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

Marius Hoggenmueller
School of Architecture, Design and Planning
The University of Sydney
Sydney, Australia
marius.hoggenmueller@sydney.edu.au

Luke Hespanhol
School of Architecture, Design and Planning
The University of Sydney
Sydney, Australia
luke.hespnahol@sydney.edu.au

Alexander Wiethoff
LMU Munich
Munich, Germany
alexander.wiethoff@ifi.lmu.de

Martin Tomitsch
School of Architecture, Design and Planning
The University of Sydney
Sydney, Australia
martin.tomitsch@sydney.edu.au

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

ACM Reference Format:

Marius Hoggenmueller, Luke Hespanhol, Alexander Wiethoff, and Martin Tomitsch. 2019. Self-Moving Robots and Pulverized Urban Displays: Newcomers in the Pervasive Display Taxonomy. In *Proceedings of the 8th ACM International Symposium on Pervasive Displays (PerDis '19), June 12–14, 2019, Palermo, Italy*. ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3321335.3324950

PerDis '19, June 12–14, 2019, Palermo, Italy

ACM ISBN 978-1-4503-6751-6/19/06…$15.00
https://doi.org/10.1145/3321335.3324950

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 [23]. 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 [52] and in-situ projections [36], 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 [35]. 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, 31]. Considering current trends in architecture and design, where robots are increasingly used to build architectural structures [43], 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, 52, 54]. 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 [25]. A series of works also explored the digital manipulation of natural phenomena [19, 24, 49], 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 [34] and ubiquitous robotics [35], 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 by conference venues, such as PerDis and MAB.

2.1 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 [41]. 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 [45]. 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 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 [40]. We argue that more mobile forms of pervasive displays could address some of these drawbacks, such as the oversaturation 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 [60], 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, 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" [61], summarized under the umbrella term media architecture [9, 30]. 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 [25]. 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 [35] and organic interfaces [42] 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. We use Vande Moere and Wouter's [40] 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).

3.1 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 [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

Physical Integration of Content	
Attached	The content is perceived as a self-contained layer, which is clearly separated from its carrier.
Blended	The perceived content is affected by its carrier.
Physicalized	The content is part of the carrier, manifested in a physicalized form.
Mobility of Display Technology	
Fixed	The display system is fixed, which implies that also the content is "rendered" in a steady location.
Portable	The display system can be moved to various locations.
Self-moving	The display system can move by itself to various locations.

Figure 1: Overview of the integration-mobility taxonomy.

of implicit meaning [44]. 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 [40].

3.1.1 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 [39], the missing physical integration can cause a contextual disconnect between the display and the environment [40].

3.1.2 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].

3.1.3 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.

3.2 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.

3.2.1 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 [25].

3.2.2 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.

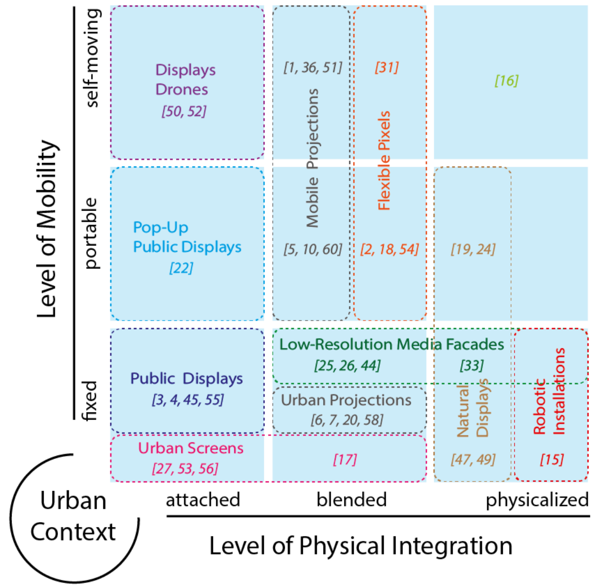

Figure 2: Classification for pervasive urban displays according to their level of physical integration of content and mobility of display technology.

