ABSTRACT
When designing interactive architectural systems and environments, the ability to gather user feedback in real time provides valuable insight into how the system is received and ultimately performs. However, physically testing or simulating user behavior with an interactive system outside of the actual context of use can be challenging due to time constraints and assumptions that do not reflect accurate social, behavioral, or environmental conditions. Employing evidence-based, user-centered design practices from the field of human–computer interaction (HCI) coupled with emerging architectural design methodologies creates new opportunities for achieving optimal system performance and design usability for interactive architectural systems. This paper presents a methodology for developing a mixed reality computational workflow combining 3D depth sensing and virtual reality (VR) to enable iterative user-centered design. Using an interactive museum installation as a case study, user pointcloud data is observed via VR at full scale and in real time for a new design feedback experience. Through this method, the designer is able to virtually position him/herself among the museum installation visitors in order to observe their actual behaviors in context and iteratively make modifications instantaneously. In essence, the designer and user effectively share the same prototypical design space in different realities. Experimental deployment and preliminary results of the shared reality workflow are presented to demonstrate the viability of the method for the museum installation case study and for future interactive architectural design applications. Contributions to computational design, technical challenges, and ethical considerations are discussed for future work.
INTRODUCTION

Architecture continues to stretch its disciplinary boundaries by embracing advancements in technology to include responsive, interactive systems, and methods that blur the lines between “designer” and “user” as potential pathways toward sustainability and a more democratic social order (Cross 1972). This disciplinary extension is influenced by 1960s cybernetic theory (Pask 1969; Wiener 1967) and was anticipated by Nigel Cross and the contributors to the 1971 Design Participation Conference (Cross 1972). At the same time, new tools for simulation and visualization are readily available to inform these systems and our association with them. It is in the networked structuring of technologies that the next decade of interactive architectural design research will thrive and find new territories, lying both in and between the real and the virtual. Its boundaries extend the agency of the designer while simultaneously being productively informed by external factors and forces. Like Nicholas Negroponte’s “design amplifier” (Negroponte 1975), the introduction of surrogate tools and virtual spaces into the design process disrupts traditional design modes by demanding collaborative efforts with other disciplines to address a changing palette of environment-defining technologies and emerging human–computer interaction (HCI) issues.

Design research in interactive architecture demonstrates ways in which emerging technologies alter the relationship between the user, the building system, and interior and exterior environments. Experiments have ranged from responsive smart materials (Decker 2016), sensors and imagers (Sabin 2015), and organic kinetics (Kretzer 2013), to interactive metallic surfaces (Goulthorpe et al. 2001) and adaptive distributed computing and mechanics (Beesley 2014). A common necessity among these prototypes and installations is to test degrees and outcomes of interactivity between the users, the technologies, and the environment. Gathering user feedback with these technologies can provide valuable insight for designers on how the system will be received and ultimately perform. Constructing the physical or computational infrastructure to support user testing is an important step to understanding how interactive technologies will alter the way we experience and ultimately design the future of our built world.

Existing Methods for User Testing

The idea of using human behavioral testing in architectural design has been around for decades. Methods for feedback have included computational simulation, human factors testing, and post-occupancy evaluations. In the area of environmental controls, simulation software has been developed for modeling and predicting human behavior with building technologies. While effective in translating patterns of occupancy into algorithms for environmental control (Hong et al. 2016), the logic behind simulated behavior embeds many assumptions about the social and environmental conditions of the actual context of use. Physical facilities can be used to gather feedback from participants in a dedicated testing space or laboratory. The Lawrence Berkeley National Laboratory’s FLEXLAB features testbed technologies and embedded sensors for human factors testing with building systems and controls in various settings and orientations. However, recent studies use methods for collecting user feedback that occur late in the process and tend to separate design and analysis from user testing, such as the use of high-dynamic range photographs for evaluating visual comfort or test-driving a system to confirm the final design solution (FLEXLAB 2017). While these advanced facilities offer a more realistic physical setting as compared to simulations for studying how people and systems would behave together, the studies are typically for a short and intense period of time outside of the participants’ normal working or living contexts. Post-occupancy evaluation studies are another way to investigate human behaviors and their impact on building performance. While realistic in terms of context of actual use, the findings do not necessarily inform the iterative design of a system, and instead provide guidelines for future projects.

