RETHINKING AND DESIGNING THE KEY BEHAVIOURS OF ARCHITECTURAL RESPONSIVENESS IN THE DIGITAL AGE

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Abstract. In the late 1960s the architect Nicholas Negroponte introduced that the physical environment could exhibit reflexive and simulated behaviours, an idea that has since been widely explored. Despite of this wider interest, there is not, however, a systematic approach to understanding architectural responsiveness in the digital age. This paper aims to provide a formal way to facilitate designing smart and interactive artificiality in the built environment. This paper presents a conceptual framework, through exploratory studies on recent architecture, highlighting four key behaviours: (1) tangible interaction, (2) embodied response, (3) ambient simulation, and (4) mixed reality. In addition, two essential enablers, collectiveness and immersion, are proposed to enhance these key behaviours. This framework can be used as a tool to systematically identify and characterise the responsiveness of “responsive architecture”. The creative mixtures of the key behaviours will contribute to the development of unique responsive environments.

Keywords. Responsive architecture; Responsive behaviour; Interactive art; Negroponte.

1. Introduction
The evolution of communication and networked technologies is rapidly changing our world, redefining the roles of, and access to, digital information. These progressive changes have significantly challenged the traditional values of the physical, social, and economic aspects of the world. In architectural science and design, specific examples such as ubiquitous computing, are used to embed microprocessors into everyday objects so that they can directly store and proactively communicate information. The use of advanced computational design and manufacturing technologies allows architecture to be more sensitive and responsive to human needs. Moreover, the convergence of wireless and sensor networks, advanced electronics and materials enables new types of interaction between humans and their environments. These ongoing technological
developments, design applications and philosophical debates have been loosely studied since the late 1960s, and are today more closely associated with the concept of “responsive architecture”.

More recently, ideas and prototypes of responsive architecture have drawn increasing interest from researchers, practitioners, artists and even the public. However, a critical understanding of the subject area as a whole is still largely missing. In particular, there is a lack of a systematic approach to effectively design smart interactive artificiality in the built environment. There is also a lack of cohesive guidelines for design practice to make full use of new ambient and ubiquitous interfaces.

To address these gaps, this paper provides a formal way to facilitate designing responsive architecture. This research firstly reframes responsiveness in the built environment and secondly develops four key behaviours of responsive architecture in the digital age. These behaviours are (1) tangible interaction, (2) embodied response, (3) ambient simulation, and (4) mixed reality. Through four exploratory studies, this paper examines and demonstrates the key behaviours that responsive architecture exhibits. A conceptual framework is then presented, identifying two essential enablers, collectiveness and immersion, to enhance the key behaviours. Finally, this paper concludes with a discussion about how the framework is applied to systematically build responsive architecture from hand-held applications to anonymous networked environments.

2. Reframing responsiveness in the built environment

“Responsive architecture” is a type of architecture that can change its form in responses to changing conditions (Sterk, 2005). Related ideas including Brodey’s soft architecture, Negroponte’s architecture machine, and soft architecture machine (Brodey, 1967; Negroponte, 1969; 1975) are still valid means to explore responsive architecture. “Responsive”, being adaptable or reactive, is when the environment takes an active role, initiating different degrees of changes. Responsive architecture could be a result of complex or even simple computation, or so-called “trivial-but-serious computing” (Negroponte, 1975). The idea of being responsive in this sense is distinguished from being flexible or manipulative.

Soft architecture machine was Negroponte’s experimental attempt to build a theory of responsive architecture as well as to design it, using reflexive and simulated behaviours. Negroponte proposed some examples for the first behaviour, further considering self-organising controllers, recognising mood and the enhancement of mutual involvement, while he also realised that the gestural nature of reflexive responses was still hard to imagine. The second, simulated response, is relatively easy to construct within a “simulatorium” (Negroponte, 1975). Underlying these two types of behaviours is a theoretical framework to effectively build responsive architecture, but also facilitates the understanding of the recent evolution, which further produces a variety of architectural responses. They can be used to explain and design emerging interactive, informative behaviours in the built environment.

