# Interactive Architecture: Exploring and Unwrapping the Potentials of Organic User Interfaces

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## ABSTRACT
Organic User Interfaces (OUIs) are flexible, actuated interfaces characterized by being aesthetically pleasing, intuitively manipulated and ubiquitously embedded in our daily life. In this paper, we critically survey the state-of-the-art for OUIs in interactive architecture research at two levels: 1) Architecture and Landscape; and 2) Interior Design. We postulate that OUIs have specific qualities that offer great potential for building interactive interiors and entire architectures that have the potential to –finally– transform the vision of smart homes and ubiquitous computing environments (calm computing) into reality. We formulate a manifesto for OUI Architecture in both exterior and interior design, arguing that OUIs should be at the core of a new interdisciplinary field driving research and practice in architecture. Based on this research agenda we propose concerted efforts to be made to begin addressing the challenges and opportunities of OUIs. This agenda offers us the strongest means through which to deliver a future of interactive architecture.

## ACM Classification Keywords
H.5.m Information Interfaces & Presentation (e.g. HCI): Misc.; J.5 Computer Applications: Arts & Humanities – Architecture

## Author Keywords
Organic user interfaces; Tangible user interfaces; Shape changing interfaces; interactive architecture; kinetic building skins; ambient displays

## INTRODUCTION
Organic User Interfaces (OUIs) arguably represent the flexible, adaptive and malleable version of both Tangible User Interfaces (TUIs) and Shape-changing interfaces (SCIs). Initially introduced as 'organic tangible interface' or 'organic TUI' [33], OUI evolved offering radical new materialities and form factors that underpin both input and output interactions, coinciding with Ishii's vision for the future of UI as 'Radical Atoms' [34]. Therefore, over recent years OUIs have seen increased interest amongst HCI [11], Ubicomp [76] and TEI research communities [24].


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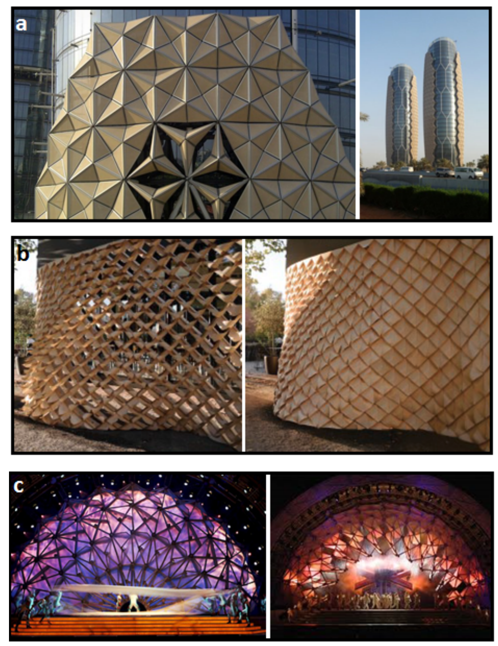


**Figure 1. Examples of OUI Architecture: a) Kinetic sun-shade: Al Bahr Towers by Aedas Architects, Abu Dhabi 2012; Photo credit: Aedas.com. b) Climactive skin: Hygroscopic Envelope Prototype, 2010 [64]; Photo credit: Steffen Reichert. c) Shape-changing: Hoberman Arch by Chuck Hoberman, Salt Lake 2002 [28]; Photo credit: hoberman.com.**

By definition, OUIs are non-planar interfaces taking any 3D shape and morphing either actively or passively, to support direct physical interaction [31, 33, 65, 76]. So, OUIs enable manipulative and bodily input (like TUIs) and kinetic interactions (like SCIs) facilitating flexible form and change of appearance as output, which matches their intended function and supports intuitive interaction. However, OUI conceptually depends on the 'shape' of the interface being the 'key' for interaction; that is: the physical 'form' conveys its function and invites users to familiar interactions such as deformable/non-deformable hand manipulations in addition to body gestures and movements, including hand, head, eye tracking, etc. [51] as means of user input; and multi-sensory auditory, visual or haptic feedback as means of output interaction. Early examples of OUIs range from surface computing, volumetric (spherical [3], polygonal [52], cylindrical [4], etc.) and bendable computers to flexible displays or paper computers [1]. Similarly OUI can utilize flexible, deformable, skin-changing and shape-changing materials in order to cover, embed and surround real-world objects and environments.

The concept of OUI builds on organic electronics or 'Transitive Materials' [11, 34] allowing displays/ devices to be malleable & actuated in an aesthetically pleasing way. Examples of such flexible and controllable displays include flexible Organic Light Emitting Diodes (OLED), Electrophoretic displays (EPDs), and Electroluminescent Lighting (EL). In addition to flexible displays, OUI can be designed using all ranges of flexible conductive materials; from paper or fabric to wood and glass that has embedded thin & flexible electronic sensors, microcontrollers and actuators, such as muscle wires, metal powder, conductives (thread, fabric and paint), optical fibres, thermochromic color-changing pigments and e-textiles. Such materials and technologies pave the way for rethinking user interfaces that can be embedded into everyday objects. Accordingly, OUI have great potential for radically new applications, e.g., dynamic artwork, pattern-changing fabrics, reactive architectural facades or even entire interactive spaces.

