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Designing Human-building Interfaces for Existing Buildings with Responsive Materials and Mobile Robots

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Recent technological advancements and a growing emphasis on circular and adaptable architectural designs within established built environments have catalyzed innovative approaches in the realm of human–building interfaces (HBIs). HBIs represent a transformative paradigm in architecture and construction, centered on integrating interactive technologies into pre-existing building surfaces. In this study, we investigate the design potential of novel interfaces tailored for existing building surfaces, employing readily available responsive materials and mobile robots. Leveraging accessible interactive technologies, we present a comprehensive review of three early-stage strategies of HBIs: PainterFace, PixelFace, and PixelGreen. These HBIs were aimed at enriching user interaction and experience within their surroundings, fostering spaces that are both adaptive and interactive. Experimental HBIs are constructed using a range of responsive materials and mobile robots, including conductive paints, spherical mobile robots, and unmanned aerial vehicles functioning as "agents" to facilitate communication, interactivity, and responsiveness on existing building surfaces. The multifaceted nature of HBIs showcased in this paper presents diverse approaches with substantial potential to transform established building surfaces into interactive and responsive environments. A comparative analysis of the three HBIs highlights potential implications and future avenues for HBIs. Moreover, the findings of these studies provide valuable insights into design considerations, challenges, and future trajectories for the development and implementation of HBIs on existing building surfaces, ushering in a new era of intelligent and responsive built environments. Future endeavors will focus on further research to address challenges and unlock the full potential of HBIs, ultimately leading to the advancement of enhanced, adaptable, circular, and sustainable architectural designs.

1. Introduction

Contemporary cities and built environments, with their dense populations, offer vast existing surface areas, including walls, facades, and roofs. Beyond their original functions such as fenestration, ventilation, insulation, and protection, these architectural surfaces present

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opportunities for increased interaction with occupants and the public. These additional layers in the built environment serve as architectural interventions, enabling interaction, communication, and information exchange between users and buildings, particularly their surfaces. They also function as responsive architectural interfaces capable of adapting to technological, social, and functional changes within existing structures, including walls and facades.

The integration of building surfaces with interfaces has become increasingly relevant, thanks to digital technology advancements, including interactive media screens and sensors. In the field of human–computer interaction (HCI), interface design plays a significant role in enabling responsive architectural surfaces, such as interactive media facades and screens.(1) Recent changes in HCI interface design have shifted from traditional graphical user interfaces (GUIs), such as keyboards, mice, and monitor screens, to tangible user interfaces (TUIs). TUIs allow users to interact with digital information and visualizations through the physical built environment.(2) These changes represent a novel way to realize Mark Weiser's prediction for the third wave of architectural computing as ubiquitous computing and a 'disappearing computer', seamlessly integrating digital technology into the physical built environment.(3) Despite TUIs offering insight into potential architectural interfaces, they are often limited to small-scale applications and devices and are rarely implemented on larger building surfaces or architectural components.(4)

While large-scale architectural interfaces such as media facades and screens have become commonplace, they predominantly offer one-way visual representation and communication, lacking engagement with users and the public. Moreover, these interfaces often lack flexibility and adaptability to accommodate future technological upgrades or changes, presenting a significant shortcoming. This creates an opportunity to explore alternative methods for designing interactive architectural interfaces that not only enable interactive connectivity but also offer flexibility to respond to diverse future needs, such as interactive public displays and vertical farming on existing building surfaces. These methods have the potential to enhance public engagement and revitalize existing building surfaces with adaptable, flexible, mobile, scalable, and future-proof materials and animated objects.(5)

The recent accessibility and availability of smart materials and mobile robotics offer new possibilities for large-scale interactive building interface design, surpassing rigid, uneconomical, and inflexible display technologies like LED screens and kinetic facades. These innovative materials and devices provide an alternative approach to display and interaction through physical motion, enhancing and retrofitting existing buildings and the built environment.(6) They can be made interactive and responsive, encouraging playful and gamelike interactions with building interfaces.(7)

Current approaches to building interfaces rely on cutting-edge technologies, such as sensors, actuators, displays, and interfaces, to enable dynamic and experiential interaction with building surfaces. Alternative technologies, such as affordable off-the-shelf smart materials and mobile robots applied as building interfaces, hold the potential to create effective public interaction, engagement, and display.(8) In this paper, we explore and review a series of human–building interfaces (HBIs) using off-the-shelf responsive materials and mobile robots to enhance interactivity and engagement of public displays and tangible interactions integrated with existing building surfaces. These approaches involve discrete, flexible, and retrofitted physical interventions, such as conductive paints, spherical mobile robots (SMRs), and unmanned aerial vehicles (UAVs) acting as 'agents' to enable communication, interactivity, and responsiveness on existing building surfaces. Three HBIs, namely, PainterFace, PixelFace, and PixelGreen, serve as early design explorations and preliminary prototypical implementations. They aim to answer the question: "What are the untapped possibilities of HBIs in enabling responsiveness and interactivity for existing building surfaces using responsive materials and mobile robots?"

