FAVECAD: An Interactive Environment for Generating Fabricable Designs in both AR and VR[*]

Anonymous for Review

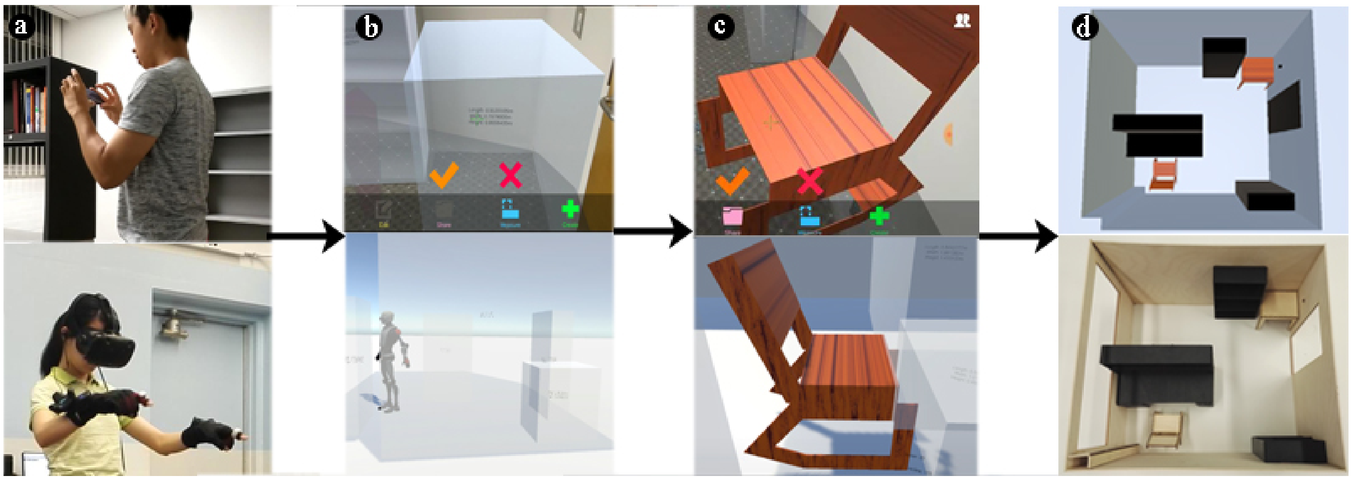

Figure 1: FAVECAD is a CAD tool that combines both AR and VR to create fabricable furniture designs: users can equip either the AR or VR equipment to access a shared design environment (a), AR users first measure their physical environment to define physical constraints of the design (b); user then design furniture together (c), which can be manufactured (d).

ABSTRACT

The combination of AR and VR allows users to immerse themselves in a realistic virtual environment while simultaneously referencing properties of the physical environment. To investigate this in a design context, we introduce FAVECAD: a CAD tool that offers a combined AR and VR environment for users to design manufacturable, flat-pack furniture. FAVECAD comprises an extensible gesture-based interface for users to expressively manipulate design parameters in 2D and 3D space. Using such gestures, a generative design engine is used to create furniture that meets manufacturable specifications. Integrating this with AR and VR, FAVECAD offers a shared environment where users can extract dimensions of their physical surroundings and design independently or collaboratively, in the same or remote environments, simultaneously or at different points in time. A design session demonstrates functional furniture created by ten non-designer participants using FAVECAD.

[*]FAVECAD is an acronym for Fabrication in Augmented and Virtual Environments for Computer-Aided Design

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CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability;

KEYWORDS

Virtual Reality, Augmented Reality, Multi-user Collaborative Environment, Design Fabrication, Gesture-based Interface

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INTRODUCTION

The advent of low-cost fabrication machines (e.g., laser cutters and 3D printers) has enabled the at-home manufacturing of custom objects; this has given rise to the Maker Culture, with its promise of personalized creation. However, in order to make use of this manufacturing ability, entry-level