Examples of OUIs that have specifically explored new materialities include FuSA [53] the furry display, ClothDisplays [42], Hairlytop [56] and uniMorph [27] a curved actuated interface that enables designers to print custom responsive OUIs in various flexible and dynamic forms. In addition, one of the key potentials of OUI is their malleability, as seen in Follmer et al. [17], who introduced a technique for enabling programmatic control of a material's stiffness enabling actuated manipulations and deformations as both input and output interactions. Several other possibilities of deformable display materials have been motivating researchers for the past few years creating leading to innovative ideas and novel flexible design materials [2].

These kinds of interactive technology have enormous potential to not only change the nature of our interactions with technology but also to change the very environments we inhabit. Computational processes and interactivity will become increasingly embedded within the environment (as per the vision of ubiquitous computing). However, those environments will also increasingly react to our presence through embedded sensing, now with the additional potential to change form and function on demand. Accordingly, technologies such as 'Reactive Architecture' [68] and 'Kinetic Architecture' [39] offer substantial scope for redefining current architecture (see Figure 1). However, such architectural interventions are quite rare, and commonly only possible as new builds (thereby ignoring existing building stock) and largely neglect interior design, focusing more on dynamic structural features or interactive service layers within the building fabric.

We believe that OUIs have significant potential for opening up a new architectural design space for the development of interactive architecture and interior design. In this paper we make a case for this and encourage researchers & practitioners to adopt OUIs as key technology for future developments in this area. We begin by examining the state-of-the-art in OUI to lay out the play-of-possibilities that they offer, before looking at current applications in interactive architecture/ interior design. We then formulate a manifesto, i.e., our vision for the role of OUIs in architectural design and then finally present an articulation of the future challenges for researchers and practitioners to realize this radical pervasive computing agenda.

## OUI: THE STATE-OF-THE-ART

Through contextualizing OUI with regards to the state-of-the-art we can formulate the research agenda for OUI as means for interactive architecture and interior design. In this section, we explore a specific subset of OUI application areas to demonstrate the general concept of Organic User Interfaces and to highlight advantages and benefits of designing interactive architectural spaces. We divide potential OUI applications into two levels matching the common classic design disciplines: 1) Architecture and Landscape; 2) Interior Design. Although, we do realize that both levels are not mutually exclusive or complementary, but are inter-related in many aspects, we tackle each level as to present OUI potentials from a holistic large-scale experience to the smallest ornamental detail. The first level focuses on the entire architecture of buildings and planning the landscape/environment around them, where OUI buildings could be reactive to people, environment or other buildings. The second level includes reactive surfaces, context-aware spaces within buildings and interactive interior elements.

### OUI Architecture

Architectural history demonstrates early adoptions of 'Organic Architecture' emphasizing how organic designs (from buildings to ornamental details) could be flowing in harmony and blended naturally with our environment whilst fulfilling their essential structural, functional and aesthetic purposes [58, 41]. Decades ago, architect Frank Lloyd Wright's philosophy of 'Organic Architecture' focused on nature-inspired organic designs for buildings to be "not only convenient but charming" imagining both the exterior of buildings, the interior areas together with furniture and decorative accessories all integrated into a design that serves and contributes to users' values concerning usability and comfort. Although how literal the term 'organic' was used back then do refer to non-rectlinear architectural designs, OUI takes it further to focus on impacting aesthetics of interactive architecture or 'architecture as user interface' that should live, grow and adapt with users along their lifetime. We believe that Wright's ideas emphasizes the motivation and need for OUI architecture harvesting the value of designing any building or artefact -even a digitally augmented one- in real-world affordances and aesthetics.

Evident ecent literature of architecture ('Dynamic Buildings' [40], 'Interactive Architecture' [36, 18, 25] and 'Responsive Landscapes' [8]) and practice (Diller & Scofidio, Jean Nouvel, Chuck Hoberman, Ned Kahn) architects started envisioning the future of architecture using smart materials that can sense, react and integrate with their architectural designs. Some authors even proposed the integration of physical computing, robotics and sensor technologies. However, collaboration with HCI communities, UI and UX designers and researchers to fully realise the potential of these novel interfaces is still quite limited. For example, 'Kinetic Facades' [49] started to be adopted in architecture as means for energy-efficiency using flexible sun-shade envelopes that cover several buildings nowadays around the world. This is one kind of interaction with the environment. OUI Architecture concept incorporates a broader meaning and understanding of dynamic architecture in a way that would be more interactive and organic. For example, climactive architectural skins that react to environmental changes such as sun light/shadow, temperature, humidity, rain, wind, etc to create dynamic forms that would essentially change how people perceive and feel their surroundings. Figure 1 shows different examples for OUI Architecture.