In this paper, we report comparative outcomes and analyses of these three experimental HBIs within an architectural context, addressing the above question and exploring their potential implications, such as retrofitted architectural interfaces and vertical green walls.

The overall contribution of this paper includes: 1) an overview of a series of HBI mockups with their potential architectural implications; 2) early implementation of HBIs as playful media interfaces and vertical green walls for the existing built environments.

2. Architectural Interfaces and HBIs

2.1 Architectural interfaces

Contemporary existing building surfaces and facades are now capable of serving as interfaces connecting the built environment with its users, thanks to advancements in sensing and display technology. These architectural interfaces play a vital role in shaping user interactions and experiences within architectural spaces. They serve as intermediaries between the human body and the built environment, influencing sensory perception, movement, and spatial experience.(9) This underscores the importance of well-designed interfaces in enhancing user engagement and revitalizing the purpose of existing architectural elements.

Current architectural interfaces find applications in areas such as media facades and HCI.(10) Examples include the BIX facade at the Kunsthaus Graz in Austria(11) designed by realities:united in 2003 and the Tower of Winds media facade developed by Toyo Ito in 1986.(12) These are early instances of large-scale architectural interfaces with digital screens. Recent developments in kinetic facades, such as the Al Bahar Tower project in Abu Dhabi, explore how origami-inspired structures respond to lighting and climate.(13) While both digital media facades and kinetic facades offer valuable insights as architectural interfaces for communication, media representation, and climatic response, they are often integrated into building facades and lack flexibility, adaptability, and interactivity with users. In addition, there is no obvious interactivity and only one-way communication between users and these architectural facades. These shortcomings and hindrance create the potential for further development to enable the adaptation in future changes in technology and functional requirements of large-scale architectural interfaces.

Adaptable and flexible architectural interfaces can be achieved by applying a human-building interaction approach in the existing building structures and surfaces that are potentially enabled with the feasible, upgradable, or even replaceable devices and materials. Off-the-shelf materials and devices such as conductive materials, miniature mobile robots, and UAVs can serve as the "agents" to enable communication, interactivity, and responsiveness of the architectural interfaces. This approach explores the potential and new possibilities of architectural interfaces as HBIs for existing building surfaces.

2.2 HBIs

HBIs have already been explored, primarily in the fields of HCI, building comfort, and energy usage.(14) Projects like the Digital Water Pavilion by Walter Nicolino, Carlo Ratti, and Claudio Bonico, and Pixel Cloud by Jason Bruges Studio provide early examples of HBIs where digital technologies allow participants to interact and change the appearance and display of building installations.(15) However, these installations, while considered HBIs, remain as independent media facades with limited adaptability and interaction between people and the built environment. The implementation of HBIs has the potential to transform the way occupants interact with existing building surfaces, transitioning from static materials to interactive and adaptive interfaces, creating opportunities to enhance HBIs.(16) In this paper, we explore these opportunities through the review of various HBI prototypes developed using novel approaches like physical computing, responsive materials, and mobile robots.

2.3 Responsive synthetic material as architectural interface

One way to explore HBI opportunities is by utilizing simple and cost-effective off-the-shelf synthetic conductive materials as responsive elements. In one design study, instead of using this material in standalone panel-type architectural interfaces, an alternative approach of "painting" the responsive material onto existing building walls was employed to create an interventional HBI. Conductive paint is one of the materials used in this study, as it can be applied to nearly any building surface and serves as a touch sensor owing to its electrical conductivity. Inexpensive and readily available materials such as shape memory alloys (SMAs), piezoelectric films, phosphorescent pigment powder, and translucent silicone rubber are also used as responsive materials, offering various sensing and responsive capabilities for the "painted" HBI.

2.4 Interactive architectural interface and mobile robots

Miniature mobile robots and the rising popularity of UAVs have found applications in various fields, including robotics, engineering, construction, and computer science, since the 1990s.(17) However, few have explored their potential in the architecture industry, particularly in architectural design and human interaction.(18) Today's accessibility and availability of mobile robot and UAV technologies offer architectural designers and researchers new opportunities to explore and develop retrofit HBIs for the existing built environments using novel yet affordable technology. Two design studies mentioned in this paper have adopted this approach to evaluate the feasibility and potential of HBIs designed with mobile robots through early prototyping and experimentation.

