Robo-Stim: Modes of Human Robot collaboration for Design Exploration

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Abstract. Augmented and virtual reality in combination with robotics offers unique design opportunities centered around novel human machine collaboration. The coordination of these tools allows for unique modes of collaborative design, sensory stimulation and strategic deception. In this paper, we outline the components and calibration of a collaborative environment which coordinates industrial robotics, mobile augmented reality, and virtual reality. This technical setup allows for multiple modes of experimentation, encouraging reflection on the larger domain of human-robotic collaboration. As such, this work facilitates the definition of four discrete modes of robotic collaboration: Stop-Gap Collaboration, Manual-Assist Collaboration, Creative Collaboration, and Environmental Collaboration. Stop-Gap Collaboration uses humans to bridge technical gaps in automated systems. Manual-Assist Collaboration uses digital tools to augment the human execution of technical tasks. Creative Collaboration prioritizes creative expression, while Environmental Collaboration considers humans as agents in occupied and continuously evolving robotic environments. As robotics gains prominence in design and manufacturing, it becomes increasingly important to examine the role of human beings in partially automated workflows—prioritizing creativity and environmental adaptivity in design applications.

Keywords: Collaborative Robotics, Interactive Fabrication, Mixed Reality.

1 Introduction

The ubiquity of industrial robotics in design fabrication has enabled the increasingly-expeditious manifestation of predefined digital geometry into physical form [1]. Similarly, the abundance of inexpensive hardware and software solutions for immersive virtual- and mixed-reality experiences has broadened the range of intuitive interactions with geometric and physics-based computational modelling tools [2]. While tools for computer visualization and digital fabrication have conventionally been used sequentially (resulting in an inherent divide between creative discovery and actualization), collaborative interfaces which combine robotic and human capabilities are emerging which have greater potential to reconnect design exploration with materialization [3][4]. Such collaborative environments can span a wide range of applications and formats, with varying degrees of creative empowerment to designers and fabricators: yet

these processes can all fall under the same domain of collaborative robotics or interactive fabrication.
In this paper, we present a framework of hardware and software which allows for the coordination of robotic manipulators with interactive models, sensors, and multi-user collaboration in a game-like environment. Through the calibration of handheld mobile augmented-reality (AR) devices and virtual reality (VR) systems with robotic manipulators, we explore the relationship of collaborative robotics with the specific strengths of these interface tools.

As "collaborative robotics" encompasses a wide range of roles for both computational tools and human operators/designers, we use this technical framework as an opportunity to define and explore four conceptual categories of robotic collaboration:

1. Stop-gap collaboration: where humans are used to fulfill technical shortcomings of otherwise fully automated solutions.
2. Manual-assist collaboration: where robots and alternate-reality devices are used to train and assist humans in completing technical tasks more efficiently (i.e. by augmenting human physical strength, increasing precision during manual manipulation, or providing contextualized knowledge in situ)
3. Creative Collaboration: where computational tools prioritize human creative agency in design exploration, augmenting them with extended dexterity, algorithmic intelligence, material or spatiotemporal awareness in the process of design exploration.
4. Environmental collaboration: where humans inhabit robotic environments and collaboration takes the form of continuous system adaptation based on the evolving understanding of occupied space.

2 Methodology

Interaction with computational and robotic tools is generally limited specifically by the interface between the two: sensors which relay human intention and action to digital controllers, and sensory signals (visual, tactile, auditory) which convey non-human algorithmic decisions and robotic action to humans. While such interfaces have traditionally been centralized in computer displays or robotic controllers, the use of visualization tools such as augmented reality (AR) and virtual reality (VR) provides new methods for humans to understand intangible digital processes by contextualizing their display in space. These tools simultaneously provide the means by which those processes can be modified: enabling both informed-operator and operator-informed fabrication [3].