3.2.3 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.

3.3 Current Approaches to Urban Displays

3.3.1 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 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, 27] or deploying widespread consumer hardware [4, 55]. 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 3, right) [22].

Figure 3: Permanent public display (left), pop-up public display (right). Image credits (right): [22]

3.3.2 Urban Projections. When it comes to the distribution of high-res content, projections are another very common option for creating pervasive urban displays [7, 58] (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 [20]), and also by the material properties of the surface, resulting in different diffusing effects (e.g. previously explored for ice as a visualization material [6, 10, 48]). 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 [10, 60] or projectors carried by drones [1, 36, 51], capable of showing information, such as navigation cues, on the go (see Figure 4, middle and right).

3.3.3 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 [52] or projections onto a mounted canvas [50].

3.3.4 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 [46, 53, 56]. 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 [17]. 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 pixel configuration, the pixel shape and other surrounding materials which may function as secondary optic elements (e.g. diffusers, reflectors) [26, 28, 29]. Apart from light, architects have also used actuators to create kinetic low-resolution media structures [25]. 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 [33]. 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.

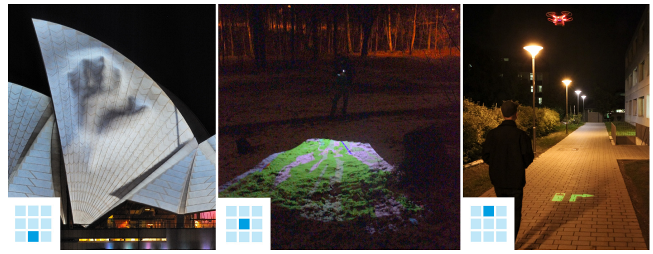

Figure 4: Projections onto Sydney Opera House (left), portable projections, with the projector carried by the user (middle), moving projections from a drone (right). Image credits: ©Jerry Dohnal (Flickr, CC BY-NC-ND 2.0), [10], [36].

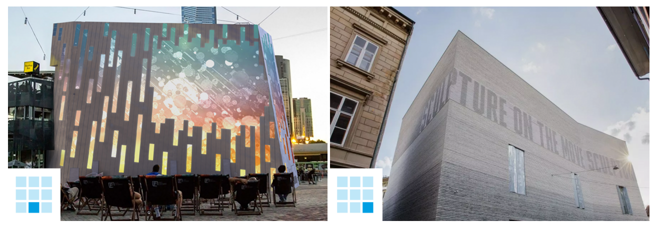

Figure 5: Urban Screen at FedSquare Melbourne, after the redesign (left); Illusion of physical transformations on the frieze of Kunstmuseum Basel (right). Image credits: ©Fed Square Pty Ltd, ©Derek Li Wan Po.

3.3.5 Flexible Pixels. Inspired by the aesthetics of low-resolution lighting-based media façades, researchers have created more lightweight and mobile low-res displays [2, 18, 54]. Autonomous pixels systems, such as Urban Pixels (see Figure 6, middle) [54] or Firefly [2], can be flexibly arranged on any surface with the content blended into the physical environment. *Floating Pixels* using arrays

Figure 6: Blended low-resolution lighting-based displays of various mobility levels (from left to right): fixed media façade, flexible pixels and floating pixels. Image credits: ©Public Visualization Studio, [54], ©Ars Electronica / Martin Hieslmair (Flickr, CC BY-NC-ND 2.0).

of drones equipped with RGB lights (see Figure 6, right) represent the next iteration of flexible pixel systems [31]: 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.

3.3.6 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.