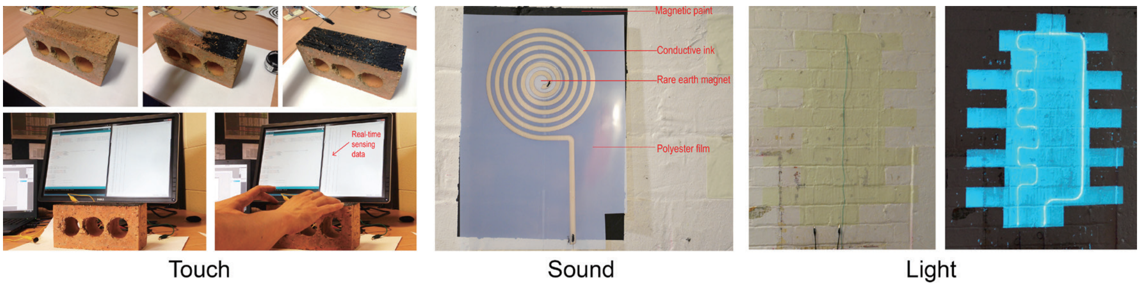
3. Design Studies of HBIs for Existing Built Environments

We initiated three design studies to explore the concept of physical prototypical HBIs. These HBI design studies are adaptable for use in both interior and exterior spaces of existing building surfaces. Each study was tailored to a unique context and implemented using different methods, as outlined in the previous section.

3.1 PainterFace

In the initial design study, we present a straightforward and cost-effective method for transforming existing walls into interactive surfaces through a process akin to 'painting'. This study, named PainterFace, is applied to the existing brick wall of a dark and narrow corridor as a retrofitted HBI. The brick wall at the site of implementation features a stretcher bond pattern, exposing the long, narrow sides of the bricks. Once PainterFace is applied, the previously ordinary and inert brick wall becomes an analog-media HBI capable of interaction. Pedestrians can engage with its touch-, sound-, and light-responsive features, as illustrated in Fig. 1. By retrofitting and applying these features to individual bricks, they serve as both input and output devices, altering the corridor's ambient environment in response to pedestrian input.

The PainterFace interface consists of three retrofitted zones, as depicted in Fig. 2. Zone 1 incorporates a series of tactile sensors coated with conductive materials to detect human touch.



(a) (b) (c)

Fig. 1. (Color online) (a) Touch: The "painted" conductive brick that senses touch data from fingers. (b) Sound: Paperlike planar speaker retrofitted to an existing brick wall. (c) Light: The "painted" luminous skin layer on the brick wall glows in the dark owing to embedded heated SMA wires.

(a) (b) (c)

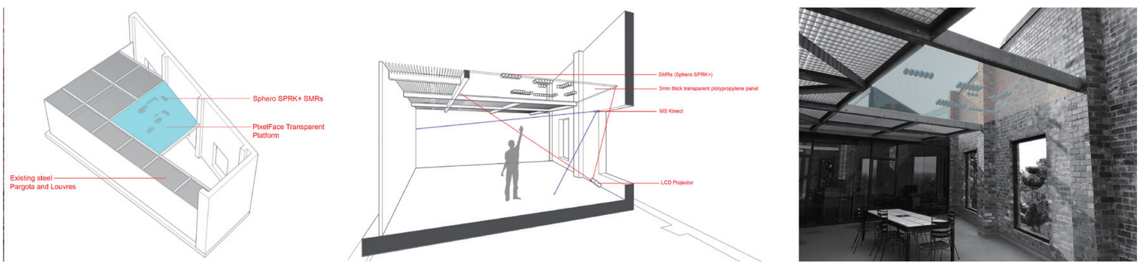
Fig. 2. (Color online) (a) Three different zones (touch, sound, and light) of the PainterFace interface. (b) Existing unaltered wall. (c) Sensing and responsive capacities of PainterFace: touch, sound, and light.

Zone 2, the audio section, is fitted with seamless polyester film speakers that produce sound notes in response to human interaction. The third zone features a luminous skin layer, “painted” with glow-in-the-dark graphical illuminations that respond to stimuli from the first two zones. Through advanced programming, the interaction among these zones is further enhanced, with audio and luminous graphics adapting to the wall’s stretcher bond pattern in direct response to pedestrian interaction. PainterFace serves as an early proof-of-concept for the “painted” HBI, functioning as an experimental implementation to unlock the interactive potential of existing walls. It showcases promising results that provide initial inspiration for future developments in responsive material interventions, potentially rendering every building surface interactive.(19)

3.2 PixelFace

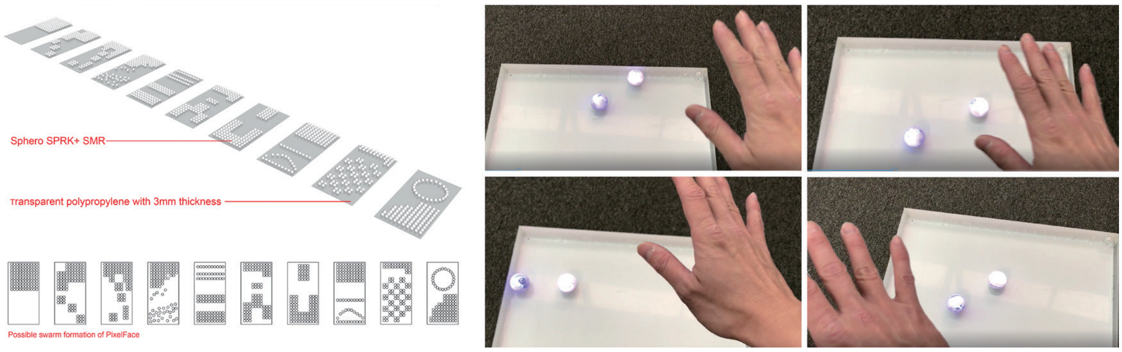
Our second design study, PixelFace, differs from PainterFace in that it acts as a proof-of-concept HBI utilizing off-the-shelf SMRs. Instead of applying PixelFace to vertical walls, it is retrofitted to the flat transparent roof above a semi-open courtyard space, thereby creating an interactive ambient environment, as shown in Fig. 3. The foundational support for PixelFace is provided by a transparent polypropylene panel measuring 4 m in length, 3.36 m in width, and 9 mm in thickness. This panel serves as a smooth horizontal surface, facilitating the seamless movement of each SMR, with light fenestration beneath the courtyard, as illustrated in Fig. 3.