In HCI, recent studies around architecture such as ‘Kinetic Organic Interfaces’ (KOI) [39] and ‘Proactive Architecture’ (ProA) [57] have developed notions of responsive actuated buildings with mass customization designed in entirely new aesthetic (curved surfaces, bent lines, organic designs, and unusual innovative structures) and responsive to both users and its surrounding environment (temperature, wind, solar radiation, etc), emphasizing the need and possibility for buildings to be dynamic and interactive enough in order to change physical form autonomously thereby reflecting context-awareness. Oosterhuis et al. describe the concept of proactive architecture as buildings that are "organic, ever-changing vehicles for processing and displaying information" [57].

Similarly, studies of ‘Adaptive Architecture’ [5, 68] attempted to create a self-sustaining, user oriented and real-time interactive ‘skin’ where building designs involve entire dynamic facades that are flexible in two opposite curvatures during their movement, with embedded sensors (light, energy, humidity) and actuators to generate kinetic adaptations that respond to, store and regulate environmental factors (sun, wind, precipitation) enhancing comfort level, social interaction and environmental conditions within the living environment. ExoBuilding [68] is an example of adaptive architecture, exploring potential biofeedback relationships between buildings and users.

Alternatively, the term ‘Interactive Architecture’ has been used. For example, Acacia [44] is a platform developed for the design of interactive building facades using organic smart materials allowing interactivity between users, buildings and the environment. In this sense, responsive architectural facades are thought to bring opportunities that redefine building skins offering impactful values being both architecturally aesthetic and interactive surfaces at the same time. Similarly, other researchers [50, 61, 39] have been motivated to study and design interactive architectural facades using OUI arguing how the visibility and size of building facades together with possible embedded capabilities create potential for utilizing them as public displays or interactive architectural surfaces.

Others envisioned ‘Display Buildings’ [69, 21] where buildings and cities will become gigantic multi-dimensional, frameless displays and entire architectural surfaces can become interactive media facades using huge screens in building scale, wrapped around surfaces that are possibly curved facades. Schoch [69] suggested that architects should design interactive buildings that can significantly change its appearance, using novel materials, describing such interface as changing ‘curtain’ covering the entire building than a distinct display.

More sustainable designs has considered the use of organic and natural materials that are responsive to different environmental conditions. Responsive materials such as hydromorphic, hygromorphic [47, 32] , photomorphic [14] or thermomorphic materials can sense changes in moisture, humidity, light or temperature respectively and autonomously react by changing their physical shape or colour. For example, Climactive wood [47, 13] that is physically programmed to respond to rain through shape-changing hygromorphic natural thin wood (see Figure1.b) and SynthMorph [62] that uses synthetic biological materials such as morphological bacteria [63] as construction elements for shape-changing architectural structures. Such OUI Architecture does not require electronic or mechanic control, or even energy-consumption but are engineered to autonomously react to certain environmental conditions creating novel dynamic spatial experiences.

Again, we refer to OUI Architecture as not just ‘literally’ organic in form or materialism, but as user interfaces that are ambient, and dynamic in a way that allows buildings and architectural structures (from bridges to sculptures) to react, express or heal us through changing their appearance or shape similar to the way humans and animals are able to communicate by simple speechless gestures or subtle reactions. OUI architectural designs can shift the appearance of exterior facades/skins, physically transform position, orientation, colour, lighting or curvature of either small modules or large blocks. Such organic interactions can be subtle, slow transformations, or reactive to people’s needs and contextual situations. Think of a stadium that autonomously reacts to spectators’ cheers or a bridge that illuminates in a way that expresses its traffic load or rain-sensitive convertible pedestrian walkways, or city skyline towers that can together chant a silent melody to celebrate.

### OUI Interior Design

Although interior spaces are typically of static nature that require an interior designer and/or architect to facilitate any changes to their appearance and function, the idea of dynamic interiors has recently gained popularity. Interior elements such as surfaces (walls, floors, ceilings) and openings (doors, windows) can be augmented with digital technology to enhance both their aesthetic impact and potential dynamic functionalities. Examples of interactive interior walls are Smartwall [16], LivingWall [7] and LivingSurface [78], while GravitySpace [6] is an interactive floor. However, ceilings seem to be neglected from similar interaction design in spite of all opportunities and potentials that could potentially be addressed especially in bedrooms where users lie down facing their normally plain ceilings.

