PROTOTYPING A HUMAN-BUILDING INTERFACE WITH MULTIPLE MOBILE ROBOTS

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Abstract. Recent advances in miniature mobile robotic research have generated possibilities and potentials in a range of fields such as the military, rescue operations, logistics and education. Within architecture, especially in responsive architecture and architectural interface disciplines, there has been minimal uptake of this technology, and so its full potential and implications have not been fully explored. In this paper, we propose a design exploration of a human-building interface (HBI) with multiple mobile robots serving as 'physical pixels', which investigates the latent possibilities of public interactive displays and media screens, potentially provoking interaction with existing built environments. The outcomes of this paper include an early-stage design study of an HBI prototype, PixelFace, which has been developed with multiple spherical mobile robots and an existing building structure. An early physical implementation of the HBI as an interactive public display with real-time physical movement that encourages playful interaction is also included.

Keywords. Human-Computer Interaction; Human-Building Interface; Mobile Robots; Responsive Architecture.

1. Introduction

Current digital technology and interface design are poised to cause vast changes in the way we interact with our existing spaces and built environment. The field of responsive architecture has been greatly influenced by these changes, enhancing public interaction between human beings and the space surrounding them (Sterk 2006). Interface design, mostly applied in the area of human-computer interaction (HCI), is now considered a crucial discipline that supports the implementation of responsive architecture such as interactive media facades and surfaces (Meagher 2014).

Additionally, recent interface design has been gradually moving from common devices for interacting with graphical user interfaces (GUIs), such as keyboards, mice and monitor screens, to tangible user interface (TUI) devices. TUIs are user interfaces that let users interact with digital information through the physical environment. These represent a new way to realise Mark Weiser's vision of

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ubiquitous computing by integrating digital technology into the fabric of the physical environment (Dourish and Bell 2011). However, most TUIs remain part of small-scale interactive devices, and TUIs are rarely explored in larger-scale contexts such as architecture and the built environment (Ibanez and Naya 2013).

Recent developments in large-scale architectural interfaces, such as media facades and screens, have been limited and undermined by a lack of engagement with users and a lack of flexibility to accommodate future technological upgrades or changes. These hindrances provide the motivation to seek alternative methods for designing a tangible architectural interface as an interactive public display, particularly for existing buildings. This would provide the advantage of increased public interaction and engagement with more flexible, mobile, scalable-and possibly future-proof-physical, animated objects (Ju and Sirkin 2010).

Also, recent research advances in miniature mobile robotics have generated possibilities and potentials in a range of fields such as the military, rescue operations, logistics and education (Tan et al. 2016). Within the disciplines of human-computer interaction (HCI) and architecture, there has so far been minimal uptake of these technologies to fully explore their potential and implications.

Instead of developing architectural interfaces with rigid, uneconomical and in flexible display technologies, such as LED screens, there is the potential to augment existing buildings or built environments. These can be made interactive, responding to physical motion in a way that encourages public interaction with a playful, game-like platform (Huizinga J 1998).

Since engagement and interactivity are the key factors in creating an effective public interaction and display (Ojaja et al. 2012), in this paper we explore different possibilities of physicality and motion that will improve the approachability of and engagement with public displays and tangible interaction devices integrated with the existing built environment. This approach is implemented with discrete, flexible and retrofitted physical interventions such as mobile robotic devices, to create a human-building interface (HBI) formed by multiple mobile robots. The proposed HBI is retrofitted to an existing building, whereby multiple mobile robots form a playful 'game' platform that encourages passers-by to engage and interact with existing building elements.

As a way to structure this approach, we adapt research into HCI and responsive architecture that refers to latent possibilities for action, which we present through a design exploration. PixelFace acts as an HBI that interacts with passers-by through multiple mobile robots serving as physical 'pixels' that perform playful interactive movement and shadow play, which encourages rapid engagement and interaction with existing building elements such as floors and ceilings. The outcomes of this research provoke design reflections on where and how miniature mobile robots can be used to increase user engagement and interaction. Discussion of those re flections is aligned with the field of responsive architectural interfaces and playful ambient environments.

