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Self-Moving Robots and Pulverised Urban Displays:

Status Quo, Taxonomy & Challenges

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Abstract After almost a decade of relentless development, pervasive urban displays have fragmented into a diversity of approaches with radically distinct characteristics in terms of how mobile they are, as well as the materials they are made of. In this article, we investigate such a diversity in terms of the relationships between key conceptual entities of pervasive urban displays, namely the displayed content, the enabling display technology and the surrounding physical environment. First, we propose a taxonomy for pervasive urban displays through two dimensions: increasing levels of physical integration of content into the surrounding environment (attached, blended, physicalised), and increasing levels of mobility of the display technology within the environment (fixed, portable, self-moving). We extend this taxonomy through looking at the relationship between content and display technology from a conceptual lens and present two categories, namely *Screens* and *Printers*. We then provide a classification of current approaches to the design of pervasive displays along these two dimensions and categories, and introduce a new class of pervasive display, which we call pulverised urban displays (PUDs). These displays represent content in a physical form, entangled with the built and natural environment which are capable of an autonomous change to their position. Drawing on urban robotic devices and their capability to sense and manipulate the environment or act as a display itself, we present examples of PUDs. Finally, this article concludes with challenges for designing self-moving robotic and pulverised urban displays.

Keywords pervasive displays · media architecture · pervasive display taxonomy · urban media · urban displays · urban robotic displays · pulverised urban displays

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1 Introduction

Robots are currently making the transition from factories and laboratories to be tested in real-world urban contexts. In cities, this has led to a rise in research and speculation about how driverless cars may transform urban life [34]. However, the opportunities of autonomous systems reach far beyond driverless cars and have the potential to fundamentally transform existing city infrastructure, including pervasive urban displays. For example, recent research explored how the external surfaces of autonomous vehicles can be activated as a swarm of public displays, thus making a case for cars as a shared resource [11]. Others investigated the concept of free-floating public displays [80] and in-situ projections [52], using drones to carry digital displays or mobile projectors. While it is certainly a good starting point to use off-the-shelf display technologies and to repurpose existing user interface design paradigms, this article argues that there is a new, rich design space for novel classes of pervasive urban displays emerging out of the intrinsic characteristics of robotics [51]. This area of pervasive displays has been relatively unexplored to date, with the exception of some preliminary manifestations in the form of artistic interventions demonstrating the use of industrial robots and drones as public displays, for example creating kinetic or swarm performances [24, 46]. Considering current trends in architecture and design, where robots are increasingly used to build architectural structures [64], it is also conceivable that robots could directly interact with the urban environment over longer periods of time, e.g. reconfiguring existing structures, or manipulating and emitting arbitrary materials or substances, thus creating multi-modal displays that are realised through physical reconfiguration.

Looking back at previous research on public and pervasive displays, there are two main aspects the community has paid significant attention to in recent years. The first refers to the design of increasingly ubiquitous forms, thereby moving away from solely fixed display deployments (e.g. display booths, shop windows, façades), towards mobile and autonomous displays [16, 80, 82]. The second aspect regards the spatial and aesthetic integration of digital technologies into the physical environment [14], with low-resolution lighting-based media façades being the most prevalent form [36]. A series of works also explored the digital manipulation of natural phenomena [29, 35, 77], thus rethinking the concept of traditional screen-based media. In this article we investigate the convergence of these two design trends in pervasive urban display research: making information more ubiquitously available through portable and self-moving displays; and seamlessly integrating media layers into the urban environment. Furthermore, in related fields, such as tangible computing [50] and ubiquitous robotics [51], we can also observe a shift towards fluid interfaces and dynamic physical materials. We thus examine how robots can enable an emerging type of pervasive urban displays, presenting information in a physicalised form, entangled with the built and natural environment, while being highly mobile and enabling easy deployment in and out of specific locations.

2 Background

Our investigation draws on previous research on pervasive and architectural displays, which has been targeted by conference venues, such as the *International Symposium on Pervasive Displays* (PerDis) and the *Media Architecture Biennale* (MAB).

2.1 Pervasive Displays

Compared to personal mobile devices, pervasive displays enable a ”push-based distribution” of content without active user involvement required [18]. However, as urban environments become increasingly saturated with displays [17, 83], and a majority are used for advertisement purposes, research reported that passers-by tend to ignore them [62]. Based on field observations, Parker et al. reported that the physical properties of the display deployment, such as size, structural design of the carrier, as well as position and location affect the awareness of pervasive urban displays [68]. These parameters are highly influenced by the environment in which the display is situated in, which in turn is subject to constant changes, including daytime dependant (e.g. sunlight exposure, number of passers-by) and long-lasting changes (e.g. architectural interventions). The analysis by Vande Moere et al. additionally includes the impact of socio-cultural shifts in local communities, and stress that the most prevalent designs of urban displays fail to respond to contextual changes [61]. We argue that more mobile forms of pervasive displays could address some of these drawbacks, such as the over-saturation with, and inflexibility of, the majority of current display deployments. While current work on portable and self-moving pervasive displays is mainly aimed at increasing their availability [94], it is timely to also consider pervasive displays to appear and disappear in the environment as needed.

2.2 Architectural Displays

With the rise of pervasive urban displays, architects also began to discuss the implications of these novel technologies for their own practice. While there seems to be a widespread scepticism towards displays that are attached onto existing buildings and structures, architects have often approached digital media as a dynamic building material ”that blends in with the architectural expression” [96], summarised under the umbrella term *Media Architecture* [15, 44]. Most prevalent manifestations take the form of either projection mapping or low-resolution media façades incorporating light-emitting (LED) technology to transform the outer shell of a building into a large public screen [36]. However, we can clearly note a recent, yet significant, shift in the field towards non-screen based technologies and designs of various forms and scales: examples include hybrid architectural structures mixing low-tech and high-tech display solutions, physical kinetic façades, and - in a more drastic departure from the paradigm - ubiquitous robotic [51] and organic interfaces [63] creating responsive architectural structures. The emergence of robotic interfaces with the potential to become ubiquitous represent a paradigm shift for the field of pervasive displays, both in terms of the kind of devices understood as 'displays' and the ways they disseminate content across urban precincts. In the following sections, we analyse this new landscape, and propose a taxonomy to support future research in the field. While previous reviews of media architectural interventions focused on the communicative aspects, such as experience-oriented analyses [33] and introducing genres of media architecture according to the level of participation [4], our work adds new knowledge through an analysis of the display artefact itself and their physical integration into the environment.

3 Pervasive Urban Displays: Entities and Relationships

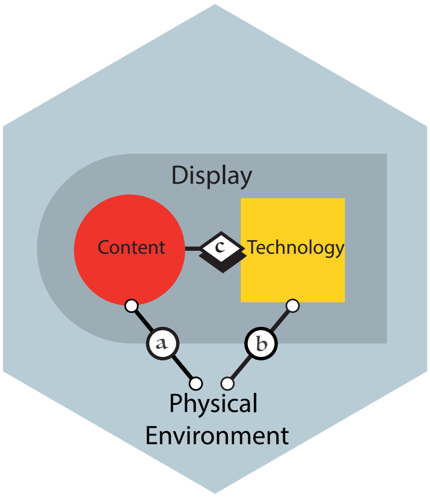

Fig. 1 Overview of the conceptual entities of a pervasive urban display and the relationships discussed within this article: a) integration of content and b) mobility of display technology within the physical environment, considered in the integration-mobility taxonomy in Section 3.1, and c) relationship between content and technology discussed in Section 3.2.

Pervasive displays provide great potential to integrate digital media in the context of the city. The rise of novel technologies enabling a more seamless integration, and making use of materials with dynamic properties has led to a variety of approaches to display content apart from one-directional, static screen-based displays. Increasingly, those are manifested as creative, playful and interactive encounters with the urban built environment. In order to gain a clearer understanding of this paradigm shift, in this section we first discuss two perspectives of pervasive computing, manifested in the following two relationships (see Figure 1): (a) the seamless integration of *content* ("something" that is communicated by a display) into the physical environment, and (b) the mobility of the *display technology* (the means to communicate content), enabling flexible deployment in and out of specific locations within this physical environment. In our analysis, we focus on displays that use visual means to deliver content. Additionally, we use Vande Moere and Wouter's [61] definition of *carrier* to refer to the physical support linking the display to the environment. Hereafter, we first define the different stages along the two design dimensions (see Figure 2). We then take a closer look at the relationship between display content and technology by introducing two categories of pervasive displays, namely Screens and Printers, and how these categories have influence on the scope of integration and mobility. In Section 4, we classify current approaches of pervasive urban displays based on examples from research and design practice (see Figure 4) along the here introduced taxonomy and categories. The taxonomy was iteratively developed based on the thorough analysis of existing approaches. However, to improve the flow of the article, we first introduce the conceptual framework, and then classify and discuss the various genres of pervasive urban display along this framework.

3.1 Integration-Mobility Taxonomy

3.1.1 Physical Integration of Content

The level of physical integration refers to the extent to which the content is integrated into its surrounding physical environment, including landscape, architecture and urban infrastructure [14]. Thereby, for pervasive urban displays, the notion of content is broad, ranging from visual elements, such as text and images with explicit meaning, to the architecture itself delivering content of implicit meaning [66].