In general, research on building interactive surfaces and walls has taken two approaches: either wall-sized emissive displays or subtle ambient designs. Wall-sized displays are either light-emissive (i.e. LED displays) or projection-based, while subtle tactile designs focus on embedding interactivity in normal coating, lighting or different finishing materials, such as wood panels, ceramic tiles, wallpaper, ..etc. An example for the first approach is Smartwall [16] where the wall display is divided into large pixel-like, reconfigurable cells that users can select

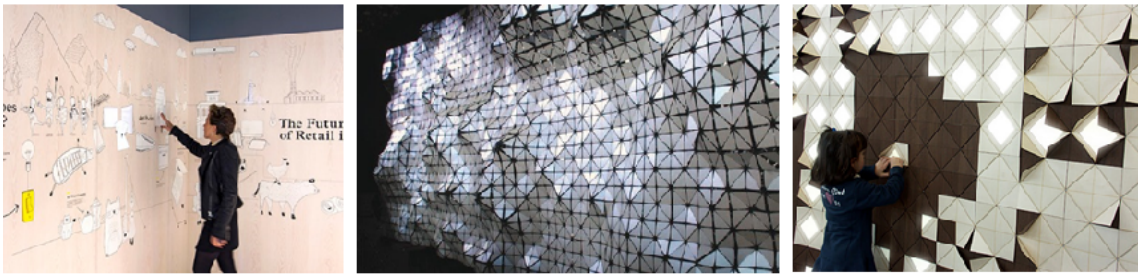


Figure 2. Examples of OUI Interior. Left to right: a) Engaging Retail Space, Dalziel & Pow, 2015 [dalziel-pow.com] b) Aegis Hyposurface, Mark Goulthorpe, 2000; Photo credit: Mark Burry c) Light-Form interactive wall, Francesca Rogers, 2010; Photo courtesy: Daniele Gualeni Design Studio.

and/ or drag each cell representing a certain function, utilizing room dividers and interior walls in user interaction design. Similarly, GravitySpace [6] is an interactive floor designed for smart rooms using real-time tracking, detecting multiple users, their positions/ orientations, and furniture through the pressure-sensitive, back-projected floor.

On the other hand, LivingWall [7] is an interactive wallpaper that uses conductive paint layers connected to microcontrollers and LEDs for interactivity. Users not only interact with it by touching it, but also through walking beside it, which creates a playful experience for interactive interior and a large ambient dynamic wallpaper. Likewise, LivingSurface [78] is a shape-changing surface that interacts with users through its non-emissive material that rather changes its physical shape in response to sensed user physiological data, reflecting their internal body processes such as heart rate and blood volume pulse. The shape-changing interaction of LivingSurface is designed using cutouts in the wallpaper that is actuated to form different interesting 3D shapes. Actuation is deployed in a back layer embedded with hidden servo-motors, vibration motors and small fans controlled using Arduino microcontrollers. The same effect could be implemented without motors using non-mechanical linear actuators such as muscle wire or Shape-Memory Alloys (SMA) that are light-weight thin wires with strong and silent actuation capabilities.

We believe that non-emissive responsive surfaces are much more appropriate to be widely adopted in our environments as they do not constantly stand out and capture attention like with emissive wall displays. Therefore, non-emissive materials and ambient ubiquitous interaction are more appropriate to designing and creating entire interactive interior spaces rather than just a single actuated surface or wall. Still, some examples have used lighting techniques in ambient interactivity such as Light-Form by Francesca Rogers (see Figure2.c) and Luminous by Philips [59] creating interesting playful experiences. Figure 2 shows examples of interactive interiors.

Likewise, other interior elements that range from furniture and decorative art to soft furnishing such as cushions, curtains and carpets can be transformed into OUI devices employing haptic interactions they already afford, serving both beauty and function. Previous work on interactive furniture includes interactive tabletops [35] and shape-changing furniture such as EmotoCouch [48] and shape-changing bench [26]. Other interior elements have also been investigated in OUI research creating haptic interior artefacts such as interactive Tablecloths [20, 72], interactive curtains [19, 71], wall art [75], lampshade [37] and other interior 'Soft User Interfaces' [70].

The above examples form rich inspiration for artists, designers and architects, but only scratch the surface of possibilities for promising smart and dynamic interiors yet to come. General benefits of interactive interiors have been discussed in related prototype installations [20, 46, 48]. By generalizing the concept, we come closer to the vision of ubiquitous computing where technology quite literally weaves into the fabric of everyday life [77], providing inhabitants with potential benefits at both the emotional and physical level. The emotional and psychological effect of changing interiors, e.g., colours, lights, shapes and textures, can have significant impact on inhabitants, potentially leading to improved quality of life through novel, possibly serendipitous experiences and sensory stimulations.

## A MANIFESTO FOR OUI ARCHITECTURE

Although previous work on OUI has mentioned art and architecture as interesting applications of OUI, e.g. [12, 31, 65, 76], no systematic research has been undertaken investigating, questioning and discussing how 'OUI Architecture and Interior' can be designed, perceived and lived with. This is a missed opportunity, as instead of having our built environments as static structures built from static materials, designing them as OUIs can create dynamic, responsive and thus context-aware architecture. OUI Architecture can be actuated to modify its appearance, spaces and surfaces as a response to interaction with users, other devices (or buildings), and the surrounding environment. All of which emphasizes the motivation, opportunities and potentials of designing architectural elements that can be interactive, responsive and, consequently, have the potential for fundamentally changing the way architecture and interior design is done leading to radically different ways of interacting with the built environment.

