Environmental physical intelligence: Seamlessly deploying sensors and actuators to our everyday life

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ABSTRACT

Weiser has predicted the third generation of computing would result in individuals interacting with many computing devices and ultimately can "weave themselves into the fabric of everyday life until they are indistinguishable from it" [17]. However, how to achieve this seamlessness and what associated interaction should be developed are still under investigation. On the other hand, the material composition, structures and operating logic of a variety of physical objects existing in everyday life determine how we interact with them [13]. The intelligence of the built environment does not only rely on the encoded computational abilities within the "brain" (like the controllers of home appliances), but also the physical intelligence encoded in their "body" (*e.g.,* materials, mechanical structures). In my research, I work on creating computational materials with different encoded material properties (*e.g.,* conductivity, transparency, water-solubility, self-assembly, etc.) that can be seamlessly integrated into our living environment to enrich different modalities of information communication.

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile computing systems and tools**.

KEYWORDS

Physical intelligence, ubiquitous computing, printed electronics, tangible interfaces

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1 INTRODUCTION

To enable an off the desktop world of ubiquitous computing, there should be more computational devices weaved in our everyday built environment. Currently, we still rely on separate smart home devices to construct the networked living environment (*e.g.,* smart speaker). Most of the spaces are only filled with limited number of these smart devices which are meanwhile functionally distinguishable and leave us a gap towards a world that is filled with seamless interaction. We need to rethink how we can computationally design and construct our environment from the material level to provide interaction in a more natural way.

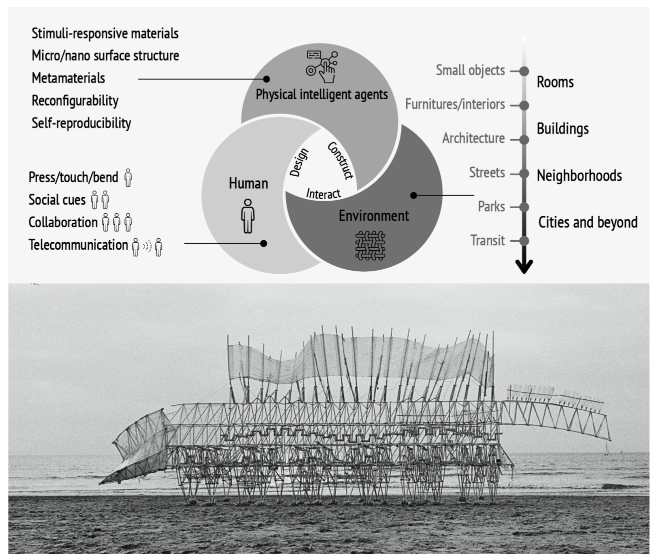

Figure 1: Top row: Physical intelligence encoded environment can provide versatile interaction at different scales. Bottom row: A typical example for physical intelligence around us: Theo Jansen's kinetic art machines moving without any electrical components.

In the bottom Figure 1, a famous art machine from Artist Theo Jansen called Strandbeests is moving on the beach. The entire assembly is the accumulations of stiff plastic tubes without any electronic components and the moving behaviors (*e.g.,* speed, direction) are triggered by the wind as external stimuli and determined by its structure and material property. Such "physical properties determine behaviors" is widely existed in our living environment. Why our door handle is designed curved (*structure*)? Why the anti-fog spray is hydrophobic (*texture*)? And why copper is chosen to make heat sink (*property*)? While even the physicality largely impacts our behavior and determines how we interact with them, they are still inert without computational capabilities and barely looped in this ubiquitous computing world. I argue that one day 3D printing

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chocolates may encode Wi-Fi access password and be securely disposed of by simply eating; a vivid artificial flower made of shape changing materials can deliver emotional interactions; and window glass coated with novel micro structures can selectively show hidden messages when touched. In one example from *Silver Tape* [5], we can utilize the intelligence encoded in the inkjet printed circuit on water soluble substrate (PVA, Polyvinyl alcohol) as a natural water leakage sensor (Figure 2).