This paper will, then, report on the study of an HBI through an early design exploration and preliminary prototypical implementation. This exploration begins from two enquiries: a) What are the latent possibilities of HBI to encourage public interaction with existing buildings through the use of multiple mobile robots with physicality and motion capabilities?; b) How can interactive public interfaces be designed that incorporate physical motion over on-screen or projection displays?

Overall, the contributions of this paper include: 1) An early-stage design study of a human-building interface prototype, PixelFace, which is developed with multiple spherical mobile robots; 2) Early physical implementation of the HBI as an interactive public display that encourages playful physical movement.

2. Interactive architectural interfaces and mobile robotics

2.1. ARCHITECTURAL INTERFACES

Architectural interfaces are not new, and most of their current design implications and applications are recognised in the areas of media facades and HCI (Mignonneau and Sommerer 2008). Architectural media facades such as the BIX facade in the Kunsthaus Graz in Austria (Elder and Elder 2003) designed by realities:united in 2003, and the Tower of Winds media facade developed by Toyo Ito in 1986 (Chiu 2009) are considered earlier precedents for large-scale architectural interfaces. Although the interfaces took different approaches to design implementation of lighting display, they are each considered pioneers of the architectural media facades developed recently for communication, social interaction and climatic purposes. However, most of these architectural interfaces have remained media facades that do not function as fenestration devices with permeability properties that allow moderation between interior and exterior spaces (Khoo and Salim 2012). Also, lack of flexibility and adaptability in these architectural interfaces becomes the main hindrance for future improvement when the technology becomes obsolete or the functional requirements change.

Flexible large-scale architectural interfaces can be achieved by applying a human-building interaction approach to existing building structures and surfaces, if those interfaces are created with flexible or even replaceable devices. Miniature mobile robots, especially wheel-based spherical robots, demonstrate potential as devices through which to explore the new possibilities of architectural interfaces as HBI. The following subsection briefly discusses this potential in relation to selecting an off-the-shelf spherical mobile robot (SMR) to design an architectural interface.

2.2. DESIGNING ARCHITECTURAL INTERFACES WITH MOBILE ROBOTS

In many fields, including robotics and computer science, applications for miniature mobile robots have been proposed, and their implications investigated, since the 1980s (Dudek et al. 1993). Yet, few have explored their application in the discipline of HCI, let alone architectural design. The accessibility, affordability and advancement of current micro-mobile robot technology, especially in SMRs, allow researchers and designers to explore relevant design implications, especially in responsive architectural surfaces and interfaces.

Figure 1. Left: Sphero programmable spherical mobile robots. Right: Sphero SPRK.

Sphero, as an off-the-shelf SMR, has been selected to explore the development of HBI, instead of creating a mobile robot from scratch, due to its affordability, accessibility and programmable flexibility. Sphero was originally developed as a programmable spherical robot to inspire students and children to learn coding and programming through a creative and inventive robotic platform (Figure 1). Besides functioning as an educational tool for programming, Sphero demonstrates vast potential when programmed with an algorithm and control system. The outer sphere of Sphero is protected by a durable UV-coated polycarbonate shell to prevent damage to its internal devices and mobile mechanism. It is equipped with Bluetooth connectivity up to a range of 30m and has a speed of 2m per second. The built-in LEDs can also be programmed to light up in different colours. These technical specifications of the Sphero make it the most appropriate wheelbased SMR to apply in the physical implementation of PixelFace.

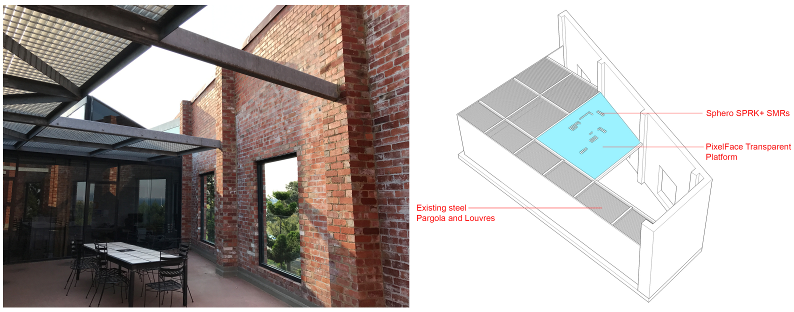

Figure 2. Left: A semi-open courtyard space serves as the 'backdrop' for PixelFace. Right: A 3D diagram of PixelFace retrofitted on a steel pergola structure, and its overall context in an existing courtyard. .