In the sections above we have identified the potential of OUI for substantially opening up a design space that offers new opportunities for Interactive Architecture and Interior Design. Adopting this direction would emphasize how technology can support future architecture in a way that is beyond contemporary techniques of Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM) and Computer-Aided Engineering (CAE) applications.

In the following we present a manifesto outlining the key considerations for OUIs as a core technology underpinning our vision for the future of architecture and interior design.

1. **Ubiquitous Interaction**: OUI interaction is defined as intuitive and familiar affordance of everyday objects in our physical world[23, 22, 30]. This allows to employ both explicit and implicit interactions we perceive and perform on a daily basis into the fabric of future interactive spaces, fulfilling Weiser's vision of ubiquitous computing [77]. OUI explicit input interactions could range from physical hand manipulations (both deformable and non-deformable) to in-air gestures, body motions and speech [22] resembling more intuitive human-physical and human-human interactions [65]. Implicit input may be triggered by other activities, motion or presence, psychological or physiological sensing or environmental stimuli. Output interactions range from simple visual and haptic feedback such as light, sound or motion to richer sensory and morphological actuation, e.g., skin-change or shape-change. In this sense, people will engage effortlessly through their normal daily interactions with real-world objects and environment, and step into immersive experiences of a ubiquitous dynamic world.

2. **Context-Awareness**: With OUIs, architectural and interior designs can be context-aware for both occupants and the surrounding environments. A user's environment can be seamlessly embedded with technology that captures, analyses and understands different situations and contexts changing around. Earlier work on smart environments has led to robust but not necessarily non-intrusive sensing and inference systems (e.g., [66, 67]). Morphological natural or manufactured responsive materials [47, 32] that sense changes in humidity or temperature and react -by transforming their shape or colour- are rich materials for context-aware building envelopes and fabrics, at no energy cost. Equally, there is clear potential to leverage the strength of the emergent Internet of Things (IoT) to support this seamless networking of OUIs (e.g., [74, 38]). This furthers the vast potential to leverage interaction with everyday objects as sources of data and user input to interactive environments and offers opportunities for interactive interfaces to be based on our interactions with familiar objects. For example, OUI Walls can expect user actions and therefore emerge hidden parts or layers, i.e. bring out a hidden shelf when user holds something needs to put down; or bring out a hidden seat when user seams tired and looking to sit down. In this sense, a new generation of context-aware smart buildings and smart homes can emerge, i.e., rooms that can change their size based on occupants and context of use, decorations that can change their skin based on temporal or social events, and exteriors that can be interactive as well.

3. **Dynamic Nature**: Advances in organic smart materials will allow interfaces to be malleable, deformable, change colour or shape, and be actuated, giving us unprecedented opportunities to design dynamic architecture and interior designs that are not necessarily static like most contemporary designs. OUIs will offer the flexibility of dynamically changing structures and spaces, either on demand (passively) or autonomously (actively). Changing tastes or interests will be accommodated instantaneously. And likewise with exterior architecture, which no longer has to be fixed, using smart OUI materials, a building will be able to alter its facade or even dynamically reconfigure its internal spaces to suit the needs of inhabitants. Essentially, this vision requires re-thinking current architectural methodologies in different ways as it is not that obvious yet, but would also solve historical dilemmas for architects such as orientation towards sun light, view and natural ventilation through dynamic adaptive architecture. Some are already considering buildings that rotate with the sun [49]. So we can foresee the future of having skin-changing and shape-changing architecture being feasible, practical and efficient.

4. **Seamless and Seamful Sensing**: Possibly complete houses and entire buildings can be embedded with intelligence through technology to allow seamless and spatial data sensing. Such embedded intelligence when employed in our everyday objects, furniture and surfaces will allow them to do much more than they already afford. OUIs can eventually replace current health sensor devices in a ubiquitous and seamless implicit interaction [60, 29]. The simplest example could be a duvet/blanket that can measure heart rate, blood pressure, etc. or a sofa arm that senses stress levels. A bigger picture is where –through OUI spaces– architects can design buildings that are able to capture different neurophysiological and psychological data for both the analysis and better understanding of user behaviour and user experiences within interior spaces, buildings and landscapes. On the other hand, seamful ubiquity [9] is also necessary for solving issues of ambiguity and uncertainty of interaction and sensing that might occur in some seamless systems [10]. For example, to design interactive interior spaces, we don't have to achieve completely seamless interaction in every surface and object but could exploit the representation of seams allowing the user to understand the edges of connectivity. Not only is this approach useful for user interaction regarding awareness, ambiguity and control challenges of ubiquitous interaction [15]. It will also provide flexibility for designing both public and private spaces in terms of social concerns such as privacy and personal data. Therefore, incorporating both seamful interation and implicit or seamless data collection through proper appropriation can together support a better user experience and simpler acquiring of the information and knowledge needed to improve the quality of living experience. In addition, such appropriation will support efficient management of urban flows aimed by researchers of smart cities and smart grids, who are already open to such opportunities through big data capabilities and tackling personal data protection challenges[45, 73].