To add computation at scale and within versatile materials as described, our everyday environment, from 2D surfaces to 2.5D textures or even 3D artifacts should cover more sensing or actuating capabilities. Throughout my PhD study, I seek ways to build the future computational material encoded environment which consists of "robotic materials" that can sense the environment and deliver information outputs. I mainly ask myself the following three research questions:

(1) What fabrication tools and approaches do we need in order to augment our environment with novel interactions?

(2) What form factors, sensing and actuation mechanisms for the physical intelligent agents should we develop to provide more natural interaction?

(3) How can we better democratize technologies for building this networked environment and enabling everyone to experience it or create their own?

To answer the above questions and truly enable natural human-computer-environment interaction, we need to build computation into everyday physical things as the new type of ambient interface. I construct materials from scratch and build digital fabrication machines (*e.g.,* circuit drawing robots) to augment our environment (RQ1). I apply human-centered approaches to gain a situated understanding from users to ensure the novel physical intelligent interfaces can facilitate the communication as well as understand the cognitive and contextual states from users (RQ2). I also build toolkits and carry out extensive user study to democratize the technologies to make it highly accessible and customizable for all (RQ3).

2 RELATED WORK

Physical intelligence is ubiquitously around us and can be defined as physically encoding sensing, actuation [4], or controlling logic [2]. For example, a micro-structure patterned glass can be sensitive to different level of pressure and exhibits corresponding structural color [8]. Within HCI community, tangible interface related work is also largely overlapping with physical intelligence vision. Researchers have developed 3D printed shape changing interfaces, where its behavior is determined by the printing speed, layer height and also the filament's own material property [1, 16], or utilizing pneumatic chambers with different size and flow rate for different pressure sensing purposes [15]. Most recently, Luo *et al.* demonstrated how to use machine kitting to create different patterned fabrics layers as a skin for soft actuators with versatile sensing and actuating behaviors [11]. Besides, researchers have also tried designing structures internally with unit cells to encode the operating logic for different output mechanical behaviors [7, 9].

Augmentation of our living environment with sensors or actuators from the material level is another body of literature that is related to my research. *Wall++* shows how we can turn our living walls into capacitive sensors to do indoor localization or human gesture detection [20]. *Duco* is a large-scale circuit drawing robot that extends the idea by turning everyday surfaces into not only sensors, but also FM energy harvester or even make 2D cutouts to re-assembly 3D interactive artifact [3]. Besides, *OptiStructures* has shown embedding the fiber bragg grating optical sensors into our living environment as both input sensors and display output [14]. Researchers also demonstrate several other novel techniques to augment our environment with interactivity, including transferring the inkjet printed trace to add LED decoration to windows [5], spraying electroluminascent inks to make interactive bollard for providing audible information [18], or coating lenticular lenses across a lamp with tunable surface color patterns [19].

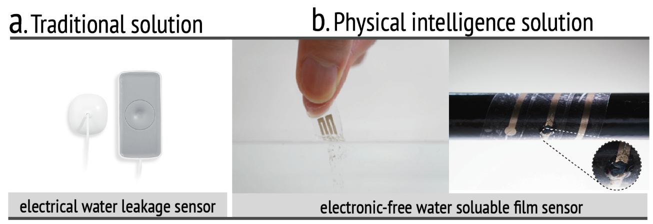

Figure 2: (a) Traditional water leakage sensor made of electrical components. (b) Utilizing the water-soluble feature of PVA sheet to detect water leakage.