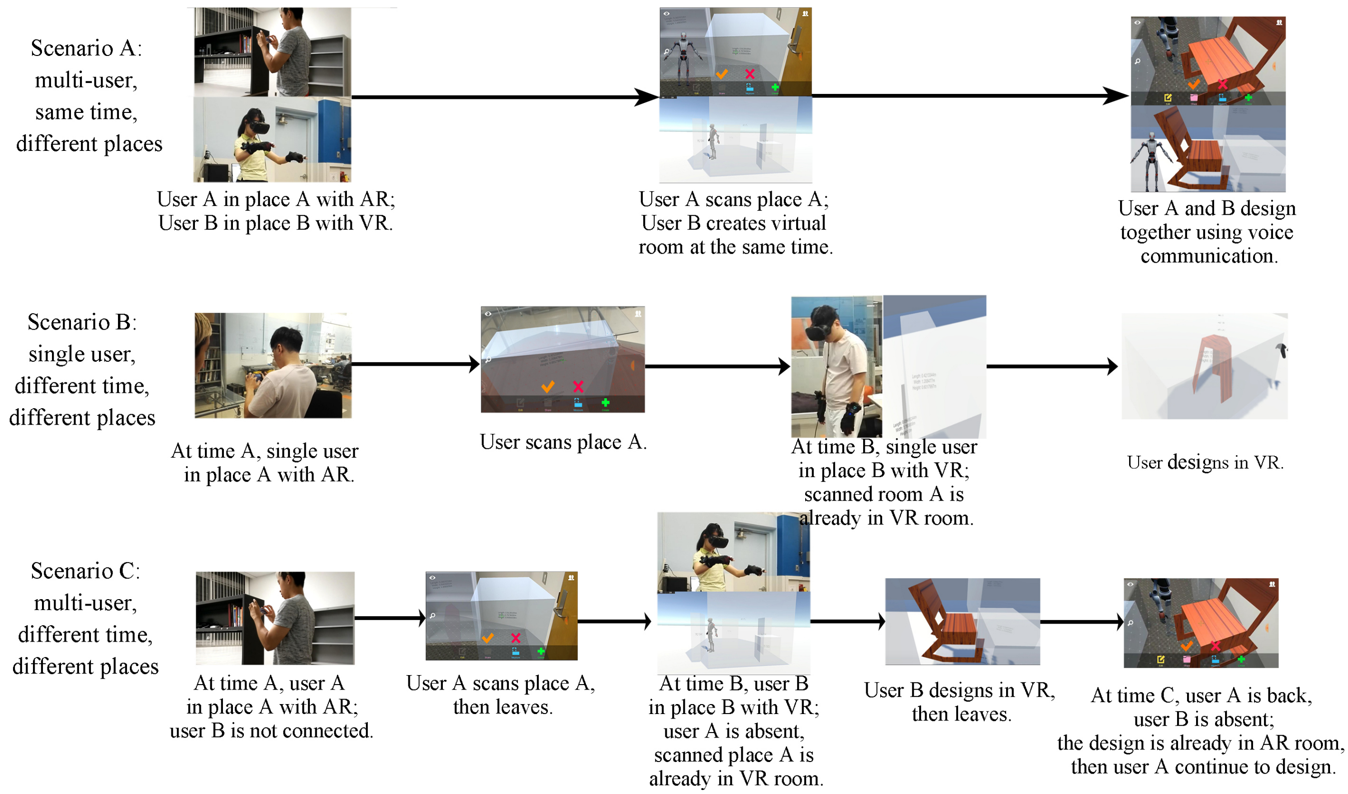

Figure 2: Three example scenarios show that FAVECAD system offers a shared environment where users can design independently or collaboratively, in the same of remote environments, simultaneously or at different points in time.

designers often face a steep learning process for the abundant software-specific computer-aided design (CAD) utilities necessary to realize their visions.

Designers must learn prescribed keyboard and mouse commands to quantitatively modify engineering representations of their designed objects. These 3D virtual objects are presented and navigated using traditional 2D graphical interfaces, which exacerbates the learning curve required to use CAD in their work [38]. Also, when addressing real-world design needs, designers are required to extract and reference the characteristics of the physical environment where their designs are implemented [16]. However, existing CAD systems often confine users to a computational environment, requiring them to manually quantify the real world in order to incorporate its information into their design artifacts.

Furthermore, casual designers often benefit from collaboration, working in teams of peers or directly with experts. With limited support in industry standard CAD tools for different types of interactions between end-users, designers often resort to inefficient and low-bandwidth methods of file-sharing such as emails and shared cloud drives, which reduce productivity and communication among users throughout the design process [22, 36].

To overcome these limitations, we present FAVECAD: Fabrication in Augmented and Virtual Environments for Computer-Aided Design. We employ both Virtual Reality (VR) and Augmented Reality (AR), developing novel methods for users to create and interact with their designs. VR systems provide enhanced immersive first-person experiences in CAD, by displaying virtual environments in 3D using head-mounted displays [36, 39]. With additional hardwares such as VR controllers and gloves, users' physical movements in the real world are also translated into the virtual environment, thus achieving a hedonic design experience. AR, on the other hand, bridges the void between the physical environment and virtual objects by utilizing camera and motion sensor to spatially map the physical environment and overlay virtual objects on top of it. Libraries such as Apple's ARKit and Google's ARCore, in particular, have introduced AR in widely available mobile devices. These advancements not only make AR more accessible to casual (non-expert) users, but also offer methods of extracting data from the physical environment into the virtual world.

Within this environment, we leverage advancements in generative design, which have reformed the traditional design process, allowing users to create engineering designs from a small set of design parameters. Generative design is particularly amenable to AR/VR as it allows users to express an design idea with high-level input, dispensing with expertise driven low-level geometric manipulation typical of engineering CAD.

Ultimately, FAVECAD lowers the barrier to entry for new makers, providing an intuitive, interactive design experience with minimal knowledge and hardware overhead necessary to create custom physical objects. In this work, we focus on the creation of flat-pack furniture, which places strong constraints tying its design to user preferences as well as characteristics of the built environment. Figure 2 illustrates three representative interactive scenarios enabled by our FAVECAD.