Virtual Reality (VR) and 3D Depth-Sensing Systems

Alternative methods for visualizing adaptive architectural systems and for incorporating human behavior models, or real-time user interaction, have evolved with new mixed-reality technologies that combine physical input with virtual data. Prevalent visualization tools for designers include the Cave Automatic Virtual Environment (CAVE) and virtual reality (VR) head-mounted display (HMD) technologies (Kim et al. 2013). The various applications of mixed-reality (MR) technology to architectural applications range from wearable systems implemented in the design process, to digitally archiving historical context, to augmenting reality (AR) on construction sites, to integrating VR and AR tools in academic design studios (Wang and Schnabel 2009). The possibility of these MR technologies to simulate real-world settings and human preferences within them will prompt architectural researchers and practitioners to continue to develop virtual environments for evaluation, model building, and remote collaboration (Heydarian et al. 2015).

The availability of color and depth (RGB-D) sensing systems and VR environments has opened many opportunities for tracking user patterns and capturing feedback on how a building or system performs. 3D depth sensors are able to provide point-cloud data at a high frame rate, which can be readily used in real-world applications, thus simultaneously improving common computer vision tasks and reducing the overall computational
They effectively address privacy concerns with occupant
detection, since users’ identities cannot be revealed from point-
clouds or depth maps. Diraco et al. (2015) used RGB-D sensing
systems to collect 3D depth data for occupancy detection and
profiling for building energy management without compromising
privacy. Whelan et al. (2012) explored the scanning of large
environments to generate virtual representations in interactive
3D environments that allow the sensors to move around the
environment being scanned. Lesniak et al. (2017) used 3D mesh
reconstruction algorithms and real-time rendering techniques to
capture physical objects in the real world and represent their 3D
reconstruction in an immersive virtual reality environment with
which the user can then interact.

One of the major limitations to existing methods is a lack of
integrated design, visibility, and feedback from both user and
architectural system in real time. When recorded 3D datasets of
the users are disconnected from their locations or the associated
responsive system behavior, or if this data is later processed on a
separate machine, the designer is removed from the process. In
these situations, the designer is prevented from moving around
in or fully visualizing the user reactions and scene as it is being
created or modified. Thus, the implications of design decisions
are not viewed in a seamless feedback loop, and instead require
interpretation and evaluation by the designer through other
recorded or documented means.

Research Question and Objectives: Towards a Shared
Reality Workflow
Examining user behavior with an interactive architectural system
outside of the actual context of use can be challenging and
misleading due to a range of issues related to time constraints
and assumptions that do not necessarily reflect accurate social,
behavioral, or environmental conditions. How can designers
more accurately collect user-behavior feedback in a realistic
setting while in the early design or iterative prototyping phases
of a project? In addressing these challenges, this paper argues for
the use of evidence-based, user-centered design practices from
the field of human–computer interaction (HCI) (Abras et al 2004),
coupled with emerging architectural design methodologies, to
improve design usability for interactive architectural systems.

The objective of this research is to develop a mixed-reality
computational workflow combining 3D depth-sensing and VR
to enable iterative user-centered design. Using an interactive
museum installation designed by the authors as a testbed, user
pointcloud data is observed and recorded in VR at full scale and
in real time for a new type of design feedback experience. The
specific aims of this shared reality workflow are fourfold: 1) to
allow the designer to work and observe remotely so that users
can interact candidly in the actual physical museum context; 2)
to reduce time and resources needed for conducting a study
of observed user behavior; 3) to record user data for later
observation and analysis while protecting privacy; 4) to allow multiple designers to experience design changes in VR while observing user reactions in real time.

**METHODOLOGY**

The proposed method improves upon existing systems by providing an integrated shared reality workflow. Through this method, the designer is able to virtually position him/herself among the museum installation visitors in order to remotely observe their actual behaviors in context and iteratively make modifications in real time. In essence, the designer and user share the same prototypical design space in different realities. This allows the designer to intimately view visitors’ gestural movements and make observations and iterative design modifications in real time (Figure 1).