Combining interactive hardware with industrial robotics towards these ends depends on the careful calibration and management of transformations between a large number of local coordinate systems both fixed and moving. Robotic controllers are generally equipped with standard solutions for easily managing change of basis transformations for local work objects, and a number of plugins for CAD software provide opportunities for managing interactive sensor inputs and view frustums of virtual cameras [5][6]. For this research, and for more fluid interactivity and real-time management of multiple cameras and transformations, we use the Unity game engine [7] to create a synchronized and calibrated mixed-reality scene which incorporates mobile-phone-based augmented reality, virtual reality, and robotic feedback and control (Figure 1, 2).

This framework allows for multiple users to preview and run robotic motions at scale (both on site and remotely), design spatial meshes and toolpaths collaboratively, and to synchronize virtual models with moving robots in real time. This setup provides a multisensory environment where the augmented-reality-users benefit from the trusted social- and spatial- context of the real world, while virtual-reality users can benefit creatively from the selective deception provided by an immersive and adaptive digital environment. This deception can be rewarding, but can also be detrimental to the perceived personal fulfillment of labor, as demonstrated by a manually-built wall that is—unbeknownst to the builder—continuously robotically deconstructed.

The setup consists of the following components, which can all be used simultaneously, or as a reduced combination of subcomponents:

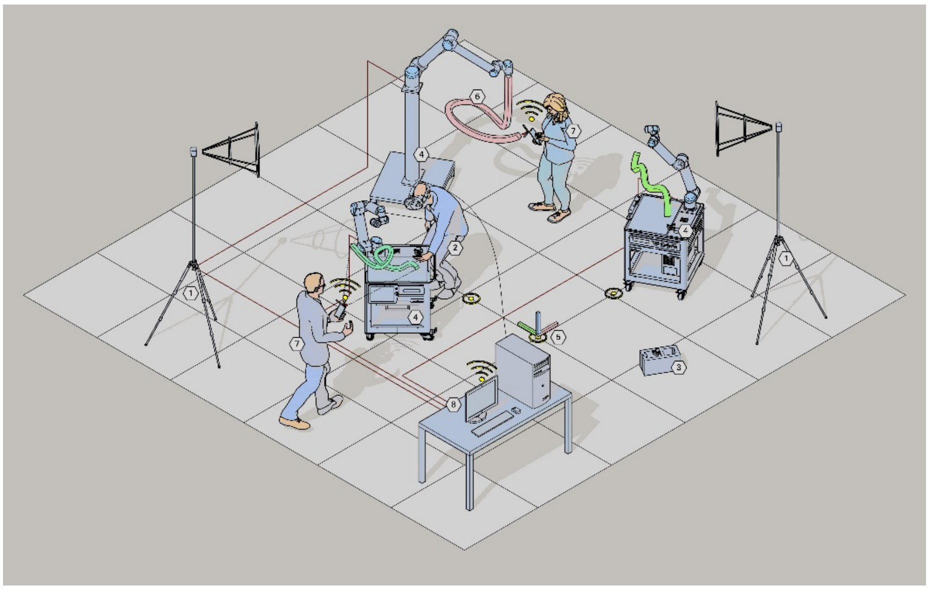

Fig. 1. Coordination of AR, VR, and robotic controls in a single scene. Lighthouse stations (1) track the position of the VR user (2), tracked objects (3), and robot carts (4). VR and mobile coordinate systems are aligned with robotic manipulators using a probed reference plane (5). Gestured paths (6), position and trajectory information are streamed wirelessly between mobile users (7) and the desktop PC (8) that controls the VR headset and communicates bidirectionally with the robot controllers.

Robotic Manipulators. Bidirectional communication between human users and the robotic manipulators is funneled through a single network-connected PC that communicates directly with each robot arm. With the collaborative Universal Robots (UR) arms, joint and sensor information is streamed via TCP/IP connection from the robot controller using the Real-Time Data Exchange (RTDE) protocol, which allows for updated joint angles to be received by the desktop computer at ~125 hz. The 6 joint-angle values are then used to drive a rigged forward-kinematic model of the robot (in Unity) that mirrors the motions of the physical arm. User-defined robot motions (whole paths or individual poses for instantaneous trajectory following) are converted into URScript commands in a custom C# script in Unity and sent to the robot controller by the TCP/IP interface. An inverse kinematic model of the arm is used to display preview motions of selected robotic toolpaths prior to execution.