3 PHYSICAL INTELLIGENCE ENCODED ENVIRONMENT TO DELIVER DIFFERENT INFORMATION

3.1 Digital fabrication techniques and tools to augment our living environment

In order to further leverage the pervasiveness of IoT devices, we are motivated to develop novel fabrication techniques/tools that can allow the users to manufacture computational capabilities into "things" (*e.g.,* table, chair, etc) that are seamlessly weaved within the environment. Silver Tape is a simple yet novel fabrication technique leveraging the inkjet printing circuits to transfer silver traces from paper onto versatile substrates, without any post-treatment [5]. This method allows users to quickly apply silver traces with a variety of unconventional properties like heat-resistive, water-soluble, high transparency or flexibility (shown in the top row of Figure 3). Human environments are filled with large open spaces that are separated by structures like walls, facades, glass windows, etc. Most often, these structures are largely passive offering little to no interactivity. Duco is a large-scale electronics fabrication robot that enables room-scale & building-scale circuitry to add interactivity to everyday surfaces [3]. Duco negates the need for any human intervention by leveraging a hanging robotic system that automatically sketches multi-layered circuity to enable novel large-scale interfaces. The key idea behind Duco is that it achieves single-layer or multi-layer circuit fabrication on 2D surfaces as well as 2D cutouts that can be assembled into 3D objects by loading various functional inks (*e.g.,* conductive, dielectric, or cleaning) to the wall-hanging drawing robot, as well as employing an optional laser cutting head as a cutting tool (shown in the bottom row of Figure 3).

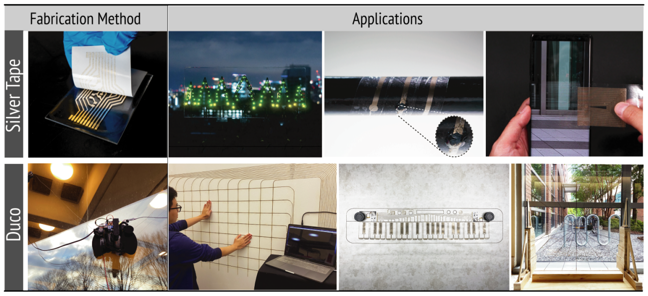

Figure 3: Top row: Inkjet printing and transferring method with substrates of different physical properties for Silver Tape. Bottom row: Duco system and large-scale circuits applications to augment our living environment.

3.2 Form factor, sensing and actuation

With the help of different types of digital fabrication machines that can help with manufacturing the computational devices to augment everyday surfaces, the next research question is what form factor or sensing and actuating capabilities we should encode in our built environment to help deliver different information to bring users closer. Global pandemic made people into the situation experiencing emptiness that none of the existing digital messaging platforms can satisfy. PITAS emphasizes how we can encode tangible information within the environment to bring closeness or other novel interactivities to the users [6]. PITAS is a custom synthetic "robotic sheet", that is embedded with sensing and actuating capability. Like copper tape or other craft sheet materials, those who enjoy DIY-making projects could purchase a roll and use it as needed, apply widely available cutting methods, and connect it with existing hardware parts for self-sensing and actuating scenarios. The uniqueness of PITAS is that the system is capable of conveying different types of physical information about shape, temperature, color and texture to users within a single material matrix and can be easily transformed into different shapes or applied diversely on everyday surfaces (Figure 4).

3.3 Democratization for creating new possibilities

Currently, emerging technologies (*e.g.,* novel sensing, actuating techniques) are still "blackboxed" and " centrolised" which are heavily limited to the research community. To broaden the impact and design space to encode versatile computationality into our environment, we need a decentralized approach. Democratization provides unique opportunities for learning and creating through expressive making. We aim to provide versatile platforms that everyone can innovate on their own, in their own timeframes. Take Printed Paper Actuator as an example, which demonstrates how we can utilize off-the-shelf 3D printing filaments and commodity 3D printers to

Figure 4: (a) Overview of the artificial rose and leaves fabricated by PITAS; (b) Delivering color change (colorless to pink) and flower blossom to partners remotely when missing each other; (c) Delivering the depression by enabling the color change (green to yellow) and leaf hanging down remotely.

