Research Statement

[Tengxiang Zhang](#)

My research aims to make the world more computer-friendly to benefit humans. I design and deploy wireless tags pervasively to add ‘colors’ in the physical world for computers. Then I build smart wearables (*e.g.*, glasses, rings), develop sensing algorithms (*e.g.*, for gestures/facial actions), and design interaction interfaces (*e.g.*, with AR/MR) to understand and merge the tagged physical world, the digital metaverse, and the humans. Finally, I apply the research outputs to benefit humans. More specifically, I develop novel wearables to support natural input, localize digital contents and physical tags for a consistent selection experience, and propose a semantic-based interaction paradigm for spontaneous interaction (Figure 1). Thus, my previous work falls into three categories: **Smart Wearables, Tag-aided Spatial Computing and Resource Selection,** and **Interaction Abstraction Theory**. Such efforts have led to over ten publications at top venues, including SIGCHI and IMWUT, with two paper awards.

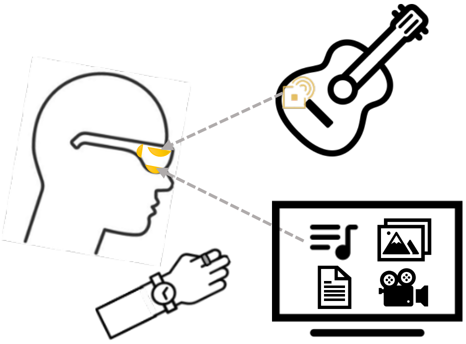

Figure 1: Head and hand wearables facilitated interaction with digital contents and tagged physical objects.

1. Smart Head and Hand Wearables

I focus on smart rings and smart glasses to sense both explicit and implicit interaction intents. Our smart glasses prototype (Figure 2) deploys two electrooculography (EOG) electrodes on nose pads and one between eyebrows to sense upper facial action units. It places two Inertial Measurement Units (IMU) close on the skin below the ears to sense lower facial action units. The project was demonstrated at the MobileHCI 2022 Student Design Competition and later invited for video demonstration at Huawei Developer Conference 2022.

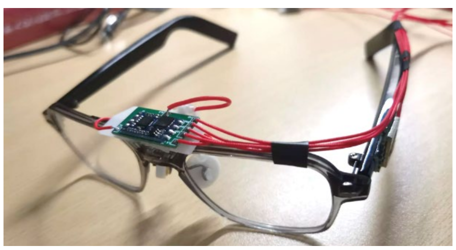

Figure 2：Smart glasses-based facial action units sensing with EOG and IMU.

Finger wearables can support accessible and subtle gesture inputs. However, finger wearables are challenging to design due to their size constraints. The small size further limits the available computing, I/O, and power resources on such computers. To overcome the limitations, I design a modular smart ring (Figure 3). Instead of integrating all functions into one piece of hardware, **ModularRing** [1] uses switchable I/O modules for interaction. The novel design allows the I/O module to be separated from the wireless MCU and battery. Users can then switch the module and combine multiple rings with different I/O modules to form the desired interaction interface. For example, one ring with a microphone module and one with a speaker module can work together as an audio interface to make calls. ModularRing won the Finalist in the 2018 Global Innovation Competition, leading to three patents. The hardware design is open-sourced [1].

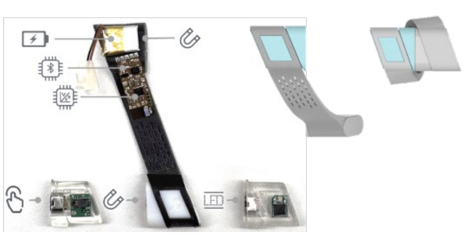

Figure 3：ModularRing adopts a modular design for smart rings.

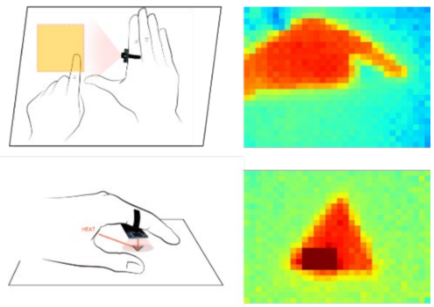

Figure 4: Thermal imaging of a hand and a passive tag.