Attached. The displayed information in the form of visual content is framed and bounded to the display. The content is separated from its environment in

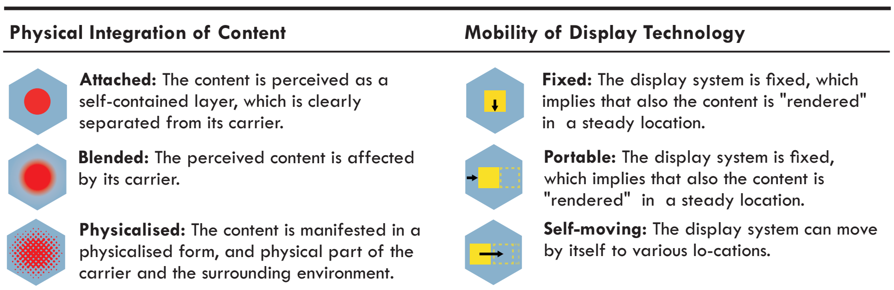

Fig. 2 Overview of the integration-mobility taxonomy.

the sense that there is no intended influence on the visual perception of the content. The display stands out from its surrounding physical environment, with the display's frame clearly distinguishable from the carrier, which in turn merely provides structural support for the display. Often, these type of pervasive urban displays rely on standard high-resolution LCD/LED screens. Even if the displayed content is situated in the sense that it relates to the local context [60], the missing physical integration can cause a contextual disconnect between the display and the environment [61].

Blended. A pervasive urban display referred to as "blended" means that the visual content is interconnected with the physical environment, shaped by and responding to its characteristics. This can be achieved through spatial integration, for example when the display's form is aligned with the architectural shape of its carrier (e.g. a building), and/or through material integration, which means that the display's intrinsic qualities refer back to the material properties of its carrier. Here, the display becomes an aesthetic material in itself, rather than purely a technological means to frame visual content [21]. When turned off, blended displays either completely disappear (e.g. projections) or they still work as an aesthetic architectural element (e.g. embedded LED displays) without a sense of malfunctioning [19].

Physicalised. Here, the visual content is entirely manifested in a physicalised form, and is a physical part of its carrier and/or the surrounding environment. Thereby, the content can be decoupled from the technological means that creates the display, for example in the case of an actuator that creates the content through physically manipulating the environment. In some cases, the actuator that creates the displayed information stays invisible from the viewer and the content can persist in a static form in the environment, even if the actuator is turned off or completely removed out of the location.

3.1.2 Mobility of Display Technology

Mobility here refers to the extent a display technology can be deployed to and removed from specific locations without compromising the integrity of the surrounding built environment. In other words, it refers to the flexibility it affords to change its physical location without loss of functionality or significant compromise to content. In that sense, we classify displays as fixed, portable or self-moving (see Figure 2).

Fixed. Most pervasive urban displays that are permanently installed at a certain place are referred to as "fixed", which means that they cannot be easily deployed at another location without considerable effort. This includes building-scale displays where the display technology is integrated into the façade, or even fused with the building material and structural system [36].

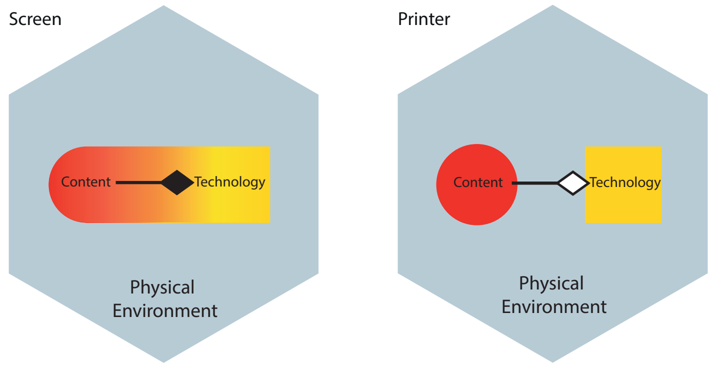

Fig. 3 Two categories of pervasive urban displays: (1) Screens where the content is intrinsic to the technology producing it and (2) Printers where the physical material is extrinsic to the compounds producing the content.

Portable. A pervasive urban display system that is "portable" can be carried from one location to another with reasonable effort, which means that no construction work needs to be done, offering plug-and-play functionality. Depending on the intended deployment location and the degree of portability, portable displays operate autonomously in the sense that they are battery- and/or solar-powered, communicate wireless and re-calibrate to different environments.

Self-Moving. A pervasive urban display is considered "self-moving" when the display system can move freely through an (unmanned) ground or aerial vehicle. Depending on the carrying vehicle, content can be deployed in a certain area only or anywhere in public space. The positioning of the display is either remote-controlled or performed in fully autonomous manner.

3.2 Relationship between Content & Display Technology

To gain a better perspective on the range of different media technologies currently available - and how urban robots can disrupt them - we propose to take a step back from their technical specifications, and instead analyse media technologies in terms of the conceptual relationships between the content produced, on the one hand, and the device (in the sense of a technical assemblage of parts) actually producing that content on the other hand. To that end, displays can be broadly classified into two categories, which we will henceforth generally refer to as Screens and Printers (see Figure 3). We will use capital letters to notate them throughout this article, to convey the fact that those are not necessarily actual screens or printers, but instead classes of media devices with particular characteristics associated, respectively, to screens or printers, within the scope of our analysis.

3.3 Screens

For the first group, Screens, the content which is produced is intrinsic to the technology producing it: this means that the material parts of the device producing the content are the same or fully integrated into the parts through which that content is visualised. For example, cathode-ray tube TVs and digital LCD screens are physically constituted of electronic parts that both produce and render visual content. They cannot be dissociated from each other: if we move the parts producing the content to a different location, the actual content - or, rather, the physical material through which it is visualised - moves along with it. Likewise, if the physical parts producing the content are 'reset', 'switched off' or even physically destroyed, the content disappears altogether. Consequently there is a strong one-to-one relationship (i.e. composition) between the content produced and the display technology producing (and carrying) it.

3.4 Printers

In contrast, technologies in the second group, Printers, distinguish themselves from Screens in the sense that the physical material through which content is visualised is physically separate from the physical parts producing the content. Like in traditional printers, there is a module within the device which needs to be loaded with some kind of third-party rendering material, and the function of this module is precisely to transfer such rendering material into another medium, external to itself, with enough precision to convey visual meaning. Unlike Screens, which produce content intrinsic to their material structure and compound, Printers produce content which is materially extrinsic to them. If they move around, the content they produce does not necessarily move with them. Likewise, if the Printer is 'reset, 'switched off' or even physically destroyed, the content it produced does not necessarily disappear as a consequence. Furthermore, this content can be produced *en masse* and spread around larger and multiple areas, that is, unlike Screens, Printers hold a one-to-many relationship (i.e. aggregation) with the content they produce.

4 Classification of Current Approaches to Pervasive Urban Displays

This section examines a range of pervasive urban display genres and examples from research and design practice. We classify and discuss these examples along the two design dimensions of physical integration of content and mobility of display technology, and the categorisation into Screens and Printers (see Figure 4). In the subsequent Section 5, we take a closer look at pulverised urban displays (PUDs), which we identified as a new class of pervasive displays. PUDs have the capability to autonomously change their position and represent content in a physical form (see Figure 4, upper right area in the design space).

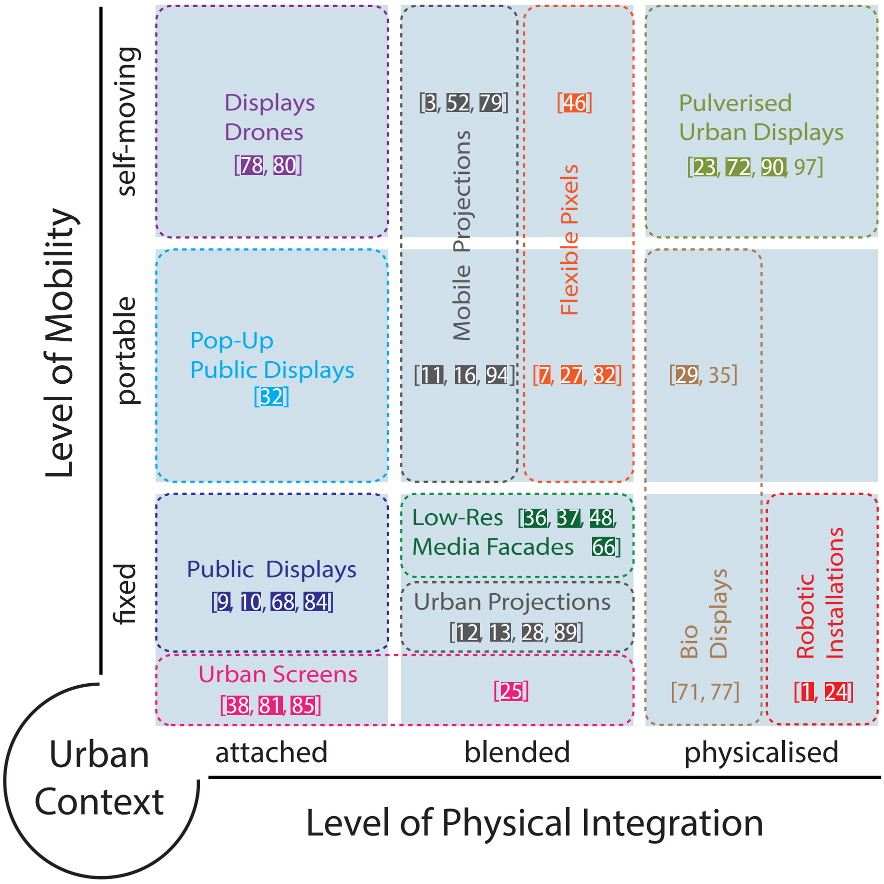

Fig. 4 Classification for pervasive urban displays according to their level of physical integration of content and mobility of display technology. The highlighting of the reference indicates whether the respective example belongs to the category of a Screen or Printer, e.g. [32] represents an example of a Screen, [71] represents a Printer.