Contributions

Our main contribution is a shared AR and VR environment for generative design that demonstrates rich interaction possibilities beyond AR or VR alone: users can extract dimensions of their physical surroundings and design independently or collaboratively, in the same or remote environments, simultaneously or at different points in time. An intuitive multi-modal design interface lets casual users create flat-pack furniture with geometric and aesthetic constraints, as confirmed in a design session of non-expert designers.

RELATED WORK

Our work builds upon existing research pertaining to one of the following five categories: AR, VR, and systems involving collaboration between AR and VR.

Augmented Reality Design Environment

AR enables manipulating virtual objects in the context of the real physical environment. For example, WireDraw [37] uses an extruder pen for users to design virtual objects on a surface augmented with fiducial markers. However, the sketching mechanism does not extract or communicate to users the physical characteristics of the design environment. SymbiosisSketch is a system that allows a user to first anchor a sketch onto a real-world object and then perform fine editing on a tablet [1].

AR also opens new possibilities for gesture-based interactions with virtual objects, as users can freely interact in 3D space, in relation to objects in their physical surroundings. [21] created a human-centered augmented design environment that takes voice-based commands and references the relative positions of the user's body parts to define a fabricable design. [28] also scans the physical interface of household appliances and generate custom add-on controls based on user preference. [38] and [8] introduce AR systems that track user's hand and body movements, which is then used to transform the virtual objects they see in augmented space.[3] allows users to generate 3D designs by sketching on a 2D touchscreen interface. Similarly, [12] implemented an AR system for users to position, rotate, and translate virtual objects in front of the mobile view-port using joystick controls. [20] manipulates physical objects in an augmented environment by placing AR markers on physical objects, used to create virtual replicas of them in the AR environment.

Although these systems are capable of referencing users' physical surroundings, they never incorporated properties from the physical space into the design, such as the dimensions of a room and locations of other objects in the same space. In contrast, we have deployed our sensing components on commodity mobile devices that are able to import the properties of the users' physical surroundings into the design environment shared across AR and VR.

Virtual Reality Design Environment

As with AR design environments, VR enables users to visualize virtual environments and objects in 3D. However, unlike AR, users have access to more expressive gestures and realistic design experiences. For instance, [26] implements hand gestures for users to precisely manipulate virtual object intuitive. Similarly, Google Tiltbrush [10] introduced a freehand sketching interface that extracts user's physical movements with a VR controller, and transforms them into persistent meshes in their virtual environment. Nobrega et al. enable 3D modeling by taking a photo of an environment, and then adding 3D virtual objects within the 2D image [25]. Sra and Schmandt developed a multiuser VR system where the physical world is used as a template of the environment and virtual objects can be created in it [33].

While the above systems demonstrate hedonic methods for design, using gestures to manipulate virtual objects reduces the precision of the design itself, and thus would require further modifications to ensure designs are fabricable. VR systems such as [11] offer a solution by allowing users to design with a combination of hand gestures and voice commands, but adds logical rules and constraints to ensure designs meet fabrication specifications. Similarly, [5] and [14] introduce assembly techniques for users to accurately manipulate components of a virtual design using hand gestures and assemble them into a fabricable whole. To accurately translate the user's physical movements into the virtual environment, [9] implements precise force detection that receive touch and grip inputs for transforming virtual nanotubes.

One limitation of VR design environments is that users are unable to reference their physical surroundings during the design process. [25] and [32] employ 3D reconstruction to create a virtual mesh of the physical environment; however, these methods do not capture real-time changes in the user's surroundings, and require continuous scanning to synchronize the virtual environment with the external world. With

FAVECAD, users can maximize the capabilities of AR to measure and communicate the characteristics and changes in the physical environment for designing in VR.

Combined Virtual and Augmented Environments

Although AR and VR have proved to be useful in many interactive scenarios, surprisingly few have combined both AR and VR together to explore their complementary benefits. Magicbook [4] gives users the choice of either immersing themselves in VR as portrayed in a picture book, or use AR to view virtual environments in the storybook as they flip through the pages. For design tools, [33] attempts to extract physical properties of the environment into a shared VR system by obtaining an image of the physical environment, which is used as the background for a shared social environment. However, this system does not offer real-time multi-user interaction, and users are unable to extract dimensions of their surroundings. In general, there is lack of exploration or understanding of how to combine AR and VR to create a design environment, and what unique interaction possibilities are available beyond AR or VR alone.

Gesture-Based Interface

Advancements in gesture sensing allowed users to interact with virtual objects using physical movements in either 3D or 2D space. This is demonstrated in Arora et. al's (2018) SymbiosisSketch: a fabrication system that uses freehand sketching gestures in both 3D and 2D space to produce designs in AR [2]. Their interface enables users to design on tablets using the touchscreen, which detects 2D gestures, which detects gestures in 3D space. Our system also adopts SymbiosisSketch's approach to establish a 2D and 3D gesture vocabulary. On one hand, we believe 2D gestures using touch-screen devices are more accessible to casual end-users; however, 3D gestures also offer embodied interactions, which are more immersive and intuitive. This gesture set is extensible across our library of parameterized designs, and allows users to perform [the same design manipulations using either 3D or 2D gestures].