In **ThermalRing** [2], I use a low-power, low-resolution thermal camera for the gesture and tag inputs. ThermalRing analyzes the heat silhouette of the hand to recognize drawing gestures on flat surfaces (Figure 4). A bag-of-word model is trained to recognize gestures based on movement distance and angle of the hand. I also proposed ThermalTag, passive tags that can be easily made using materials with high heat reflectivity (e.g., copper tape). When covered by hand, ThermalTag reflects the heat radiated from the hand and thus can be imaged. This demonstrates how the on-body wearables can work together with off-body tags, enabling more interaction possibilities. The firmware of the project is open-sourced [2].

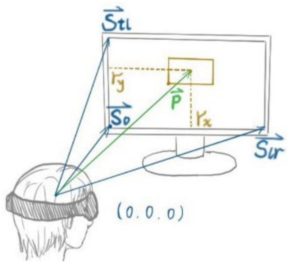

Figure 5: ScreenJump localizes on-screen resources by combining the screen spatial coordinates with their on-screen positions.

2. Tagging, Localizing and Selecting Digital and Physical Resources

With digital and physical worlds merged, users should be able to interact with digital content and physical objects similarly. This calls for a unified description of both resources, i.e., assign digital IDs for physical objects and spatial coordinates for digital contents. **ScreenJump** [3] (Figure 5) uses an AR headset to calculate the spatial coordinates of on-screen digital resources (e.g., images, texts) by localizing the screen and retrieving pixel positions of such resources from the corresponding computing device. Users can thus select and manipulate such fine-grained digital resources by intuitive gazes and gestures.

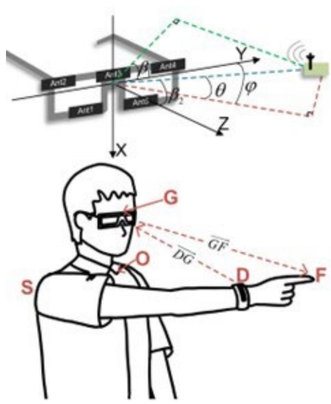

Figure 6: BLEselect deploys an antenna array on smart glasses to detect AoA of broadcasting wearables and tags for intuitive gesture selection of physical objects.

BLEselect [4] (Figure 6) enables intuitive nodding, pointing, and encircling head and hand gestural selection of physical objects tagged with Bluetooth 5.1 advertisers. A compact antenna array is fitted on a pair of smart glasses to estimate the Angle of Arrival (AoA) of IoT and wrist-worn devices' advertising signals. We then developed a sensing pipeline that supports all three selection gestures with lightweight machine-learning models trained in real-time for both hand gestures. Extensive evaluations show our system is accurate, low-power, and privacy-preserving despite the small-size antenna array.

Figure 7: Bluetooth-compatible backscatter sensing tag (33x22mm).

However, a large amount of battery-powered tags would introduce huge maintenance efforts and cause significant damage to the environment. So, I developed maintenance-free backscatter wireless tags that offload many hardware components (e.g., power source, RF oscillator) to resource-abundant edge devices. This minimizes communication power consumption and makes it possible to power such tags with harvested energies. I made a Bluetooth-compatible backscatter tag (Figure 7) that broadcasts the IMU data as Bluetooth advertisements, which commercial devices like smartphones and laptops can receive. The average broadcasting current is only 800uA, which is one-fourth of the commercial Bluetooth chip (3.5mA).

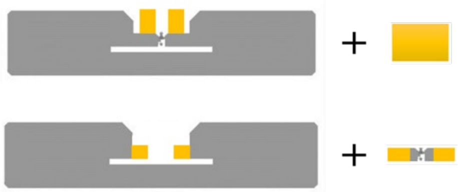

Figure 8: BitID tags enabled by shorting the IC (top) and separating the IC with the antenna (bottom)

In **BitID** [5], I modify commercial-off-the-shelf (COTS) low-cost and passive UHF RFID backscatter tags to behave as binary sensors. The tag's readability is modulated by externally switching the antenna matching impedance, which is achieved by changing the electrical connection around the chip, as shown in Figure 8. Users can easily make and deploy BitID sensors to detect the binary states of various objects. Codes for a complete BitID system, including sensor registration, definition, and event recognition, are open-sourced [5].

