Research Statement

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Research Vision and Contribution

Goal: Harness embodied interaction to make XR natural and efficient across users with different backgrounds and expertise.

The term Extended Reality (XR) is an umbrella for AR, VR, and MR. Blending virtual and real information and experience, XR creates exciting new opportunities for people to interact with computing resources, impacting the practices of not only entertainment but also training, maintenance, medicine, education, accessibility, and **robotics**. However, compared to the rich content bandwidth that XR technologies can provide, **the interaction bandwidth between humans and XR remains limited**, with barriers caused by mismatches between conventional 2D interfaces and innate 3D content in XR. To broaden this bandwidth, I aim to **make XR technologies natural and efficient across users with different backgrounds and expertise through human body embodiment**. Human body itself is a complex and delicate system after millions of years of evolution that embodies vast **implicit knowledge carved in human genes**. By turning the body into an interaction medium (Fig. 1), **embodiment is the key to transferring user knowledge of human body to unseen interaction**.

To achieve this goal, I propose the concept of **Embodied Interaction for XR** – turning body into XR interfaces through embodiment – and explore how to **design interaction techniques and invent enabling technologies for body-embodied interfaces**. With interdisciplinary research across **science, engineering, and design**, I will achieve my goal by iterating **technologies and techniques that mutually reinforce one another**, shaping the next-gen human-XR interaction, and finally creating an era of spatial computing accessible to all.

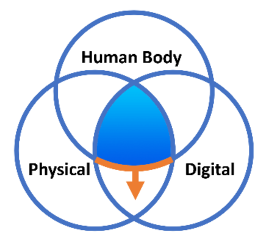

Figure 1: Embodied Interaction for XR.

My **research contribution** unfolds in two synergistic lines:

① **Design Perspective**: I shape the scope of embodied interaction for XR, progressing from **digital entities** [Hand Interfaces, CHI '22 🏆; Finger Switches, CHI '24] to **physical entities** [Arm Robot, in submission to UIST '25], from freehand interaction to **full-body embodiment** [Work Bubbles, in submission to ISS '25; Embodied Exploration, ASSETS '23], filling the **knowledge gap** in this emerging field, **creating metaverse systems** for embodied interaction, addressing practical challenges in entertainment, education, **human-robot interaction**, workplace collaboration, and **accessibility.**

② **Science and Engineering Perspective**: I develop sensing principle and technologies of **non-instrumental force sensing** [Force Sight, UIST '22 🏆], and haptic artificial muscle skin [Haptic Skin, Science Advances], **building systems with novel modalities** for bodily interaction and robot perception.

1. Shaping the Scope of Embodied Interaction for XR

1.1 Embodying Digital Entities

XR provides access to a wide variety of digital entities, i.e., spray can in 3D drawing. To select a tool, users have to choose from a long menu. To free users from the tedious selection, I design the hand-embodied interaction technique for **efficient tool selection and manipulation** [Hand Interfaces, CHI '22 🏆]. The new design opportunity is to **embody digital entities with hands by mimicking their shape and dynamics**. For example, when users perform a "peace" gesture (Fig. 2q), their hand will turn into a pair of virtual

Figure 2: I propose the concept of Hand Interfaces – embodying concrete digital entities with hands by mimicking their shape and dynamics.

scissors. I designed a wide variety of hand-embodied entities that users can easily summon (Fig. 2), with **considerations of shape similarity, kinematic similarity, comfort** and **social acceptance**. For accurate detection, I built a **template-matching-based pipeline with customized sensitivity matrices** over finger joints for object retrieval and interactive control. Through a study (N=17), I contribute knowledge on how **real-world experience, visual alignment and tactile feedback influence the perception of realism** during hand embodiment, helping XR designers effectively prioritize design choices. I developed an AR app for ubiquitous control in smart environments (Fig. 3), where Hand Interfaces enhance efficiency and convenience in retrieving, interacting with, and dismissing digital entities.

Figure 3: Hand Interfaces allows users to quickly control a smart lighting system by retrieving a digital toggle switch, a joystick for orientation, and a spherical color picker. The user can easily dismiss the tools by taking hands back.

