Self-Moving Robots and Pulverized Urban Displays: Newcomers in the Pervasive Display Taxonomy

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ABSTRACT
In this paper, we investigate current approaches to the design of pervasive urban displays through two dimensions: increasing levels of physical integration of content into the surrounding environment (attached, blended, physicalized), and increasing levels of mobility of the display technology (fixed, portable, self-moving). We provide a classification of pervasive displays along these two dimensions and introduce a new class of pervasive display, which we call pulverized urban displays (PUDs). These displays represent content in a physical form, entangled with the built and natural environment, and are capable of autonomously changing their position. Drawing on urban robotic devices and their capability to sense and manipulate the environment, the paper lays out five characteristics of future forms of PUDs.

CCS CONCEPTS
• Human-Centered Computing → Interaction Design.

KEYWORDS
Pervasive displays, media architecture, urban media, urban displays, urban robotic displays, pulverized urban displays.

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 [22]. 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 [5]. Others investigated the concept of free-floating public displays [51] and in-situ projections [35], 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 paper argues that there is a new, rich design space for novel classes of pervasive urban displays emerging out of the intrinsic characteristics of robotics [34]. 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 [15, 30]. Considering current trends in architecture and design, where robots are increasingly used to build architectural structures [42], 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 [10, 51, 53]. The second aspect regards the spatial and aesthetic integration of digital technologies into the physical environment [8], with low-resolution lighting-based media façades being the most prevalent form [24]. A
series of works also explored the digital manipulation of natural phenomena [18, 23, 48], thus rethinking the concept of traditional screen-based media. In this paper 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 [33] and ubiquitous robotics [34], 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 physicalized 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, inter alia, by conference venues, such as PerDis and MAB.

Pervasive Displays

Compared to personal mobile devices, pervasive displays enable a "push-based distribution" of content without active user involvement required [13]. However, as urban environments become increasingly saturated with displays [11], and a majority are used for advertisement purposes, research reported that passers-by tend to ignore them [40]. 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 [44]. 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). Vande Moere et al.'s analysis additionally include 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 [39]. 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 [59], it is timely to also consider pervasive displays to appear and disappear in the environment as needed.

Architectural Displays

With the rise of pervasive urban displays, also architects began to discuss the implications of these novel technologies for their own practice. While there seems to be a widespread skepticism 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" [60], summarized under the umbrella term media architecture [9, 29]. 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 giant public screen [24]. 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 [34] and organic interfaces [41] 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 analyze this new landscape, and propose a taxonomy to support future research in the field.

3 INTEGRATION-MOBILITY TAXONOMY

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, this paper considers two perspectives of pervasive computing: (1) the seamless integration of content ("something" that is communicated by a display) into the environment, and (2) the mobility of display technology (the means to communicate content), enabling flexible deployment in and out of specific locations. In our analysis we focus on displays that use visual means to deliver content.

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Figure 1: Overview of the integration-mobility taxonomy.
We use Vande Moere and Wouter’s [39] 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 1), followed by a classification of pervasive urban displays with examples from research and design practice (see Figure 2).

**Physical Integration of Content**

The level of physical integration refers to which extent the content is integrated into its surrounding physical environment, including landscape, architecture and urban infrastructure [8]. 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 [43]. We propose a classification of pervasive displays into the three categories described below, based on increasing levels of integration between the content communicated and the physical architecture ‘carrying’ it [39].

*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 the sense that there is no intended influence on the visual perception of the content. The display stands out of 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 [38], the missing physical integration can cause a contextual disconnect between the display and the environment [39].

*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 a 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 a 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 a technological means to frame visual content [14]. When turned off, embedded displays usually completely disappear (e.g. projections) or they still work as an aesthetic architectural element (e.g. embedded LED displays) without a sense of malfunctioning [12].

*Physicalized.* Here, the visual content is part of its carrier, entirely manifested in a physicalized form, that is decoupled from the technological means that creates the display. Often the actuator that creates the displayed information stays invisible for the viewer. In some cases 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.

**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.

*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 [24].

*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, displays in this category operate autonomously in the sense that they are battery- and/or solar-powered, communicate wirelessly and re-calibrate to different environments.

**Figure 2:** Classification for pervasive urban displays according to their level of physical integration of content and mobility of display technology.
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.

Current Approaches to Urban Displays

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 centers and airports, and often come in mass-produced, generic forms (see Figure 3, 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 [3, 26] or deploying widespread consumer hardware [4, 54]. More mobile systems exist in the form of Pop-Up Public Displays, which are for example temporary 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 3, right) [21].