Fig. 2. Coordinated environment for mobile robotics and multi-user AR and VR.

Mobile Augmented Reality. The acceleration of mobile phone hardware and software has enabled new models for accessible augmented reality, while providing alternatives to relatively rarified, dedicated mixed-reality-headsets. The release of Apple's ARKit [8] and Google's ARCore [9] provides a framework which uses monocular vision and markerless SLAM (Simultaneous Localization and Mapping) [10] for 3D feature mapping and position tracking. Both frameworks offer similar capabilities, can be programmed in Unity, and provide simple methods for tracking the extrinsic camera transformations, and for determining the 3D intersection of screen touches with planar surfaces or anchor points.

We create a simple app for overlaying virtual robotic models over physical ones, allowing multiple users to easily preview future robot motions, and to create new toolpaths by moving their mobile device along the desired path with the desired orientation (Figure 3). In order to align the virtual robot with the physical one, the app uses three predefined reference points in the robot's coordinate space which define a transformation matrix (or work object frame). Once converted to the Unity convention, the inverse of this matrix can be used to determine the location of the virtual robot in the phone's coordinate space by applying it to the corresponding reference plane on the mobile device. Currently the software allows this reference plane to be defined by tapping three points (origin, x-axis, y-axis) on the screen, or by using a physical marker [11] that has been probed by the robot or VR-controller. This base coordinate system allows for multiple devices to share geometric information, and can be synchronized across multiple devices and device types (Android / iPhone) using ARCore's Cloud Anchors (Figure 4).

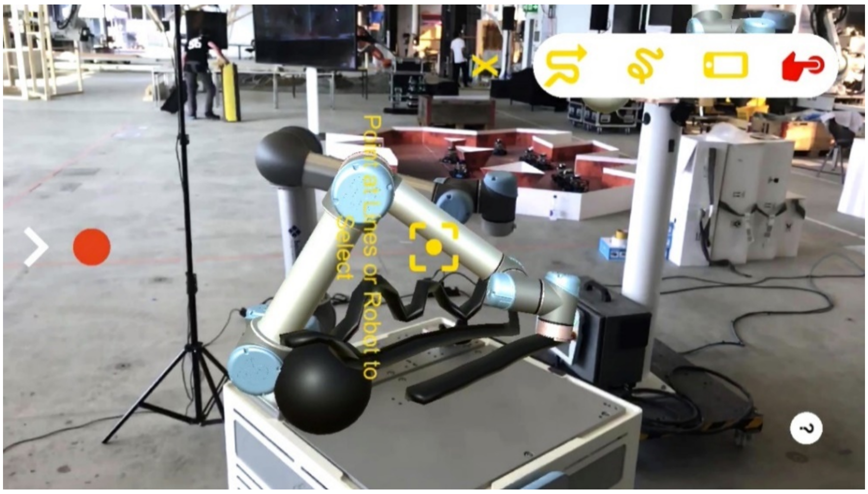

Fig. 3. Mobile and VR applications allow for instant virtual previewing of robot motions for drawn paths, prior to execution of motion.

Fig. 4. A gestured path and previewed robot motion are observed simultaneously by two mobile users (iPhone and Android).

Virtual Reality. As opposed to AR (or mixed reality), VR in combination with robotics allows various forms of decoupling physical experience from visual experience. This strategic deception can include the use of simplified physical props for tactile feedback to match varied visual experience in VR: enabling the tactile sensation of geometrical complexity with simple physical objects [12], the sensation of physical contact through electrically stimulated muscle reactions [13], or the false perception of infinite space through the calibrated misalignment of physical and virtual surfaces [14]. Time can also be accelerated, slowed down, or replayed in order to extrapolate design consequences or learn from past experiences [15].