5. **Visualizing the Unseen**: OUI buildings open frontiers for visualizing hidden data in new ways by translating the unseen data into visual, peripheral and tangible representations in the space. For example, displaying energy consumption of a house or a building through colour-changing interior elements. Another application might be for office buildings where the OUI space can visualize employees' satisfaction or engagement through sensing work loads, social interaction or stress levels and giving feedback through ambient texture-changing OUIs. Applications for healthcare spaces (patient rooms, senior homes, etc) can be similarly designed

to give biofeedback to certain health conditions and thresholds through peripheral OUIs. Even gentle breezes can be sensed and interpreted by wind-responsive architecture [43] or an actuating force, such as the work of Ned Kahn [54] (facades of flexible metal panels moving with wind force revealing impressive patterns of wind turbulence).

6. **Aesthetic Computers**: Concomitant with the third generation of computing is the desire to explore how computational devices can be made more aesthetically engaging. The rise of lifestyle brands such as Apple demonstrate consumers' desires for aesthetically pleasing products. OUI provides a design space allowing both researchers and designers to collaborate and innovate around new, dynamic forms of decorative artefacts, harvesting the potential of creating aesthetic computers that can exist in any shape. These devices embed both digital technology -with all its capabilities- and decorative beauty -with all its artistic values- together in one integral interface that can live, engage and influence people's lives over years. Using this paradigm, a lace tablecloth, a shaggy cushion or a Persian rug can become a computational device. Furthermore, aesthetic interaction -which is similarly important and impactful- aligns well with OUI interactions being more intuitive, familiar and manipulative than earlier user interface paradigms. Additionally, OUI can provide a user-friendly interface alternative for complex embedded systems in simple metaphors. For example, tangibilizing power utilization trends through colour-changing tangible clouds hanging as decorative elements.

7. **Sustainability**: OUI architecture contributes to sustainability on four different levels. First, less need for re-design or refurbishment, if interiors and/or exteriors of spaces and buildings are able to change their appearance (colour, shape, pattern, state, texture, etc) either autonomously or responding to occupants' interactions and/or needs. Second, OUI materials such as flexible bendable OLEDs, energy-efficient RGB LEDs and other organic electronics and polymers offer low-power alternatives and energy-efficient technologies [17, 50, 76] that do not compromise energy sustainability. Third, OUI responsive materials that sense and react to changes in humidity, light or heat requires zero energy consumption and can be physically programmed to solely act as sensing, processing and actuating complete system of adaptive architecture. Finally, we've got a missed opportunity of utilizing wasted energy sources that are literally pouring, facing and blowing towards every architectural structure anyway. Such natural resources can be either directly utilized as actuating stimuli [54, 47] creating natural behavioural patterns or employed in a more complicated processes. Nature powers of wind, sun radiation, wasted rain water (storm drain) and even greywater drains are all considered nature's gift to sustainable architecture researchers and should inspire interaction designers as well.

8. **Expressiveness**: Both personalization and playfulness are two important aspects of interaction design in general and in OUI design in particular. OUI interactive and manipulative interfaces have been found to be playful and enjoyable by users. Ubiquitous computing environments are believed to add a pleasure dimension leading to more user-friendly architectural design [50]. OUI interactions such as air gestures and direct hand manipulations are not only intuitive but pleasurable as well. This explains how children nowadays often enjoy playing with technology more than ever before. In her study of interactive architecture in a pleasure-based methodology, Mounajjed [50] stated that "accommodating aesthetic elements that appeal to the emotions is critical to the development of a user-centric design", where the pleasure factor influences the behavioral patterns of users. Therefore, OUI interactions accommodate pleasure as both a cause and an effect in where it encourages user participation and enhances the user experience in an enjoyable and pleasurable flow, influencing their emotions and visceral responses. On the other hand, expressing personalization -in some cases- is beneficial. When tangible art pieces and decorative surfaces become OUIs that are digitally aware of occupants' presence, and perhaps identity, then profiling and real-time customization can be easily implemented so that the same artefact or room can look differently for different occupants as they use a space. Moreover, OUI materials can help transform the same object into different other personalized appearances that suit its owner/user.

9. **Expand Creativity**: Art and architecture are about inspiration, questioning and creativity, provoking people's curiosity and thinking differently. When augmenting an artifact with actuated capabilities, allowing it to dynamically transform, creativity fosters conversations that alter meanings and aesthetics conveyed each time it generates a new form or appearance. OUI Architecture enables such creativity in different designs not only in residential interiors, but also in public spaces such as museums, galleries and showrooms. Commercial spaces are also a candidate for designers who consider technology in their installations to incorporate tangible and tactile interactions to draw innovative, surprising, experimental and engaging user interaction experiences. For example, retail designers Dalziel and Pow recently designed the 'EngagingSpace' at Retail Design Expo 2015 (Figure 2.a) where they installed an interactive animated space to engage visitors in an entertaining novel user experience through simple tactile interactions with interactive wallpaper. In this sense, we have to promote that technology should not be means to performing tasks, solving problems and improving efficiency and productivity only, but rather as well support us to be human, expanding the unique human abilities of vision, creativity and imagination and thus enhancing our quality of living and potentials.