The reliability and straightforward control mechanism of wheel-based SMRs make them the preferred type of mobile robot for developing PixelFace. Sphero was chosen as the off-the-shelf SMR for PixelFace development because of its efficiency, reliability, durability, and programmability. Initially, it was suggested to employ 100 SMRs as the spherical ‘pixels’ of PixelFace to execute various formations and patterns, as depicted in Fig. 4. However, instead of a full physical implementation, only two hacked Spheros were utilized as the physical ‘pixels’ in the early design study of PixelFace. They were integrated with an interactive digital projection of simulated SMRs to create a hybrid ambient HBI. This method of integrating physical and digital projections not only reduces development costs and technical complexities but also enhances the flexibility and scalability of PixelFace to accommodate updates, refinements, changes, and advancements.(20)



(a) (b) (c)

Fig. 3. (Color online) (a) 3D diagram of PixelFace retrofitted on a steel pergola structure and its overall context in an existing courtyard. (b) Cross-sectional diagram to illustrate the overall mockup of PixelFace and the relative placement of each component: SMRs (Sphero), Kinect, and LCD projector. (c) Potential shadow play of PixelFace in an existing semi-open courtyard space.



(a) (b)

Fig. 4. (Color online) (a) PixelFace is formed by the Sphero SMRs on top on the transparent polypropylene surface with ten formations and patterns that could be represented by 100 SMRs. (b) Hand-gesture interaction, through Kinect, with two Spheros as physical 'pixels' performing leader–follower behavior.

The overall design and setup of PixelFace present a feasible implementation through a hybrid approach involving digital projection and SMRs, aimed at achieving applicability and manipulating the ambiance of the existing courtyard space as a horizontal form of HBI, as depicted in Fig. 3. This hybrid setup provides an adaptable and flexible platform capable of accommodating potential changes to facilitate a novel interactive ambient experience for participants. This experience is characterized by changeable performative attributes such as interactive shadow play and lighting, delivered through the varying movement patterns of the SMR lighting.

These SMRs are embedded with a leader–follower algorithm, enabling them to respond to human movements captured by the motion-sensing input device, Microsoft Kinect. The leader–follower algorithm designates one SMR as the leader, whose motion dictates the path for the entire group of follower SMRs that position themselves in accordance with the leader's position and orientation.[21]

In the design study of PixelFace as an HBI composed of a series of SMRs, the preliminary outcomes outline challenging possibilities and potential implications for large-scale horizontal architectural interfaces. This approach not only encourages public interaction with existing buildings using multiple mobile robots equipped with physical motion capacities but also represents an early and promising starting point for HBIs created with mobile robots, as demonstrated through digital simulation and initial physical implementation in Fig. 5. This type of HBI offers a flexible and easily replaceable architectural interface that is considered to be "future-proof" owing to its ability to adapt to changes in technology and requirements.

3.3 PixelGreen

PixelGreen is implemented as a retrofitted HBI on the existing walls of a building, with the aim of investigating the potential of architectural interfaces in addressing the limitations of these surfaces. In the densely populated central area of Hong Kong, as depicted in Fig. 6, a series of potential firewalls have been identified as suitable locations for the installation of PixelGreen.

