Research Statement Te-Yen Wu

The goal of Ubiquitous Computing is to seamlessly integrate computers into everyday objects, to create a smart environment that can predictively understand and fulfill users' needs. However, today technologies are leading to a bottleneck, as most hardware components (e.g., touchpads) are not easily compatible with everyday objects (e.g., garments) and too technical to use (e.g., knowledge about circuit design). To overcome this barrier, my research vision is to **create a smart environment using smart everyday materials that can be seamlessly integrated into daily objects at large scale using established methods (e.g. cutting and assembly).** To achieve this vision, I first studied **human-material interactions (HMI)** to understand how smart materials should be made to empower people to create smart environments. My research approach is need-driven, which first explored the interaction needs from humans and invented new smart materials to support the interaction. This approach often leads my PhD research to building new smart materials from scratch, which involves (1) new design of novel electronic structures (e.g. antenna) in common materials (e.g. textile and wood), (2) machine simulations and experiments of the new structures to optimize the performance (e.g. sensitivity) of smart materials and simplify their fabrication process, (3) customized computing and communication units to operate smart materials, and (4) personalized sensing and machine learning algorithms to enable smart materials to support new interactions. My research is highly interdisciplinary and requires collaborations in various fields such as HCI/CS, ECE, and Materials Science. It brings up new smart materials that can be used to create smart environments (e.g., home and office) to facilitate our everyday life (e.g. cooking).

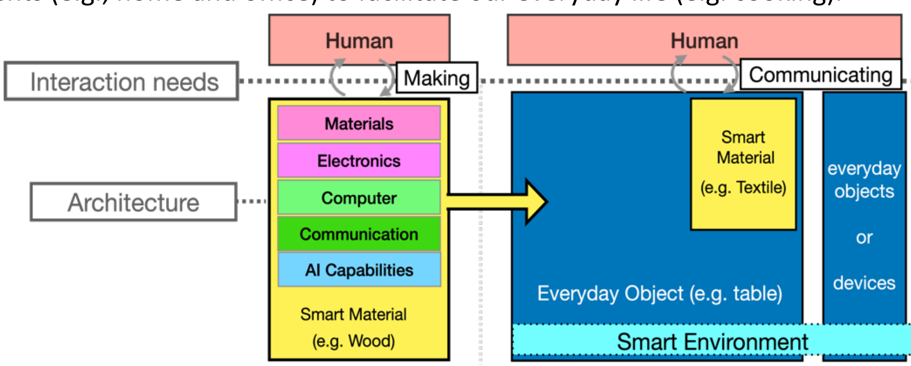


Fig 1. Smart environment can be created using smart materials integrated into everyday objects at large scale. My research approach is need-driven, which first explored interaction needs and develop new smart materials, combining common materials, electronics, computers, communication, and AI capabilities to support the interactions.

PhD Research

To understand what user interactions are necessary for smart materials, I explored a wide range of human-material interactions and concluded with two interaction areas important for smart materials. **The first interaction area is to allow humans to frictionlessly communicate with digital services (e.g., virtual assistant, and TV) in a smart environment through everyday objects made of smart materials.** It includes explicit interactions (i.e. user inputs) and implicit interactions (i.e. user activities) on smart materials. **The second interaction area is to empower people to easily integrate smart materials into everyday objects using established methods.** The common fabrication operations (i.e. making interactions) on the materials, such as cutting and screwing, are in this interaction area.

To allow humans to easily control digital services in a smart environment through everyday objects made of smart materials, I first developed smart materials to support common **explicit interactions** such as touch interactions and midair gesture interactions. For example, ThreadSense (CHI'20) is one of my research projects that enables one-dimensional touch input on a single thread using impedance sensing. This thread can be seamlessly integrated into everyday objects (e.g. cushion) to enable touch everywhere interactions. For instance, a user can touch the symbolic pattern on the sofa cushion made of smart textile to control the smart TV while lying on the sofa. Aside from it, Fabriccio (CHI'20) further extends the sensing capability of touch input to meaningful midair gestural inputs on smart textiles. It uses a pair of textile loop antennas to sense the hand or finger motions based on the Doppler effect. In that project, the antenna types, configurations, transmission lines, and operating frequency were carefully chosen based on the simulation results to balance the complexity of the fabrication of smart textiles and the sensitivity of midair gesture sensing at a 10 cm distance. Fabriccio can enable many applications such as supporting waving gestures as a greeting command or allowing user interactions to occur in the scenarios where physical touch is undesired. For instance, when hands are unclean or busy eating snacks, the user can instead use midair gestures to control the smart TV without physical contact with the cushion or sofa. From these research projects, I also found explicit interaction on smart materials is compelling because it can allow humans to frictionlessly and unobtrusively control smart environments in different scenarios through any nearby object made of smart materials.