Hand-based gestures, specifically finger-based movements and interactions, have increased in popularity, allowing end-users to intuitively manipulate virtual objects as they would with everyday items. [35] and [18] defined hand-gesture-based interfaces that separated the user's physical motions from its interaction with the virtual object. With that distinction, they then defined a finite set of hand gestures, each of which could be used in different contexts to achieve different types of design manipulations. These interfaces are not only extensible for multiple virtual objects, but also . However, these gestures have only been limited in virtual design environments, and fail to consider object transformations in multiuser interactions. Our system comprises a gesture vocabulary extensible across AR and VR systems, for users to design both independently and collaboratively with shared virtual designs.

SYSTEM OVERVIEW AND SETUP

In this section, we describe the components of FAVECAD and the processes involved in achieving our combined AR and VR system. Specifically, our system contributes the following novel components for combining AR and VR as a new design environment:

- an architecture for real-time sharing and synchronizing design information between AR and VR;
- a unified gesture vocabulary that works across input methods spanning both 2D (e.g., touch screen for mobile AR) and 3D (e.g., VR space);
- an API that enables the mapping of users' input in AR/VR to create parameterized design artifacts.

To ensure FAVECAD was accessible to the

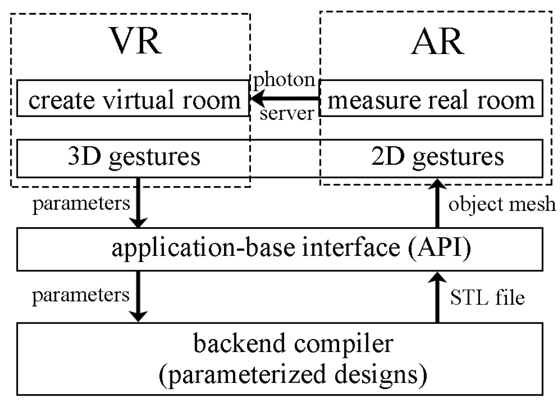

Figure 3: System Overview. FAVECAD system uses a backend compiler to create parameterized furniture designs, which connect to user in AR and VR through an API.

Parameterized Design Engine

To transform user's gestures into a precise, fabricable design, FAVECAD defines a database of parameterized designs that users could reference to fabricate flat-pack furniture. The server, shown in Figure 3, takes a finite set of parameters to produce a manufacturable, 3D virtual mesh that could be exported and visualized in either virtual or augmented design environments.

The manufacturability of resulting designs remains a concern in the computer graphics community[7, 17, 27]. One proposed solution to guarantee the manufacturability of the resulting furniture designs is to involves fabrication-aware design [6, 13, 19, 23, 24, 29–31] in our parameterized scheme, which predefines manufacture specifications to generate fabricable models. These designs are based on digital parameterization of building models and then implemented using built-in algorithms to involve physical constraints. The fabrication-aware designs are accessible to novice users lacking design skills to fabricate complex models. Inspired by these approach, our proposed systems makes use of finger joint to connect different planar elements to generate furniture designs. Similar to [34], these joints are rapidly fabricable due to their 2D geometries. However, a greater set of designs is enabled by the use of various rigid and compliant joints.

To demonstrate the capabilities of FAVECAD, we have selected 4 pieces of flat-pack furniture designs from our library of parameterized designs, shown in Figure 4.

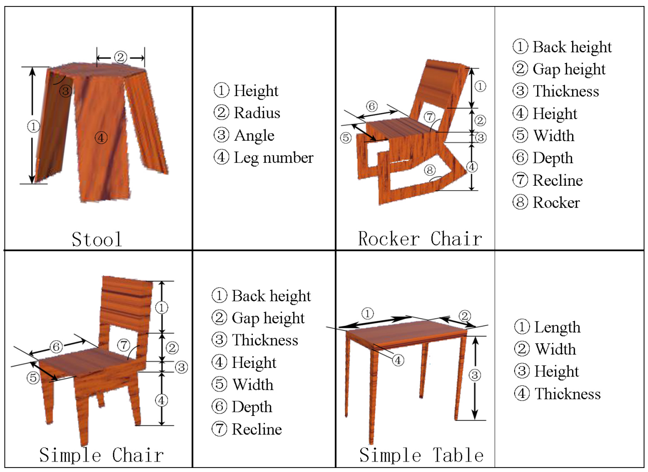

Figure 4: Four pieces of example furniture from furnituree library and their parameters.

Application Programming Interface

For non-expert designers to intuitively interact with this design engine, we defined an API for users to create, delete, modify and transform the virtual mesh of a parameterized design. To interpret and transform the bytes obtained from the STL file into a virtual mesh, we referenced an open-source Unity STL Importer and Exporter known as pb_STL [15]. Finally, we applied a separate UV mesh and texture to the resulting object, so that the mesh would receive correct lighting and texture, which add realism to the virtual design.

AR-Specific Implementation

In addition to the lighting and physics of the object, the augmented design environment included methods of extracting the properties of the surrounding physical space. To do so, we implemented a "virtual tape measurer" that could calibrate the absolute distance between two points in physical space. This was done using Unity's ARCore Library package: a variation of Google's ARCore library that is compatible with Unity 2017 and later. This tool enabled users to scan and track vertical and horizontal planes in physical space, using frames sampled from the a mobile camera. The resulting measurements were then saved and displayed in the augmented space, shown in Figure 5.