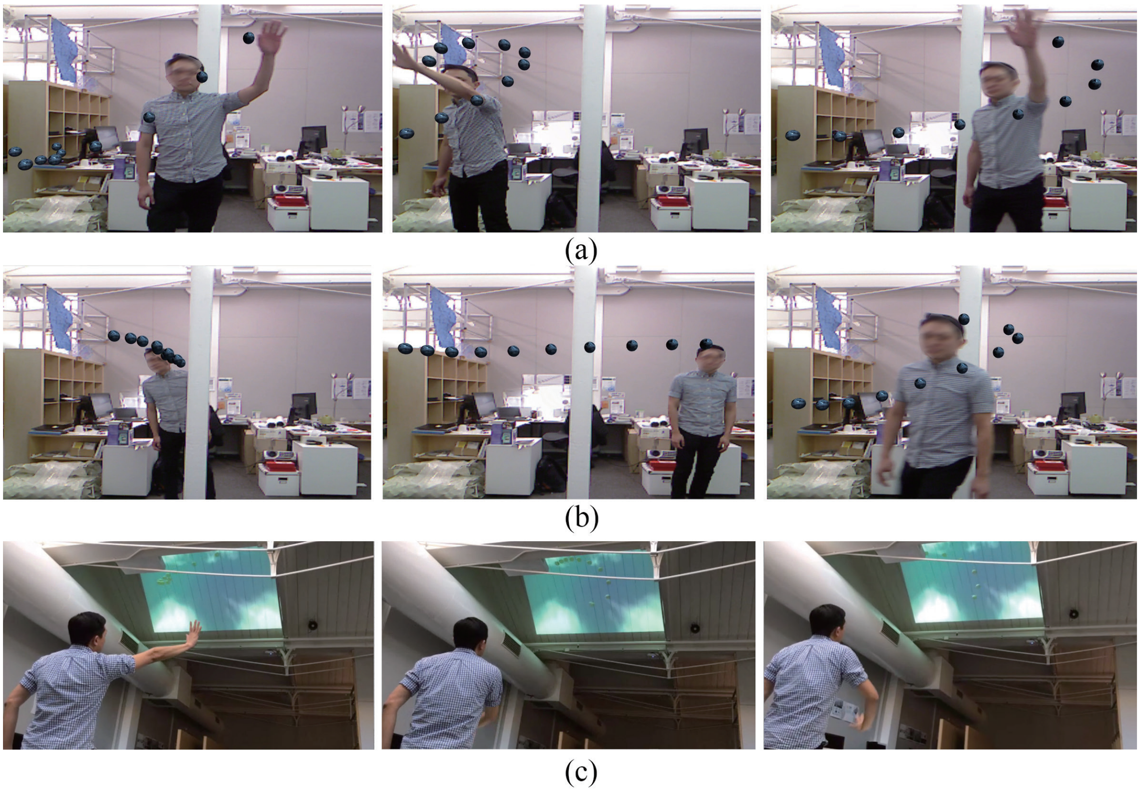


Fig. 5. (Color online) (a) Sequential images of the initial study of natural hand-gesture interaction with digitally simulated SMRs in an augmented environment. (b) Ten digitally simulated SMRs forming a linear spline formation interact with the user's head motion. (c) A digital simulation study of PixelFace involving projection of a courtyard skylight that allows interaction between users and multiple digitally simulated SMRs.

Fig. 6. (Color online) The identified vertical building surfaces (highlighted in green) serves as the 'sites' or 'platforms' for PixelGreen in a dense area of Hong Kong.

These identified firewalls, located on high-rise buildings, offer viable vertical spaces for PixelGreen, enabling it to function as a reciprocal hybrid green media wall system. PixelGreen serves the dual functions of media-related activities and micro-vertical farming concurrently. Its adaptable modular system allows for customization in terms of size and shape, making it suitable for various configurations to accommodate the diverse shapes and conditions of existing firewalls.

The initial concept of PixelGreen is explored through a schematic design study, wherein the mediated content is represented by multiple species of edible plants in different colors. PixelGreen takes the shape of a flexible modular system comprising 25 rectangular "pigeonholes", each serving as an analogue "pixel", capable of hosting various species of edible plants. This modular system offers flexibility in configuration to suit differently shaped vertical building surfaces.[22]

A full-scale mockup of the modular system has been developed as a physical proof-of-concept to evaluate the feasibility of PixelGreen. As illustrated in Fig. 7, the physical mockup involved various experiments and tests, primarily focusing on the simple programming schema for the UAV to sow seed capsules containing edible plant seeds. Although the overall planting