4.1 Public Displays

Even though the notion of public display refers in the first place to the communication of visual content to the general public instead of specific individuals, the term is nowadays widely associated with medium-sized screen-based displays used for digital signage or general information. These displays are usually fixed, deployed in streets, public plazas, shopping centres and airports, and often come in mass-produced, generic forms (see Figure 5, left). The surrounding physical environment only functions as a structural support, external to the actual display, with the visual content attached as a self-contained layer. Academic research has also mostly favoured this kind of displays, given the benefits of falling back on existing public display infrastructure [10, 38] or deploying widespread consumer hardware [9, 84]. More mobile systems exist in the form of *Pop-Up Public Displays*, which are for example temporarily deployed at events and on construction sites for navigation support, and also previously applied in research as flexible platforms for local community engagement (see Figure 5, right) [32].

4.2 Urban Projections

When it comes to the distribution of high-res content, projections are another very common option for creating pervasive urban displays [13, 89] (see Figure 6). Increasingly, projections in urban spaces no longer adopt projection screens, rather using the existing city architecture as target surface. These types of displays can thus easily disappear when no longer needed [19]. Projections are blended displays in the sense that the visual content is influenced by the shape and aesthetic features of the architecture it is projected on (e.g. purposely used for projection mappings [28]), and also by the material properties of the surface, resulting in different diffusing effects (e.g. previously explored for ice as a visualisation material [12, 16, 73]). With the rise of pico-projectors, researchers have intensively investigated their potential in public space, referred to as *Mobile Projections*: for example through body worn projectors [16, 94] or projectors carried by drones [3, 52, 79], capable of showing information, such as navigation cues, on the go (see Figure 6, middle and right).

4.3 Display Drones

In contrast to mobile projections via drones that use the physical surroundings as canvas, here the content layer is attached to the aerial vehicle itself - which, in turn, is free moving. While still in a fairly experimental stage, researchers have already investigated various display technologies, such as lightweight e-ink displays [80] or projections onto a canvas mounted to the drone [78].

4.4 Building Size Displays

Several terms exist for fixed building-scale displays attached to or integrated into the built environment. The term *Urban Screen* is nowadays associated with large-scale displays in public spaces, often showing information-rich, high-resolution content, such as news, sporting events or content related to the local context, sometimes of artistic and playful nature [69, 81, 85]. Originally, the majority of urban screens were simply attached onto buildings, not only because electronic components were still bulky and not very flexible, but also due to the convenience of relying on mass media television. A shift towards more architectural integrated urban screens can be observed at Federation Square, Melbourne, which has recently revamped its iconic big screen with a new integrated multi-screen platform (see Figure 7, left). The new screen now wraps

Fig. 5 Permanent public display (left), pop-up public display (right). Image credits (right): Fredericks et al. in [32].

around two sides of the building, with its main section surrounded by stripes of smaller screens incorporating the original tile structure of the façade [25]. Thus, the content is no longer perceived as a self-contained layer, but spanning multiple physical screens and blending with the architectural form.

On the smaller end of the resolution spectrum are *Low-Resolution Media Façades*, predominantly with light-emitting diode (LED) technology embedded into the outer shell of the building (see Figure 8, left). Here, each pixel becomes an intrinsic architectural element itself. The visual content is not only influenced by the outer screen shape, but also the pixel configuration, the pixel shape and other surrounding materials which may function as secondary optic elements (e.g. diffusers, reflectors) [37, 39, 43]. Apart from light, architects have also used actuators to create kinetic low-resolution media structures [36]. Here, the content is "rendered" in an entirely physical form and is manifested in the architecture itself. The façade of the Kunstmuseum Basel (see Figure 7, right) demonstrates the rich design space of low-resolution building displays, and also that the definition of blended and physicalised content can - in terms of the perception - in fact be transient: in a three-meter-high frieze, white LED pixels are integrated in the joints of the façade's bricks to create content of dynamic text and patterns. The brightness of the LEDs, which are not visible from the street, but only reflected by the bricks, is adjusted to the natural ambient light outside, in order to match the "activated" bricks to the appearance of the rest of the façade. During the day, the interplay of light and shadows leads to the illusion that the display emerges from moving solid bricks, simulating a physicalised integration of content [48]. Qualities as such offer a rich design space, which makes the visual perception of content unique for each particular façade, and puts some of the creative process of designing digital urban media back into the hands of architects.

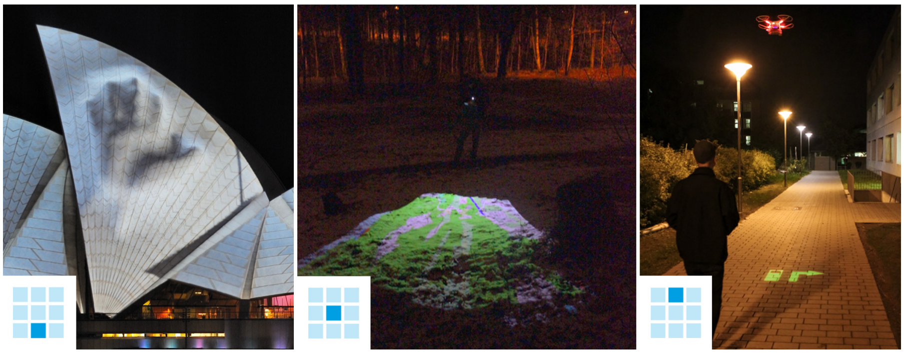

Fig. 6 Projections onto Sydney Opera House (left), portable projections, with the projector carried by the user (middle), moving projections from a drone (right). Image credits (from left to right): ©Jerry Dohnal (Flickr, CC BY-NC-ND 2.0), Dancu et al. in [16], Knierim et al. in [52].

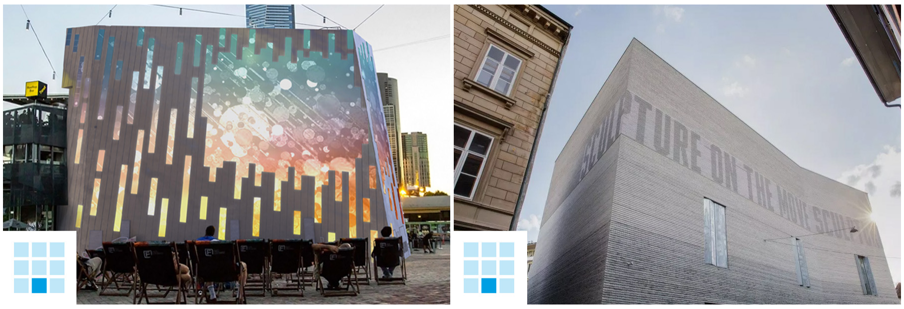

Fig. 7 Urban Screen at FedSquare Melbourne, after the redesign (left); Illusion of physical transformations on the frieze of Kunstmuseum Basel (right). Image credits (from left to right): ©Fed Square Pty Ltd, ©Derek Li Wan Po.

Fig. 8 Blended low-resolution lighting-based displays of various mobility levels (from left to right): fixed media façade, flexible pixels and floating pixels. Image credits (from left to right): ©Public Visualisation Studio, Seitinger et al. in [82], ©Ars Electronica / Martin Hieslmair (Flickr, CC BY-NC-ND 2.0).

4.5 Flexible Pixels

Inspired by the aesthetics of low-resolution lighting-based media façades, researchers have created more lightweight and mobile low-res displays [7, 27, 82]. Autonomous pixels systems, such as Urban Pixels (see Figure 8, middle) [82] or Firefly [7], can be flexibly arranged on any surface with the content blended into the physical environment. *Floating Pixels* using arrays of drones equipped with RGB lights (see Figure 8, right) represent the next iteration of flexible pixel systems [46]: dynamic content can still be rendered similarly to a traditional screen, yet the display is also capable to physically move and rearrange itself in space.

4.6 Robotic Installations

Industrial robots have lately been explored as emergent form of pervasive urban display [1, 24]. Unlike kinetic building structures, where actuators manipulate façade elements "behind the curtain", here the actuator itself becomes an intrinsic element of the displayed content, which can be manifested through object manipulations or the spatial configuration and movement of robotic arms.

4.7 Bio Displays

Artists and researchers also repeatedly engaged with the creation of physicalised displays by manipulating natural phenomena and organic materials, some of them developed in practice while others just conceptually. Due to the wide range of natural materials and substances, and their diverse characteristics, the applied processes and technologies that create the display are highly bespoke, ranging from augmented manual procedures [77] to purpose-built electromechanical machines [29, 35]. Some of the display technologies are fixed - for example, the building-sized art installation by realities:united, originally designed for the top of Copenhagen's Amager Bakke waste-to-energy plant, by Bjarke Ingels Group (BIG), which would indicate CO2 emissions from the plant using smoke rings [71]. In contrast, other systems developed as prototypes include sunlight pixels by Fischer et al. [29] or the plant-based controllable display by Gentile et al. [35] which can be portable and autonomous. While all examples of the previously presented genres belong to the category of a Screen, bio displays often take on the characteristics of a Printer, as in the case of the example from realities:united, where the content (i.e. the smoke rings) is a third-party material, emitted by the technology producing the content. Even if the display technology is turned off, the smoke rings still persist until the particles disperse.

