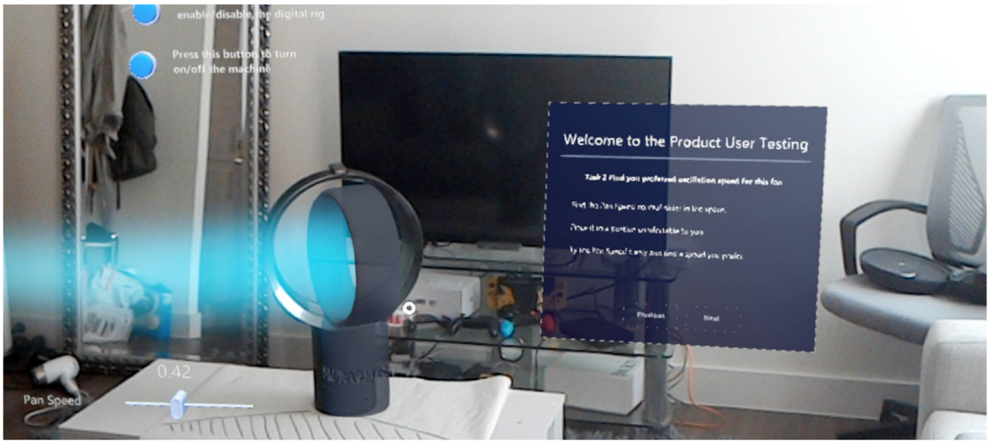

Figure 5 The AR interface with the digital rig, task information panel, and part of the control panel. The training session panel is on the le side of this scene, failing to be captured in this screenshot

— **Control panel:** The control panel gives users access to controlling the oscillation feature. By dragging the sliders or pressing the buttons users can easily alter the device's behaviour. The state changes are immediately reflected on the digital rig.

The AR user interface (Figure 6) was created carefully to highlight its strength instead of being rigorously unified in terms of user interface elements from the conventional prototyping method in Section 3.3. Ignoring the different natures

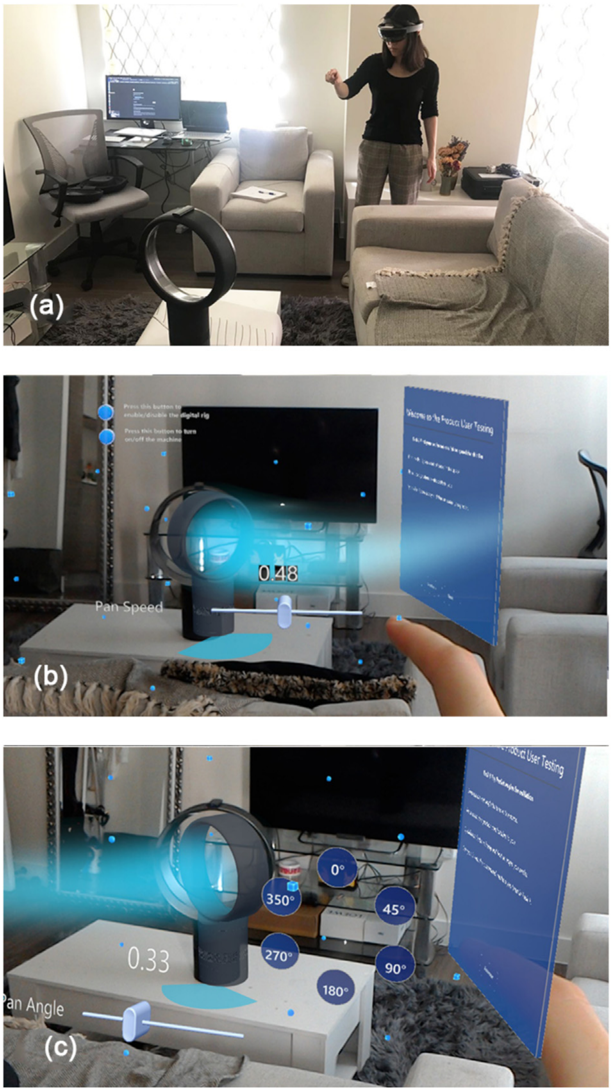

Figure 6 The AR prototyping method used to probe users' preference for attributes related to the fan oscillation feature. (a) The participant is changing the oscillation angle in AR. (b) The participant is choosing a preferred oscillation speed in AR. (c) The participant is comparing UI patterns in AR

of the media or how different prototyping media are implemented in practice in exchange for the unification of user interfaces would diminish the authenticity of the research. For example, the advantages of AR would be undermined if 2D animations were directly transplanted from the computer screen to the AR device in Task 2.