In [Finger Switches, CHI '24], I further utilized the concept of hand-embodied digital tool to controlling 3D UI behaviors, addressing the **often-overlooked issue** – UI mobility in XR design. Through a need-finding study, I categorized UI positions into static UI, dynamic UI, and self UI (Fig. 4), and then **embodied a three-mode switch with the index finger**, mapping the three modes respectively. I built the metaverse system combining **gaze and pinch**, and demonstrated the effectiveness through a study (N=14).

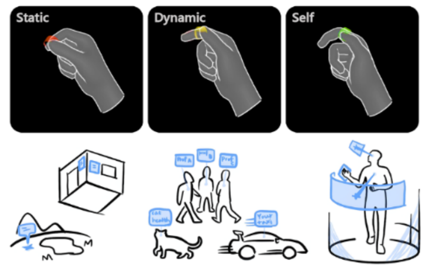

Figure 4: Finger Switches allow users to switch a UI type between static, dynamic, and self UI.

1.3 Embodying Physical Entities

Expanding embodiment from digital to physical entities, I focus on **robot arm control through embodied interaction** [Arm Robot, in submission to UIST '25]. Robot arms are vital in assistive technologies but lack sufficient data. Controlling robot arms through human arm movements, combined with augmented visual cues, simplifies data collection compared to traditional programming. However, through expert interviews, I identified **three key challenges** in the learning cycle of embodied control, particularly for users without robot expertise: (1) lack of understanding of robot motion, (2) limited action space, and (3) inaccurate observations caused by occlusion and delay (1~3s). After iterations I designed hand-embodied gripper, and introduced **flexible mapping of embodiment** with features of *Freeze/Unfreeze*, *Scale Mode*, and *Mirror Mode* (Fig. 5). Furthermore, I visualized **human-robot correspondence** and **zero-delay digital twin of robot** using AR. I built the AR-enhanced robot control system with 6-DoF AUBO i5 series, high-fi digital twin and BioIK solver for inverse kinematics solution in Unity, and motion smoothing with radius blending and predictive arrival. The study (N=18) shows the effectiveness of flexible mapping and AR visualization, generates knowledge on how users leverage each feature in various tasks. The investigation of manual control contributes to the balance of **human agency** in **human-AI collaboration**.

Figure 5: The user is embodying the robot arm under "Mirror" mode to pour beans into the large bowl.

1.4 Full-Body Embodiment for Accessibility Assessment

Expanding the embodying medium from hands to full body, I created a **fully interactable metaverse system** for wheelchair users to remotely assess the accessibility of unfamiliar places [Embodied Exploration, ASSETS '23]. For accurate assessment, I generated **personalized full-body avatars of wheelchair users**, embodying their biometric details such as seated eye level, arm length, and spatial dimensions of their specific wheelchair model (Fig. 6). I then created **digital twins** of indoor environments using 3D technologies and incorporated **realistic interactions** in these environments. For example, users can open a window by pulling the handle, or grab a mug and fill in with water. In such an interactable metaverse, users move their heads, roll the wheels, and extend their arms to evaluate visibility, locomotion, and manipulation -- three key factors identified in a need-finding study. Daily wheelchair users in our study found Embodied Exploration **the most truthful replicate of their real-life experience to support personalized accessibility**, e.g., whether their wheelchair can fit through a narrow corridor or under a conference table. My high-fidelity system contribution facilitates remote assessments, eliminating guesswork and the need for costly physical visits for wheelchair users.