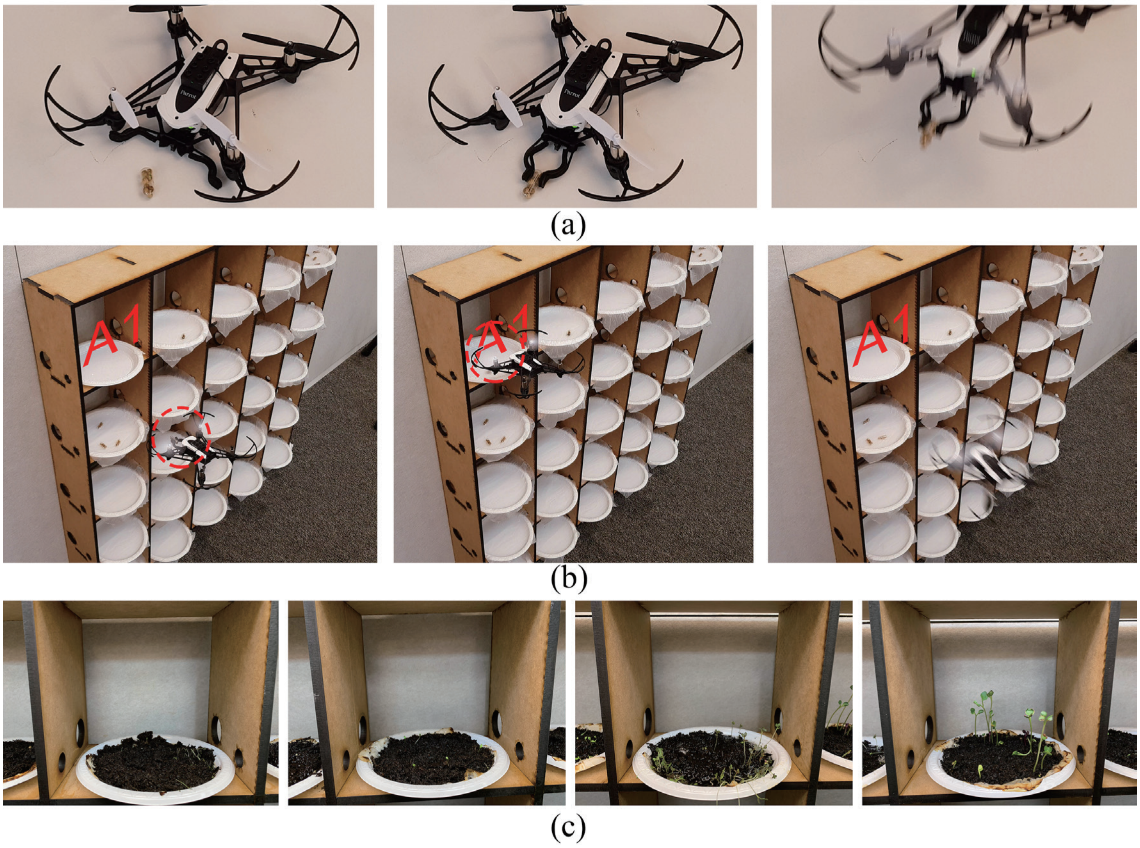


Fig. 7. (Color online) (a) Seed capsule in its designated position and UAV taking off with its grabber closed. (b) Initial test of sowing seed capsule at designated coordinate (A1) using a manually controlled UAV. (c) Screenshots of the growth timeline for edible plants in the fertilized soil of 'pigeonhole pixel'.

cycle of PixelGreen comprises three steps (sow, grow, and harvest), as depicted in Fig. 8, because of resource constraints, only the “sow” step was tested initially.

The programmed UAV autonomously followed a designated flight path to specified coordinates in the “sow” step, based on a straightforward schema. In the initial test, each “pigeonhole pixel” was allocated a specific coordinate to enable the UAV to place the seed capsules. Coordinates A1 and A2 were selected for the early feasibility test of the “sow” step. As shown in Fig. 9, the UAV autonomously completed the “sow” step for two “pigeonhole pixels” (A1 and A2), simultaneously sowing different seed capsules.

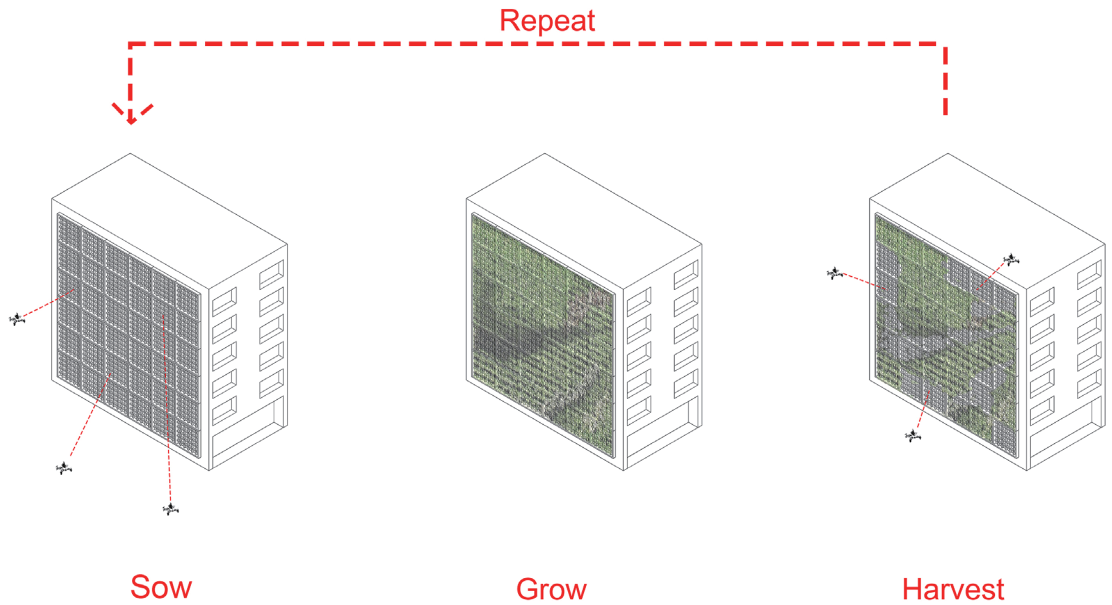
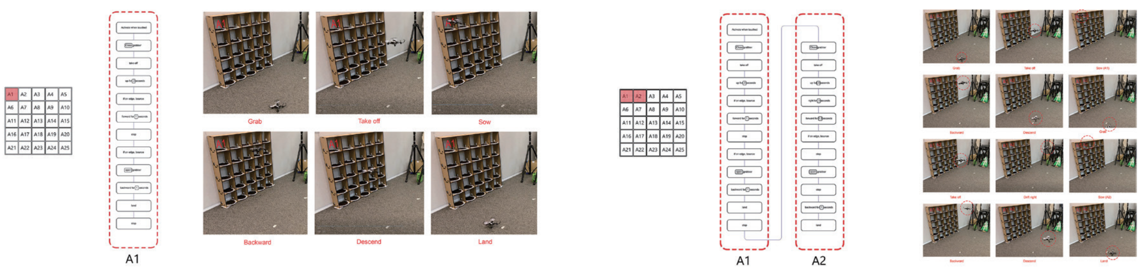