**Testbed: Interactive Multi-Projection Museum Installation**

The installation used as a testbed for the proposed methodology is part of a museum exhibition designed by the authors that interactively displays digital information in two formats. The installation features a large 8 x 15 ft vertical screen display combined with a 13 x 9 ft scaled physical model of a city that uses 3D projection mapping techniques for the dynamic display of information (Figure 2). Visitors can walk around the model and gesturally explore energy data visualizations in a customized user-friendly way. For example, a visitor can point to an area of the city, select a dataset to view as an overlay, and view more detailed information about that specific location as it relates to energy. One ceiling-hung projector displays information on the vertical screen, and three ceiling-hung projectors display imagery onto various surfaces of the physical model. Two 3D depth sensors are located above the vertical screen, pointing towards the area around the model, and are used for tracking visitors’ positions and gestures with the installation through 3D depth pointcloud data (Figure 3).

One of the major challenges that the authors faced with initially designing the interactive installation dealt with the on-site exchange of digital information and collaborative decision-making, which is time consuming and difficult to coordinate in a fully functioning science museum space. Another challenge was the collection and analysis of anonymous user feedback for design decision-making, which is essential for understanding how to program an interactive system that people of different ages and backgrounds will find meaningful and comprehensible. These challenges were tackled through the integration of 3D modeling tools, VR, and 3D depth-sensing systems using vvvv.

**Setup of vvvv Design Environment**

The 3D city model was digitally constructed using geographic information system (GIS) data and Rhinoceros 3D modeling software, and it was used as a template to build the physical model.
for the museum installation. After the display screen, physical model, and projectors were installed in the museum space, the digital model was calibrated using vvvv, a live-programming environment designed to integrate large datasets and media environments with physical interfaces and real-time motion graphics that can interact with many users simultaneously (vvvv 2017).

In the authors' interactive museum installation, vvvv provides an immersive visualization platform and graphical user interface (GUI) for importing 3D architectural models built in software such as Rhinoceros. By importing 3D geometric, texture, and energy simulation data into vvvv, architectural designs and associated data sets can be viewed and experienced in a dynamic way through large screen interactive displays, web/app-based user interfaces (UI), and through a VR HMD. For the museum installation, the goal was to allow users to interact with multiple datasets to better understand relationships between architectural design and energy resource and demand at the urban scale. These datasets included spatial and temporal maps of monthly solar radiation simulated in DIVA-for-Rhino, wind flow simulations using Autodesk CFD, building-use type using GIS data, tree coverage, traffic patterns, and other mapping overlays (Figure 4).

Acquisition of 3D Depth Data for Users
The traditional methods of 3D user tracking with depth cameras, via Open Natural Interaction (OpenNI) and Kinect Software Development Kit (SDK) skeleton tracking, proved to be too limited for these kinds of applications due to restrictions on camera placement and the number of users that could be continuously tracked. Fortunately, most gestural interaction only requires the tracking of each user’s head and hands, which can be fairly easily deduced directly from a user pointcloud, which itself is derived from the overall pointcloud via a simple grouping algorithm. From the head and hands 3D positions, it can be deduced where the user is pointing as well as when they make gestures such as swiping and tapping. By operating on the raw pointcloud, multiple cameras can be used in arbitrary positions, and their pointclouds combined to give good spatial and angular coverage, including being able to track gestures right up to a surface such as a table or screen directly in front of the user (Figure 1). This also allows tracking an arbitrary number of users, unconstrained by SDK skeleton limitations.

Recordings of complete pointclouds versus just skeleton joint positions provide much greater fidelity for live interaction and later analysis and development use. The utility of this approach has been demonstrated in applications including an interactive climbing wall installation (designed by one of the authors), where over thirty climbers have been tracked simultaneously. A key feature of our approach is the ability to maintain user tracking continuity even with a partial pointcloud so that the interaction context is preserved; this allows each user to make a selection that then stays associated with them. For example, each user can select what data type they wish to see, and see their data displayed where they point at the model independently of what
data other users are viewing. This has the added benefit of making the interaction process a social one, as users can see the results not only of their own interactions, but those of other users as well.