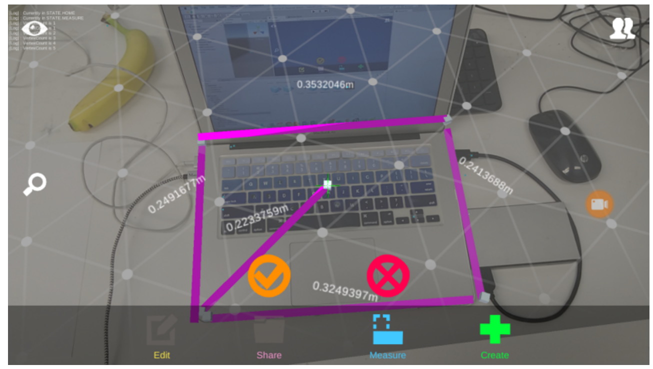

Figure 5: Remarks of AR measurement

VR-Specific Implementation. To virtualize the physical environment, we have simplified the virtual design environment into a cuboid room, defined by its length, width and height. This room can be configurable by either the user, or using dimensions passed on from an AR user's device (in the situation where multiple users are collaborating). Thus, as demonstrated in Figure 7, users within the virtual environment can either configure the room upon starting up their system, or while interacting with multiple users.

Gesture Set

To reduce the level of entry required to fabricate in CAD, our gestures were designed with the following goals:

(1) Gestures are intuitive and natural for users to learn and master
(2) Users can fabricate and transform all designs with a small, finite set of gestures.
(3) Users have the freedom of selecting and reconfiguring the types of gestures they would like to use for a given type of transformation.

Creating a Gesture Set. To address the first and second design goal, we proceeded to define gestures in AR and VR corresponding to the parameters generated by our generative design engine. To make FAVECAD accessible to casual non-designer users, we developed gestures compatible for smartphone devices, who perform gestures on a touchscreen in 2D space, and users equipped with head-mounted displays and hand controllers, who perform gestures in 3D space. Defining a 3D and 2D gesture for every associated motion ensures that our system is compatible with any AR or VR equipment they used. Furthermore, by designing gestures in isolation from design-specific transformations, we ensure our gesture-based interface is usable across multiple contexts, making it scalable for existing and future designs. For complex designs defined by a large number of parameters, we have separated designs into its basic components, such that gestures performed on specific components of a design will result in a specific type of transformation. Figure 6 displays the resulting set of 8 gestures defined for both 2D and 3D space.

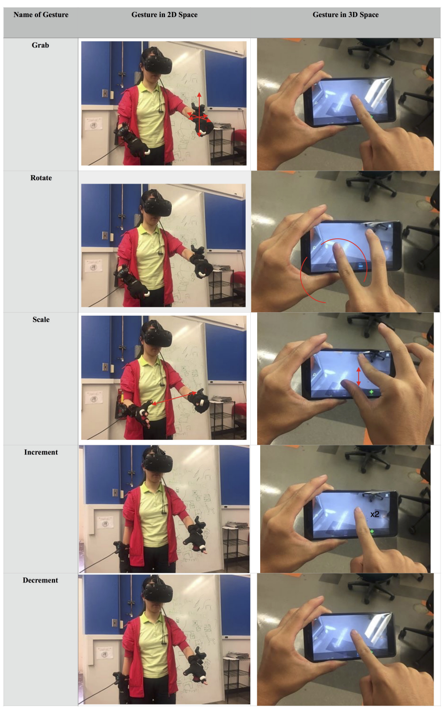

Figure 6: A set of gestures were defined for our CAD tool FAVECAD, which allows users to interact with parameterized designs in both 2D space, on a touchsceen, or 3D space, using hand-sensing utilities available in FAVECAD's VR system.

Collaborative Virtual Environment

We define a collaborative design environment between two users as one that involves two parties: the designer that modifies a given design, and the observer that observes the synchronous changes made by the designer. To avoid synchronization issues, only one designer can modify a shared fabricated design at any given instance. Furthermore, designers are prohibited from modifying multiple fabrications at a given instance. Figure 7 defines the possible interactions between designer and observer.