10. **Tangible Decor**: Because domestic environments are required to be both comfortable and beautiful for a lifetime, architecture and interior design (including furniture, decorative accessories, fabrics, e.g., curtains, linens, upholstery) need to serve and contribute to the usability values of occupants in simple synthetics and impacting aesthetics that could live with occupants for years, interact and adapt with them along their lifetime. Domestic decorations can be designed and manufactured as OUIs with slow technology that allows them to respond and interact with occupants calmly and seamlessly over the years, manifesting their physical

pre-existing function and form, in addition to all their potential contribution to enhancing the quality of domestic living, being embedded computers; moreover, provoking inspiration, anticipation and self-reflection. Another important aspect of home decoration is the problem of habitual blindness. Over long periods of time, decorative home artefacts tend to lose their ability to 'stand-out' as they do when first brought-in and blend in a way that stops attracting our attention by time [20] losing a lot of their intended aesthetic values. OUI decorative artifacts that change their appearance, create subtle movements or form alterations, avoid blindness towards them, and create a renewable sense of awareness and perception of these decorative elements and thus a charming atmosphere influencing people's perception of value and meaning of such artefacts over time [55].

## WAY FORWARD

We have explored the need, motivation and opportunities OUI provide for developing interactive architecture, both exterior and interior. However, the vision of OUI as key technology for interactive architecture requires substantial efforts to become a reality, which effectively defines the research agenda for the field. In what follows we outline what we have identified as the most important aspects that future research on OUI for interactive architecture has to address.

a) **Radical Interdisciplinarity**: Bridging the gap between involved parties, e.g., computer scientists, material physicists, architects, interior designers, OUI and UX researchers is an essential requirement for realizing the vision of OUI for interactive architecture. More than in any other domain truly interdisciplinary collaborations are essential meaning that where researchers and practitioners from different core subject areas need to go out of their way and work together on creating what eventually will turn into an entirely new research area. Such radical interdisciplinarity needs to be formalized and -more importantly- "lived" in everyday practice of researchers and practitioners. Staying in -certainly comfortable- silos of core disciplines will not lead to the realization of OUI-based architecture be it related to either interiors or exteriors. Although it may sound obvious to some, we have identified this as a key problem for the development of this research area: both architecture and HCI researchers and academics work separately from one another, yet with the same vision. What is ultimately necessary is that, for example, classical architects not only utilize new materials and technologies but rather also actively contribute to their research and developments. Conversely, core technical research disciplines need to engage in thinking like architects and appreciate OUI from a UX and general user perspective. As such a new generation of researchers and practitioners will be able to develop and employ radically new methods, tools, and materials and thus be able to transform both architecture and interaction technologies.

b) **Appropriation and Retrofitting**: An interesting design space emerges not only for designing new buildings with embedded OUIs, but also for retrofitting existing buildings and interior spaces. This requires less structural intervention and allows new OUI layers to cover entire pre-existing interior or exterior surfaces. Considering that interior elements (furniture, decorative accessories and soft furnishings etc) can be appropriated as interactive surfaces through the design of OUIs there is a broad space through which interior designers and OUI researchers can come to collaborate. Similarly, utilizing OUI in architectural exterior facades creates numerous possibilities for exploration. The design space for OUI in architecture is unique in the sense that it bears an intrinsic conflict of conceiving, designing, and developing new objects that effectively implement Organic User Interfaces vs the need for altering, adapting and extending existing objects that are not necessarily straightforward to modify. Especially the latter is the predominant case for existing buildings, which requires retrofitting and approaches of opportunistic modification.

c) **Tackling Scalability**: Addressing scalability of OUI is a fundamental challenge for the field. Scalability hereby refers to moving on from prototypical or exemplary developments to large scale uptake of OUI in everyday scenarios of interactive architecture & interior design. Scalability of large interfaces, e.g., building exteriors, is much more challenging than small-sized interior interfaces. Designing OUIs in ways to be skinned on architectural structures requires many different considerations and functional testing than just lab research. Such considerations are required due to the large scale and reliability required for building envelopes in addition to surviving different environmental conditions. As any newly introduced building material, OUI architectural skin materials must prove durability in terms of sun, rain, wind and fire resistance. If designed as a structural material (holding some building weight), it needs to be tested for load resistance as well, as architecture is non-risk tolerant. Other considerations that require further research and testing are lifespans, vandalism and maintenance approaches of such subtle materials. Once OUI materials are proved to stand such testing and be produced into building components with qualified and quantified specs for architects and structural engineers, pioneers can start using them with confidence and we can start witnessing a new era of responsive and organic architecture as reality.