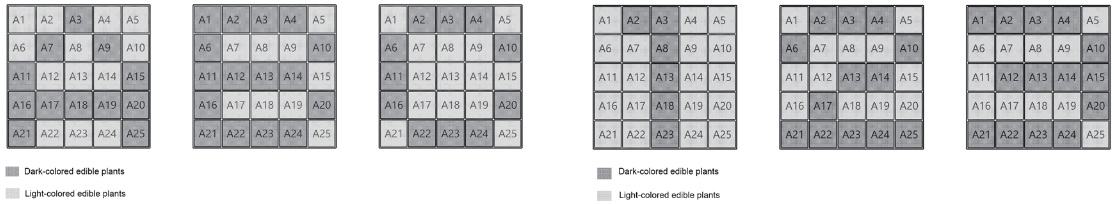
Fig. 8. (Color online) Design of PixelGreen with mediated content formed by multiple species of edible plants within ‘pigeonhole pixels’. Progress through three repeatable steps—sow, grow, and harvest—is controlled and maintained by programmed UAVs.



(a) (b)

Fig. 9. (Color online) (a) Simple schema for the flight path of the UAV as it sows a seed capsule at the A1 coordinate (grabbing, taking off, sowing, moving backwards, descending, and landing). (b) Simple schema for the steps followed by the UAV in sowing the seed capsule to the A1 and A2 coordinates (grabbing, taking off, drifting, sowing, moving backwards, descending, and landing).

The encouraging results of the initial experiment with the physical module of PixelGreen, which involved programmed UAVs, offered valuable insights into representing mediated content using various species and colors of edible plants cultivated in the fertilized soil within the 25 "pigeonhole pixels", as depicted in Fig. 9. For instance, Fig. 10 shows the potential binary representation of text and numbers of edible plants using two contrasting colors (light and dark). Additionally, Fig. 11 illustrates the hypothetical implementation of PixelGreen as a vertical



(a) (b)

Fig. 10. (Color online) (a) Potential binary text representation of dark- and light-colored edible plants. (b) Binary numeric presentation formed through the specific arrangement of dark- and light-colored edible plants.

(a) (b)

Fig. 11. (Color online) (a) Hypothetical implementation of PixelGreen in the dense urban context of Hong Kong. (b) Potential sites that combine vertical and horizontal surfaces (highlighted in green) of existing high-rise buildings in the development of PixelGreen.

Table 1
Details of three design studies of HBI with the attributes to apply under various conditions of existing building surfaces.

Attributes	Three HBIs		
	PainterFace	PixelFace	PixelGreen
Surface	Vertical	Horizontal	Vertical
Material/device	Conductive paint/Polyester film/Transparent silicone rubber/Phosphorescent pigment powder/Shape memory alloy	SMR/Transparent polypropylene panel/Motion-sensing input device	Edible plants/UAV
Sensing	Touch	Hand and body movement	Programmed pathway
Response	Sound and light	Motion and formation of mobile robots	Sow and harvest
Potential HBI applications	Interactive wall and ambient built environment	Replaceable architectural interface/Interactive ambient environment	Media facade/Green wall/ Vertical edible farm

edible farm in a temporary market in Hong Kong, demonstrating its design feasibility within the relevant context. This setup could function as a commercial media facade while also yielding edible plants that could be harvested and distributed within the existing community market.