3. Pixelface as human-building interface

PixelFace serves as the proof of concept of an HBI formed from a series of SMRs, which can be applied in the interior and exterior spaces of an existing built environment. The proposed PixelFace is retrofitted above the semi-open space of an existing courtyard to create an interactive ambient environment (Figure 2). The structural base of PixelFace is afforded by a transparent polypropylene panel 4m long × 3.36m wide × 9mm thick, which provides a smooth surface to allow seamless locomotion of each SMR and allows light fenestration below the courtyard.

Due to its advantages of reliability and a simple control mechanism, the wheel based SMR is the preferred type for developing PixelFace. Instead of developing a new type of wheel-based SMR, Sphero was selected due to its efficiency, reliability, durability and programmability. A total of 100 SMRs were proposed to serve as the spherical 'pixels' of PixelFace to perform various formations and patterns (Figure 3). However, only two hacked Spheros serving as physical 'pixels' have been applied in the early use of PixelFace, integrated with an interactive projection of the other SMRs, digitally represented, to form a hybrid ambient architectural interface. This integration of a physical and digital approach not only minimises the cost and technical issues involved in the overall set-up, but also increases the flexibility and scalability of PixelFace to accommodate future developments and changes.

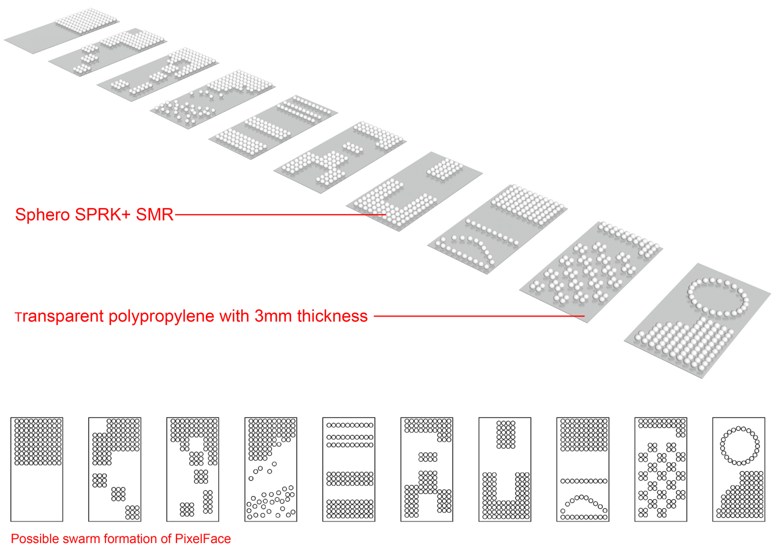

Figure 3. Top: PixelFace is formed from a transparent polypropylene surface and Sphero SMRs. Bottom: Ten formations and patterns PixelFace could represent with 100 SMRs.

The initial set-up of PixelFace reveals the feasibility of its implementation through a hybrid approach with digital projection and SMRs, and its applicability for manipulating the ambience of existing spaces and as a form of horizontal HBI (Figure 4). The hybrid approach creates a flexible and adaptable platform that can accommodate future changes and provides a novel interactive ambient experience for users through its performative attributes of interactive shadow play and lighting, which produce various visual and graphical patterns (Figure 3). These attributes are delivered by the SMRs, which are embedded with a leader-follower algorithm that enables them to respond to human movements as inputs, including hand and body gestures registered by the Microsoft Kinect, a motion-sensing input device. The leader-follower algorithm approach allows one SMR acts as a leader whose motion defines the path for the entire groups of the follower SMRs that position themselves in accordance with the position and orientation of the leader SMR (Madhevan ann Sreekumar 2013)