Advances in computation have significantly enabled the emergence of robotics
and Artificial Intelligence (AI) technologies. Sensory interaction would be a fundamental behaviour explaining responsiveness. For example, audiences in many interactive art exhibitions actively participate in the interactive process of an artwork. The audience is not a passive one, but an active part of the artwork. They become the listeners as well as the composers, conveying a similar process of self-organising behaviours in architecture. This creates two-way simultaneous communication. Effectively, process replaces product, just as system supersedes structure (Ascott, 1969). That is, as art becomes a form of behaviour, the built environment can be software beyond hardware. These sorts of behavioural effects can influence individuals, communities and cultures connected by continuous sensory data to dynamic architecture. This is one potential way that responsiveness in the built environment may arise in the digital age (Kolarevic, 2004). Thus, responsive architecture can be regarded as a dynamic built environment interacting with constantly changing bits captured by ubiquitous sensor networks.

Architecture was often socially framed in its long history and has recently become an operable equipment, e.g., home automation and smart home (McCullough, 2005). Although computing was traditionally separated from socially framed architecture, architecture has since combined with computing to form both inhabitable and operatable environments. The high flexibility of the urban system, combined with the fantasy of a responsive environment capable of feedback, was symptomatic of the 1960s belief that inhabited spaces could be rendered adjustable to the changing needs of their inhabitants (Colombino, 2012). In the meantime, since Negroponte’s conceptual development of responsive architecture, computers have become faster, cheaper, smaller, and capable of being injected into a very small object. Pervasive computing, also called ubiquitous computing, is realised by embedded microprocessors and sensors in everyday objects, buildings and environments. It is globally networked and gradually inserted into “everything”. Thus, everyday devices and objects have become the Internet of Things (IoT).

Kroner (1997) identified the potential of transforming the built environments from a collection of static objects into a world of dynamic and interactive built forms. Emerging architectural technologies enable representing and facilitating a complex set of personal non-linear interactions. That is, architecture has become information dense, real-time interactive and constructive (Yoon, 2008). It exists in a “thick air” (Velikov et al., 2012) of information and interaction surrounding us. In order to explore these sorts of responsive processes in the digital age, this paper proposes four key behaviours as categorised in Table 1.

<table>
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<tr>
<th>Table 1. Reframing key behaviours of responsive architecture.</th>
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<tr>
<td>Reflexive</td>
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<td>Tangible interaction (Hornecker and Buur, 2006)</td>
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While tangible interactions and embodied responses evolve out of Negroponte’s reflexive behaviour, his simulated behaviour can be extended...
to ambient simulation and mixed reality in the current digital age. Reframing key
behaviours is designed to critically understand recent innovative responsiveness
as well as to provide conceptual directions for explanatory research on responsive
architecture, as discussed in the next section.

3. Four key behaviours of responsive architecture

This section illustrates four key behaviours of responsive architecture through
a critical literature review and case studies. These case studies demonstrate
each behaviour and have been conducted on artworks selected from various
interactive art exhibitions, including the Borderless Reality exhibition supported
by International Symposium on Mixed and Augmented Reality (ISMAR) 2010,
Incheon International Digital Art Festival (INDAF) 2010, Vivid Sydney 2014,
19th and 20th Biennale of Sydney, and interactive systems reported in recent
literature.

3.1. TANGIBLE INTERACTION

The first key behaviour of responsive architecture is tangible Interaction. This has
been widely investigated in the field of Human Computer Interaction (HCI) under
the topic of Tangible User Interfaces (TUI). Ullmer and Ishii (2000) described TUI
as “giving physical form to digital information” that can be understood as certain
responses in the environments reflecting on their surrounding contexts. Hornecker
and Buur (2006) extended it to social interaction. By contrast, our exploration
starts with the “graspable interface” (Fitzmaurice et al., 1995).