In the AR system, horizontal sliders (Figure 6(b)) and round buttons with pre-set values (Figure 6(c)) controlling the oscillation parameters of the digital rig were augmented in the HoloLens. Users can adjust the oscillation angle and speed value freely by dragging a slider or pressing a pre-set button, observing the working state change of the fan, as shown in Figure 6. Augmented elements such as the blue fan-shaped region indicating the scanning area of the airflow helps with the observation and analysis of the users before reporting their preferences with confidence. The angle and speed parameter shown in AR was converted to real numbers from 0 to 1 without providing the actual values to participants immediately. In this way, we were hoping to eliminate the interplay between the methods during the user studies.

In this paper, we focus on the direct influence the AR prototyping method has on the participants in a user study and, therefore, estimate the potential of this approach becoming prevalent among designers and product teams. Obviously, it is not viable to create real airflows using a low-fidelity prototype without a motor, PCBs, or other key electronic and mechanical components. Thus, participants will detect their preferred oscillation angle and speed visually without any sensation of the airflow blown from the fan. Though the experience will not be as authentic as that of high-fidelity models, we argue this is a common situation in the early stage of product development. To simplify the user study so that the process can be more fluid, we only probe users' preference on the control of Pan oscillation.

4 Method

We designed a user study to explore the feasibility, effectiveness, and overall experience of this AR system in the process of requirement elicitation. The Conventional prototyping method acts as a calibration point that allows us to establish the relative strengths and drawbacks of the AR approach.

4.1 Participants

The study investigated if such an AR-enhanced approach would be plausible to help designers understand potential users. Therefore, we only explicitly sample users rather than designers in this study. Since the target audience for such a device would be consumers who have decent incomes and value products that are technologically advanced, we sampled young, educated people who had purchased relevant smart home devices (e.g., smart speakers, video doorbells, connected kitchen scales, etc.) in the last year. Twelve participants (four female, eight male) aged between 23 and 32 (mean = 26, SD = 2.6) were recruited through flyers advertising the study. They were carefully balanced insofar as possible in terms of their professional backgrounds (physics, medicine, biology, sociology, etc.). Seven participants had experience in using AR-related apps while none of them had tried a HoloLens device before. Nine participants reported having purchased relevant smart home devices While the quantitative data collected was limited by the number of participants and thus insufficient to draw rm conclusions about the strengths of the AR method, a semi-structured interview was subsequently conducted to expand the evidence base and collect participants' subjective attitudes towards the method. The time to complete the study averaged 80 min. All studies in this paper had approval from the local ethics committee and informed consent was obtained from all participants.

4.2 Study design

Due to the difficulties in controlling the prototype variables (e.g., differences in the UI design) and user variables (e.g., learning rates of the participants) rigorously in AR user studies, a mixed-methods study was considered to be reliable to gain valuable insights (Arici et al., 2019; Rüger et al., 2020; Squires, 2018) and provide a more panoramic view of the research landscape (Shorten & Smith, 2017). The mixed-methods research approach was used to study AR prototyping in two orthogonal directions: (1) sequential exploration of the efficacy and usability of the AR system in three tasks; and (2) parallel comparison with the conventional method in each task to understand the nuanced positive and negative qualities provided by the AR prototyping approach. Note that this mixed-methods study tries to tease out the potential implications and limitations in adopting AR prototyping for user requirements elicitation in an industry case, it should not be considered as a controlled study demonstrating a causal link between AR and prototyping efficiency in general.

— **Conventional Method (CM):** Participants comprehend the oscillation feature and make decisions on attributes with conventional prototyping media, as shown in Figure 4.
— **AR System (AR):** Participants comprehend the oscillation feature and make decisions on attributes with the AR-enhanced prototyping system we developed for the study, as shown in Figure 6.

Three tasks were designed to probe users' preferences and each of them was built to encapsulate the two prototyping methods. The order of the two methods was counterbalanced in the tasks. The task sequence for P1–P6 was Task 1 (CM then AR), Task 2 (AR then CM), and Task 3 (CM then AR), while for P7–P12 it was Task 1 (AR then CM), Task 2 (CM then AR) Task 3 (AR then CM). After collecting the demographic characteristics (age, gender, educational level, related experience, etc.) of the participants, we briefed them on the study protocol and fitted them with the HoloLens before the AR method in each task. Following each task, participants were requested to complete questionnaires regarding their experience with each method.