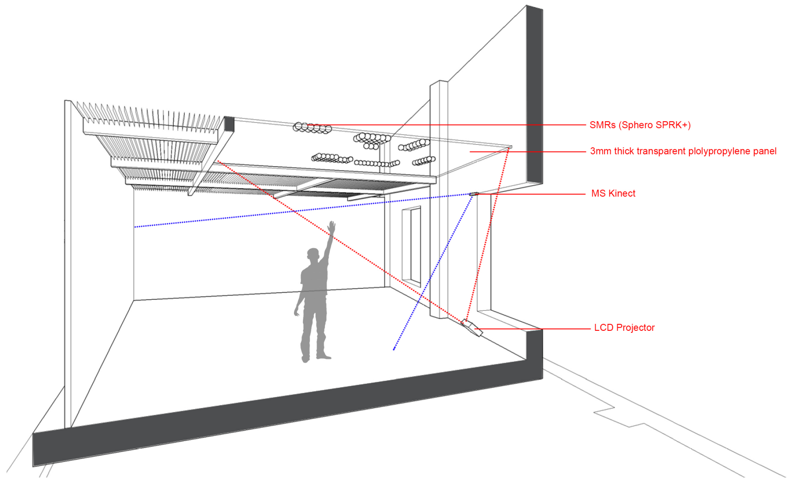

Figure 4. Sectional diagram to illustrate the overall mock-up of PixelFace and the relative placement of each component: SMRs (Sphero), Kinect and LCD projector.

One of the major challenges in developing HBIs with SMRs is achieving cooperative control of multiple robots. The requirements include that each robot's behaviour is affected by its neighbour's actions and that, instead of each robot performing individually, the group must perform as a team (Dong 2011). In the last two decades, many studies have been done and methods proposed to overcome this challenge; solutions explored have included behaviour-based control, a virtual structure for cooperative control and a leader-follower approach (Dong 2011). The following section will explore the initial design of PixelFace around a behaviour-based control method with digital and physical simulation.

4. Design exploration with digital and physical simulation

There are several user interaction (UI) devices that enable interaction with multiple SMRs using the leader-follower approach. Instead of conventional UI devices such as a touchscreen display, keyboard and mouse, a natural user interaction (NUI) device such as Kinect is used for this approach, as it offers a more immersive user experience, usually through natural hand gestures or body movement (Miura et al. 2016). Before the physical simulation of PixelFace with Sphero, a digital simulation of multiple SMRs based on the leader-follower algorithm of the Unity gaming platform was developed as a pilot study and early evaluation of the interactivity aspect of PixelFace in an augmented environment. In this study, the Kinect served as an interactive input device offering natural interaction with digitally simulated SMRs.

Figure 5. Sequential images of the early study of natural hand-gesture interaction with digitally simulated SMRs in an augmented environment.

Figure 6. Ten digitally simulated SMRs forming a linear spline formation interact with the user's head movement. .

4.1. DIGITAL SIMULATION

Multiple simulated SMRs are digitally represented as 10 spheres that perform leader-follower behaviour when interacting with two types of user movement (hand and head) as inputs in the augmented environment. Figure 5 illustrates the initial study of the interaction, in an augmented environment, of the multiple digitally simulated SMRs with natural hand gestures through the Kinect input device. In this setting, the leader of the 10 spheres follows hand movements to perform leader-follower behaviour in a linear spline formation. This behaviour is also able to interact with different inputs, such as head movement, due to the advanced motion-sensing abilities of the Kinect (Figure 6). Both inputs serve as examples of gestures users may actually use to interact with the final physical implementation of PixelFace.