3.3.7 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 [50] to purpose-built electromechanic machines [19, 24]. 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 CO_2 emissions from the plant using smoke rings [47]. In contrast, other prototype systems, for example Fischer et al.'s sunlight pixels [19] or Gentile's plant-based controllable display [24], 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

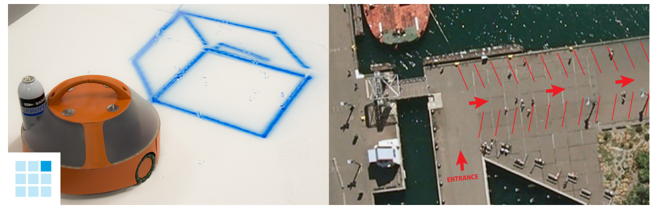

Figure 7: ChalkBot (left) is capable to recreate digital drawings with chalk in public space, based on vector graphics positioned over satellite images (right). Image credits: ©Louis Elwood-Leach.

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 [34]. 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 a 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 [38].

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 [32], 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 [37].

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 [21, 62]. 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 [59]. 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 [37] 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 [22, 37, 57]. 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.

ACKNOWLEDGMENTS

We thank the anonymous PerDis'19 reviewers for their constructive feedback and suggestions how to make this contribution stronger, including the proposal of a more relevant title for this paper. We also thank Jathan Sadowski for the fruitful discussion about this work.

REFERENCES

[1] Anke M. Brock, Julia Chatain, Michelle Park, Tommy Fang, Martin Hachet, James A. Landay, and Jessica R. Cauchard. 2018. FlyMap: Interacting with Maps Projected from a Drone. In *Proceedings of the 7th ACM International Symposium on Pervasive Displays (PerDis '18)*. ACM, New York, NY, USA, Article 13, 9 pages. https://doi.org/10.1145/3205873.3205877

[2] Angie Chandler, Joe Finney, Carl Lewis, and Alan Dix. 2009. Toward Emergent Technology for Blended Public Displays. In *Proceedings of the 11th International Conference on Ubiquitous Computing (UbiComp '09)*. ACM, New York, NY, USA, 101–104. https://doi.org/10.1145/1620545.1620562

[3] Jorgos Coenen, Sandy Claes, and Andrew Vande Moere. 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 (PerDis '17)*. ACM, New York, NY, USA, Article 9, 9 pages. https://doi.org/10.1145/3078810.3078819

[4] Jorgos Coenen, Niels Wouters, and Andrew Vande Moere. 2016. Synchronized Wayfinding on Multiple Consecutively Situated Public Displays. In *Proceedings of the 5th ACM International Symposium on Pervasive Displays (PerDis '16)*. ACM, New York, NY, USA, 182–196. https://doi.org/10.1145/2914920.2929906

[5] Ashley Colley, Jonna Häkkilä, Meri-Tuulia Forsman, Bastian Pfleging, and Florian Alt. 2018. Car Exterior Surface Displays: Exploration in a Real-World Context. In *Proceedings of the 7th ACM International Symposium on Pervasive Displays (PerDis '18)*. ACM, New York, NY, USA, Article 7, 8 pages. https://doi.org/10.1145/3205873.3205880

[6] Ashley Colley, Antti-Jussi Yliharju, and Jonna Häkkilä. 2018. Ice As an Interactive Visualization Material: A Design Space. In *Proceedings of the 7th ACM International Symposium on Pervasive Displays (PerDis '18)*. ACM, New York, NY, USA, Article 14, 6 pages. https://doi.org/10.1145/3205873.3205895

[7] Peter Dalsgaard and Jonas Fritsch. 2008. Media Facades Beyond Interaction. *Position paper for Workshop on Public and Situated Displays to Support Communities, OzCHI 2008.*

[8] Peter Dalsgaard and Kim Halskov. 2010. Designing Urban Media Façades: Cases and Challenges. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 2277–2286. https://doi.org/10.1145/1753326.1753670

[9] Peter Dalsgaard, Kim Halskov, and Alexander Wiethoff. 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 (CHI '16)*. ACM, New York, NY, USA, 2562–2573. https://doi.org/10.1145/2858036.2858318