make novel shape changing interfaces [16]. Printed paper actuator is a low cost, reversible and electrical actuation/sensing approach that utilizes the bilayer bending actuation and the shape memory effect of the thermoplastic. This project showcased how to simply print a single layer conductive Polylactide (PLA) on a piece of copy paper via a desktop FDM 3D printer to construct a variety of shape-changing paper artifacts that can be deployed in our space (shown in the top left of Figure 5 a.) Besides utilizing highly accessible materials and toolings, through my Ph.D. career, I also pay attention to other aspects including providing design editors to facilitate users' design (Figure 5 c) [12], and apply human-centric approaches to validate the technique (Figure 5 b) [1, 3, 10]. In Figure 5 d, we also show the final artifacts that participants have demonstrated out of the workshop sessions for Silver Tape and PITAS respectively.

4 IN PROGRESS

Aligning with my Ph.D. research direction, there are more ongoing projects to extensively enrich our built environment with more physical intelligent agents.

4.1 Adding interactive 2.5D texture

I previously explored PITAS, which maintains a thin-sheet 2D planar form factor that can be transformed into 3D artifacts, while 2.5D patterns or textures are also widely existed in our environment. One ongoing project tries to locally create 2.5D swelling surface patterns with inherent sensing capabilities. This simple technique will allow users to create a wide range of interactive devices with combined tactile and sensing capabilities. It leverages the a special material which will expand under heating treatment and we introduce a digital fabrication approach to make the heating elements. Unlike most of the interactive devices that are either 2D or 3D, This project is bridging the gap to augment everyday surfaces with interactive 2.5D surface patterns.

4.2 Printing transient water leakage sensor

Physical intelligence covers a broad spectrum of aspects, and utilizing the material property to build novel interaction is a crucial one.

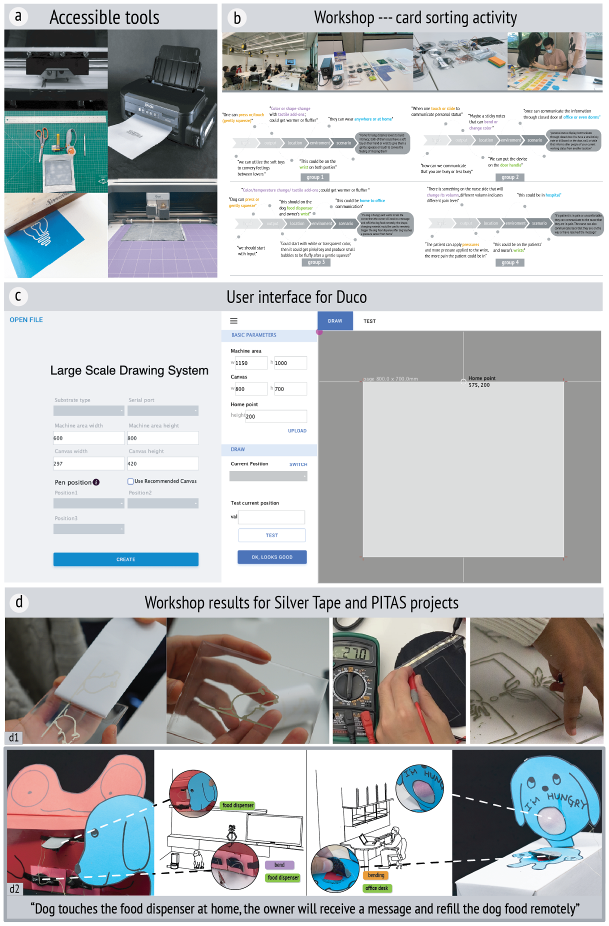

Figure 5: (a) Accessible tools, materials and fabrication methods. (b) Card sorting activity to validate the usability of the technique. (c) Design editor to allow broader spectrum of users to access the system. (d) The artifacts that participants have demonstrated from the workshop.

In the current era of IoT, most of the devices and their circuits are permanent, build upon like semiconducting materials. While the end of Moore's law reminds us that we need to rethink the way of how we construct these devices.