This project makes use of an HTC Vive headset and controllers [16], which uses light emitting base stations (Fig 1-1) and device-mounted photoreceptors and inertial measurements to provide 6-DoF tracking of controllers, headsets, or any object which has been connected to a wireless tracker.

In order to calibrate the fixed coordinate system of the Vive with that of an industrial robot (and in turn a number of other devices), we must first obtain a known tool point on a given digital controller. This is achieved by fixing a sharp point to the handheld Vive controller, and calibrating this tooltip using a four-point-calibration method, similar to that which is used to define the tool-center-point (TCP) of an industrial robot [17] This tip can then be used to create 3 or more point-pairs between the robot or AR coordinate system, and these points can be used to calculate the change-of-basis transformation to- and from- that system.

As the UR robots are attached to wheeled mobile carts in this application, additional wireless Vive trackers are mounted to each cart to continuously track their positions. The real-time joint-angle information from the UR controllers, combined with the updated cart location from the tracker allows for VR users to reach out and touch and move both components, as the physical objects are aligned with the virtual cart and robot models in the simulated environment. This feature provides an uncanny sensation of being able to feel virtual objects in the VR mirror world. As users quickly begin to trust this tactile experience, they attempt to reach out and touch other digital geometry that does not exist in the physical world (such as spatially drawn mesh curves), and are often surprised to find that there is nothing there to feel (Figure 5, 6).

Multi-device Communication. The collaborative environment makes use of the Photon Unity Networking (PUN) framework, a cloud-based networking service for real-time multiplayer games and applications, to synchronize multiple devices in the same "room" [18]. Users can add virtual objects to a shared space, and the positions and orientations of those objects are distributed in a uniform coordinate system across the network for other users to experience. Robot joint angles, cart positions, and mobile device locations are also shared across this network from the primary desktop computer.

The server also automatically registers each device's location, such that if users log-in from different locations, their virtual coordinate systems are synced to their own local coordinate space. In this way, outside users can be telepresent in the space, getting some experience of the shared activity, but not experiencing the live overlay directly.

Fig. 5. Real time spatial tracking of robots on moving carts allows for intuitive tactile sensing and manipulation. Ability to physically touch robots and carts in VR provokes the user to reach out for other objects which only exist in the digital world.

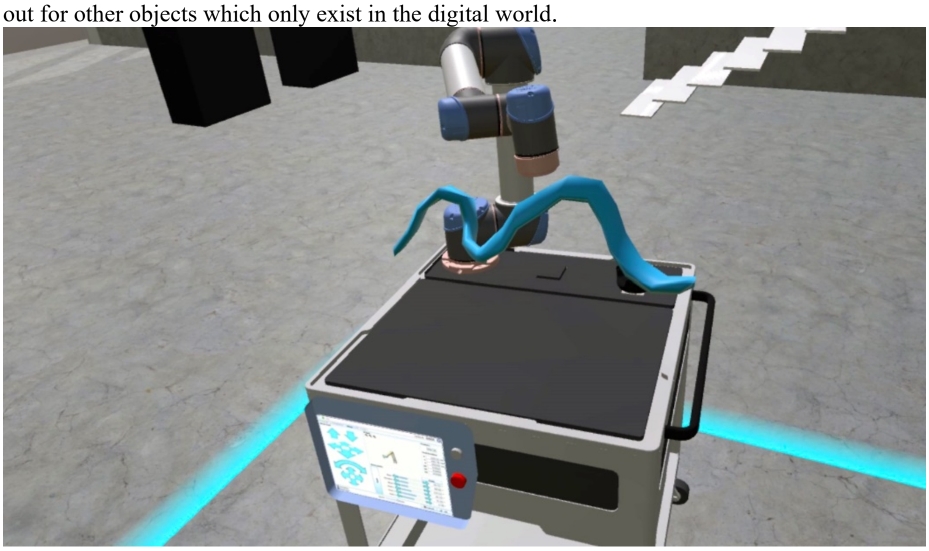

Fig. 6. VR scene replicates select aspects of physical world with low latency, allowing for interaction with robots and moving carts.