The task sequence was not only designed to show the progressive complexity of three tasks, but also an increasing demand for the users' understanding of the oscillation feature and the corresponding controls. The oscillation angle in Task 1 is related to a static attribute, simply being represented by a blue fan-shaped region in AR. The oscillation speed in Task 2 is related to dynamic attributes, requiring participants to observe how the product behaviour changes. Additionally, Task 3 involved advanced decision-making to compare two UI patterns, partially based on experience accumulated from the previous tasks.

4.3 Procedure

At the beginning of the study, a mediator explained to the participants that they would be shown a product that was still in development. The physical rig was the last generation product of this series and only worked as an appearance prototype. The oscillation feature we described and tested was still in its infancy stage and had not yet been realized on this physical rig. Further, the participants were reminded that we were interested in their honest feedback and that we thus required them to think aloud while being as open as possible. Participants were asked to complete a HoloLens training session before the formal tasks to get used to the interactions in the HoloLens: picking, dragging, etc. Subsequently, participants were asked to complete three tasks and rate their experience on a 7-point Likert scale based on their feelings, impressions, and attitudes after each task.

To explain why people prefer some systems over others, factors such as emotional experiences play an important role in addition to instrumental aspects (Thuring & Mahlke, 2007). We used the User Experience Questionnaire (UEQ) (Laugwitz et al., 2008) to gather users' opinions of the experience of using a product. UEQ enables quick and easy assessments of different aspects of experience, including attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty (Hinderks et al., 2019). Each UEQ item comprises a pair of terms with opposite meanings (e.g., complicated—easy). These dimensions can be further grouped into composite indicators, such as pragmatic quality and hedonic quality.

After the task sessions, we carried out a semi-structured interview based on the research questions to obtain participants' rationale for opinions. We further explored participants' attitudes towards the study as well as the proposed feature to probe the feasibility of the prototyping methods. For example, participants were asked to explain the oscillation feature in detail to demonstrate their comprehension of it and we explored whether a physical

Table 2 Samples of the interview question

1. *Do you have a better understanding of the oscillation feature now compared to the beginning of the study? Can you explain the feature to us in your own words?*
2. *We have noticed that you have very different answers to Question X with the two methods. Can you explain to us what might lead to such a significant difference?*
3. *Was there any issue in the process that made you feel frustrated?*
4. *Can you tell us the most impressive part of the entire experience?*
5. *Which method helped you better in finishing the tasks, the AR one or the non-AR one? Can you let us know why?*
6. *Overall, how do you feel about the two prototyping methods in the study?*
7. *What do you think needs to be improved about the AR system?*
8. *Would you like to try other AR tools in future studies?*

rig was necessary during the study for future implementations. Approximately 10−20 questions were asked per participant depending on their individual circumstances (see Table 2).

5 Results

The results and conclusions were drawn from four aspects of the data: (i) participants' self-reported answers to questions asked during the study; (ii) the questionnaire results collected from participants; (iii) observed behaviours of participants in each task; and (iv) qualitative information collected from follow-up interviews. Overall, the AR system did not perform significantly better than the conventional method in all three tasks. However, it consistently received high praise in terms of its positive effects on improving the overall experience of the user study.

5.1 Task results

Figure 7 (left) presents the preferred oscillation angles collected from Task 1. From the graph, we can observe that most values fall into the range of (50°,

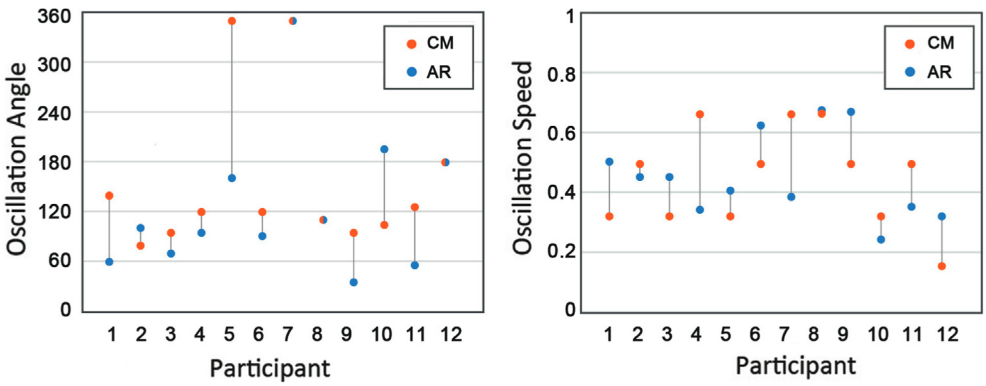

Figure 7 User data of preferred oscillation angle (le) and speed (right) collected with the conventional method (CM) and the AR system in Task 1 and 2 separately