Tangible interaction starts by tangible manipulation that relies on material
representations with distinct tactile qualities. Under this, the physically
manipulated interactions are often enhanced by ubiquitous and mobile computing
to support the so-called “space multiplex design”. For example, The Wikitude
world browser, introduced in 2008, projects local information such as landmarks
onto the camera view of a smart phone. This kind of AR has already been
commercially used in the context of Social Network Service (SNS). With the
support of this social context, this new responsive behaviour can realise the sharing,
collaboration, and interactivity of personalised contents, which can encourage and
evoke collective intelligence.

3.2. EMBODIED RESPONSE

Embodied responses are often exhibited in a ubiquitous environment that blur and
merges both physical and digital spaces. The design of these smart environments
is, therefore, closely supported by many emerging technologies: pervasive and
mobile computing, sensor networks, robotics, multimedia computing, middleware
and agent-based software (Cook and Das, 2007). Negroponte also predicted
the integration of computing into the built environment and highlighted that
context recognition would be an important component of responsive architecture.
Emerging architecture that embodies responses can recognise users’ behaviours
and needs through the context-aware inference, and then provides suitable,
personalised services (responses). Embodied interaction (Dourish, 2004) relates
to embodied cognition focusing on unconscious or intuitive interactions in space. It further highlights human input and output mechanisms in a “human-machine system”. This phenomenon can also be interpreted in terms of two components - spatial interaction and embodied facilitation - derived from Hornecker and Buur’s framework. Spatiality is an inherent property of a tangible interface and interaction and facilitation are embedded and situated in physical space, and users need to move in real space when interacting. Interactions are not restricted to touching and moving objects in space, but rely on moving one’s body (Hornecker and Buur 2006).

Embodied response, in responsive architecture, is highlighting a kind of spatial interaction, which is accommodated in physical space and operated in software space. Ishii and Ullmer (1997) introduced the term ‘tangible bit’, to represent interactive surfaces, coupling of bits and atoms, and ambient media, in which computational power is seamlessly integrated into the objects and environment. As a result, computers have “disappeared”, but computation is embedded everywhere (Weiser, 1991). After implementing the computing infrastructure, the question of how to exhibit appropriate architectural responses is a core issue for responsive architecture.

3.3. AMBIENT SIMULATION

Ambient simulation creates immersive virtual environments enclosing us in architecture and the associated virtual reality (VR) and AR devices. These sorts of responsive environments often adopt wearable devices or large displays that isolate the users from the real context, and place them into a virtual or augmented realm. Examples can include VR/AR eyewear like the Google glass, which can be considered as a more contemporary and economical version of Sutherland’s head mounted display, but most ambient simulation includes the use of large displays and surrounding interfaces. Many VR/AR systems - e.g., CAVE system, iDome, and VR museums - have typically supported the interactive and immersive aspects of ambient simulation.

The level of immersion can range from non-immersive ones (i.e. desktop systems) to more immersive systems varying on the level of invasiveness (wearable devices are considered more invasive than non-wearable ones). Ideal VR systems would be enabling both non-invasive immersion and natural interaction. Carrozzino and Bergamasco (2010) highlighted that VR systems allowing for naturalness recognise natural human behaviours through sensor networks (such as motion-capture devices and speech-recognition systems). That is, ambient simulation seeking for high immersion and a more direct correspondence with users’ actions needs to consider natural interaction - similar to ‘embodied response’ discussed above - rather than non-interactive or mediated interaction.

On a different scale, massive light projections, like “Vivid Sydney”, largely occur outdoors in many cities. These light projections, often on the facades of large buildings, are mostly a one-way interaction, but can also provoke sensory immersion because of the massive scale of the ambient projections. For example, “Play Me at Customs House” for Vivid Sydney 2014 projected a series of gigantic
images onto the outer skin of the Customs House in Sydney. Large-scale simulation of this type can generate a high level of immersion, in spite of limitations of the interface for projection and interaction. Pedestrians are often struck by the “massiveness” of such installations, which can arguably be defined as an alternative ambient simulation.