Can one day the physical intelligence encoded materials compensate of even replace the functions of the current electronics? Extending from the water leakage sensor example in (Figure 2), we currently try to innovate a digital fabrication approach to directly print transient electronics. The previous transfer-based method shown in *Silver Tape* is largely limited to the size of the water soluble tape we purchased from 3M company, while we are currently working on an alternative way to directly print conductive traces on PVA or other water soluble sheets without any post-treatment or material limitations. When the film encounters with water, it will be dissolved, and it will allow users to utilize this physical transience for different applications.

5 CONCLUSION AND FUTURE WORK

As a material-application-driven HCI researcher, I consider inventing new fabrication tools, the formfactors and sensing/actuation mechanisms for the physical intelligent agents in the environment. Also, democratization is another key aspect that can greatly broaden the creativity and design space, which will ultimately help with scaling up the production process.

Besides the above projects, I have also planned two future research directions to exemplify my research vision for deploying physical intelligent agents in our living environment. In my future career, I believe advancing sustainable and energy-efficient computing enabled by physical intelligence will be my next move. The current computation of IoT devices are power hungry which is also one of the bottlenecks for having more connected devices within our household. Relying on manufacturing more electronic devices will not be an option because of the termination of Moore's law and Dennard scaling and designing devices with computational materials will be a new way to make it sustainable and scale-able. Another research direction will be exploring how we can automatically construct the environment made of these manufactured computational material devices in various scales or locations. 3D printing house becomes a hot topic these days, while it is mostly focusing on printing the structural components for a house, can we combine other digital fabrication techniques (*i.e.* inkjet printing) to directly print a living space with integrated sensors?

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REFERENCES

[1] Byoungkwon An, Ye Tao, Jianzhe Gu, Tingyu Cheng, Xiang'Anthony' Chen, Xiaoxiao Zhang, Wei Zhao, Youngwook Do, Shigeo Takahashi, Hsiang-Yun Wu, et al. 2018. Thermorph: Democratizing 4D printing of self-folding materials and interfaces. In *Proceedings of the 2018 CHI conference on human factors in computing systems*. 1–12.

[2] Priyanka Bhovad and Suyi Li. 2021. Physical reservoir computing with origami and its application to robotic crawling. *Scientific Reports* 11, 1 (2021), 1–18.

[3] Tingyu Cheng, Bu Li, Yang Zhang, Yunzhi Li, Charles Ramey, Eui Min Jung, Yepu Cui, Sai Ganesh Swaminathan, Youngwook Do, Manos Tentzeris, et al. 2021. Duco: Autonomous Large-Scale Direct-Circuit-Writing (DCW) on Vertical Everyday Surfaces Using A Scalable Hanging Plotter. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 5, 3 (2021), 1–25.

[4] Tingyu Cheng, Guori Li, Yiming Liang, Mingqi Zhang, Bangyuan Liu, Tuck-Whye Wong, Jack Forman, Mianhong Chen, Guanyun Wang, Ye Tao, et al. 2018. Untethered soft robotic jellyfish. *Smart Materials and Structures* 28, 1 (2018), 015019.

[5] Tingyu Cheng, Koya Narumi, Youngwook Do, Yang Zhang, Tung D Ta, Takuya Sasatani, Eric Markvicka, Yoshihiro Kawahara, Lining Yao, Gregory D Abowd, et al. 2020. Silver tape: Inkjet-printed circuits peeled-and-transferred on versatile substrates. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 4, 1 (2020), 1–17.

[6] Tingyu Cheng, Jung Wook Park, Jiachen Li, Charles Ramey, Hongnan Lin, Gregory D Abowd, Carolina Brum Medeiros, HyunJoo Oh, and Marcello Giordano. 2022. PITAS: Sensing and Actuating Embedded Robotic Sheet for Physical Information Communication. In *CHI Conference on Human Factors in Computing Systems*. 1–16.