4. Conclusions

The previous sections provided a review of three distinct but highly relevant HBIs, shedding light on the initial potential and myriad possibilities of HBI implications for existing building surfaces. These studies not only showcase the diverse implications for interactivity within the built environment but also unveil feasible design avenues for the provision of interactive public services, gaming experiences, and artistic expressions in modern urban settings. A comprehensive summary of these studies, namely, PainterFace, PixelFace, and PixelGreen, is presented in Table 1, provides a comparative summary of three HBI design studies and their respective attributes for application on existing building surfaces. PainterFace primarily operates in a vertical orientation, utilizing materials such as conductive paint, polyester film, transparent silicone rubber, phosphorescent pigment powder, and SMA to sense touch and respond with sound and light, making it suitable for interactive walls and ambient built environments. PixelFace, on the other hand, is designed for horizontal surfaces and employs SMRs, transparent polypropylene panel, and motion-sensing input device to detect hand and body movements. Its response involves the motion and formation of mobile robots. PixelFace offers potential applications in replaceable architectural interfaces and interactive ambient environments, focusing on vertical surfaces and utilizing unconventional materials like edible plants and UAVs for following programmed pathways. Its response involves actions like sowing and harvesting, enabling applications such as media facades, green walls, and vertical edible farms. Overall, each design study reveals unique capabilities and potential applications, catering to different conditions and requirements of existing building surfaces.

Building upon this early evaluation, it becomes apparent that each experimental HBI holds promise for vertical or horizontal application on existing building surfaces. The materials and devices employed in developing these prototype HBIs, ranging from off-the-shelf conductive paint to mobile robots and motion-sensing devices, underscore the flexibility and accessibility inherent in their potential applications within the built environment. While all three experimental HBIs exhibit the ability to sense touch and movement, their responses vary, offering interactive feedback in the form of sound, light, and motion tailored to diverse situational needs. These initial proof-of-concept demonstrations highlight the potential of HBIs to foster interactive media experiences, shape ambient environments, and contribute to the proliferation of green and media infrastructure on existing building surfaces. Moreover, they pave the way for the realization of full-scale architectural interfaces that not only hold commercial and social value but also bear environmental significance, further enriching the fabric of urban landscapes.

The initial execution of the three HBI design studies presented here offers preliminary insights into the diverse potential uses of interactive architectural interfaces on current building surfaces, employing easily obtainable devices and materials. While the HBIs examined in this paper signify the early stages of design and implementation, the trials and experiments involving physical modules and prototypes, combined with straightforward programming techniques, demonstrate encouraging outcomes for integrating HBIs into architectural practices. Specifically, they show promise in enhancing the responsiveness and interactivity of the existing built environment.

Comparing the design study of PainterFace with that in Ref. 16 (Sect. 2.2), we find a shared focus on leveraging digital technologies to create interactive architectural media skins and facades. However, while Tomitsch[16] delved into interaction technologies involving sensors and devices, he overlooked the discussion on responsive materiality as an integral component of the "sensor" and interactive media. In PainterFace, we employ "painted" responsive materials both as sensors and output displays, presenting a seamless and cost-effective approach that endows the existing wall or facade with interactive capabilities.

Furthermore, juxtaposing the design study of PixelFace with that in Ref. 5 (Sect. 1), we observe a mutual emphasis on utilizing the physical motion of animate objects to foster public interaction. However, PixelFace takes a step further by exploring the integration of physical and digital animate objects, resulting in a more versatile and adaptable HBI. This approach allows for flexibility in responding to various conditions and accommodates technological updates and requirements seamlessly.

Lastly, in comparing the study of PixelGreen with that in Ref. 18 (Sect. 2.4), we see that both discussions revolve around enabling autonomous mobile robots and UAVs to establish automated frameworks for the outdoor environment of existing buildings and facades. While Ref. 18 was primarily focused on 3D laser scanning and visual data collection, PixelGreen introduces programmed UAVs for maintenance and harvesting of the HBI. This innovative approach transforms HBI into a hybrid green media wall system for existing walls, offering enhanced functionality and sustainability.

These comparative studies and their outcomes mark a pivotal moment in the design evolution of HBIs, ushering architecture and people into a promising era buoyed by the accessibility of cutting-edge advancements in material science and robotic technology. The contemporary landscape will encompass materials and devices endowed not only with capabilities such as sensing, actuation, illumination, and audio but also with the potential to facilitate autonomous performance through seamless integration with AI systems. This convergence sets the stage for the creation of an interactive built environment within existing infrastructure, where building surfaces can dynamically respond to their surroundings and engage with inhabitants in novel and meaningful ways.

The findings of the three studies provide the basis for the initial insights to design feasible alternative HBIs on existing buildings by exploiting the flexibility and adaptability of responsive materials and accessible mobile robotic technologies. The outcomes of these studies also provide valuable perspectives on design considerations, obstacles, and future pathways for integrating HBIs onto current building surfaces, ushering in a new age of intelligent and smart built environments.

Future efforts will concentrate on further research aimed at resolving the remaining challenges and fully realizing the potential of HBIs, thereby propelling the evolution of enhanced, flexible, circular, and sustainable architectural designs. This forthcoming research will encompass the refinement of HBIs integrated with potential AI capabilities to facilitate social and playful interaction between building surfaces and individuals through artistic installations. It will delve deeper into exploring both vertical (walls) and horizontal (roofs) surfaces within the existing built environment. Moreover, comprehensive user studies will be conducted to compare various HBI approaches, gathering feedback and data crucial for evaluating the iterative development of HBI designs. These measures are intended to address any lingering issues and ensure the effective implementation and utilization of HBIs in architectural contexts.

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