These rather straightforward studies of the leader-follower behaviour for the SMRs, controlled via the Kinect, are followed by a further feasibility study as a prologue to the subsequent physical simulation of multiple SMRs. As an extension of previous studies of user inputs to multiple SMRs in an augmented environment, this prologue study of PixelFace uses a slightly different approach. It projects the simulated skylight of a proposed semi-open courtyard space with interactive simulated SMRs on an existing ceiling, forming a simple study of the ambient qualities of PixelFace (Figure 7). The outcome of this simple approach provides early insights and experience related to PixelFace with a minimum of cost and technical complexity. In this study, the number of spheres in the formation, and their behaviour, remain identical to those in previous studies for consistency. Although this simulated interactive display offers a certain degree of accuracy, and insights into the interactive ambient experience for users in terms of leader-follower formations and visual patterns, there are limitations. It is almost impossible to demonstrate PixelFace's shadow-play and illumination capabilities, which can only be generated by the physical SMRs as they respond in various external and internal lighting conditions.

Figure 7. A preliminary study of PixelFace involving projection of a courtyard skylight that allows interaction between users and multiple digital SMRs.

This simple study using digitally simulated SMRs not only provides some early insights and understandings useful for the further development of the design implementation of PixelFace, but also identifies early challenges to seamless interaction with a group of physical SMRs (Spheros) on a flat physical surface using the Kinect as an input device. Subsequent section of this paper will concisely address these challenges and use a simple approach to overcome them and produce an early implementation of PixelFace using simple leader-follower algorithm from the Unity game-development platform.

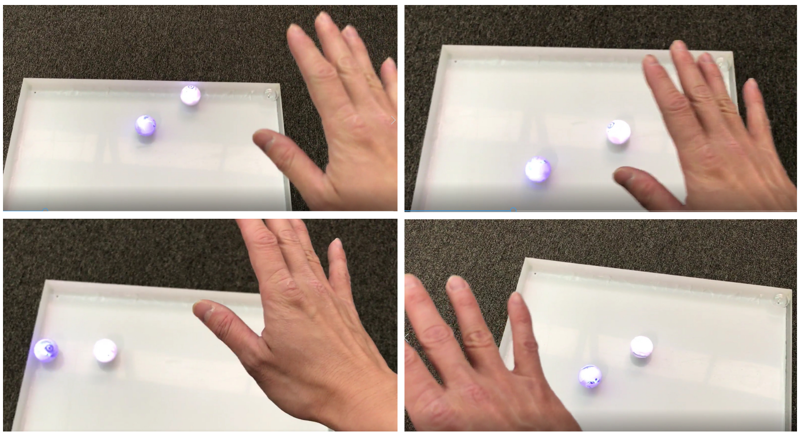

Figure 8. Hand-gesture interaction, through the Kinect, with two Spheros as physical 'pixels' performing leader–follower behaviour.

4.2. PHYSICAL SIMULATION

Instead of a full-scale physical prototype, we initiate a first-stage physical mock-up of PixelFace to reveal the feasibility and applicability of its physical implementation. In this mock-up, two physical Spheros simulate the leader-follower behaviour. This physical simulation is considered a pilot study to evaluate the feasibility of the physical implementation of PixelFace. The two

Spheros serve as physical 'pixels' that interact with hand gestures through the Kinect input device (Figure 8). The outcome of this simulation provides early observations and evaluations of physical interaction with PixelFace constructed with the Sphero SMRs.

Figure 9. Potential shadow play of PixelFace in an existing semi-open courtyard space.

This physical simulation will eventually facilitate a flexible and adaptable platform that can accommodate future changes, which provides a novel interactive ambient experience for users or participants through its performative attributes of interactive shadow play and ambient lighting producing various visual and graphical patterns (Figure 9).

5. Conclusion and future work

Design exploration of PixelFace as an HBI composed of SMRs has provided preliminary yet insightful research outcomes. These outcomes demonstrate the challenging possibilities and potentials of large-scale architectural interfaces in encouraging public interaction with existing buildings through the use of multiple mobile robots equipped with physicality and motion capabilities. This approach has been proposed to deliver an early and promising starting point for HBIs created with mobile robotics, through digital simulation and an initial physical implementation. This type of HBI could provide a flexible and replaceable architectural interface for existing buildings, which might be considered 'future-proof' through its ability to adapt to changes by aligning with technological advancements to provide updated functions. Future work will include a full physical implementation of PixelFace and evaluation through a limited user study to further validate the potential implications of PixelFace as a public HBI.

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