200°). The largest oscillation angle, 350°, was only chosen by two participants (P5, P7) with the conventional method. P5 later reduced the value dramatically from 350° to 160° after trying the oscillation angle setting in AR. The smallest angle reported was 35° collected from P9, who explained that he would place the fan in the corner of the study room facing his desk while working at home. Nine out of twelve participants (75%) reported different answers and seven of those (78%) picked an oscillation angle with AR smaller than that with the conventional method. An oscillation angle larger than 180° was considered to be unnecessary or wasteful by most participants. Overall, participants in Task 1 tended to make adjustments to their preferred angles when exposed to different prototyping methods.

Figure 7 (right) presents the preferred oscillation speed collected from Task 2. Since the conventional method only provided discrete values of the speed from 0 to 1 (with an average interval of 0.14 approximately), we would consider the value a participant set in AR as the same value as the conventional method if the interval between them was less than 0.14. Unlike Task 1, where most participants tended to choose a smaller value in AR, we cannot identify a similar tendency in Task 2, with five participants choosing a higher speed with the AR system and three choosing a lower speed. P2, P5, P8, and P10 gave the same answers with two methods.

No obvious difference in terms of participants' preference was detected between the two methods in Task 3 (Table 3). The attitudes towards the preferred UI solution of most participants were not influenced by the presence of AR. Several participants even gave their answers immediately when the mediator asked the question without trying the prototypes and did not alter their answers afterwards. Only one participant (P6) altered her answer from customized buttons to pre-set buttons after switching the prototyping method.

5.2 *Quantitative results*

In this section, we calculated and analysed the data collected from the questionnaires. We mainly adopt three representative factors: overall user experience, hedonic quality, and dependability, to conduct the analysis for brevity.

We measured overall user experience by averaging all items being rated, such as perspicuity, dependability, stimulation, novelty, etc. (Hinderks et al., 2019).

Table 3 User preferences on UI patterns in Task 3

Participant ID	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Pre-set Value		✓				✓		✓				
Customized Value	✓		✓	✓	✓	✓	✓	✓		✓	✓	✓

This item can be seen as an integrative reflection on the AR system's performance in facilitating the task. We performed statistical significance tests using Wilcoxon signed-rank at a significance level of $\alpha = 0.05$. The overall experience of the AR system, as shown in Figure 8, is higher than the conventional method with significant differences in Task 1 ($\chi^2 = 6.75, p < .05$), Task 2 ($\chi^2 = 8.33, p < .05$), and Task 3 ($\chi^2 = 5.33, p < .05$).

It has been argued that user experience research should go beyond the task-oriented approach of traditional HCI and pay more attention to the hedonic aspects such as fun and pleasure (Hassenzahl & Tractinsky, 2006). Additionally, hedonic experience has been shown to be positively correlated with the motivation of participants (Higgins, 2006). Considering that participants easily become demotivated and fatigued in user studies, we took the hedonic quality as an important assessment of prototyping methods. Ratings on items of stimulation (not interesting–interesting, and boring—exciting) and novelty (conventional—inventive, and usual—leading edge) were averaged for hedonic quality in our study (Hinderks et al., 2019).

The hedonic quality, shown in Figure 9 (left), is consistent with the previous observations on the overall user experience. The hedonic quality of the AR system is higher than the conventional method with significant differences in Task 1 ($\chi^2 = 12, p < .05$), Task 2 ($\chi^2 = 8.33, p < .05$), and Task 3 ($\chi^2 = 12, p < .05$). A small decline in the hedonic quality can be observed as users proceeded with the tasks throughout the study, which we consider normal in this context. Several participants clearly expressed their tiredness when wearing the HoloLens in Task 3, inevitably influencing their opinions of the AR system.