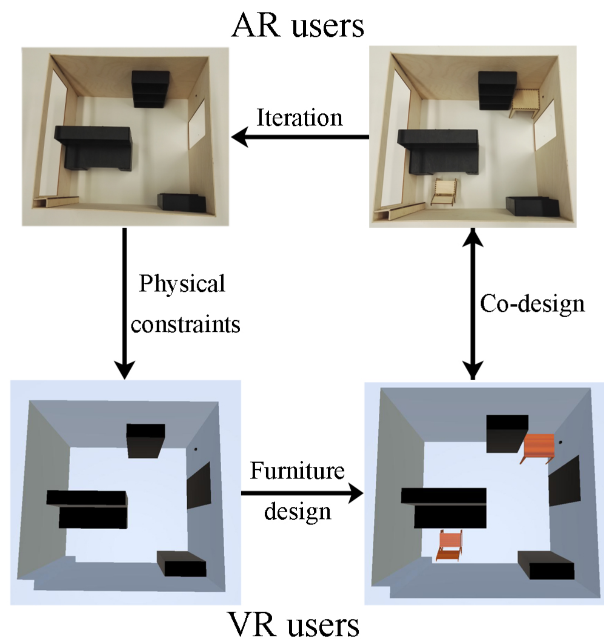

Figure 7: Collaborative Design

To implement the synchronization across collaborative environments, we utilized the Photon Unity 3D Network (PUN) framework, a free networking library that allows synchronous multiuser interactions in Unity-based applications. The inclusion of multiuser interactions required modifications to our initial API, by adding Remote Procedural Calls (RPC) interfaced within the PUN library. Such procedure calls ensured that users could interact and view changes with shared objects regardless of the device they were using.

In particular, AR users can communicate the characteristics and dimensions of the measured surfaces and objects with collaborating VR users, as demonstrated in Figure 7.

Visual Communication. To enable users to visualize modifications to their design, and observe their interactions with other users, we have design simple virtual avatars that move and interact with the fabrications in place of the user. Using the RPC interface all additional changes to shared objects are synchronized and visualized in the user's local interface.

Verbal Communication. 32 One limitation we identified with the visual communication, was that the virtual avatar could not communicate complex thoughts or speech. Methods such as text messages were slow and required further gesture definitions that would compound to the level of mastery required to utilize our CAD system. Thus, we required additional methods for users to convey their ideas remotely. Drawing from the human-based voice command interface designed in [21], we decided to design a human-centered voice communication interface, which allowed users to communicate verbally as they designed. This was achieved by employing the Photon Voice library: an additional library that utilizes the PUN API to record, send and share audio across multiple users in real time. The final collaborative system thus deployed both verbal and visual channels of communication.

Manufacturing the Design

As shown in Figure 8, FAVECAD incorporates an "Export" feature that allows users to save their fabricated design for future manufacturing. This tool uses the pb_STL library to extract the vertices from the selected virtual mesh, convert them into a binary-encoded STL file and save the resulting file in the application's local directory. The resulting STL file can be used to visualize a prototype. This system can also export Drawing Interchange Format (DXF) files for 2D fabrication (e.g. laser cutting and waterjet). In addition, DWG files and Scalable Vector Graphic (SVG) files are available as well owing to the back-end compiler. Figure 8 summarizes the typical process of transforming a fabricated design into a manufactured product in FAVECAD, and displays a manufactured furniture based on the exported design.

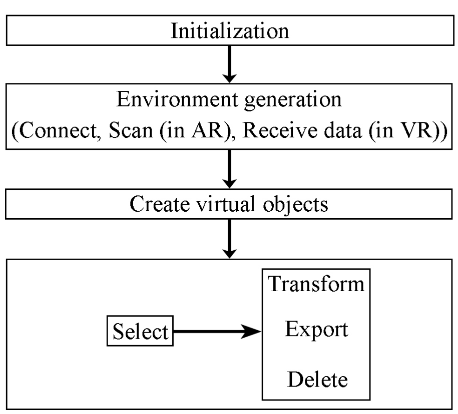

Figure 8: UI interface

DESIGN SESSION

To evaluate whether our system achieved our initial contributions, we hosted a design session for participants to complete a series of design tasks using our equipment. This session had the following goals:

(1) Introduce FAVECAD's AR and VR systems, and the different methods by which users can design using the combination of both systems.
(2) Demonstrate the strengths and limitations of AR and VR as two separate systems.
(3) Evaluate the ease of use and intuitiveness of our gesture-based vocabulary.
(4) Demonstrate the benefits of FAVECAD's combined AR and VR system in a CAD context.

Participants

Participants comprised of college students studying in a local university (N = 10; 7 male, 3 female; age: 20 - 24) who had little to no prior experience with CAD. All participants had no experience using a VR head-mounted display, but had experience using a mobile device with a touchscreen. Participants were obtained through convenience sampling, and agreed to participate without any financial incentives.

Prior to the experiment, participants were paired together based on the times at which they could attend the session. Participants in each pair were asked to undergo the evaluation process at the same time. Two of the ten participants arrived independently due to rescheduling; the others performed collaborative tasks using our system.

Data Collection

To record and evaluate the results from our study, we have designed 4 questionnaires, one for each of the design tasks. Both of the independent design tasks use an identical questionnaire, which comprises of 5 multiple choice questions where users are asked to rank their proficiency and experience with the given equipment on a Likert scale from 1 to 10. The remaining two questionnaires for the two collaborative design tasks comprise of 7 multiple choice questions where users are asked to rank their proficiency and design experience on a Likert scale from 1 to 10.

A qualitative survey is also designed for users to add any comments or feedback pertaining to their overall design experience. Most importantly, users were asked 3 open-ended questions about FAVECAD, allowing them to offer suggestions and feedback from their overall experience.

In addition to the questionnaires, we also set up 2 cameras to provide a 3rd person perspective of the participant's interactions with our CAD system. Furthermore, in all tasks, we recorded the participant's screen as shown in their head-mounted display when they use the HTC Vive, and the mobile phone screen as participants use the Nokia phone. Doing so, we can conduct further qualitative analysis of the users' behavior as they interact with our system.