[10] Alexandru Dancu, Zlatko Franjcic, Adviye Ayça Ünlüer, and Morten Fjeld. 2015. Interaction in Motion with Mobile Projectors: Design Considerations. In *Proceedings of the 4th International Symposium on Pervasive Displays (PerDis '15)*. ACM, New York, NY, USA, 61–68. https://doi.org/10.1145/2757710.2757728

[11] Nigel Davies. 2018. Saturated Display Environments. *Keynote at International Symposium on Pervasive Displays (PerDis â18)* (2018).

[12] Nigel Davies, Sarah Clinch, Mateusz Mikusz, Oliver Bates, Helen Turner, and Adrian Friday. 2017. Better off: When Should Pervasive Displays Be Powered Down?. In *Proceedings of the 6th ACM International Symposium on Pervasive Displays (PerDis '17)*. ACM, New York, NY, USA, Article 19, 9 pages. https://doi.org/10.1145/3078810.3078821

[13] Nigel Davies, Marc Langheinrich, Rui Jose, and Albrecht Schmidt. 2012. Open Display Networks: Towards A New Communication Media for the 21st Century. *IEEE Computer* 45, 1 (2012).

[14] Tobias Ebsen. 2013. *Materia Screen â Intersections of media, art, and architecture.* Ph.D. Dissertation.

[15] Schieck Ava Fatah gen. Ecem Ergin, Andre Afonso. 2018. Welcoming the Orange Collars: Robotic Performance in Everyday City Life. In *Proceedings of the 7th ACM International Symposium on Pervasive Displays (PerDis '18)*. ACM, New York, NY, USA, 17:1–17:7. https://doi.org/10.1145/3205873.3205893

[16] Louis Elwood-Leach. 2013. ChalkBot - Recreate Digital Drawing in the Physical Space with Soluble Chalk Paint. https://elwoodleach.com/chalkbot, *last accessed: April 2019.*

[17] Fedsquare. 2018. Fed Square's New Digital Experience Initiative.

[18] Patrick Tobias Fischer, Franziska Gerlach, Jenny Gonzalez Acuna, Daniel Pollack, Ingo Schäfer, Josephine Trautmann, and Eva Hornecker. 2014. Movable, Kick-/Flickable Light Fragments Eliciting Ad-hoc Interaction in Public Space. In *Proceedings of The International Symposium on Pervasive Displays (PerDis '14)*. ACM, New York, NY, USA, Article 50, 6 pages. https://doi.org/10.1145/2611009.2611027

[19] Patrick Tobias Fischer, Eva Hornecker, Johann Gielen, Johannes Hartmann, Marco Schmandt, Anna Rack, Marie Bornemann, and Felix Dondera. 2015. Exploring the Potential of Depictions with Sun Reflections. In *Proceedings of the 4th International Symposium on Pervasive Displays (PerDis '15)*. ACM, New York, NY, USA, 217–224. https://doi.org/10.1145/2757710.2757712

[20] Patrick T. Fischer, Anke von der Heide, Eva Hornecker, Sabine Zierold, Andreas Kästner, Felix Dondera, Matti Wiegmann, Fernando Millán, Jonas Lideikis,

Aidas Cergelis, Reinaldo Verde, Christoph Drews, Till Fastnacht, Kai G. Lünsdorf, Djamel Merat, Aryan Khosravani, and Hesam Jannesar. 2015. Castle-Sized Interfaces - An Interactive Facade Mapping. *Proceedings of the International Symposium on Pervasive Displays (PerDis'15)* 1969 (2015), 91–97. https://doi.org/10.1145/2757710.2757715

[21] Marcus Foth and Glenda Amayo Caldwell. 2018. More-than-Human Media Architecture. In *Proceedings of the 4th Media Architecture Biennale Conference (MAB18)*. ACM, New York, NY, USA, 66–75. https://doi.org/10.1145/3284389.3284495