Dependability is a key factor to evaluate the pragmatic quality of products. Good dependability means that the product/system should be predictable, secure, and meet users' expectations (Hinderks et al., 2019). Dependability

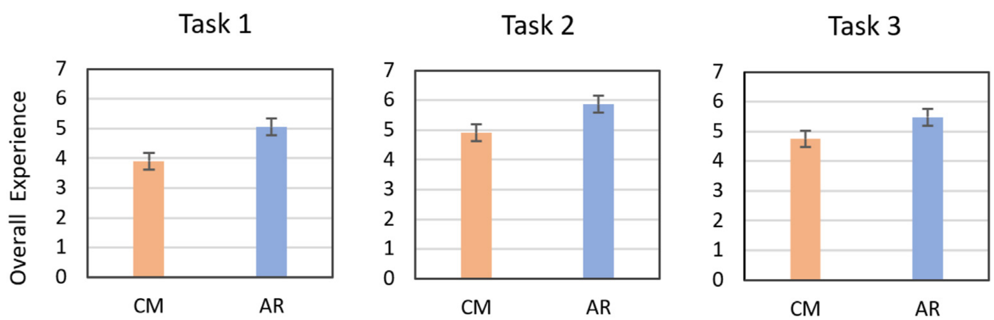

Figure 8 Overall user experience with standard error of the conventional method (CM) and the AR system (AR) in the three tasks. Error bars show standard error

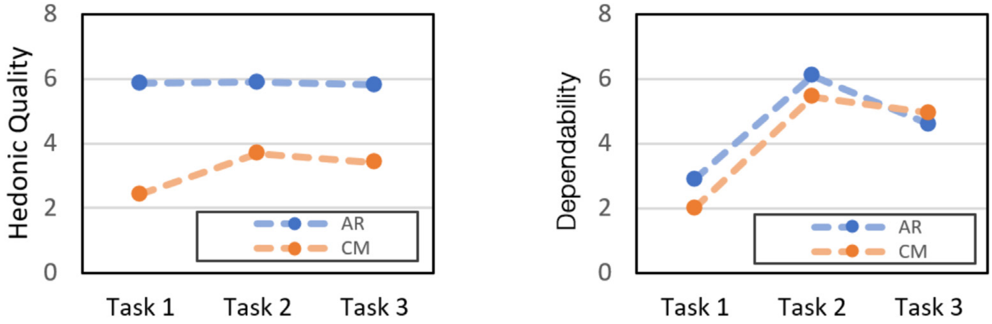

Figure 9 Mean self-report ratings on the hedonic quality (le) and the dependability (right) of the two methods in three tasks across all participants

(obstructive—supportive) is an individual variable rated on a 7-point Likert scale. Figure 9 (right) presents the depend-ability of the two methods in three tasks. While the differences between the AR system and the conventional method are not significant in Task 1 ($\chi^2 = 3, p = .08$), Task 2 ($\chi^2 = 3, p = .08$) and Task 3 ($\chi^2 = 3, p = .08$), the AR system is considered to be more supportive in the determination of the preferred angle and speed. Both prototyping methods received markedly better ratings in Task 2 than in Task 1, indicating that participants had a higher demand for visual representations in dynamic attribute evaluation. With the direct control and instant visual feedback, we assumed the comparison of the two UI patterns would be more intuitive for participants in AR. However, the result reveals that the AR system scores lower, though not significantly so, than the conventional method in Task 3.

5.3 *Qualitative results*

Insights in this subsection mainly arrive from the researchers' observations during the study and the feedback from participants in the follow-up interviews. On average, each participant spent approximately 15 min completing the interview, which is not a long period of time but was sufficient for us to collect supplemental data to verify the efficacy of the two methods and tease out participants' attitudes towards them. With consent from the participants, we recorded the audio for later coding and analysis. We analysed and coded answers from participants. Participants recognized that the method without the involvement of AR was relatively simple and accessible. Being handy is the most salient advantage of the conventional method in this study. However, most of the participants did see the potential in the AR method. We categorized the feedback into three themes *improved comprehension*, *strengthened sense of control*, and *enhanced spatial perception*.

User preferences for the proposed oscillation angle, speed, and corresponding UI pattern were successfully elicited with both methods in three tasks.

According to our observations, it generally took participants more time to think and explore using the AR system before they reported their answers. On one hand, this observed behaviour pattern might partially result from participants' lack of familiarity with the AR headset. From this perspective, it is unarguable that the conventional method was easier to use for most participants without relevant experience of using HoloLens or other kinds of AR headsets. On the other hand, the increased time might also indicate that a larger thinking space was formed for participants to make more deliberate decisions when conducting tasks with the AR system.