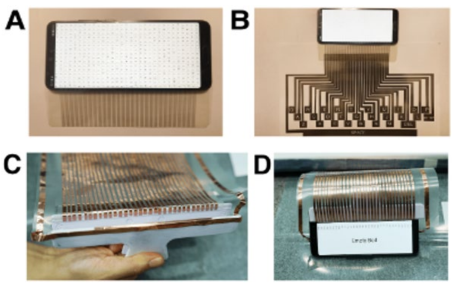

Figure 9: FlexTouch connects conductive strips to a smartphone for large-area sensing.

The RFID reader used in BitID is expensive and not widely available yet. So, I also leverage more accessible computers to power and compute for the resource-constrained tags. **FlexTouch** [6] (Figure 9) uses conductive strips to extend the sensing range of the capacitive touch screen on a regular smartphone to a larger area (e.g., a Yoga mat). Aside from reducing tag power, I have also worked on novel power transfer mechanisms. I invent the concept of **Interaction-based Power Transfer (IPT)** [7], which leverages the contact and closeness between user and object during interaction to transfer power. IPT is especially suitable for devices that only need to be powered during interaction (e.g., mouse, remote controller). The concept was validated with a glove-based IPT prototype **TouchPower** (Figure 10), which transfers DC power through contacts of electrodes on the glove and objects. With careful design of the transfer interface, energy can be transferred with little impact on the original interaction.

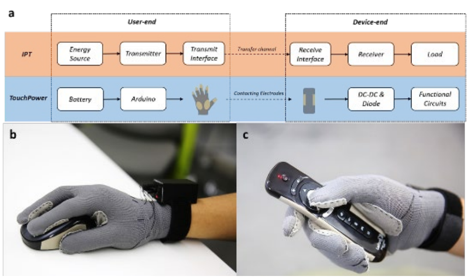

Figure 10: Components of IPT systems (a). TouchPower used with a mouse (b) and a remote control (c).

Aside from wearables-based selection methods, I also studied selection methods on resource-constrained interfaces. **Tap-to-Pair** [8] supports spontaneous device association based on the temporal correlation of two signals. Users can tap on an IoT device to induce periodic wireless signal strength changes, which are then correlated with the blinking patterns of target devices for association (Figure 11). A follow-up work [9] proposes a 2D design space and guidelines for blinking patterns by applying Bayesian models of user tapping behaviors. Such optimization enables the technique to support robust selection among more targets. A functional Tap-to-Pair application for Linux systems is open-sourced [9].

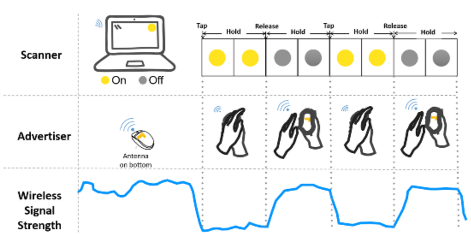

Figure 11: Tap-to-Pair associates two wireless devices by synchronous tapping.

3. Semantic-based Interaction Abstraction Theory

The world with merged physical and digital contents calls for a new interaction paradigm. To better define the paradigm shift, I propose abstracting each interaction intent in a similar form to the computer instruction set. An interaction instruction consists of a command, a resource, and a state (if necessary), which changes a resource to a state as specified by the command (Figure 12). The resource can be digital services or physical objects. Under this representation, the current

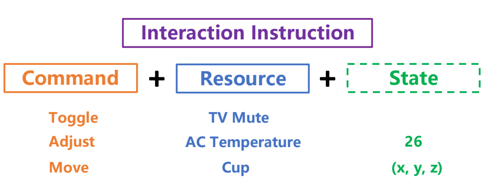

Figure 12: Interaction abstraction inspired by the structure of computer instruction sets.

interaction paradigm is entirely selection-based. Users select both the command (e.g., font change) and the resource (e.g., a paragraph of text) to express their intentions. Such an interaction paradigm relies heavily on graphical user interfaces (GUI) and designated input devices like mouses and touch screens. Thus, it does not support spontaneous interaction anytime, anywhere.