3D Depth Data and VR Integration Using vvvv

The vvvv environment is a "live" visual and textual programming system, which means that there is no edit/compile/run cycle, and changes made to the running system are immediately visible. As a result, developing an interaction experience is a directly interactive process in itself. The open architecture of vvvv has resulted in a large number of user-contributed "plug-ins", notably in this case one for the OpenVR (2017) library which allows simple integration of the HTC Vive VR system as an input/output device. However, the need to constantly take the HMD off to make a change in vvvv at the keyboard and then put the HMD back on to test it broke the direct and continuous process inherent in vvvv. To address this, a process was developed to allow users to work directly and continuously in VR.

The first step was to get the programming environment into the VR experience: to do this, the open-source program Screen Capturer Recorder (2017) is used, which captures the PC desktop and presents it as a video input device. Most if not all 3D programming systems allow the capturing of video streams for display on a surface in the 3D model, and in this way the PC desktop can be placed in the VR world (Figure 5). The next step was to put a view of the real-world keyboard and mouse in the VR world, so the developer can fully interact with the virtual desktop just like the real one. This could be done by placing a video camera over the work area and displaying that in VR, but the Vive headset has a built-in slightly downward-facing video camera on its front. As this camera appears to software as a standard video device, its live video is also easily incorporated into the VR scene.

By properly placing the virtual desktop and inserted video display in the VR model, the user can see a larger-than-life programming environment, and directly interact with it while seeing their hands, keyboard, and mouse (Figure 6). This preserves the full interaction and development process without the limitations of systems that use VR controllers for click-and-drag kinds of interactions, and does so without any specific programming. Also, the desktop and keyboard can be made to disappear until the user is in proximity and actively looking at them. Additionally, to address situations where the developer is working with other people in the same physical space, the complete overlay of the Vive camera can be activated by a keyboard key or controller button, so the developer can see the full real-world environment through the HMD. Using this system while "in" VR, the developer can watch a user pointcloud interacting with the installation, make changes to the interaction process, and then immediately replay the user interaction or see the live user data and view the effect of the change.

EXPERIMENTAL RESULTS AND DISCUSSION

The shared reality workflow allows the designer to collect data on the gestural interaction with the interface, the activity levels of the installation, and the types of content being selected for display. Data can be observed in the form of 3D user pointclouds (analyzed in real time or through our activity logs), and measured through algorithms in vvvv that quantify the frequency and sequencing of datasets being viewed. Our preliminary study focused on observing pointcloud data on the gestural interactions in order to improve usability of the interface.
Observations of Real-Time User Pointcloud Data
The actual user-behavior pointcloud data gathered in context through this shared reality workflow produced many useful insights that cannot be gathered by conventional means. Only direct observation or video recording can inform evidence-based design improvements to the installation’s physical and interaction designs. The effect of our design alterations was immediately obvious as we continued to observe pointcloud user interaction with the changed design. This real-time feedback helped us further refine the design (e.g., determine when specific gestures were attempted but failed, or see how many “hits” certain data-sets got when prioritizing the display of content). We were then, in turn, able to observe, analyze, and produce yet another iteration of refinements. In this agile, iterative fashion, we continue to refine the installation’s design, and hence, continue to improve its user experience.

One specific insight observed from the pointcloud data was the benefit of one-handed interaction versus two. Many people were physically carrying things when they interacted with the installations (e.g., children, books, bags, cups, etc.), and one-handed interaction allowed them to experience it more fluidly. Another insight from pointcloud data dealt with the way people treated the interface like a phone while oblivious to on-screen instructions. By reviewing the activity logs and pointcloud data and making adjustments to the design interface, the use (per-user engagement time) of the installation tripled as a result.

Advantages of the Shared Reality Workflow
In addressing the broader research question of how to accurately collect unbiased user feedback in a realistic setting, the preliminary experiments demonstrate that the shared reality workflow supports this goal in several ways. First, it enables us to make design changes remotely while observing real-time user behaviors in an unobtrusive way. This is important since users are not influenced by our presence and thus interact candidly in the actual context of use. Second, working remotely in VR cuts down on time and resources needed for conducting a user-feedback study by making it flexible, so we can observe whenever, wherever, and for however long we need to. This allows us to take note of particular times when user engagement is high, potentially straining the UI. Third, the anonymous pointcloud data protects users’ privacy while being recorded for later observation and analysis. This is helpful to observe patterns of use in the activity logs. Finally, working in VR allows our entire design team to share the experience of observing the same user interactions, either in real time or as a playback, making the collaborative design process more inclusive and fluid.