[22] Joel Fredericks, Luke Hespanhol, Callum Parker, Dawei Zhou, and Martin Tomitsch. 2018. Blending pop-up urbanism and participatory technologies: Challenges and opportunities for inclusive city making. *City, Culture and Society* (2018). https://doi.org/10.1016/j.ccs.2017.06.005

[23] Rodrigo MarÃ§al Gandia, Fabio Antonialli, Bruna Habib Cavazza, Arthur Miranda Neto, Danilo Alves de Lima, Joel Yutaka Sugano, Isabelle Nicolai, and Andre Luiz Zambalde. 2019. Autonomous vehicles: scientometric and bibliometric review. *Transport Reviews* (2019). https://doi.org/10.1080/01441647.2018.1518937

[24] Vito Gentile, Salvatore Sorce, Ivan Elhart, and Fabrizio Milazzo. 2018. Plantxel: Towards a Plant-based Controllable Display. In *Proceedings of the 7th ACM International Symposium on Pervasive Displays (PerDis '18)*. ACM, New York, NY, USA, Article 16, 8 pages. https://doi.org/10.1145/3205873.3205888

[25] M. Hank Haeusler. 2009. *Media facades: history, technology, content.* avedition.

[26] Kim Halskov and Tobias Ebsen. 2013. A framework for designing complex media facades. *Design Studies* (2013). https://doi.org/10.1016/j.destud.2013.04.001

[27] Luke Hespanhol, Martin Tomitsch, Ian McArthur, Joel Fredericks, Ronald Schroeter, and Marcus Foth. 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 (C&T '15)*. ACM, New York, NY, USA, 29–37. https://doi.org/10.1145/2768545.2768553

[28] Marius Hoggenmueller and Luke Hespanhol. 2017. P+: A Test Fit Platform for Generative Design of 3D Media Architecture. In *Proceedings of the 6th ACM International Symposium on Pervasive Displays (PerDis '17)*. ACM, New York, NY, USA, Article 15, 7 pages. https://doi.org/10.1145/3078810.3078816

[29] Marius Hoggenmueller, Martin Tomitsch, and Alexander Wiethoff. 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 (CHI '18)*. ACM, New York, NY, USA, Article 259, 12 pages. https://doi.org/10.1145/3173574.3173833

[30] Marius Hoggenmueller, Alexander Wiethoff, Andrew Vande Moere, and Martin Tomitsch. 2018. A Media Architecture Approach to Designing Shared Displays for Residential Internet-of-Things Devices. In *Proceedings of the 4th Media Architecture Biennale Conference (MAB18)*. ACM, New York, NY, USA, 106–117. https://doi.org/10.1145/3284389.3284391

[31] Horst Hörtner, Matthew Gardiner, Roland Haring, Christopher Lindinger, and Florian Berger. 2012. Spaxels, Pixels in Space - A novel mode of spatial display. In *Proceedings of International Conference on Signal Processing and Multimedia Applications.*

[32] Simo Hosio, Jorge Goncalves, Hannu Kukka, Alan Chamberlain, and Alessio Malizia. 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 (PerDis '14)*. ACM, New York, NY, USA, Article 174, 6 pages. https://doi.org/10.1145/2611009.2611012

[33] iart.ch. 2016. Light Frieze - New Building for the Kunsthaus Basel. https://iart.ch/en/-/lichtfries-neubau-des-kunstmuseums-basel, *last accessed: April 2019.*

[34] Hiroshi Ishii, DÃ¡vid Lakatos, Leonardo Bonanni, and Jean-Baptiste Jb Labrune. 2012. Radical Atoms : Beyond Tangible Bits , Toward Transformable Materials. *Interactions* (2012). https://doi.org/10.1145/2065327.2065337