3 Discussion

The aforementioned strategies for the synchronized coordination of AR, VR, and robotics provides a framework for implementing spatially-contextualized interfacing between humans, robots, and computational systems. They also serve as a technical toolset in our exploration of the collaborative design models discussed in this section.

While the shift towards collaborative robots is an essential one, the term is currently employed in a manner which accommodates a broad range of applications, where often the roles of each agent (human and robotic) are not consistently balanced. In order to clarify the scope of collaborative robotics and provide a framework for further discussion, we define and discuss a spectrum of collaborative models, presented through sample implementations.

3.1 Stop-Gap Collaboration

Likely the most prevalent form of human-robot collaboration, we define *stop-gap collaboration* as the use of human dexterity and adaptability to bridge current technological shortcomings in what might otherwise be fully-automated or "lights out" fabrication environments.[19] In these systems, human operators fulfill responsibilities which are not particularly creative or engaging in order to preserve time or research resources, or to overcome technical challenges of vision, complex decision making, or dexterity. Examples include the manual gluing of robotic assemblies, [20] the manual loading of bricks for automated stacking [21], or the performance of complex two-handed tasks such as tying knots [22].

3.2 Manual-Assist Collaboration

Manual-assist collaboration centers on using robots and digital tools to augment the human completion of technical challenges. This can be used to train humans to complete tasks which they will eventually complete without aid (such as driving simulations) [23], or to provide continuous augmentation of strength (mechanized exoskeletons)[24] or vision (overlaid instructions and guides)[25]. Manual-assistive devices can also be integrated with sensor feedback to correct or inform human motion [26][27], or to precisely time interventions to where they happen only when the tool is in the correct place [28]. Manual-assistive methods can be understood through the concept of "virtual fixturing" in which perceptual overlays augment human capabilities, just as a ruler augments the hand's ability to draw a straight line [29].

Though manual-assist collaboration can increase a user's technical proficiency, it can also lead to concerns over questions of fulfillment and authorial agency if the level of corrections is excessive.

We use the calibration of a VR system and robotic manipulator to present one novel exercise which can be understood as employing robots for the physical training of humans to build a precision block wall. In an immersive virtual environment, the user sees a block arriving on a conveyor (Fig. 7) and physically picks up this block. Once they have stepped away, a template appears (Green, Fig. 8) which informs them where to place this block. After successful placement, the worker moves back towards the loading station to await the arrival of the next block. The process repeats until a wall has been built.

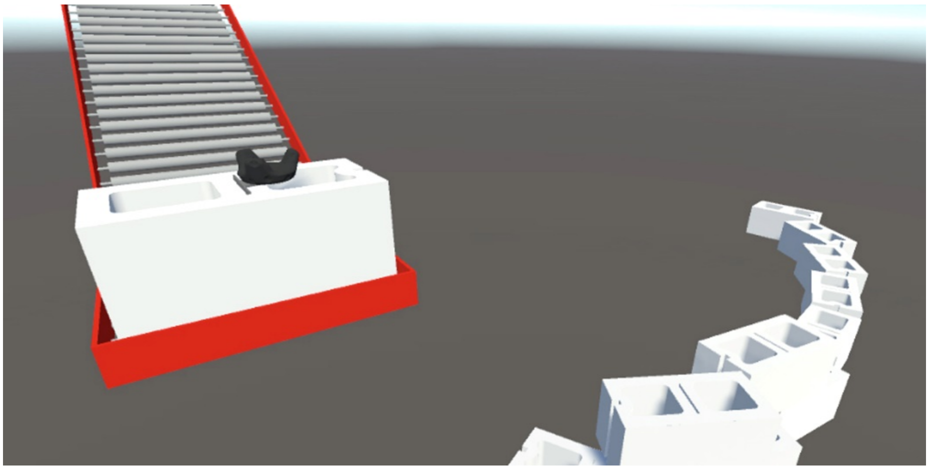

Fig. 7. Physical block arriving on virtual conveyor.