Contributions to Computational Design and Architecture
Unlike visualization renderings or animations provided by existing commercial simulation or interaction tools, the shared reality workflow supports real-time and iterative design prototyping that includes unpredictable behaviors and responses from both users and the system. In terms of process, it transforms the linear stages of research and development (e.g., design, prototyping, analysis, user-testing, evaluations) into a multilayered adaptive design feedback loop (Figure 7). Linking 3D depth-sensing systems and VR using vvvv, the designer gets a better sense of scale, interactive usability, and legibility of the installation in relation to the human body before construction. In terms of observing user interactions, the designer can maintain an invisible ghost-like presence within the context of use while uniquely viewing user pointclouds from any vantage point (Figure 8). This allows the designer to better understand the implications of their design choices instantaneously, which was previously impossible. The shared reality workflow consists of independent but related environments that build upon each other to create an interconnected digital–physical condition that is occupiable by different people in different realities and at multiple scales (Figure 9). It blurs boundaries of “designable” and “occupiable” space, adding a new dimension to Nigel Cross’s concept of design participation.

The potential of this workflow for other architectural applications is significant. If responsive façade systems, interactive environments, or environmental heating, cooling, or lighting control technologies do not meet user needs or comfort preferences, they risk being unaccepted and unused. Evidence-based user-centered design workflows like this one can address unforeseen issues early on, while reducing time and resources necessary for human factors testing. For interactive systems—especially those that are already using pointcloud data—the disruptive innovation of the VR experience transforms conventional means of behavioral simulation modeling, human factors testing, and even 3D depth-sensing into a zone of heightened design awareness.

Limitations to the Methodology
While the methodology presented offers many previously unavailable advantages, limitations exist. The physical setup for gathering user pointcloud data requires 3D depth-sensing cameras and computing equipment to be strategically placed in the context of use, which requires additional physical infrastructural support. Within our particular installation, the designer has control over the digital content but not the physical. In the context of other interactive architectural systems, such as physical interactive prototypes actuated through sensors and controls, the algorithms could be modified in VR, allowing for input to both the digital and physical space.
Furthermore, there are ethical and security implications to this application of 3D sensing and VR technology. Though an individual user’s identity remains anonymous, this detection and response system raises questions about surveillance and involuntary participation in future interactive architectural systems. Does the public need to be informed that their presence and behavior is being monitored? Who is doing the monitoring, and what risk-benefit analyses are required prior to implementation? Additionally, as this technology evolves and the control mechanisms expand to include not just designer-triggered digital responses, but physical ones as well, there may be life safety concerns to consider.

CONCLUSION AND FUTURE WORK

Shared Realities exists as a physical, virtual, and in-between mechanism to address the expanding need to predict and address shifting parameters quintessential to both interactive systems and human-centered design. This need for a dynamically responsive design tool capable of reacting to changing environmental and user-driven conditions is evident in the intention of the precedent work. Shared Realities uniquely links the designer to these dynamic conditions in a way that facilitates immediacy through virtual positioning and close access to user feedback. This simultaneously gives agency to the designer and enables informed and evolved instruction of responses when the designer is not present.
Future work focuses on analyzing quantitative data of activity and content, and on enhancing the workflow’s user-centered design capabilities. Currently users can interact with pre-analyzed environmental datasets, but cannot view design scenarios. Next steps involve developing a design feedback loop that allows users to make digital changes to the city and explore environmental impacts of those choices. This would enable the widespread design support of the workflow and make it truly participatory. Relating to this is the link to the Internet of Things to expand content, broaden user participation, and feed real-time data to the model. For example, streaming live weather station data or connecting the visualizations to environmental sensors around the city could illuminate issues related to water quality, building energy consumption, and renewable resources.

Shared Realities embodies Negroponte’s design amplification. It broadens, multiplies, and intensifies design agency. It prolongs the design phase indefinitely with increasing and evolving input from users. It creates an environment that the architect and user can share simultaneously, and thus intensifies engagement by compressing representation and production into a single VR experience.

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IMAGE CREDITS
All drawings and images by the authors.

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