5 Towards Pulverised Urban Displays

Our design space analysis of pervasive urban displays indicates the increasingly wide range of options to deploy digital media in the urban environment, beyond stationary screen-based displays. While an increasing interest towards physically integrated and mobile forms is clearly prominent in the community, there is a remaining gap in the exploration of pervasive displays that combine both characteristics: highly physicalised and ubiquitous forms of digital urban media. To better understand this gap, we introduce the concept of pulverised urban displays (PUDs), which we foresee as an emerging type of 'fine-grained' display technology capable of *rendering* content in a physicalised form while also being highly mobile. With 'pulverised' we here don't refer to the use of small particles for displaying content, such as chalk particles. We use the term in a more conceptual sense to describe the increasing mobility and physical integration into the environment of these types of new displays. That, of course, begs the question: what kind of existing technologies, if any, could evolve into PUDs? In that regard, in terms of mobility, we would argue that urban robots are particularly strong precursors of PUDs - for example, in the form of ground and aerial vehicles, with their ability to manipulate and sense the environment [51]. Likewise, in the long-term, novel material creations might pave the way for the next radical shift in pervasive urban display research, where display technology and content are fully merged [50].

5.1 Example Applications

In the following, we illustrate some of the characteristics of PUDs by means of two examples: the ChalkBot, created by the designer Louis Elwood-Leach [23], as example of a Printer PUD; and the cockroach-like soft-robot, developed by robotic researchers from the University of California, Berkeley [97], as an example of a Screen PUD.

The Chalkbot (see Figure 9, left) is an omni-wheel ground vehicle with a spray can attached for drawing on the pavement with a customised chalk-like powder. The drawings are based on digital vector graphics which are recreated in a physicalised form in public space. As it creates content that is static and external to the producing device, ChalkBot falls in the category of a PUD Printer. A similar concept has been recently also developed by the design office CRA-Carlo Ratti Associati: instead of using a robot, they deployed a swarm of drones equipped with a spray-paint can to create a collaborative artwork on a vertical canvas [72]. Vempati et al. describe the implementation of PaintCopter, which is a sophisticated implementation of a spray painting drone system that allows drawing on three-dimensional surfaces and taking into account texture appearance [90].

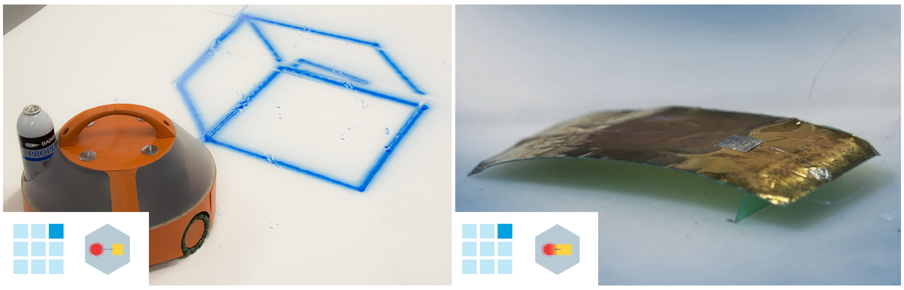

Fig. 9 Two potential technologies for creating PUDs: (1) ChalkBot (left) is capable to recreate digital drawings with chalk in public space, based on vector graphics positioned over satellite images. (2) Inspired by living organisms, the cockroach-like soft-robot (right) is characterised by its fast locomotion and robustness. Image credits (from left to right): ©Louis Elwood-Leach, Wu et al. in [97].

At a size of two centimetres, the insect-scale soft-robot (see Figure 9, right) can move with a speed of 20 body lengths per second. The soft-robot is made of a thin layer of piezoelectric material, which expands and contracts when applying a voltage. In its current version, the soft-robot still needs to be connected to a thin wire for power supply, however, the authors are currently working on a battery-powered autonomous prototype. While the researchers speculate on its use as a sensing device (e.g. detecting dangerous fumes in small and hard-to-reach spaces), soft-robots also provide great potential for the realisation of PUD Screens: for example, soft-robots could visualise information through their direction of movement, motion sequences or spatial distribution when appearing in a swarm-like configuration [51].

5.2 Design Implications

The two examples above illustrate three core features of PUDs, which in our view can radically reshape the understanding and potential of pervasive displays. Firstly, PUDs are largely flexible, not only in terms of scalability, but also due to the fact they are capable of seamless adapt to a range of different environments. In that sense, they fulfil a global scope, for not being confined to a single spatial location. At the same time, due to their properties of material integration, they can also be highly customised to specific spatial locations, that is, they can enable highly situated and contextualised deployments, while still retaining the ability to remove themselves from an environment and leave it as it was prior to their intervention.

In other words, PUDs have breadth, depth and resilience: they demonstrate potential to move globally, adapt locally, and sustain themselves overtime with minimal environment impact. In the subsections below, we expand and comment on those capabilities by referring back to our examples of the ChalkBot and the cockroach-like soft-robot. In the process, we outline relevant implications for the design of future PUDs.

5.2.1 Global Scope: Flexibility

Ad-hoc deployment. While ChalkBot could be used to create various types of urban visualisations, for the sake of an example we speculate about its usage in the context of construction sites, which has been previously identified as a relevant application context for pervasive urban displays [58]. Construction sites exist only over a limited period of time, making it usually not economically viable to fall back on a fixed public display system. PUDs such as ChalkBot could bring the strengths of digitally created content to construction sites, providing flexible and low-cost dissemination of information, such as navigation support, project status or advertisement. While the permanent deployment of public displays requires time and cost consuming construction work [47], the ChalkBot could be deployed within minutes, only restricted by its speed and the distance to its base station. In the context of navigation, previous research has demonstrated that augmenting the physical environment with navigation instructions, leads to a higher awareness and memorability of real-world points of interests [52]. However, providing navigation support on fixed public display systems, requires a dense coverage of screens [10]. In contrast, a swarm of soft-robots could provide, on the go, navigation cues directly located in the physical environment, without the user carrying any sort of (augmented reality) AR hardware, such as glasses or mobile projectors. Compared to drone-projected solutions [52] or service robots made of rigid materials [95], soft-robots could also reach densely treed or roofed pathways as well as rough terrain. To generalise, it can be concluded that PUDs come with less infrastructural restrictions compared to fixed and portable pervasive displays, and can arguably be deployed everywhere and when it matters, similarly to non-digital public displays [53].

Responsive to contextual changes. Fitted with sensors or receiving data from a distributed sensor network, ChalkBot could quickly respond to contextual changes: e.g. upon changes on the physical surroundings of the construction site overtime, ChalkBot would recreate content at novel locations.

5.2.2 Local Scope: Situatedness

Manipulation of the environment. PUDs represent content through manipulation of the immediate physical surroundings. This enables great potential for situated and embedded data representations, defined as the deep connection between information and their physical referents [93]. For public constructions, ChalkBot could draw on the rising structure the amount of public money spent to date, expressing building progress related to costs. The symbiosis of content and physical environment also adds transient qualities [53] to the display, such as erosion through rain and passers-by, thus providing subtle layers of implicit information.

Ambient and privacy-preserving. The concept of ambient information displays has been widely applied to the design of pervasive urban displays [36, 82, 92]. Besides the key function of presenting information at the periphery of users' attention requiring little mental effort [49], research also investigated its benefits for encoding personal information in public space, which can otherwise cause privacy concerns [44] and social embarrassment [74]. Being a natural augmentation of the physical environment, PUDs could further elaborate on that matter, through visualising information in an unobtrusive manner. For navigation support, insect-scale soft-robots adapting characteristics of living organisms, would act as a less conspicuous companion compared to, for example drone-enabled displays and projectors [52, 80], which are visible for others from a far.

Enabling tangible interaction. The materially and affordances of non-digital public displays have been previously reported to attract people and enable natural tangible interactions [32, 53, 87]. PUDs, such as ChalkBot, afford similar interactions for digitally created content. For example, people could create and extend content by manually drawing with chalk sticks on the ground, enabling a barrier-free interaction modality without the requirement of a digital user interface. Soft-robots, being highly robust yet also flexible, and thus providing enough safety for humans when interacting with them, enable novel interaction experiences with self-moving displays, that are tactile instead of remote [5].

5.2.3 Long-Term Value: Sustainability

Eco-friendly and sustainable displays. LED or projection based displays require intensive amount of infrastructure and, once deployed, cannot easily be changed or adapted to new urban contexts and circumstances (e.g. architectural modifications of the surrounding infrastructure). In contrast, the conceptual approach of PUDs is expressed through an ever-changing, fast paced media technology. Likewise, their output is temporary, adaptable, ephemeral and can be quickly customised to new situations. Light pollution is another controversial topic that is currently discussed among researchers and practitioners in this domain [31, 98]. Working with renewable and eco-friendly materials in the realm of PUDs addresses these issues as content may be fully degradable and therefore fosters a more careful utilisation of resources. The designer of ChalkBot, for example, experimented with various materials to develop a soluble chalk paint that can be washed away easily. In the realm of soft-robots, new material creations might pave the way towards pervasive displays in which all components are fully biodegradable [75].

Robustness and resistant to obsolescence. Another challenge which has been widely discussed within the field, is the demand for increased robustness when it comes to designing displays for the urban realm [14]. In particular for media architectural displays, where display technology and building material is deeply interwoven, the mismatch in durability of these components can cause severe problems that can affect a project's long-term value, e.g. either on a technical level through display failures that are expensive to repair or on an aesthetic level through fast-paced technological innovation [57]. While there is certainly a wide range of reported measures that can be followed also for the design of more conventional pervasive urban displays [57, 67], we see the following advantages of pulverised displays: PUD Printers which manipulate existing physical structures create content that is external to the producing technology, which means that the content itself comes with the durability and obsolescence characteristics of the rendering material or the manipulated physical structure. Through their flexibility, the content producing components can be exchanged without compromising the integrity of the surrounding structure. Speculating on soft-robots as a future technology for the design of PUD Screens, even though still in its early phases, the compliant materials they are made of demonstrate high robustness whilst staying flexible. The cockroach-like soft robot, for example, reported to withstand the weight of an average human's footstep [97], provides radical new design possibilities as a display material.