[7] Jun Gong, Olivia Seow, Cedric Honnet, Jack Forman, and Stefanie Mueller. 2021. MetaSense: Integrating Sensing Capabilities into Mechanical Metamaterial. In *The 34th Annual ACM Symposium on User Interface Software and Technology*. 1063–1073.

[8] Amy E Goodling, Sara Nagelberg, Mathias Kolle, and Lauren D Zarzar. 2020. Tunable and responsive structural color from polymeric microstructured surfaces

enabled by interference of totally internally reflected light. *ACS Materials Letters* 2, 7 (2020), 754–763.

[9] Alexandra Ion, Johannes Frohnhofen, Ludwig Wall, Robert Kovacs, Mirela Alistar, Jack Lindsay, Pedro Lopes, Hsiang-Ting Chen, and Patrick Baudisch. 2016. Metamaterial mechanisms. In *Proceedings of the 29th annual symposium on user interface software and technology*. 529–539.

[10] Yunzhi Li, Tingyu Cheng, and Ashutosh Dhekne. 2022. Travelogue: Representing Indoor Trajectories as Informative Art. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts*. 1–7.

[11] Yiyue Luo, Kui Wu, Andrew Spielberg, Michael Foshey, Daniela Rus, Tomás Palacios, and Wojciech Matusik. 2022. Digital Fabrication of Pneumatic Actuators with Integrated Sensing by Machine Knitting. In *CHI Conference on Human Factors in Computing Systems*. 1–13.

[12] Jung Wook Park, Tingyu Cheng, Dingtian Zhang, Yuhui Zhao, Rosa I Arriaga, Thad Starner, Mohit Gupta, Yang Zhang, and Gregory D Abowd. 2021. Applying Compute-Proximal Energy Harvesting to Develop Self-Sustained Systems for Automobiles. *IEEE Pervasive Computing* (2021).

[13] Metin Sitti. 2021. Physical intelligence as a new paradigm. *Extreme Mechanics Letters* 46 (2021), 101340.

[14] Saiganesh Swaminathan, Jonathon Fagert, Michael Rivera, Andrew Cao, Gierad Laput, Hae Young Noh, and Scott E Hudson. 2020. OptiStructures: Fabrication of Room-Scale Interactive Structures with Embedded Fiber Bragg Grating Optical Sensors and Displays. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 4, 2 (2020), 1–21.

[15] Carlos E Tejada, Raf Ramakers, Sebastian Boring, and Daniel Ashbrook. 2020. Airtouch: 3d-printed touch-sensitive objects using pneumatic sensing. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–10.

[16] Guanyun Wang, Tingyu Cheng, Youngwook Do, Humphrey Yang, Ye Tao, Jianzhe Gu, Byoungkwon An, and Lining Yao. 2018. Printed paper actuator: A low-cost reversible actuation and sensing method for shape changing interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–12.

[17] Mark Weiser. 1991. The Computer for the 21 st Century. *Scientific american* 265, 3 (1991), 94–105.

[18] Michael Wessely, Ticha Sethapakdi, Carlos Castillo, Jackson C Snowden, Ollie Hanton, Isabel PS Qamar, Mike Fraser, Anne Roudaut, and Stefanie Mueller. 2020. Sprayable user interfaces: Prototyping large-scale interactive surfaces with sensors and displays. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.

[19] Jiani Zeng, Honghao Deng, Yunyi Zhu, Michael Wessely, Axel Kilian, and Stefanie Mueller. 2021. Lenticular objects: 3D printed objects with lenticular lens surfaces that can change their appearance depending on the viewpoint. In *The 34th Annual ACM Symposium on User Interface Software and Technology*. 1184–1196.

[20] Yang Zhang, Chouchang Yang, Scott E Hudson, Chris Harrison, and Alanson Sample. 2018. Wall++ room-scale interactive and context-aware sensing. In *Proceedings of the 2018 chi conference on human factors in computing systems*. 1–15.