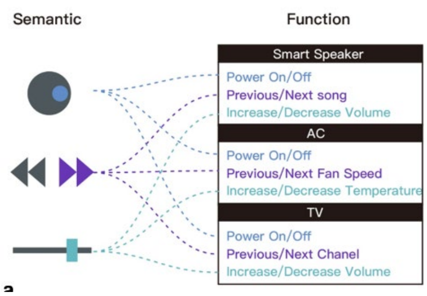

Figure 13: Mapping semantics to different functions on different devices.

So, I propose a new interaction paradigm by extracting services' and objects' semantics, which describe the kind of inputs the service or object takes. Users express semantics to designate commands instead of selecting commands on a GUI. **BoldMove** [10] implemented and evaluated a semantic-based IoT device control mechanism with three commands (*Toggle, Switch, Adjust)* on a ubiquitous touch interface (Figure 13). Such a set of commands can also be easily implemented on touch screens (e.g., long click for *Toggle*) and AR headsets (e.g., fist for *Toggle*).

Future Research Directions

I am eager to collaborate with colleagues with various backgrounds to apply my HCI, computer science, and electrical engineering skills to new application domains, including but not limited to smart buildings, smart cities, education, etc. Topics that I plan to work on include

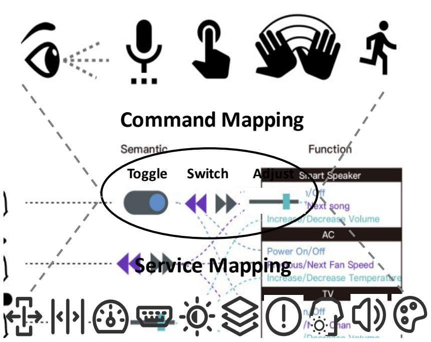

Figure 14: Multi-modal intentions map to available services through an instruction set.

1. Interaction Instruction Set based Interactive System

BoldMove only evaluates an IoT device control instruction set. I plan to propose a generic interaction instruction design methodology and evaluation benchmarks. It is also vital to recognize the expressed command from complementary multi-modal inputs and map them to recommended services (Figure 14). Thus, I also plan to develop multi-modal command recognition and service recommendation algorithms.

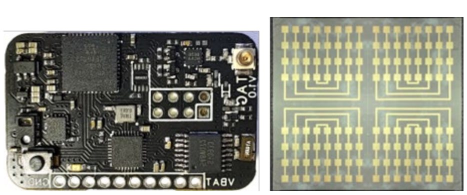

Figure 15: Backscatter tag with two-way communication (left) and Van Atta array based tag antenna for monostatic 60GHz FMCW radar (right).

2. Radar-based Gesture Sensing and Tag Localization

The Bluetooth smart glasses and backscatter tags have limited localization precision. I plan to deploy a miniature 60GHz FMCW radar and Bluetooth transceivers on smart glasses for power-efficient and accurate tag localization. I also plan to leverage the Van Atta array (Figure 15) to estimate tag orientations, which makes it possible for wireless tag-based simultaneous localization and mapping (SLAM). Such radar can also detect macro and micro gesture inputs.

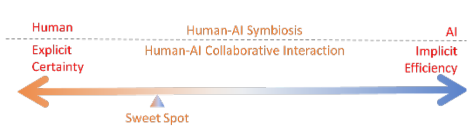

Figure 16: Human-AI collaboration and interaction

3. Human-AI Interaction and Collaboration

I'm utterly curious about the sweet spot between the explicit and implicit interactions (Figure 16), where it is optimal for users (in terms of naturalness, efficiency, etc.) and for AI (in terms of ability, lag, etc.) to collaborate. I will formulate fundamental theories and develop human-in-the-loop interactive AI systems to take advantage of the strengths of both humans and AI.

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