6 Research Challenges

Motivated by the increasing interest in the research community towards ubiquitous forms of pervasive urban displays, we have provided a systematic classification of current approaches by the means of a taxonomy along two dimensions: level of mobility and physical integration. Indicating that there is a gap in the exploration of highly physicalised and mobile pervasive urban displays, we introduced the concept of PUDs by the means of two speculative example applications enabled by robotic technologies that are already available or currently being researched. Based on our analysis, we identified four research challenges for the field going forward: information design, prototyping methods, interdisciplinary collaborations on material research and strategies for adoption. These challenges are not exclusive to the design of pulverised urban displays, but might also address some of the open questions that apply to other classes of pervasive displays along our taxonomy.

6.1 Information Design

In most cases, the aim of a pervasive urban display is to communicate some form of information to the viewer, either explicit or implicit in meaning. When it comes to the information design of non-conventional displays, the visual means to deliver information can be limited and highly dependent on the display's characteristics. For low-resolution media façades, Offenhuber and

Seitinger proposed a taxonomy that identifies different visual means (e.g. color, movement, text and image) according to the display's resolution [66]. Further, they stress that for physically integrated content - in this case through the fusion of architecture and digital media - the building, in other words the physical environment, even though implicitly, becomes part of the message. For physicalised displays, the visual means to convey information can be even more specific and restricted to the display's materially: e.g. how quickly can content be changed, does the display consists of individually-controllable elements, and whether such elements are capable of conveying binary information only, or perhaps also more continuous content, such as gradients [35]. When it comes to self-moving displays, information can be conveyed not only by the spatial distribution, but also by the motion of the object itself [51]. Here, again, 'meaning' can be understood as having a more implicit character: for example, for drones, Cauchard et al. investigated how various movement parameters may be related by humans to certain emotions and personalities [6]. In order to support researchers and practitioners to design content that conveys information, the establishment of an understandable visual language is important. To avoid "reinventing the wheel", especially with the increasing number of pervasive urban displays, we propose a thorough analysis of existing approaches related to the aspect of information design, extending the work from Offenhuber and Seitinger from low-resolution media façades to the whole range of pervasive urban displays. Our taxonomy and classification can be a starting point to systematically analyse different classes of pervasive urban display in terms of their information density, the visual means to encode information and the sort of meaning that is transmitted.

While the analysis in this article focused on 'primary' display objects - in other words, those whose primary function is the communication of content - there is also a large application area for 'secondary' displays: for instance, those that are attached or embedded into self-moving and autonomous objects, which however have another primary function, for example the transportation of people. Given the likely increasing number of autonomous and self-moving objects (e.g. driverless-cars, delivery robots) in the near future [64], and an over saturation of the environment with displays [17], implicit visual means (e.g. motion [6], dynamic lighting [43, 45]) can become important as an information channel, for example, for communicating safety and trust [65]. This might be also the case for 'primary' displays enabled through urban robots: while the robot's primary task is the creation of content, a 'secondary' display, for example in the form of an integrated low-res LED display, can be important to communicate to humans its internal state, direction of movement or even just to express a form of friendliness. A further investigation of such 'secondary' displays can prevent self-moving and autonomous entities from being released as foreign bodies in public space.

6.2 Prototyping Methods

The creation of prototypes is an essential aspect in human-computer interaction (HCI) and design research. Prototypes support the envision of future interface designs and the evaluation of interaction techniques with prospective users. Prototypes at various fidelity levels and resolutions can thereby filter specific aspects in a design solution [54]. Inspired by physical computing platforms, such as Arduino, media architecture researchers developed a range of toolkits with the aim to support architects and designers with limited programming skills to test early interactive concepts [41, 42, 91], but also to allow laypeople to actively create their own interventions in public space [4]. Through fast-paced technological improvements in simulation hardware and software, coupled with a wide availability of virtual reality (VR)-headsets at affordable costs, VR has found increasing popularity among HCI researchers as a prototyping and evaluation platform: for example to evaluate interactions with autonomous vehicles, a technology which is still mostly limited to test-bed environments and can cause harm to participants [65]. In regard to pervasive urban displays, it is apparent that researchers still mainly fall back on physical prototypes embedded in a real-world urban context. The reason for this may be that aesthetic [21], spatial [26] and contextual aspects [61] are difficult to address in a purely simulated urban environment, inter alia, because they still lack on realism due to a limited representational fidelity. However, as a consequence, emerging display concepts which are difficult to prototype by the means of common prototyping materials, may remain underrepresented as spotted by our analysis.

For the further development of pervasive urban displays, such as those that are highly mobile and entangled with the built and natural environment, and therefore often require specialist know-how in robotic and/or material engineering, we propose to consider and adapt the following methods and tools for early design explorations: (1) *Design Fiction* can be a powerful technique to explore and critically discuss future interface designs without actually making them [2]. In section 5, introducing the examples of ChalkBot and cockroach-like soft robots, we used fictional elements to speculate on design implications for PUDs. Although both example scenarios are grounded on existing research prototypes, they have not yet been studied in the application contexts proposed by this article. (2) To evaluate speculative pervasive urban displays with actual users, VR simulations should be considered: for example, the cockroach-like soft robot as a navigation helper, could be designed in VR with relatively little effort in order to assess general acceptance, potential interaction techniques and how information can be successfully encoded. To overcome the lack of representational fidelity in VR, we recently have proposed the concept of hyperreal VR prototypes, combining 3D 360-degree video recordings with virtual rendered objects [40]. In the future, we are planning to implement a hyperreal prototype design of the cockroach-inspired navigation display and compare it with a simulation in AR to evaluate the two prototypes in terms of realism. Other researchers are currently working on immersive simulators for supporting haptic feedback and tactile sensations for collocated interactions with drones [5]. Combining those research efforts aiming to improve VR experiences may hopefully lead to a wider usage in the pervasive display community and support the exploration of emerging pervasive urban displays.

6.3 Interdisciplinary Research on Smart Materials & Robotic Engineering

Considering our proposed taxonomy, and looking back at the examples that are situated on the end of its integration dimension (re: physicalised), it is apparent that those are still of a highly experimental nature. Often researchers adapt available products (e.g. robots, drones) and prototyping tools, in order to create first manifestations of future visions of pervasive displays [28, 35, 77]. This is a common approach also in other related fields of human-computer interaction (HCI), for example in tangible computing, to develop and evaluate interaction techniques for shape-changing devices, which are not mass-produced yet but might be available in the near future [70]. While building low-fidelity prototypes, simulations are important to evaluate future interactive designs (re: Section 6.2: Prototyping & Evaluation Techniques), HCI researchers increasingly stressed for more interdisciplinary exchange with engineering and material science to gain a deeper understanding of material properties and how they can unwrap future interface designs [63, 70]. We believe that more interdisciplinary collaboration is also essential for the next step in researching highly physicalised urban displays, and therefore propose the following actions to be carried out by the pervasive display community: 1) conducting a thorough review of enabling technologies, such as smart materials and robotics, and how their characteristics can inspire novel forms of pulverised urban displays. Soft robotics can serve here again as an example technology, initially with a focus in medical and manufacturing applications, however, increasingly found interest among HCI researchers to be applied in various contexts [59]. 2) In order to make physicalised displays - such as those based on natural and organic materials - scalable and applicable in the real-world, pervasive display researchers should bridge the gap towards a deeper understanding of those materials. “Cyborg Botany” recently presented at the Conference on Human Factors in Computing Systems [76] illustrates well the next step to be taken in using plants as a display material: instead of using external manipulators [35], they strived for “a deep integration of technology within plants” by growing a nanowire inside the xylem, thus enabling a direct interface to use the plant as a sensor or display.

6.4 Strategies for Adoption

As with every new pervasive technology to be successfully adopted, for a paradigm shift to occur, the new technology needs to be widely used and accepted. Previous work on public displays has pointed out the mismatch between the premise of pervasive displays becoming a widespread platform of social change and the actual number of long-term display deployments - notwithstanding those that are purely used as an advertisement medium [47]. One difficulty pointed out in this regard is the alignment of all stakeholders interests [14], such as building managers and display owners, who need to be convinced about the real-world value and impact to justify the high costs associated with deployment and operation [22, 47]. Further, external factors (e.g. weather, vandalism and characteristics of the surrounding deployment space), while difficult to control, have been previously found to influence a public display deployment negatively, therefore raising additional concerns among stakeholders [56]. The absence of researchers after project completion, who usually also act as facilitators promoting it [53], can lead to a decline in engagement with the display [47, 86]. The same also applies to the *novelty effect*, which usually diminishes over time as people become familiar with and used to the newly introduced technology.

The benefits and design implications that we previously outlined for PUDs comply with some of the strategies that have been suggested for creating sustainable public display deployments: for example, the circumstance that PUDs are not fixed and permanently installed at a certain location, offers more freedom in terms of adaptation and repurposing [47] and the ability to use them as a shared resource [11]. Urban robots, as the enabler for pulverised urban displays, have the potential to be designed as social agents, thereby acting as a facilitator for placemaking strategies and compensating the presence of a researcher.

PUDs also come with a range of new challenges, linked to current limitations and yet-to-be-explored questions, that need to be addressed. Here we identify four challenges that offer opportunities for future research studies. First, at the current stage, PUDs are more complex in nature [23], requiring more maintenance, which means that they are currently not in a position to compete with digital public displays in terms of their plug-and-play ease of use. Second, PUDs, such as ChalkBot, have limitations in terms of the visual content that can be rendered, which might make it more difficult to convince potential stakeholders who are used to the high-resolution and colour depth that conventional public displays provide. Third, pervasive displays, which are enabled through urban robots, not being fixed or attached to a building carrier, raise new questions when it comes to ownership and how to best manage such resources. Fourth, urban robots might be more vulnerable to vandalism, potentially making them yet another contributor to e-waste, as currently seen with other shared urban technologies being rolled out, for example, shared bikes and electric scooters [20]. In this vein, for PUDs to fully comply with their promise of providing a more sustainable alternative to conventional displays, new alternative strategies that consider and involve more-than-human perspectives (e.g. other living beings [8, 30], but also robotic agents [55]) needs to be considered in the design process of pervasive urban displays and smart cities functioning as their *operating system* [88].