[35] Lawrence H. Kim and Sean Follmer. 2017. UbiSwarm: Ubiquitous Robotic Interfaces and Investigation of Abstract Motion As a Display. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 3, Article 66 (Sept. 2017), 20 pages. https://doi.org/10.1145/3130931

[36] Pascal Knierim, Steffen Maurer, Katrin Wolf, and Markus Funk. 2018. Quadcopter-Projected In-Situ Navigation Cues for Improved Location Awareness. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 433, 6 pages. https://doi.org/10.1145/3173574.3174007

[37] Lisa Koeman, Vaiva Kalnikaitė, Yvonne Rogers, and Jon Bird. 2014. What Chalk and Tape Can Tell Us: Lessons Learnt for Next Generation Urban Displays. In *Proceedings of The International Symposium on Pervasive Displays (PerDis '14)*. ACM, New York, NY, USA, Article 130, 6 pages. https://doi.org/10.1145/2611009.2611018

[38] Nemanja Memarovic. 2015. Construction on Display: Exploring the Use of Public Displays on Construction Sites. In *Proceedings of the 4th International Symposium on Pervasive Displays (PerDis '15)*. ACM, New York, NY, USA, 155–162. https://doi.org/10.1145/2757710.2757711

[39] Andrew Vande Moere and Dan Hill. 2012. Designing for the Situated and Public Visualization of Urban Data. *Journal of Urban Technology* (2012). https://doi.org/10.1080/10630732.2012.698065

[40] Andrew Vande Moere and Niels Wouters. 2012. The Role of Context in Media Architecture. In *Proceedings of the 2012 International Symposium on Pervasive Displays (PerDis '12)*. ACM, New York, NY, USA, Article 12, 6 pages. https://doi.org/10.1145/2307798.2307810

[41] Jörg Müller, Dennis Wilmsmann, Juliane Exeler, Markus Buzeck, Albrecht Schmidt, Tim Jay, and Antonio Krüger. 2009. Display Blindness: The Effect of Expectations on Attention towards Digital Signage. In *Pervasive Computing*, Hideyuki Tokuda, Michael Beigl, Adrian Friday, A. J. Bernheim Brush, and Yoshito Tobe (Eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, 1–8.

[42] Sara Nabil, Thomas Plötz, and David S. Kirk. 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 (TEI '17)*. ACM, New York, NY, USA, 89–100. https://doi.org/10.1145/3024969.3024981

[43] Michael Nagenborg. 2018. Urban robotics and responsible urban innovation. *Ethics and Information Technology* (2018), 1–11. https://doi.org/10.1007/s10676-018-9446-8

[44] Dietmar Offenhuber and Susanne Seitinger. 2014. Over the Rainbow: Information Design for Low-resolution Urban Displays. In *Proceedings of the 2Nd Media Architecture Biennale Conference: World Cities (MAB '14)*. ACM, New York, NY, USA, 40–47. https://doi.org/10.1145/2682884.2682886

[45] Callum Parker, Martin Tomitsch, and Judy Kay. 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, Article 73 (July 2018), 24 pages. https://doi.org/10.1145/3214276

[46] Susa Pop, Tanya Toft, Nerea Calvillo, Mark Wright, Gabriella Arrigoni, Lesley Taker, Christina Mandilari, and Sarah Langnese. 2016. *What Urban Media Art Can Do: Why When Where and How.* avedition.