Fig 2 shows the smart textiles that can sense touch and midair gestural input to support explicit interactions. a) ThreadSense enables a single thread to locate user touches on the cushion. b) Fabriccio is a smart textile able to recognize midair gestures.

In addition to explicit interactions, I also explore **implicit interaction** on smart materials, which means the human interactions that implicitly change the contexts of uses of smart materials (e.g., placing food on a tablecloth made of smart textiles). Implicit interaction is especially important as it can support smart environments to understand and fulfill humans' intention and needs in the background. To achieve that, I developed a smart textile called Capacitivo (UIST'20) that can recognize nonmetallic items placed on it, such as fruits and different types of drinks. It can be seamlessly integrated into tablecloth to enable smart environments to give recipe suggestions based on the fruit detected by it. In addition, it can also be made as a fabric coaster to enable the diet tracker of drinks for healthcare applications. Capacitivo's prototype is composed of a grid of electrodes, made from conductive fabric attached to a textile substrate in a simple fabrication method. I designed the size and separation between the electrodes to maximize the sensing area and sensitivity. A customized machine learning pipeline is also developed to recognize the items based capacitive footprint sensed by the smart textile. Another project built upon it is a pocket-based smart textile that can recognize a diverse set of objects (e.g. wallet) in wearable conditions. It is made of the integration of four textile sensors (i.e. pressure, capacitive, inductive and NFC sensor). A sensor-fusion machine learning algorithm is built to recognize objects in tight wearable condition. This pocket-based textile can be integrated into a pair of jeans to enable applications such as reminding users of a wallet missing in the pocket. Through these explorations, I also realized that smart materials are also unique to enable fine-grain implicit interactions because smart materials will be everywhere interactions may occur (e.g. pocket) and then be better aware of the detailed context of interactions (e.g. objects in pocket).

Fig 3 shows the smart textiles being aware of the contexts to support implicit interactions. a) Capacitivo is a smart textile able to recognize nonmetallic objects on it. b) Tasca is a pocket-based textile able to sense objects in a wearable pocket.

Finally, to support smart materials to be seamlessly integrated into daily objects at large scale using established methods, I investigated **making interactions**, which generally refer to the common fabrication operations on materials, such as cutting and screwing. Making interaction is crucial as it is also a key for democratization of smart materials**.** However, most smart materials do not afford making interactions, which means smart materials would be malfunctional while suffering fabrication operations. As the first attempt, I created iWood (UIST'22), a smart plywood that can withstand common woodworking operations such as sawing and screwing, and also be capable of sensing vibration for activity recognition. iWood is made of a layer of triboelectric material sandwiched between two layers of electrodes, each attached to a plywood substrate. Unlike the existing sensors based on triboelectric effect, the electrodes of iWood were designed to stagger with each other to avoid short-circuiting caused by fabrication operations. Through a series of experiments and machine simulations, we carefully chose the size of the sensor electrodes, the type of triboelectric materials, and the bonding method of the sensor layers to optimize the sensitivity and fabrication complexity. iWood can be easily used to create everyday objects using established methods. For example, a nightstand can be created using iWood through sawing, drilling and screwing operations. Inherited from iWood's sensing capability, the nightstand can recognize user activities such as taking a book from the drawer or putting it back, which can enable a system to log users' daily habits for healthcare applications. Besides, a cutting board can also be made by laser-cutting iWood. The cutting board can recognize common cooking activities, such as chopping, slicing, and meat to enable new applications for skill assessment and development.