7 Conclusion

After almost a decade of continuous development and increasing diversification, pervasive urban displays have fragmented into a diversity of approaches with radically distinct levels of mobility in time, as well as material integration with the physical space around them. While this translates into growing complexity of design strategies, it also enables designs with greater level of customisation and adaptability to the environments they are deployed to. In this article, we adopted levels of mobility and material integration to propose a taxonomy capturing such an evolution of pervasive displays. We also proposed the notions of Screens and Printers to describe two categories of pervasive displays, specified through the content produced on the one hand and the device actually producing the content on the other hand. We then classified existing pervasive displays according to the two taxonomy dimensions and the two categories, and discussed examples for the different approaches emerging from the classification. In the process, we revealed a gap in the design space defined through the taxonomy dimensions, represented by a degree of ultimate pervasiveness, which we described as pulverised urban displays (PUD). We then discussed potential characteristics of PUDs and pointed towards robotic urban displays as potential protagonists to enable the transition from the current state-of-the-art to a potential future in which PUDs play a greater role in supporting everyday urban life. The taxonomy, classification and definitions laid out by this article contribute to providing a foundation for future research on pervasive displays and framing the analysis of the field going forward.

References

1. ABB (2014) Teaser trailer luminale festival 2014 opens with robotic light art. https://www.abb-conversations.com/2014/03/teaser-trailer-luminale-festival-2014-opens-with-robotic-light-art/, *last accessed: January 2020*
2. Blythe M (2014) Research through design fiction: Narrative in real and imaginary abstracts. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, CHI '14, pp 703–712, DOI 10.1145/2556288.2557098, URL http://doi.acm.org/10.1145/2556288.2557098
3. Brock AM, Chatain J, Park M, Fang T, Hachet M, Landay JA, Cauchard JR (2018) Flymap: Interacting with maps projected from a drone. In: Proceedings of the 7th ACM International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '18, pp 13:1–13:9, DOI 10.1145/3205873.3205877, URL http://doi.acm.org/10.1145/3205873.3205877

4. Caldwell GA, Foth M (2014) DIY media architecture: open and participatory approaches to community engagement. In: Proceedings of the 2nd Media Architecture Biennale Conference on World Cities - MAB '14, pp 1–10, DOI 10.1145/2682884.2682893, URL https://doi.org/10.1145/2682884.2682893
5. Cauchard J, Sharlin E (2019) "come to me nice butterfly" drone form in collocated hdi. In: 1st International Workshop on Human-Drone Interaction, Ecole Nationale de lAviation Civile [ENAC], Glasgow, United Kingdom
6. Cauchard JR, Zhai KY, Spadafora M, Landay JA (2016) Emotion encoding in human-drone interaction. In: The Eleventh ACM/IEEE International Conference on Human Robot Interaction, IEEE Press, Piscataway, NJ, USA, HRI '16, pp 263–270, URL http://dl.acm.org/citation.cfm?id=2906831.2906878
7. Chandler A, Finney J, Lewis C, Dix A (2009) Toward emergent technology for blended public displays. In: Proceedings of the 11th International Conference on Ubiquitous Computing, ACM, New York, NY, USA, UbiComp '09, pp 101–104, DOI 10.1145/1620545.1620562, URL http://doi.acm.org/10.1145/1620545.1620562
8. Clarke R, Heitlinger S, Light A, Forlano L, Foth M, DiSalvo C (2019) More-than-human participation: design for sustainable smart city futures. Interactions 26(3):60–63, DOI 10.1145/3319075, URL https://eprints.qut.edu.au/128763/
9. Coenen J, Wouters N, Moere AV (2016) Synchronized wayfinding on multiple consecutively situated public displays. In: Proceedings of the 5th ACM International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '16, pp 182–196, DOI 10.1145/2914920.2929906, URL http://doi.acm.org/10.1145/2914920.2929906
10. Coenen J, Claes S, Moere AV (2017) The concurrent use of touch and mid-air gestures or floor mat interaction on a public display. In: Proceedings of the 6th ACM International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '17, pp 9:1–9:9, DOI 10.1145/3078810.3078819, URL http://doi.acm.org/10.1145/3078810.3078819
11. Colley A, Häkkilä J, Forsman MT, Pfleging B, Alt F (2018) Car exterior surface displays: Exploration in a real-world context. In: Proceedings of the 7th ACM International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '18, pp 7:1–7:8, DOI 10.1145/3205873.3205880, URL http://doi.acm.org/10.1145/3205873.3205880
12. Colley A, Yliharju AJ, Häkkilä J (2018) Ice as an interactive visualization material: A design space. In: Proceedings of the 7th ACM International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '18, pp 14:1–14:6, DOI 10.1145/3205873.3205895, URL http://doi.acm.org/10.1145/3205873.3205895
13. Dalsgaard P, Fritsch J (2008) Media Facades Beyond Interaction. In: Position paper for Workshop on Public and Situated Displays to Support Communities, OzCHI 2008

14. Dalsgaard P, Halskov K (2010) Designing urban media façades: Cases and challenges. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, CHI '10, pp 2277–2286, DOI 10.1145/1753326.1753670, URL http://doi.acm.org/10.1145/1753326.1753670
15. Dalsgaard P, Halskov K, Wiethoff A (2016) Designing media architecture: Tools and approaches for addressing the main design challenges. In: Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, CHI '16, pp 2562–2573, DOI 10.1145/2858036.2858318, URL http://doi.acm.org/10.1145/2858036.2858318
16. Dancu A, Franjcic Z, Ünlüer AA, Fjeld M (2015) Interaction in motion with mobile projectors: Design considerations. In: Proceedings of the 4th International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '15, pp 61–68, DOI 10.1145/2757710.2757728, URL http://doi.acm.org/10.1145/2757710.2757728
17. Davies N (2018) Saturated Display Environments. Keynote at International Symposium on Pervasive Displays (PerDis '18) URL https://pervasivedisplays.org/2018/program.htmlkeynote
18. Davies N, Langheinrich M, Jose R, Schmidt A (2012) Open Display Networks: Towards A New Communication Media for the 21st Century. IEEE Computer 45(5):58–64, DOI 10.1109/MC.2012.114
19. Davies N, Clinch S, Mikusz M, Bates O, Turner H, Friday A (2017) Better off: When should pervasive displays be powered down? In: Proceedings of the 6th ACM International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '17, pp 19:1–19:9, DOI 10.1145/3078810.3078821, URL http://doi.acm.org/10.1145/3078810.3078821
20. Dickinson K (2018) Bike-share companies accused of creating e-waste mountains. https://resource.co/article/bike-share-companies-accused-creating-e-waste-mountains-12784, *last accessed: February 2020*
21. Ebsen T (2013) Material Screen: Intersections of media, art, and architecture. PhD thesis
22. Elhart I, Langheinrich M, Memarovic N, Rubegni E (2016) A good balance of costs and benefits: Convincing a university administration to support the installation of an interactive multi-application display system on campus. In: Proceedings of the 5th ACM International Symposium on Pervasive Displays, Association for Computing Machinery, New York, NY, USA, PerDis 16, p 197203, DOI 10.1145/2914920.2915029, URL https://doi.org/10.1145/2914920.2915029
23. Elwood-Leach L (2013) Chalkbot - recreate digital drawing in the physical space with soluble chalk paint. https://elwoodleach.com/chalkbot, *last accessed: April 2019*
24. Ergin E, Afonso A, Schieck AFg (2018) Welcoming the Orange Collars: Robotic Performance in Everyday City Life. In: Proceedings of the 7th ACM International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '18, pp 17:1–17:7, DOI 10.1145/3205873.3205893, URL

http://doi.acm.org/10.1145/3205873.3205893
25. Fedsquare (2018) Fed Square's New Digital Experience Initiative. URL https://fedsquare.com/
26. Fischer PT, Hornecker E (2012) Urban hci: Spatial aspects in the design of shared encounters for media facades. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, CHI '12, pp 307–316, DOI 10.1145/2207676.2207719, URL http://doi.acm.org/10.1145/2207676.2207719
27. Fischer PT, Gerlach F, Acuna JG, Pollack D, Schäfer I, Trautmann J, Hornecker E (2014) Movable, kick-/flickable light fragments eliciting ad-hoc interaction in public space. In: Proceedings of The International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '14, pp 50:50–50:55, DOI 10.1145/2611009.2611027, URL http://doi.acm.org/10.1145/2611009.2611027
28. Fischer PT, von der Heide A, Hornecker E, Zierold S, Kästner A, Dondera F, Wiegmann M, Millán F, Lideikis J, Cergelis A, Verde R, Drews C, Fastnacht T, Lünsdorf KG, Merat D, Khosravani A, Jannesar H (2015) Castle-Sized Interfaces - An Interactive Facade Mapping. Proceedings of the International Symposium on Pervasive Displays (PerDis'15) (1969):91–97, DOI 10.1145/2757710.2757715
29. Fischer PT, Hornecker E, Gielen J, Hartmann J, Schmandt M, Rack A, Bornemann M, Dondera F (2015) Exploring the potential of depictions with sun reflections. In: Proceedings of the 4th International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '15, pp 217–224, DOI 10.1145/2757710.2757712, URL http://doi.acm.org/10.1145/2757710.2757712
30. Forlano L (2016) Decentering the human in the design of collaborative cities. Design Issues 32(3):42–54, DOI https://doi.org/10.1162/DESI$_{a0}$0398
31. Foth M, Caldwell GA (2018) More-than-human media architecture. In: Proceedings of the 4th Media Architecture Biennale Conference, ACM, New York, NY, USA, MAB18, pp 66–75, DOI 10.1145/3284389.3284495, URL http://doi.acm.org/10.1145/3284389.3284495
32. Fredericks J, Hespanhol L, Parker C, Zhou D, Tomitsch M (2018) Blending pop-up urbanism and participatory technologies: Challenges and opportunities for inclusive city making. City, Culture and Society 12:44 – 53, DOI https://doi.org/10.1016/j.ccs.2017.06.005
33. Fritsch J, Brynskov M (2011) Between experience, affect, and information: Experimental urban interfaces in the climate change debate. In: From Social Butterfly to Engaged Citizen: Urban Informatics, Social Media, Ubiquitous Computing, and Mobile Technology to Support Citizen Engagement, MIT Press, p 115, DOI 10.7551/mitpress/8744.003.0013
34. Gandia RM, Antonialli F, Cavazza BH, Neto AM, Lima DAd, Sugano JY, Nicolai I, Zambalde AL (2019) Autonomous vehicles: scientometric and bibliometric review. Transport Reviews 39(1):9–28, DOI 10.1080/01441647.2018.1518937