An example of how AR prompted more deliberate responses is provided by P6, who stated that she preferred the slider with continuous values to control the oscillation function after she tried the conventional method in task 3. Yet in the second half of this task, she spent more time thoroughly comparing the two UI patterns and observing the product behaviours in AR, concluding that buttons with pre-set values were more suitable for her. We conjecture that she experienced a struggle between her occupation habit (quantitative researcher with a personal preference for accurate data) and her personality (*"I'm a hopeless slacker [in daily life]"*) according to her self-analysis. In this case, the answer given by P6 after trying the AR system seems to be more reliable than her original report.

An increased engagement was also captured among participants during their use of AR in tasks. The hedonic quality and interactive feature of the AR system clearly sparked the motivation of participants, creating an active atmosphere closer to a participatory design process among researchers and participants When using the AR system, participants were more willing to express their opinions about the oscillation feature, and the comments collected were of higher quality and quantity. This indirectly but clearly shows that most participants held positive attitudes towards the capability of AR in facilitating them with the tasks. Their compliments on the AR prototyping method are mainly reflected in the following three aspects:

5.3.1 Improved comprehension

Seven participants admitted that AR improved their comprehension of the proposed oscillation feature. Visual manifestations of the abstract information, such as the simulated airflow and the fan-shaped oscillation region, were thought to be beneficial during the task: *"I was wondering how you were going to compensate for the missing airflow from a real machine in AR … you used the animation to replace the real wind. It's not perfect … but better than nothing"* (P4). Even for the same design, participants felt it was more vivid and helpful to have them shown in full size with the AR system than on the screen of a laptop or a cell phone. For example, P8 praised some elements in AR even though the conventional method contained the same element:

"the blue, fan-shaped area makes it easier for me to observe the effective area of the fan directly. Otherwise, I'll have to remember where the rotation starts and ends by myself".

5.3.2 Strengthened sense of control

The direct manipulation of the oscillation feature parameters was also well recognised since this since this allowed participant to immediately witness how their actions control the visual representations of abstract information in a real usage scenario with rich home details. Five of these seven participants specifically mentioned the "sense of control" from the AR system, which was something missing in the conventional method: *"I would say it [the AR system] feels totally different …* When I *was shown the animations [the conventional method in Task 2] just now, it was like taking a test or something. But now I feel like I'm using a real machine. Well, sort of" (P4).*

5.3.3 Enhanced spatial perception

In task 1, P5 reduced her preferred oscillation angle from 350° to 160° after trying the angle setting in AR: *"it sounded rather appealing to me to have the largest oscillation angle at the very beginning. That made me feel the money was well spent … but when I actually saw the machine rotating in AR I realized it was way more than what I really need."* In task 2, most participants mentioned that the same speed setting felt different in the conventional method as compared to the AR system, *"when looking at that small fan rotating on the screen, the speed I chose felt appropriate. But when I watched a real-size fan with an AR headset in the real scene, the same speed felt much slower than I expected"* (P3).

While recognizing the wider benefits of AR, two participants struggled to master interaction using the HoloLens. P5 experienced difficulty in dragging the slider due to her small hand size. P12 persistently raised complaints about the flaws of the visual design: *"Cold air should go down instead of up, right? It really distracts me"*. This can be ameliorated by the further development of AR technology. Additionally, three participants admitted that the discomfort of the hardware partly compromised the advantages of the AR system.

6 Discussion

After analysing the data and searching for precise reasons for participants' decision-making in the three tasks, we conclude that the AR system and the conventional method can achieve similar levels of performance regarding user requirement elicitation. However, the AR system shows more potential in providing a coherent overall experience and stimulating engagement and conversation of participants. This section elaborates on these findings, reinforces the study motivation, and contextualizes the opportunities for the AR prototyping method for product development.

6.1 Similar levels of performance on requirement elicitation

Overall, the preferences of participants collected with the two methods approximate each other well, with relatively large differences observed in only a few cases. In this process, AR demonstrates distinct advantages in (1) providing participants with the manifestation of otherwise inaccessible abstract information of interactive features; and (2) allowing for direct manipulation of augmented parameters in the context of three-dimensional usage without relying on intermediate tools. For most participants, these advantages establish a solid foundation for the elicitation accuracy of their requirements in the study. Further, most participants expressed that AR gave them more realism than the conventional method, which also contributed to the reliability of their answers in the three tasks. Since there are no significant differences in the requirements elicited with the two methods, we can conclude that the performance of the AR system is similar to that of the conventional method from the quantitative and qualitative analyses.