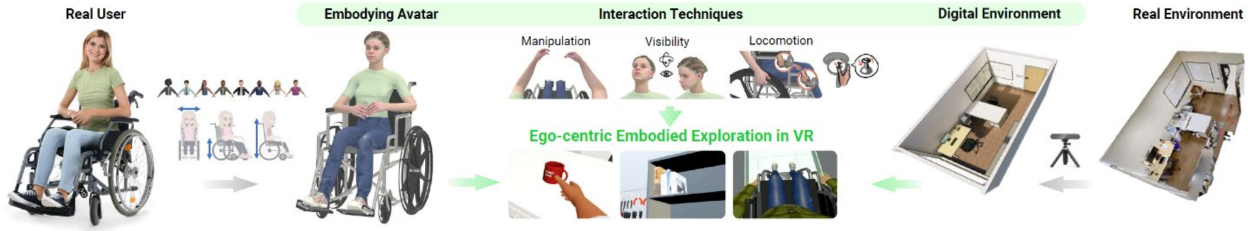

Figure 6: Embodied Exploration consists of three components – a digital environment, an embodying avatar, and interaction techniques. The user is embodied by an avatar, which is generated with biometric information about users and their specific wheelchair model.

2. Inventing Enabling Technologies for Embodied Interaction

2.1 Non-instrumental Force Sensing

Force sensing is crucial for interactions between the human body and the environment. Beyond detecting binary touch, understanding the applied force enables richer interactions, such as force-aware direct manipulation of objects. While traditional instrumental sensing is either inflexible or costly to scale, I explored **non-instrumental force sensing** on ubiquitous surfaces with laser speckle imaging [ForceSight, UIST '22 🏆]. My key observation is that laser speckles, generated by interference of diffusively reflected beams, shift significantly at minute surface deformations caused by applied force. I mathematically **modeled both the surface deflection and laser speckle patterns** to establish **the linear relationship** between force and speckle motion. With laser-enhanced deformation signals, **a robot arm gains non-contact force perception**, enabling delicate object manipulation without the risk of wear and tear associated with contact-based sensors (Fig. 7).

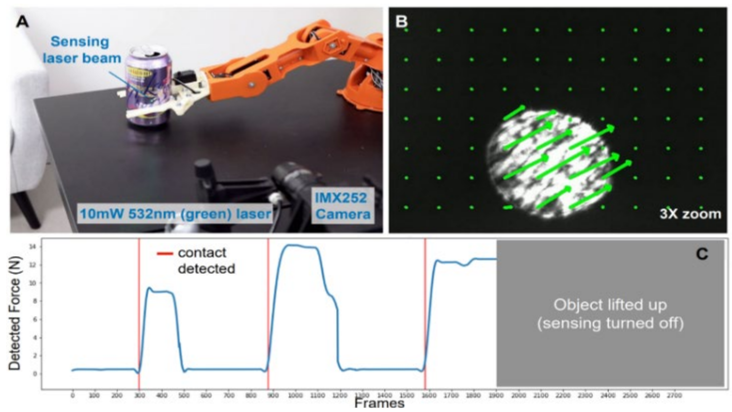

Figure 7: Remote force sensing for handling delicate object. A: A robot arm grasps a soda can sequentially with light, strong, and medium force. B: Integrated Laser Speckle Velocity. C: Detected force.

2.2 Haptic Artificial Muscle Skin

The embodiment of digital entities often lacks realistic haptic feedback, which limits immersion. To address this, I collaborated with researchers in Material Science for a **high-fidelity, lightweight haptics solution in XR – ideally as light as human skin** [Haptic Skin, Science Advances]. I built an **XR system combining both software and hardware components**. It not only allows users to experience tangible raindrops with body embodiment (Fig. 8), but also incorporates **communication mechanisms** to send raindrop locations at varying intensity and frequency to modulate working voltage of the haptic actuators, simulating light and heavy rain. Experiments demonstrate that HAMS **provides complex tactile feedback with high perception accuracy**, seamlessly integrated into the XR experience.

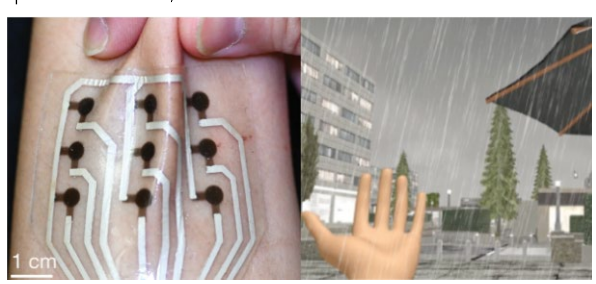

Figure 8: A user is experiencing virtual rain with haptic skin.