Procedure & Tasks

The evaluation employed a repeated-measures design. Each participant performed 4 design tasks, and were required to complete a 5-minute qualitative survey at the end of the study.

Training and Briefing (20 minutes). Participants were first given a 10-minute briefing on the equipment available for the study. Each briefing introduced the device, described its functions, and the basic controls associated with that device. Participants then proceeded to equip the device and see how the device should be used, as demonstrated by the researchers. Participants are also asked to complete the first 2 parts of the qualitative survey.

Task 1: Independent Design Task in VR (10 minutes). Participants were required to equip the HTC Vive and MiiGloves. Once the system was setup, they were asked to fabricate a stool with 4 legs, with a height of 50cm and radius of 30cm. Once the task is created, participants were asked to fill out a short quantitative survey evaluating their experience fabricating the stool.

Task 2: Independent Design Task in AR (20 minutes). Participants were required to equip the Nokia phone and open the ARCore application titled "FAVECAD". Once the system was setup, they were asked to fabricate a table with 4 legs, with a height of 50cm, width of 80cm, and length of 40cm. Once the task is created, participants were asked to fill out a short quantitative survey evaluating their experience fabricating the table.

Task 3: Collaborative Design Task in VR + AR (20 minutes). Participants were asked to equip the HTC Vive and MiiGloves. Then, after their partner had equipped the Nokia phone, they were asked to connect to the same shared room. Once both participants were connected, researchers asked participants to work together and create a rocking chair in the conference room shown in Figure 7. Participants using the VR equipment were required to move the object to its suitable position in the room. Once the task was completed, participants were asked to complete a quantitative survey evaluating their experience fabricating the rocking chair. Next the participants switched roles (AR vs. VR users) and perform the design again.

Feedback and Discussion

All design tasks were evaluated qualitatively using participants' self-reported data and feedback in our surveys. Videos and audio recordings from the design session were also analyzed to evaluate ways participants interacted with the AR and VR systems to complete the specified design tasks. Data was analyzed using a method akin to the Affinity Diagram approach, where responses were organized recursively to identify recurring themes and ideas from our results.

Designing in AR. 8 of the 10 participants expressed that designing on the AR system was simple and intuitive because of its mobile implementation. In contrast to the VR system, participants stated that FAVECAD's AR design environment required less setup and equipment (P7), was easy to learn (P3, P6, P10), and had intuitive gestures users typically use with smart-phones (P3, P10).

Our findings indicate the capabilities of AR systems in CAD, which can enable designers to reference and extract the dimensions of their physical surroundings to accurately create fabricable designs for future manufacturing. It also showcases the intuitiveness of our 2D gesture-based interface, which compliments with touchscreen devices and makes CAD more portable and accessible to mobile end-users.

Designing in VR. In contrast to the AR system, the VR system consistently offered more realistic and immersive design experiences. All participants indicated that FAVECAD's VR system was more immersive than its AR system, which helped them focus on the design task (P10), and get a realistic experience of creating furniture even if they were not physically in front of them (P3, P7).

Combination of AR and VR. For multi-user design tasks, participants expressed that the combination of AR and VR was helpful in not only extracting physical dimensions, but also cooperating simultaneously with other users. In particular, most participants would use AR as a measuring tool, because users could extract properties from the physical environment, and then ask VR users to modify the design, because it offered more immersive and expressive design experiences (P3, P4, P5, P6). To verify the furniture could fit the design constraints of the physical environment, participants in AR would then move the object to the correct position in the physical world.

Participants' behavior was also consistent with their qualitative feedback, when asked to brainstorm scenarios where they would find themselves using our system. In most cases, participants described scenarios where VR users would design the furniture while AR users would fine-tune the resulting design to fit the physical space it will be implemented in.

P3: "*Design from remote locations or from workshop to office, where technology is limited to the single VR and single AR, when designed at actual site (actual dimensions) and fabricated elsewhere.*"

P6: "*The designer adjust the design (dimension, location for the furniture), and the customer use VR to 'see' the design and determine whether he/she is happy with the current design or not. If he does not feel happy with the design, the designer* *could adjust the design immediately. This interaction between customer and designer is pretty convenient and prompt (real-time).*"

P7: "*The AR and VR system could be useful for prototyping in VR and fine-tuning in AR...*"

Consistent with the initial goals of FAVECAD, these findings demonstrate ways participants could benefit from using both AR and VR in one combined system, to design immersively and expressively while simultaneously ensuring the design fits within the constraints of the physical environment.

Gesture-based Interface. The intuitiveness of both systems is also attributed to the gestures that participants used to create, edit, and transform their furniture. In both VR and AR, participants expressed that gestures were intuitive, on a touchscreen and in 3D space. These findings further demonstrate the simplicity and effectiveness of FAVECAD's unified gesture vocabulary, which allows users to modify design parameters easily.

P6: "*[The VR system] helps the person who are not specializing in furniture design gain an intuition about how large the furniture is and the relative location between different objects...I can pull, lift, or even throw the furniture, which is pretty cool.*"

P3: "The AR system was very easy to use...Using [finger gestures] on a phone screen was the best part."