Ambient simulation originates from Negroponte’s simulated behaviour, which is often an easier and more economical way to realise responsiveness in the “hard” architecture. In this context, we highlight both embodied interaction and immersion as two important factors to effectively facilitate this type of simulated behaviour. The future of ambient simulation should go beyond supporting the natural responses to static or pre-recorded/defined visualisation, but also allow for real-time simulation that is addressed in the next section as “mixed reality”.

3.4. MIXED REALITY

Mixed reality refers to real-time interaction and registration in the digital world across the boundaries between the real and the virtual. Milgram and Kishino (1994) defined it with reality-virtuality continuum ranging from augmented reality (discussed above as AR) to augmented virtuality. Augmented virtuality can be considered as a kind of ambient simulation for the virtual environment, while the seamless responsiveness of the AR environment is a characterised feature of mixed reality.

As a critical survey on this field, Azuma et al. (2001) identified nine areas for consideration when commonly adopting AR environments, which include applications for responsive architecture. Mixed-reality environments build interactive relations between persons, objects and locations, using ubiquitous and mobile computing, and overlay computer-generated visualisations and realistic visualisation in the physical world. Such systems connect the built environment with geometric information as well as virtual citizens through the social network. “SLARIPS” (Second Life Augmented Reality in Physical Space) project (Stadon, 2009) represented one such attempt to extend the Second Life virtual community into mixed reality.

More recently, the advent of the smart phone has extended and personalised mixed reality. “EYEPLY” (Hurwitz and Jeff, 2009) allowed for personalised marketing and promotion of products and services to individual users at stadiums, parks, conventions or shopping malls to the individual displays of smart phones. There are further mobile applications operating through Location-Based Service (LBS) and SNS. When presented through smart phones, mixed reality is often associated with tangible interaction, through the direct input and manipulation of these mobile devices.

Most cases, nevertheless, use more conventional architectural surfaces as projection screens for mix-reality environments. For example, "Mirror Scrutinizer", developed by V2_Lab, projects two facial images - one is a physical audience’s face and the other is a corresponding facial image in a digital database - onto a glass wall (Figure 1.a). Biometric video-analysis software is used to support the matching. In contrast, "Positive Feedback", one of the key interactive
installations for Vivid Sydney 2014, projects participants’ bodies at various scales in unfamiliar settings, featuring multiple shadows (Figure 1.b). Audiences enjoy dancing and jumping in front of the wall screen due to such interactivity. Although the installation does not show the common mixture of real and virtual images, the participants’ transformed silhouettes enable responsiveness and therefore supports the audiences’ engagement. Ideas demonstrated in these mixed-reality applications, can be easily adapted for different architectural surfaces. This mixed reality has also been used for the immersive collaborative design environment (see Figure 1.c), which generates a new augmented, immersive design space.

4. A conceptual framework

As demonstrated in Section 3, the convergence of wireless technologies, advanced electronics and materials, as well as sensor networks has enabled new types of everyday experiences in the built environment. With Artificial Life (Langton, 1995), for example, local interactions and self-organising behaviours in architecture, enable individuals to seamlessly interact with the environment, such that the four responsive behaviours discussed above can emerge. In response, this section proposes a conceptual framework for understanding and evaluating these responsive behaviours (Figure 2) for the development of responsive architecture.

Each behaviour independently has its distinct responsive phenomenon in architecture, but reflexive-originated behaviours often exist together with those of ambient simulation and mixed reality. For example, tangible interaction often adopts mixed reality to emphasise spatial experience through mobile computing. Ambient simulation often becomes more pervasive through embodied responses, the so-called “naturalness”, using ubiquitous computing. Thus, the creative mixture of the four responsive behaviours can enhance the experiences in responsive architecture.