[47] Joe Quirke. 2015. Architect seeks funding to make worldâs biggest smoke rings. http://www.globalconstructionreview.com/news/architect-seeks-funding-make-wo8rl6d8s-biggest/, *last accessed: April 2019.*

[48] Erica Robles and Mikael Wiberg. 2010. Texturing the "Material Turn" in Interaction Design. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '10)*. ACM, New York, NY, USA, 137–144. https://doi.org/10.1145/1709886.1709911

[49] Jürgen Scheible and Markus Funk. 2016. DroneLandArt: landscape as organic pervasive display. *Proceedings of the 5th ACM International Symposium on Pervasive Displays - PerDis '16* 4 (2016), 255–256. https://doi.org/10.1145/2914920.2939883

[50] Jürgen Scheible and Markus Funk. 2016. In-situ-displaydrone: Facilitating Co-located Interactive Experiences via a Flying Screen. In *Proceedings of the 5th ACM International Symposium on Pervasive Displays (PerDis '16)*. ACM, New York, NY, USA, 251–252. https://doi.org/10.1145/2914920.2940334

[51] Jürgen Scheible, Achim Hoth, Julian Saal, and Haifeng Su. 2013. Displaydrone: A Flying Robot Based Interactive Display. In *Proceedings of the 2Nd ACM International Symposium on Pervasive Displays (PerDis '13)*. ACM, New York, NY, USA, 49–54. https://doi.org/10.1145/2491568.2491580

[52] Stefan Schneegass, Florian Alt, Jürgen Scheible, and Albrecht Schmidt. 2014. Midair Displays: Concept and First Experiences with Free-Floating Pervasive Displays. In *Proceedings of The International Symposium on Pervasive Displays (PerDis '14)*. ACM, New York, NY, USA, Article 27, 5 pages. https://doi.org/10.1145/2611009.2611013

[53] Ronald Schroeter, Marcus Foth, and Christine Satchell. 2012. People, Content, Location: Sweet Spotting Urban Screens for Situated Engagement. In *Proceedings of the Designing Interactive Systems Conference (DIS '12)*. ACM, New York, NY, USA, 146–155. https://doi.org/10.1145/2317956.2317980

[54] Susanne Seitinger, Daniel S. Perry, and William J. Mitchell. 2009. Urban Pixels: Painting the City with Light. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. ACM, New York, NY, USA, 839–848. https://doi.org/10.1145/1518701.1518829

[55] Fabius Steinberger, Marcus Foth, and Florian Alt. 2014. Vote With Your Feet: Local Community Polling on Urban Screens. In *Proceedings of The International Symposium on Pervasive Displays (PerDis '14)*. ACM, New York, NY, USA, Article 44, 6 pages. https://doi.org/10.1145/2611009.2611015

[56] Mirjam Struppek. 2006. The social potential of Urban Screens. *Visual Communication* (2006). https://doi.org/10.1177/1470357206065333

[57] Martin Tomitsch. 2014. Towards the real-time city : An investigation of public displays for behaviour change and sustainable living. *Proceedings of the 7th Making Cities Liveable Conference, PANDORA Archive.* July, 10–11.

[58] Nina Valkanova, Sergi Jorda, Martin Tomitsch, and Andrew Vande Moere. 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)*. https://doi.org/10.1145/2470654.2466476

[59] Wesley Willett, Yvonne Jansen, Pierre Dragicevic, Wesley Willett, Yvonne Jansen, Pierre Dragicevic, Embedded Data, Representations Ieee, Wesley Willett, Yvonne Jansen, and Pierre Dragicevic. 2017. Embedded Data Representations To cite this version : Embedded Data Representations. (2017).

[60] Christian Winkler, Julian Seifert, David Dobbelstein, and Enrico Rukzio. 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 (CHI '14)*. ACM, New York, NY, USA, 4117–4126. https://doi.org/10.1145/2556288.2557365

[61] Niels Wouters, Koenraad Keignaert, Jonathan Huyghe, and Andrew Vande Moere. 2016. Revealing the Architectural Quality of Media Architecture. In *Proceedings of the 3rd Conference on Media Architecture Biennale (MAB16)*. ACM, New York, NY, USA, Article 5, 4 pages. https://doi.org/10.1145/2946803.2946808

[62] Karolina M. Zielinska-Dabkowsk. 2018. Make lighting healthier. *Nature* 553 (2018), 274–276. https://doi.org/10.1038/d41586-018-00568-7