Existing Problems and Suggested Features. Participants also identified challenges with certain furniture-specific interactions, particularly when they had to change certain parameters with very similar gestures. For example, P1, P2, P3, P5, and P7 all stated that there were instances where the VR system would mistake their gestures and produce an incorrect parameter modification. Additionally, furniture would sometimes fly out of the design space, because an incorrect force would apply onto the furniture if it overlapped with the floor. P1 had to delete and create a new chair every time it when out of bounds, because it would require disconnecting the entire HTC Vive headset. P10 made a comment that the issues he faced from the VR kit was due to hardware limitations: during his design task, when he held a fist, his fingers in the VR world were bent outwards, which suggested that the glove sensors were not accurately detecting the position of his hands.

P1: "*The VR system could use distinct hand gestures to control the parameters of the virtual model. Sometimes the system would confuse one gesture of another. Rather than having physics features like gravity, the VR system can let the object model float in the air while it is being customized. This would save the user from having to chase the model around a room. The angle adjustment should happen at real-time corresponding to the gesture of the user. This way the angle the legs assume can be better controlled rather than guessing with the degree measurement.*"

P2: "*...change the controls for angle because I found it difficult to use or ended up changing it on accident Add a control for walking over to the furniture so I don't have to get up and physically walk to it.*"

Likewise, participants found it challenging to smoothly interact with furniture on the AR mobile device, because it would overheat after designing with it for an extended period of time. In particular, P1, P2, P3, P7 and P10 agreed that the gestures were sometimes unresponsive on the small, 2D touchscreen, or that the gestures were too similar and limited so the incorrect interaction would be detected.

P1: *The model in the AR system is definitely harder to control and customize. Gestures don't seem to work well on such a small screen. Perhaps this system can benefit more from buttons. The space grid generation that is required before the use of the AR modelling also makes the system harder to use.* "

Other comments included library-specific issues such as losing track of a plane in the AR mobile system (P8, P9, P4, P8). This, however, was attributed to Google's ARCore and its ability to detect and maintain persistent planes in the augmented world. Another limitation was the Nokia device and its ability to design for an extended period of time. Due to instances of overheating, participants would have 1 to 2 second delays between their gestures and the updated furniture modification. This would indicate that, while our initial goal was to make FAVECAD accessible to casual end-users, particularly smart-phone users, the system has performance issues that may limit the design experience.

Designs Created by Participants. Figure 9 showcases 6 pieces of furniture that we have selected from participant-generated designs for manufacture. Among all designs, we observed that participants would spend a lot of time transforming and repositioning the furniture, rather than modifying the parameters themselves.

Limitations and Future Work

Real-Time 3D Reconstruction in Virtual Reality.

Expanding our Design Fabrication System. Users have expressed interest in fabricating different designs within our system. To improve support for our system across a multitude of designs, we are currently multiple systems for users to define their designs. In addition to parameterized designs, we are exploring methods of hierarchical designs, generative designs, and abstracted designs that can be augmented through our back-end compiler and algorithms. The addition of these design methods ensure that users can fabricate designs beyond the realms of furniture, which will offer designers more creative freedom.

Figure 9: From the creations of the ten non-designer participants that attended our design session, we selected six furniture designs participants had made, and manufactured 1/8 scale models.

Generative Designs Through Sketching Gestures.

Physical Validation for Design. While our system creates designs that are guaranteed fabricable, their mechanical properties are as yet not validated. Often, after a furniture has been designed to implement a desired functionality, a subsequent validation steps must ensure that the object behaves as expected. One of the challenges in this process is to define a suitable set of properties to verify the designs. These properties could be strength of joints and stress distributions in furniture when target loading is applied. With the physical validation implemented, our system will guarantee the functionality of the resulting designs and further accelerate the design cycle.

3D Gestures in AR Mobile Devices. While 2D touchscreen gestures are more intuitive and natural for mobile users, they reduce users' hedonic design experiences during the design process. With the introduction of hand gesture detection libraries such as Manomotion, which has recently updated their library to support the latest versions of ARKit and ARCore, we are currently investigating methods for users to freely fabricate designs on their mobile device using 3D gestures. Doing so provides users with multiple options of fabricating in AR, which can further improve both the design experience and the accessibility of our design system.

CONCLUSION

Whether it be designing with peers, prototyping designs to manufacturers, or presenting fabrications to consumers, collaboration is quintessential to CAD. By maximizing the potential of AR and VR environments, FAVECAD eventually aims to fuse these two realities together into a seamless, unified CAD system where users can directly reconstruct their surroundings into their design environment and fabricate together, regardless of which AR or VR equipment they select. With this foundation, we look to expand FAVECAD beyond furniture design, to support designers across a multitude of fields, ranging from large-scaled designs such as architecture and vehicles, to small-scaled designs such as nano-robots and circuitry. Furthermore, through evaluating our user feedback and improving our gesture-based interface, we will ensure FAVECAD has a simpler learning curve than those of traditional CAD tools, to attract more casual end-users into the creative world of design and fabrication.

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