During the process, a phenomenon we noticed is that participants tended to make decisions much faster in Task 3. A plausible explanation for the reduced time could be that the mental model of the oscillation feature and the corresponding control thereof had already been ingrained in participants' minds up to this point. Changing the task sequence may help ascertain the cause of this phenomenon. However, the research questions were introduced on the basis of the users' gradual understanding of the oscillation feature as we explained in Section 4.3. Therefore, bringing Task 3 to the beginning is against this consideration and might confuse participants. Therefore, we did not counterbalance the order of the tasks. Another possible reason is that the fatigue caused by the uncomfortable AR headset outweighed the benefits of the method, leading to a low perceived benefit in using the AR system in the long run. We understand that, from the participants' perspectives, it was difficult for them to distinguish between experiencing the method (the AR-enhanced prototyping method) and experiencing the tool (the AR headset) as professionals do. The mixed-methods research approach allows us to partially remove highly subjective elements from their answers and make relatively comprehensive judgments.

6.2 The AR system provides a more coherent, realistic experience

The AR system shows distinct advantages in improving the overall experience of participants in three tasks. According to the feedback of participants, the look and feel of the oscillation feature and its control components were achieved in a truer sense with the enhancement of the AR technique compared to the conventional prototyping method. A very representative example is the comment from P4 on the different perceptions of the oscillation speed on display and in AR (Section 5.3). This comment is consistent with the rich literature on the size-speed bias, which reveals that the size of an object affects the estimation of its speed when presented on different media (Clark et al., 2013). Hence, great satisfaction has been achieved through this strengthened realism of the oscillation feature in AR. Moreover, although the AR system is only of a mixed fidelity without being able to reach the high resolution on all dimensions listed in Section 3.2, the experience of the key components has been set in context with high consistency. The conventional method, which normally has to rely on multiple media or tools to convey the design, exhibits gaps in fidelity that can lead to a poor experience.

The integrated and holistic experience of the AR system surpassed the piecemeal perceptions of the oscillation feature cobbled together from conventional media. Therefore, although the conventional method is considered to be easier to pick up and a few participants had difficulty adapting to the interactions in AR, the overall experience of the conventional method was reported as unnatural and test-like, and as an attempt to try out a new device compared to the AR method. As a result, it is unsurprising to observe that more participants were inclined to prefer the AR system in terms of being tested in a user study due to improved clarity of the visual appearance and behaviour of the device and increased controllability. Due to the coherent experience created by the AR system, we consider AR to have a high potential in playing an integral role in the proof-of-concept stage of interactive devices. The conventional method, in contrast, is less capable to form a highly integrated platform that can demonstrate the proposed feature in a realistic and integral way, which may further harm the accuracy of the elicitation results in a more complex situation.

6.3 AR stimulates engagement and conversation

In our study, most participants demonstrated the typical characteristics of early adopters of new tech gadgets. Their ability to grasp the focal points of technical solutions mostly without being hindered by some non-significant technical flaws is vital to researchers and practitioners, especially when the techniques are not mature enough to be understood or accepted by regular consumers. However, on the other hand, some issues did arise which may possibly be related to the pool of participants. For example, some of them were shy when encouraged to "think aloud" or unable to describe their feelings precisely during the tasks.

In such circumstances, the AR system stimulated a higher level of engagement and more conversation than the conventional method, which helped yield some implicit information from participants that was crucial to the design decision-making at a later stage. For example, the fact that P6 altered her answer to the preferred UI solution in AR revealed her true requirement at a deeper level—highly controlled but manoeuvrable interactions. The preference she reported in Task 3 contributed to the decision-making of the final UI pattern.

However, the shift in her thinking process while using the AR system is also intriguing and the product team would find it valuable to understand this type of user and enrich the characteristics of the corresponding persona. This finding echoes previous research which claims that AR prototyping can be coupled with conventional prototyping methods, combining their complementary affordances and mitigating their limitations (Mathias et al., 2019).

6.4 Economic potential of AR prototyping

The AR system has a similar level of performance on requirement elicitation and a relatively better user experience compared to the conventional method. Apart from these aspects, we can also substantially justify the potential of AR prototyping in product development from an economic perspective. The benefits of adopting AR are explained in four aspects which echo the four measures that can increase profit introduced in Section 2.2.