35. Gentile V, Sorce S, Elhart I, Milazzo F (2018) Plantxel: Towards a plant-based controllable display. In: Proceedings of the 7th ACM International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '18, pp 16:1–16:8, DOI 10.1145/3205873.3205888, URL http://doi.acm.org/10.1145/3205873.3205888
36. Haeusler MH (2009) Media facades: history, technology, content. avedition
37. Halskov K, Ebsen T (2013) A framework for designing complex media facades. Design Studies 34(5):663 – 679, DOI https://doi.org/10.1016/j.destud.2013.04.001
38. Hespanhol L, Tomitsch M, McArthur I, Fredericks J, Schroeter R, Foth M (2015) Vote as you go: Blending interfaces for community engagement into the urban space. In: Proceedings of the 7th International Conference on Communities and Technologies, ACM, New York, NY, USA, C&T '15, pp 29–37, DOI 10.1145/2768545.2768553, URL http://doi.acm.org/10.1145/2768545.2768553
39. Hoggenmueller M, Hespanhol L (2017) P+: A test fit platform for generative design of 3d media architecture. In: Proceedings of the 6th ACM International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '17, pp 15:1–15:7, DOI 10.1145/3078810.3078816, URL http://doi.acm.org/10.1145/3078810.3078816
40. Hoggenmueller M, Tomitsch M (2019) Enhancing pedestrian safety through in-situ projections: A hyperreal design approach. In: Proceedings of the 8th ACM International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '19, pp 29:1–29:2, DOI 10.1145/3321335.3329682, URL http://doi.acm.org/10.1145/3321335.3329682
41. Hoggenmueller M, Wiethoff A (2014) Lightset: Enabling urban prototyping of interactive media façades. In: Proceedings of the 2014 Conference on Designing Interactive Systems, Association for Computing Machinery, New York, NY, USA, DIS 14, p 925934, DOI 10.1145/2598510.2598551, URL https://doi.org/10.1145/2598510.2598551
42. Hoggenmueller M, Wiethoff A (2016) Lightbricks: A physical prototyping toolkit for do-it-yourself media architecture. In: Proceedings of the 3rd Conference on Media Architecture Biennale, Association for Computing Machinery, New York, NY, USA, MAB, DOI 10.1145/2946803.2946811, URL https://doi.org/10.1145/2946803.2946811
43. Hoggenmueller M, Tomitsch M, Wiethoff A (2018) Understanding artefact and process challenges for designing low-res lighting displays. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, CHI '18, pp 259:1–259:12, DOI 10.1145/3173574.3173833, URL http://doi.acm.org/10.1145/3173574.3173833
44. Hoggenmueller M, Wiethoff A, Moere AV, Tomitsch M (2018) A media architecture approach to designing shared displays for residential internet-of-things devices. In: Proceedings of the 4th Media Architecture Biennale Conference, ACM, New York, NY,

USA, MAB18, pp 106–117, DOI 10.1145/3284389.3284391, URL http://doi.acm.org/10.1145/3284389.3284391
45. Hoonhout J, Jumpertz L, Mason J, Bergman T (2013) Exploration into lighting dynamics for the design of more pleasurable luminaires. In: Proceedings of the 6th International Conference on Designing Pleasurable Products and Interfaces, ACM, New York, NY, USA, DPPI '13, pp 185–192, DOI 10.1145/2513506.2513526, URL http://doi.acm.org/10.1145/2513506.2513526
46. Hörtner H, Gardiner M, Haring R, Lindinger C, Berger F (2012) Spaxels, Pixels in Space - A novel mode of spatial display. In: Proceedings of International Conference on Signal Processing and Multimedia Applications
47. Hosio S, Goncalves J, Kukka H, Chamberlain A, Malizia A (2014) What's in it for me: Exploring the real-world value proposition of pervasive displays. In: Proceedings of The International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '14, pp 174:174–174:179, DOI 10.1145/2611009.2611012, URL http://doi.acm.org/10.1145/2611009.2611012
48. iartch (2016) Light Frieze - New Building for the Kunsthaus Basel. https://iart.ch/en/-/lichtfries-neubau-des-kunstmuseums-basel, *last accessed: April 2019*
49. Ishii H, Wisneski C, Brave S, Dahley A, Gorbet M, Ullmer B, Yarin P (1998) ambientroom: Integrating ambient media with architectural space. In: CHI 98 Conference Summary on Human Factors in Computing Systems, ACM, New York, NY, USA, CHI '98, pp 173–174, DOI 10.1145/286498.286652, URL http://doi.acm.org/10.1145/286498.286652
50. Ishii H, Lakatos D, Bonanni L, Labrune JBJ (2012) Radical Atoms : Beyond Tangible Bits , Toward Transformable Materials. Interactions DOI 10.1145/2065327.2065337
51. Kim LH, Follmer S (2017) Ubiswarm: Ubiquitous robotic interfaces and investigation of abstract motion as a display. Proc ACM Interact Mob Wearable Ubiquitous Technol 1(3):66:1–66:20, DOI 10.1145/3130931, URL http://doi.acm.org/10.1145/3130931
52. Knierim P, Maurer S, Wolf K, Funk M (2018) Quadcopter-projected in-situ navigation cues for improved location awareness. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, CHI '18, pp 433:1–433:6, DOI 10.1145/3173574.3174007, URL http://doi.acm.org/10.1145/3173574.3174007
53. Koeman L, Kalnikaite V, Rogers Y, Bird J (2014) What chalk and tape can tell us: Lessons learnt for next generation urban displays. In: Proceedings of The International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '14, pp 130:130–130:135, DOI 10.1145/2611009.2611018, URL http://doi.acm.org/10.1145/2611009.2611018
54. Lim YK, Stolterman E, Tenenberg J (2008) The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas. ACM Trans Comput-Hum In-

teract 15(2):7:1–7:27, DOI 10.1145/1375761.1375762, URL http://doi.acm.org/10.1145/1375761.1375762
55. Lupetti ML, Bendor R, Giaccardi E (2019) Robot citizenship: A design perspective. In: DeSForM19 Proceedings, DOI 10.21428/5395bc37.595d1e58, URL https://desform19.pubpub.org/pub/robot-citizenship, https://desform19.pubpub.org/pub/robot-citizenship
56. Mäkelä V, Sharma S, Hakulinen J, Heimonen T, Turunen M (2017) Challenges in Public Display Deployments: A Taxonomy of External Factors. Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17 pp 3426–3475, DOI 10.1145/3025453.3025798, URL http://doi.acm.org/10.1145/3025453.3025798
57. Meagher M (2014) Responsive architecture and the problem of obsolescence. Archnet-IJAR 8:95–104, DOI 10.26687/archnet-ijar.v8i3.498
58. Memarovic N (2015) Construction on display: Exploring the use of public displays on construction sites. In: Proceedings of the 4th International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '15, pp 155–162, DOI 10.1145/2757710.2757711, URL http://doi.acm.org/10.1145/2757710.2757711
59. Milthers ADB, Bjerre Hammer A, Jung Johansen J, Jensen LG, Jochum EA, Löchtefeld M (2019) The helpless soft robot - stimulating human collaboration through robotic movement. In: Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, CHI EA '19, pp LBW2421:1–LBW2421:6, DOI 10.1145/3290607.3312807, URL http://doi.acm.org/10.1145/3290607.3312807
60. Moere AV, Hill D (2012) Designing for the Situated and Public Visualization of Urban Data. Journal of Urban Technology 19(2):25–46, DOI 10.1080/10630732.2012.698065
61. Moere AV, Wouters N (2012) The role of context in media architecture. In: Proceedings of the 2012 International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '12, pp 12:1–12:6, DOI 10.1145/2307798.2307810, URL http://doi.acm.org/10.1145/2307798.2307810
62. Müller J, Wilmsmann D, Exeler J, Buzeck M, Schmidt A, Jay T, Krüger A (2009) Display blindness: The effect of expectations on attention towards digital signage. In: Tokuda H, Beigl M, Friday A, Brush AJB, Tobe Y (eds) Pervasive Computing, Springer Berlin Heidelberg, Berlin, Heidelberg, pp 1–8
63. Nabil S, Plötz T, Kirk DS (2017) Interactive architecture: Exploring and unwrapping the potentials of organic user interfaces. In: Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction, ACM, New York, NY, USA, TEI '17, pp 89–100, DOI 10.1145/3024969.3024981, URL http://doi.acm.org/10.1145/3024969.3024981