Future Research Agenda

I believe that embodied interaction holds the key to making XR experiences more intuitive, inclusive, and impactful. To realize this vision, I plan to focus on the following three aspects of interdisciplinary research to realize my vision, combining efforts in science, engineering, and design.

Expanding Sensing Capabilities and Design Space for XR Interaction

Building on my work in enabling technologies and embodied interaction design, I aim to advance sensing capabilities and broaden the design space for XR. From the sensing perspective, my interests involve non-instrumental solutions to **full-body modeling and tracking**, **robust hand tracking that supports contact detection**, and **reliable on-skin activity recognition** that people can easily use out of lab. I have preliminary results on on-skin signal augmentation (Fig. 9). The sensing approach uses **a polarized camera and polarized light source** to enhance **skin texture** which embeds signals of activities that can be used for not only general interaction (e.g., touch, pressure, dragging/swiping) but also authentication for **XR security**.

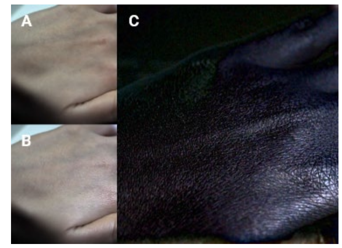

Figure 9: Polarized skin imaging: (A) without and (B) with specular reflection. (C) Enhanced skin texture.

Towards the design direction, I seek to extend embodied interaction to cover **diverse body parts** (shoulder, back, foot) and **connect XR with dance, martial arts, and workouts** through embodiment for content creation, entertainment, education, and robotics. Additionally, I aim to investigate how users can collaborate through **shared embodiment**, enriching **social XR experiences** or **shared control of robots**.

Beyond embodiment of digital and physical entities, I am also interested in **embodying experiences and identities** at a **mental and psychological** level. This concept has promising applications in **well-being**, e.g., allowing users to role-play the healthy lifestyle of another person, immerse themselves in the new daily routine, and thereby improve habits. Mental embodiment is also promising to develop empathy or enhance therapy.

Human-Robot and Human-AI Collaboration in XR

The advanced sensing and embodiment techniques in my work are important in **real-world scenarios** for collaboration with **robots** and **AI**. Manual control and AI-based automation are **complementary instead of exclusive** to each other. First, I aim to advance knowledge on understanding the **human agency in the human-AI collaboration**, e.g., the degree of agency required, methods to enable effective human intervention in AI training, and XR interfaces for providing human benchmarks for Programming by Demonstration. As a preliminary effort, my work [WheelPose, CHI '24] demonstrates how embodying users in synthetic motion skeletons can eliminate unrealistic data, thereby enhancing the **inclusiveness of vision AI** for wheelchair users. Second, I target to build XR-enhanced systems with delicate strategies of embodiment in **human-robot collaboration** that can enable asynchronous and synchronous **co-manipulation** in both industrial and domestic settings, e.g., a robot assists a human in lifting furniture.

Using Embodiment+AI to Address Accessibility Problems with XR

Humans have **diverse physical and mental abilities**, which result in different affordances for XR interaction. My research has demonstrated that **embodiment in XR is a handy tool to address accessibility problems**. For example, a wheelchair user can control a robot arm through embodiment to **expand their "arm reach"** in the environment (in Arm Robot). In the future, I aim to combine **embodiment and AI** for powerful, adaptive solutions. My first direction is creating an intelligent, adaptive gamified experience for mobility rehabilitation using **reinforcement learning** and **full-body embodiment**. I have achieved preliminary results that the game automatically adjusts its difficulty based on user performance to achieve rehabilitation efficacy. My second direction is fostering an inclusive environment for individuals with cognitive disabilities (e.g., ASD, ADHD, Dementia, anxiety) with **context-aware intelligence** and **audiovisual cues in XR**. The system will allow users to quickly alter "perception" through embodied interaction, such as highlighting key information, simplifying complex scenes, diminishing distracting elements, and augmenting facial expressions. By combining embodiment and AI, I am dedicated to **transform XR into a truly inclusive and empowering medium** that adapts seamlessly to the unique needs of every individual.

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