The four responsive behaviours are amplified further by two essential factors: collectiveness and immersion. Collectiveness here refers to the collective responsiveness to architecture, either at a varying range of spatial scales from a very small component (e.g. nanomaterial) to an entire urban area, or through from multiple to massive number of users’ participation. “Collective intelligence” highlighted the reformulation of design practices via networked communication infrastructures as well as the development of responsive environments as new
Collectiveness is not the simple aggregation of individuals, but the conjunction of the social network embodied in the environment (Halpin, 2008). The socially extended cognition is mediated by the interactive World Wide Web and updated by users’ collective authorising applications (Bruns, 2008), which can often be interfaced with hand-held devices supporting tangible interaction. It is located in the network of relationships that the individual has with the external environment and other individuals, thus focusing on the role of embodied interaction.

On the other hand, immersion is another quality pursued by responsive architecture. The interaction between sensory stimulation and environmental factors encourage participant involvement and enable immersion (Witmer and Singer, 1998). Immersion can be enhanced through “stimuli from reality”, “sensory modalities”, “field of view” and “display resolution” (Slater and Wilbur, 1997). Thus, immersion can improve the quality of ambient simulation and mixed reality. In addition, the informative behaviours based on the relationships between various entities in the environments can evoke ‘context immersion’ beyond the conventional sensory immersion.

5. Conclusion
Negroponte’s reflexive and simulated behaviours, conceptualised more than four decades’ ago, has evolved into new responsive behaviours supported by new technologies such as ubiquitous computing and mobile computing. The conceptual framework proposed in this paper facilitates the current exploration of four key behaviours for responsive architecture: tangible interaction, embodied response, ambient simulation, and mixed reality.

With the rise of responsive architecture, our everyday experiences are getting
closer to those illustrated in Langton’s Artificial Life. For example, with embodied response, seamless responsive behaviours can be exhibited in the built environment through context awareness. Responsive architecture generally requires incorporating sensory data into a central inference system to correctly interpret our needs or contexts and provides appropriate responses managed by the central controller. The architectural responses can then be distributed into small components, i.e. smart materials or nanomaterials, spreading across the environment. Responsive capacity is therefore embedded in the structure of the material or surface itself. This kind of set-up also allows for distributed (or networked) computation through a suite of building components that enables their collective responsiveness.

The main goal of most responsive architecture is to develop a proactive and performative environment based on the direct or indirect communication between people and architecture. There is obviously a two-way simultaneous communication, from people to architecture (P2A) and from architecture to people (A2P). The former has been widely researched with a focus on home network and context awareness, but the latter has still not been adequately explored due to “hard” architecture. In this regard, the two simulated behaviours in the framework have potential to improve A2P communication through different sensory responses such as visual, auditory, and/or kinetic simulation. Of course, architecture has already been accommodating various “responsive skins” such as performative building surfaces, Kinetic environment-responsive interior envelope systems, and other smart materials. Nonetheless, these behaviours of ambient simulation and mixed reality will enhance the experiences in responsive architecture.

The four key behaviours identified in this exploratory research often overlap to amplify the responsiveness. There is a close association between embodied response and ambient simulation, supported through ubiquitous computing. Tangible interaction is also strongly related to mixed reality through the use of both AR and mobile computing. Different combinations of these key behaviours for different desired effects, is an open question for the future design of responsive architecture. In addition, collectiveness and immersion add two important spectrums to consider responsive behaviours. The conceptual framework can be used for a formal tool to clearly identify and understand desired behaviours for effective design of responsive architecture. In order to successfully develop responsive architecture, we also require further investigation on, and engagement with, engineering challenges, specifically structural, mechanical and material technologies of the built environment. The framework therefore is a crucial starting point for understanding and designing responsive architecture that still requires significant research into various related transdisciplinary fields.

References