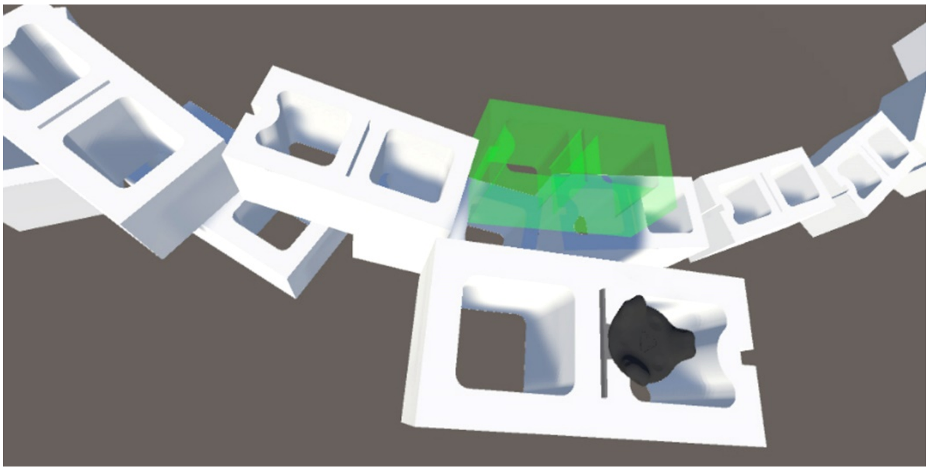

Fig. 8. Visual guide for manual block positioning.

In reality, however, the process is coupled with an industrial robot, which facilitates the illusion that a wall is being built. The robot acts both as the conveyor belt, and as the support material for each placed block: Moving to the correct location where each block is to be placed after the user picks up a block, and moving that block back to the loading station as the user waits for the next block to arrive on the conveyor (Figure 9). By moving the support platform to the designated area, the robot ensures that the human builder feels the tactile sensation of placing the physical block onto the wall they are constructing, but the robot is also the agent which undoes this effort to begin the next step.