64. Nagenborg M (2018) Urban robotics and responsible urban innovation. Ethics and Information Technology pp 1–11, DOI 10.1007/s10676-018-9446-8, URL http://dx.doi.org/10.1007/s10676-018-9446-8
65. Nguyen TT, Holländer K, Hoggenmueller M, Parker C, Tomitsch M (2019) Designing for projection-based communication between autonomous vehicles and pedestrians. In: Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, ACM, New York, NY, USA, AutomotiveUI 19, p 284294, DOI 10.1145/3342197.3344543, URL https://doi.org/10.1145/3342197.3344543
66. Offenhuber D, Seitinger S (2014) Over the rainbow: Information design for low-resolution urban displays. In: Proceedings of the 2Nd Media Architecture Biennale Conference: World Cities, ACM, New York, NY, USA, MAB '14, pp 40–47, DOI 10.1145/2682884.2682886, URL http://doi.acm.org/10.1145/2682884.2682886
67. Parker C, Hoggenmueller M, Tomitsch M (2018) Design strategies for overcoming failures on public interactive displays. In: Proceedings of the 7th ACM International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '18, pp 2:1–2:7, DOI 10.1145/3205873.3205889, URL http://doi.acm.org/10.1145/3205873.3205889
68. Parker C, Tomitsch M, Kay J (2018) Does the public still look at public displays?: A field observation of public displays in the wild. Proc ACM Interact Mob Wearable Ubiquitous Technol 2(2):73:1–73:24, DOI 10.1145/3214276, URL http://doi.acm.org/10.1145/3214276
69. Pop S, Toft T, Calvillo N, Wright M, Arrigoni G, Taker L, Mandilari C, Langnese S (2016) What Urban Media Art Can Do: Why When Where and How. avedition
70. Qamar IPS, Groh R, Holman D, Roudaut A (2018) Hci meets material science: A literature review of morphing materials for the design of shape-changing interfaces. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, CHI '18, pp 374:1–374:23, DOI 10.1145/3173574.3173948, URL http://doi.acm.org/10.1145/3173574.3173948
71. Quirke J (2015) Architect seeks funding to make worlds biggest smoke rings. http://www.globalconstructionreview.com/news/architect-seeks-funding-make-wo8rl6d8s-biggest/, *last accessed: April 2019*
72. Ratti C (2019) Ufo. https://carloratti.com/project/ufo/, *last accessed: January 2020*
73. Robles E, Wiberg M (2010) Texturing the "material turn" in interaction design. In: Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction, ACM, New York, NY, USA, TEI '10, pp 137–144, DOI 10.1145/1709886.1709911, URL http://doi.acm.org/10.1145/1709886.1709911
74. Rogers Y, Brignull H (2002) Subtle ice-breaking: encouraging socializing and interaction around a large public display. In: CSCW'02 Workshop Proceedings, pp 1–6

75. Rossiter J, Winfield J, Ieropoulos I (2016) Here today, gone tomorrow: biodegradable soft robots. In: Bar-Cohen Y, Vidal F (eds) Electroactive Polymer Actuators and Devices (EAPAD) 2016, International Society for Optics and Photonics, SPIE, vol 9798, pp 312 – 321, DOI 10.1117/12.2220611, URL https://doi.org/10.1117/12.2220611
76. Sareen H, Zheng J, Maes P (2019) Cyborg botany: Augmented plants as sensors, displays and actuators. In: Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, CHI EA '19, pp VS13:1–VS13:2, DOI 10.1145/3290607.3311778, URL http://doi.acm.org/10.1145/3290607.3311778
77. Scheible J, Funk M (2016) DroneLandArt: landscape as organic pervasive display. Proceedings of the 5th ACM International Symposium on Pervasive Displays - PerDis '16 (4):255–256, DOI 10.1145/2914920.2939883, URL http://dl.acm.org/citation.cfm?doid=2914920.2939883
78. Scheible J, Funk M (2016) In-situ-displaydrone: Facilitating co-located interactive experiences via a flying screen. In: Proceedings of the 5th ACM International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '16, pp 251–252, DOI 10.1145/2914920.2940334, URL http://doi.acm.org/10.1145/2914920.2940334
79. Scheible J, Hoth A, Saal J, Su H (2013) Displaydrone: A flying robot based interactive display. In: Proceedings of the 2Nd ACM International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '13, pp 49–54, DOI 10.1145/2491568.2491580, URL http://doi.acm.org/10.1145/2491568.2491580
80. Schneegass S, Alt F, Scheible J, Schmidt A (2014) Midair displays: Concept and first experiences with free-floating pervasive displays. In: Proceedings of The International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '14, pp 27:27–27:31, DOI 10.1145/2611009.2611013, URL http://doi.acm.org/10.1145/2611009.2611013
81. Schroeter R, Foth M, Satchell C (2012) People, content, location: Sweet spotting urban screens for situated engagement. In: Proceedings of the Designing Interactive Systems Conference, ACM, New York, NY, USA, DIS '12, pp 146–155, DOI 10.1145/2317956.2317980, URL http://doi.acm.org/10.1145/2317956.2317980
82. Seitinger S, Perry DS, Mitchell WJ (2009) Urban pixels: Painting the city with light. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, CHI '09, pp 839–848, DOI 10.1145/1518701.1518829, URL http://doi.acm.org/10.1145/1518701.1518829
83. Shepard M (2009) Extreme informatics: Toward the de-saturated city. In: Foth M (ed) Handbook of Research on Urban Informatics: The Practice and Promise of the Real-Time City, IGI Global, pp 437–449, DOI 10.4018/978-1-60566-152-0.ch029, URL https://doi.org/10.4018/978-1-60566-152-0.ch029

84. Steinberger F, Foth M, Alt F (2014) Vote with your feet: Local community polling on urban screens. In: Proceedings of The International Symposium on Pervasive Displays, ACM, New York, NY, USA, PerDis '14, pp 44:44–44:49, DOI 10.1145/2611009.2611015, URL http://doi.acm.org/10.1145/2611009.2611015
85. Struppek M (2006) The social potential of Urban Screens. Visual Communication 5(2):173–188, DOI 10.1177/1470357206065333
86. Taylor N, Cheverst K, Wright P, Olivier P (2013) Leaving the wild: Lessons from community technology handovers. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, CHI '13, pp 1549–1558, DOI 10.1145/2470654.2466206, URL http://doi.acm.org/10.1145/2470654.2466206
87. Tomitsch M (2014) Towards the real-time city : An investigation of public displays for behaviour change and sustainable living. July, pp 10–11
88. Tomitsch M (2018) Making Cities Smarter: Designing Interactive Urban Applications
89. Valkanova N, Jorda S, Tomitsch M, Vande Moere A (2013) Reveal-it! - The Impact of a Social Visualization Projection on Public Awareness and Discourse. In: Proceedings of the International Conference on Human Factors in Computing Systems (CHI'13), DOI 10.1145/2470654.2466476
90. Vempati AS, Kamel M, Stilinovic N, Zhang Q, Reusser D, Sa I, Nieto J, Siegwart R, Beardsley P (2018) Paintcopter: An autonomous uav for spray painting on three-dimensional surfaces. IEEE Robotics and Automation Letters 3(4):2862–2869, DOI 10.1109/LRA.2018.2846278
91. Wiethoff A, Blöckner M (2011) Lightbox: Exploring interaction modalities with colored light. In: Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction, Association for Computing Machinery, New York, NY, USA, TEI 11, p 399400, DOI 10.1145/1935701.1935799, URL https://doi.org/10.1145/1935701.1935799
92. Wiethoff A, Hoggenmueller M (2017) Experiences deploying hybrid media architecture in public environments. In: Wiethoff A, Hussmann H (eds) Media Architecture: Using Information and Media as Construction Material, De Gruyter, Berlin, Boston, p 103122
93. Willett W, Jansen Y, Dragicevic P (2017) Embedded data representations. IEEE Transactions on Visualization and Computer Graphics 23(1):461–470, DOI 10.1109/TVCG.2016.2598608
94. Winkler C, Seifert J, Dobbelstein D, Rukzio E (2014) Pervasive information through constant personal projection: The ambient mobile pervasive display (amp-d). In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, CHI '14, pp 4117–4126, DOI 10.1145/2556288.2557365, URL http://doi.acm.org/10.1145/2556288.2557365
95. Wollherr D, Khan S, Landsiedel C, Buss M (2016) The Interactive Urban Robot IURO: Towards Robot Action in Human Environments, Springer International Publishing, Cham, pp 277–291. DOI 10.1007/978-3-319-23778-$7_1 9, URLhttps://doi.org/10.1007/978-3-319-23778-7_1 9$

96. Wouters N, Keignaert K, Huyghe J, Moere AV (2016) Revealing the architectural quality of media architecture. In: Proceedings of the 3rd Conference on Media Architecture Biennale, ACM, New York, NY, USA, MAB16, pp 5:1–5:4, DOI 10.1145/2946803.2946808, URL http://doi.acm.org/10.1145/2946803.2946808
97. Wu Y, Yim JK, Liang J, Shao Z, Qi M, Zhong J, Luo Z, Yan X, Zhang M, Wang X, Fearing RS, Full RJ, Lin L (2019) Insect-scale fast moving and ultrarobust soft robot. Science Robotics 4(32), DOI 10.1126/scirobotics.aax1594, URL https://robotics.sciencemag.org/content/4/32/eaax1594, https://robotics.sciencemag.org/content/4/32/eaax1594.full.pdf
98. Zielinska-Dabkowsk KM (2018) Make lighting healthier. Nature 553 pp 274–276, URL https://doi.org/10.1038/d41586-018-00568-7