Urban Projections. When it comes to the distribution of high-resolution content, projections are another very common option for creating pervasive urban displays [7, 57] (see Figure 4). 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 [12]. 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 [19]), and also by the material properties of the surface, resulting in different diffusing effect (e.g. previously explored for ice as a visualization material [6, 10, 47]). With the rise of pico-projectors, researchers have intensively investigated their potential in public space, referred to as Mobile Projections: for example through body-projectors [10, 59] or projectors carried by drones [1, 35, 50], capable of showing information, such as navigation cues, on the go (see Figure 4).

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 [51] or projections onto a mounted canvas [49].

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 [45, 52, 55]. 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 5, left). The new screen now wraps around two sides of the building, with its main section surrounded by stripes of smaller screens incorporating the original tile structure of the façade. 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 6, 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
 Apart from light, autonomous pixels systems, such as Urban Pixels (see Figure 6, middle) [53] or Firefly [2], can be flexibly arranged on any pixel configuration, the pixel shape and other surrounding materials which may function as secondary optic elements (e.g. diffusers, reflectors) [25, 27, 28]. Apart from light, architects have also used actuators to create kinetic low-resolution media structures [24]. 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 5, right) demonstrates the rich design space of low-resolution building displays, and also that the definition of blended and physicalized content can 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 physicalized integration of content [32]. 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.

Flexible Pixels. Inspired by the aesthetics of low-resolution lighting-based media façades, researchers have created more lightweight and mobile low-res displays [2, 17, 53]. Autonomous pixels systems, such as Urban Pixels (see Figure 6, middle) [53] or Firefly [2], 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 6, right) represent the next iteration of flexible pixel systems [30]: 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.

Robotic Installations. Industrial robots have lately been explored as emergent form of pervasive urban display [15]. 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.

Natural Displays. Artists and researchers also repeatedly engaged with the creation of physicalized 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 [49] to purpose-built electromechanic machines [18, 23]. Some of the display technologies are fixed - for example, the building-size art installation by realities:united, originally designed for the top of Copenhagen’s Amager Bakke waste-to-energy plant, by Bjarke Ingels Group (BIG), and which would indicate CO2 emissions from the plant using smoke rings [46]. In contrast, other prototype systems, for example Fischer et al.’s sunlight pixels [18] or Gentile’s plant-based controllable display [23], can be portable and autonomous.

4 TOWARDS PULVERIZED URBAN DISPLAYS

Our design space analysis of pervasive urban displays indicate 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 patent in the community, it is also clear the remaining gap in the exploration of pervasive displays combining both characteristics: highly physicalized and ubiquitous forms of digital urban media. To describe such a gap, we introduce the concept of pulverized urban displays (PUD), which we foresee as an emerging type of "fine-grained" display technologies capable of rendering content in a physicalized form while also being highly mobile. 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. 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 [33]. The PUD gap is significant given that desirable characteristics such a class of pervasive displays would provide.

In the following, we illustrate some of those characteristics by means of an example, the ChalkBot, created by the designer Louis Elwood-Leach [16]. The Chalkbot (see Figure 7) is an omni-wheel ground vehicle with a spray can attached to draw on the ground with a customized chalk-like powder. The drawings are based on digital vector graphics which are recreated in a physicalized form in public space. While ChalkBot could be used to create various types of urban visualizations, in this example scenario we speculate on the usage in the context of construction sites, which has been previously identified as a relevant application context for pervasive urban displays [37].

Ad-hoc deployment. 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 [31], the ChalkBot could be deployed within minutes, only restricted by its speed and the distance to its base station. Compared to fixed and portable pervasive displays, PUDs come with less infrastructural restrictions, and can arguably be deployed everywhere and when it matters, similarly to non-digital public displays [36].

Respond 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.

Eco-friendly and sustainable displays. Contrary to LED or projection based displays which 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), the conceptual approach of PUDs incorporates the ever-changing, fast paced technology domain as well as their output is temporary, adaptable, ephemeral and can be quickly adapted to new situations. Lighting pollution is another controversial topic that is currently discussed among researchers and practitioners in this domain [20, 61]. 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 utilization of resources.

Manipulate 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 [58]. 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 [36] to the display, such as erosion through rain and passers-by, thus providing subtle layers of implicit information.

Enable tangible interaction. The materially and affordances of non-digital public displays have been previously reported to attract people and enable natural tangible interactions [21, 36, 56]. 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.

5 CONCLUSION

After almost a decade of relentless 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 space around them. While this translates into growing complexity of design strategies, it also enable designs with greater level of customization and adaptability to the environments they are deployed to. In this paper, we adopted levels of mobility and material integration to propose a taxonomy capturing such an evolution of pervasive displays. In the process, we reveal a gap in such a design space, represented by a degree of ultimate pervasiveness, which we named pulverized urban displays (PUD). We then discussed its potential characteristics, and pointed to robotic urban displays as strong candidates to enable the transition from the current state-of-the-art to a world of PUDs. Between now and then, it is our belief that the taxonomy and definitions laid out by this paper can assist with framing the analysis of the field going forward.
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