First, the average cost of AR-enhanced prototyping is lower than that of conventional prototyping in achieving the same level of fidelity. In this study, the planning and preparation of the conventional method (two designers) and the AR method (one engineer) both took the team about a week to complete. This means it was approximately the same development time for the conventional method as the AR method, but the AR method resulted in higher fidelity and elevated levels of user experience. In the same amount of time, the fidelity and user experience of the AR method surpassed that of the conventional method. To achieve the same level of fidelity and user experience for the oscillation feature as the conventional method, a possible way forward involves building a functional rig that can realistically present the function to potential users, as analysed in Section 3.2. Yet the cost of customization of physical, digital, and connecting modules would be obsolete for such a preliminary study, considering that desirability and feasibility, rather than viability, of the proposed feature is the primary goal (Menold et al., 2017).

Second, AR-enhanced prototyping demonstrated its ability in achieving a considerable increase in knowledge, ΔK, for the required purpose and scope of learning while minimizing cost. In our study, the flexible combination of low-cost prototyping media as a replacement for a functional rig was shown to be feasible. However, there was a serious dilution of $K(t)$ considering the lack of details and consistency of the fidelity of the prototypes. Moreover, this combination also led to inaccurate perceptions of the prototypes, or unsatisfactory experiences during the study. As participants admitted, AR interactions added more realism to the testing scene, contrary to the serious test-taking atmosphere perceived with the conventional method.

Third, the shipping and set up process of AR prototypes can be easier (compared to conventional methods) if the device in testing has a large dimension or complex structure. That means that the number of participants is directly proportional to human costs that the AR prototyping method can help to save for the product team. The initial investment for high-fidelity AR interactions is relatively low in this case: one AR headset is enough to conduct multiple user studies, which is affordable and manageable even for a small team. A prototyper can simulate AR-enhanced interactive features in a few days—an activity that may otherwise take weeks using conventional approaches. All of these benefits of AR suggest that it may revolutionize the prototyping area since economic efficiency has always been a major driver for decision-making in balancing prototyping approaches.

6.5 Limitations and future work

In Section 5.3, we reported that the participants on average spent more time thinking and exploring with the AR system before reporting their answers. We reasonably assume that AR encourages more thorough thinking by providing more realistic interactions. Ideally, it would be interesting to quantify the thinking time and yield information with different approaches. However, participants' time spent on the familiarization with AR interactions is difficult to calculate accurately since it is intertwined with the actual usage time, even with the introduction of the training section in the beginning of the study. Therefore, we did not attempt to establish an approach—time relationship in this research but leave it to future work.

Though this study demonstrates the advantages of using AR to elicit requirements in a specific study, our ultimate goal is to explore the usage of AR technology at the crucial stages of interactive device prototyping. Naturally, the tailored system in our study cannot be directly used or easily adapted by other product teams. However, our study has already demonstrated the efficacy of our AR prototype, making it likely a similar approach can be applied in related scenarios. We expect the findings to generalize, within reason, to a broad range of similar product development. Apart from that, considering the original design contexts and nuances therein were simplified, we wonder if the performance of the AR system has been weakened to an extent in this study. As some participants pointed out, some more advanced, complicated features may demonstrate the power of AR prototyping better. Such scenarios may include, for example, real-time display of speech recognition results when participants in a user study interact with a smart speaker or the presentation of different path plans from a robot cleaner to participants in a demo room.

7 Conclusions

In this paper, we designed and studied an AR-enhanced hybrid prototyping system with the Microsoft HoloLens in a given context. The purpose of the system is to facilitate the elicitation of user requirements for an interactive device when engaging with users at the early prototyping stage. We compared and contrasted the AR system for prototyping support with the conventional prototyping method in a mixed-methods study. The results revealed that AR-enhanced prototyping is a promising approach that tends to yield reliable requirements elicitation and improve the overall user experience.

Users are confronted with higher complexity when dealing with prototypes of interactive devices. The results of the study indicate that AR prototypes can serve as an alternative to the conventional method to tame such complexity in user research. This paper couples AR technology and the requirements from an industrial case and thereby studies the judicious use of AR techniques in commercialized applications in this domain. A fruitful avenue of future work is to further investigate the advantages of AR in materializing more complex features, interaction patterns, and usage scenarios of interactive devices. Hopefully, this research will encourage researchers to think beyond experimental demonstrations, leave comfortable lab environments, and explore AR implementations with better feasibility and profitability in real-life practice.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the data in the paper.

Notes

1. This scenario and the included tasks are adapted from the first author's industry experience.

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