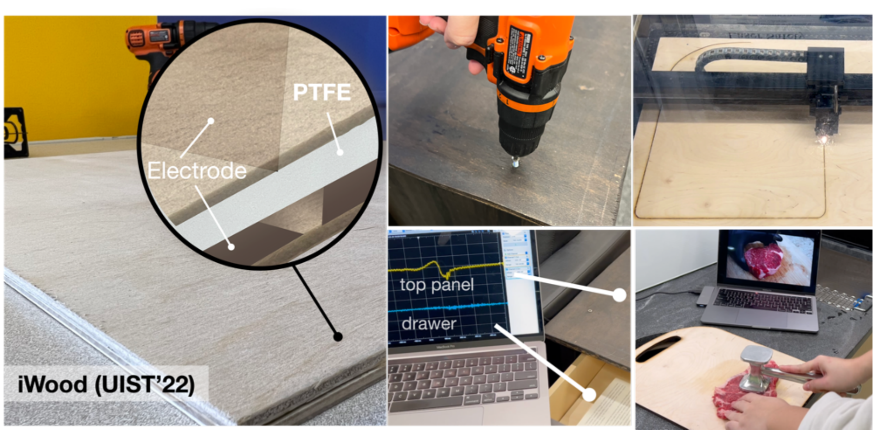
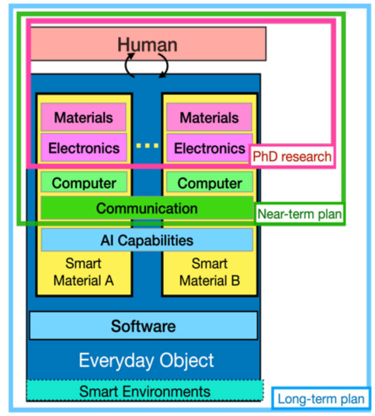


Fig 4. The smart plywood that can support making interactions (i.e. woodworking operations) while remaining functional to sense vibration. It can be used to create a nightstand to log users' daily routine. It can be laser-cut as a cutting board to aid cooking activities.

Future Research Agenda



My long-term research vision is to empower people to easily create a smart environment using smart everyday materials and established methods. To support my long-term vision, I will continue to research human material interactions, especially for the output part. In addition, I will also work on the infrastructure of smart materials to make them practical to use. It will involve using tiny and low-power computing and communication units to operate and coordinate smart materials. On top of it, my vision also requires a low-code software tool to allow people to customize AI capabilities of smart materials and build their applications in smart environment. I describe my near-term and long-term plan below.

Near-term research plan *(circled in green)***:** My PhD research mainly work on the inputs of smart materials, because I assume there would be some existing output devices (e.g. smartphone and TV) in the smart environment. However, it doesn't mean that the output of smart materials is unnecessary, especially for the haptic feedback, as humans likely physically touch materials in interactions. Thus, one of my next steps is to investigate how to provide haptic feedback on smart materials. Some possible solutions could be used, such as textile speakers and shape memory materials and microfluidic actuator. In addition to it, I also plan to work on the practical infrastructure of smart materials in the near future. Previously, I used expensive, bulky and power-hungry microcontrollers for the computing and communication of smart materials, which increases the cost of smart materials, raises form factor issues, and causes massive battery problems. To solve these issues, I will utilize the advancement in low-power computing and secure communication protocol is essential. For example, for large everyday objects such as furniture (e.g. table) and building structures (e.g. floor), it is possible to build a central workstation to connect and power all smart materials together using physical wire connections as they are not moving after the deployment. In the cases, each smart material can just have a minimum computation unit (e.g. transistor) to encode the sensor data in the signals carried in the physical wire connections, operated by the central workstation. But, for smaller everyday objects (e.g. fabric coaster), wireless approach will be preferred because they will be movable. In such cases, I plan to leverage low-power and miniature RF microchip such as NFC/RFID chips to operate smart materials and encode the sensor signals of smart materials in the RF signals returned to a remote central workstation (e.g. RFID reader) in the environment.

Long-term research plan *(circled in blue)***:** Once the infrastructure of smart materials is established, a low-code software tool is needed. For instance, a user should be able to use a tool to customize the AI model to specifically interpret certain contexts based on the composed objects (e.g. a kitchen table specifically sensing food ingredient and cooking activities). In addition to the customizable model, logic flows between smart materials should also be easily controlled in the tool. For instance, a developer can easily set "when the table sense unhealthy combination of ingredients through smart table, the garments made of smart textiles will notify the user with haptic feedback." My experience in building educational tools has equipped me with the knowledge and connections to build such software tool in the future. Once the tool is done, I will collaborate with other domain experts (e.g. doctors) and developers (e.g. IoT developers) in the far future to create smart environments using smart materials. For example, we can create a smart environment to specifically analyze users' habits for dementia or diabetes healthcare applications.