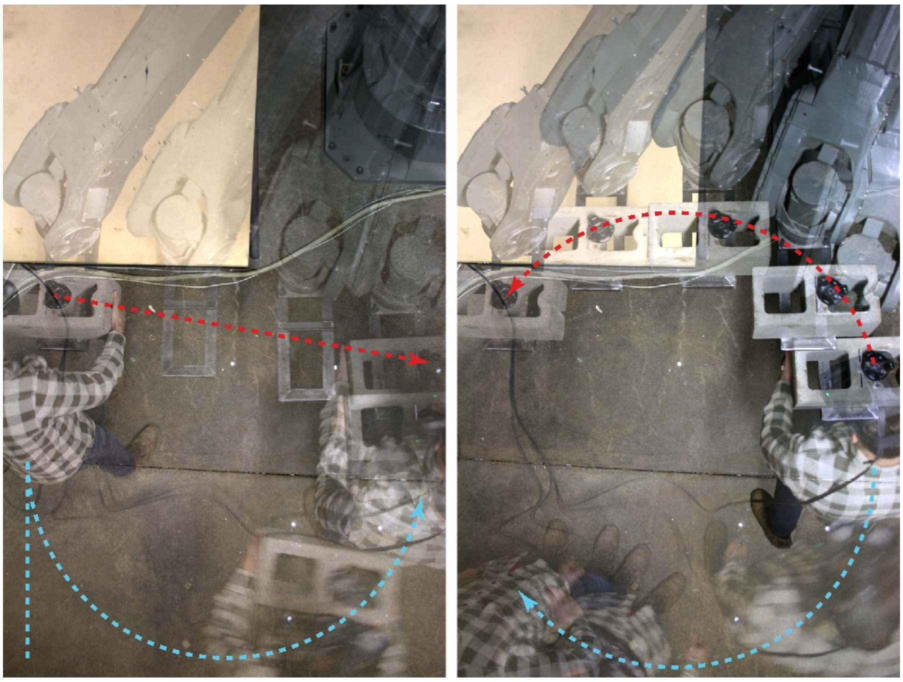

Fig. 9. Block placement cycle. Left) Human picks up block at the pickup station and positions it in the space designated in the VR world. The robot has been repositioned beneath this location to support the placed block. Right) Once placed and the human steps away, the robotic arm returns the block to the pickup station for the next iteration.

Fig. 10. Composite photograph illustrating the "wall" produced by the manual placement of the singular block over time.

In this process, the human does all of the physical labor associated with building a wall. However, the coupling of virtual deception with a synchronized robotic manipulator means that though each element of the wall exists in its correct location, it does not all exist at the same time (Figure 10). Thus, this environment can be considered either as a training tool, or as an exercise in Sisyphean futility.

While manual-assistive methods of human-robot collaboration can enable productive parahuman capabilities, system designers must remain continuously cognizant of the negative potential of these tools to disturb the perceived fulfillment provided by labor.

3.3 Creative Collaboration

Creative collaboration involves the development of processes which prioritize human creative expression over technical tasks or process optimization. Though there is no distinct line between creative-collaboration and human-assistive collaboration, it is important to distinguish between collaboration for the efficient execution of tasks, and collaboration which specifically empowers design agency. Examples include the spatial representation of form [30][31][32] or collaborative processes which augment the human hand in drawing [33]. Through 6doF positional feedback determined through monocular vision and SLAM, this spatial freedom can be gained with a simple mobile device – allowing multiple users to draw spatially on multiple devices in a single scene, and to output those paths directly to a robotic manipulator for execution (Figure 11).

Fig. 11. Gestured path in environment with multiple synchronized mobile devices and VR headset.

3.4 Environmental Collaboration

Environmental collaboration considers the human role as agents, while shifting the robotic to the architectural both in time and in scale. Living within the robotic architecture over time is understood as a form of communication that the building can pick up on and respond to through architectural degrees of freedom such as light, temperature, and apertures. By replacing the dominant machine-human interfaces of speech- and screen-based interactions with that of space, it becomes possible to negotiate the fine social cues of body language and spatial positioning as a much more subtle, but meaningful form of human-architecture expression. Thus, treating robots as performative agents that do not simply implement design intent through fabrication, but move to define spatial interactions, can open up new modes of robotic collaboration. *Embodied computation* frames design as an ongoing process that begins its adaptive cycle of learning at the moment an architecture is occupied, viewing the living in a robotic architecture as a human-machine design collaboration over architectural time scales [34].

Overcoming the notion of architecture as a static, once-fabricated backdrop to human actions allows for coordinated architectural responses to observed human and environmental changes. Examples include robotic furniture that may adapt its position based on anticipated activities, or the active control of apertures for light and air.

This opens up interesting questions of how a robotic entity expresses itself: going beyond motion or manipulation, robots becoming architectural entities, defining space, and giving behavioral abilities to everyday items.

4 Conclusion

While human-machine interaction has the potential to empower social, spatial, and formal creativity in design and manufacturing, this potential falls along a wide spectrum. The role of robotics in human machine collaboration needs to be reframed from one of mere executors of human design intent, towards an expanded role that supports flows of ideas and extends the malleability of computational environments into the physical realm. This bidirectional communication allows for creative collaboration, and is increasingly possible with emerging capabilities of VR and AR systems and advances in safer human-compatible robotic actuators. In this paper, we demonstrate a developed framework for working collaboratively with virtual- and mixed-reality devices and robotics, and use this setup to discuss potential forms of interactive modelling and their implications on the human aspects of design and manufacturing.

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