d) **Re-defining the User**: As somehow different than usual interfaces, defining who would be users of OUI architecture is rather vague and not straightforward. Traditionally, users of an indoor interface system are thought of as the inhabitants, while users of an outdoor interface are considered as the public passing-by. On the other hand, architects and interior designers may consider their users as the contractors, project owners or funding bodies of the designed building/space. In either cases, rethinking who is the user is an important point to be tackled and explored by OUI research when it comes to entire buildings as application/ design space. This is crucial from both perspectives: HCI and Architecture disciplines, both depend on building their design 'concept' on defining the users. More importantly, defining the actual users will essentially push forward a user-centric design and a post-occupancy testing or long-term evaluation of such designs/interfaces that can potentially constantly change, transform and react.

e) **Immersive Interaction Design**: as much as OUI Architecture sounds revolutionary and promising, it also triggers the need for essentially a new generation of interaction design. When re-defining architecture as user interfaces, we need to start reconsidering many interaction design fundamentals. User interaction will be immersive rather than focused, when interacting with spaces rather than devices or building-sized interfaces rather than tabletops. Crowd interaction would replace the traditional 'multiuser' notion, and would require creative methods and tools to study and evaluate. Even with small decorative OUIs, HCI research needs to create and evaluate new arrays of interaction techniques that are immersive, playful and engaging, together with designers. Several challenges require careful design for OUI interactions that would need to be ubiquitous and ambient but not entirely hidden, intuitive but not basic or mundane, surprising and enchanted but at the same time not -perceived as- completely random. Moreover, as OUI Architecture is realized, opportunities for social actions in these interactive spaces would also become an important topic in HCI. But what are the consequences of shifting users' expectations for their surroundings? When would embedded OUIs be appropriate? When would 'smart' be needed? How can we design long-term interactions?

f) **Ethical and Behavior-Shaping**: when building interiors and exteriors that can dynamically transform their shape or appearance either autonomously or interactively, new challenges for ethics and security will emerge. Sensing environments in general are advanced systems that involve complex scenarios and thus are potentially subject to 'hacking' activities as well. Special security procedures might need to emerge to protect one's wallpaper or moving furniture. An essential step forward for OUI Architecture would be considering BIM (Building Information Management) as means of embedding security techniques into OUI software not only for creating anti-hacking systems but defining who has the rights to interact -thus change- the physical appearance and form of interior elements or exterior facades. We are aware that such implications are applicable for any embedded system, yet we need to highlight this here as it would require new methodologies and considerations impacting people in their very own bedrooms. Another challenge is designing the appropriate skin-changes of the original architectural design and their possible emotional effects on residents. In theories of architecture, different colors, materials and textures have definite meanings, feelings and uses, thus consequently emotional effects on the building occupants and often the entire surrounding ecosystem. In OUI Architecture, the materials and methods of sensing, actuation and interaction will be an essential part of the architectural design, requiring careful studies in each context to control and avoid any implications that might result on families either physiologically or psychologically. When designing for domestic spaces, more challenges emerge on different technical, social and ethical levels. Since some early challenges of domestic ubiquitous computing [15] have been resolved, it seems that it is a matter of continuous studies and research to find ways to overcome more.

g) **Sustainability Dilemma**: Currently, sustainability research predominantly focuses on exploring means of building resource-efficient, energy-conservative and environment friendly architecture through Green Building and Sustainable Architecture practices. OUI exteriors can contribute to sustainable buildings through 'modularity' where component-parts can be replaced easily. In addition, any kinetic interaction employed in the interface can contribute to energy-harvesting in a way that allows micro-scale energy production that will support self-sustainable buildings. Not only buildings, but other architectural structures from bridges, tunnels and motorways to narrow streets, parks and transportation facilities. Together they form the urban glue in which indeed shapes our daily lives, is a rich space for OUI, converting them from mute structures to possible 'urban actors'. Yet, creating new urban actors would raise more sustainability challenges, and opportunities.

## CONCLUSION

Technology is converging to bring together a new generation of devices and interactions built around smart OUI materials. The vision of smart homes and ubiquitous computing environments (calm computing) has never been closer to realization. Previous visions of interactive architecture have been just that, visions, largely unrealizable at a scale that would actually impact people in an everyday context (being largely restricted to specific experimental builds). The advances in networked technology and new materials mean that it is now possible to make architectural interventions at both the exterior and interior scale, in affordable and sustainable ways. Older building stock can be retrofitted with technology to dynamically alter spaces and make environments responsive in ways not possible before. No longer do we need to make the case for building entirely new reactive architecture when older buildings can be adapted with technology to make them smart. The imminent proliferation of smart home controls is making the general populace more switched on to the idea of technologically enhanced and reactive environments. Now is therefore the time to invest in thoroughly exploring a new future of interactive, dynamic and reactive architecture. This requires a fundamental attack from multidisciplinary and interdisciplinary researchers to begin to address the challenges and opportunities of OUIs, which offer us the strongest means through which to deliver a future of interactive architecture. In this paper we have sought to outline some of those challenges and to begin to galvanize a community that might seek to explore how OUIs can fundamentally alter the way we live.

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