Towards e-Cities: An Atlas to Enhance the Public Realm Through Interactive Urban Cyber-Physical Devices

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Abstract: Cyber-physical devices are the backbone of a postdigital society in which the virtual and real spaces are seamlessly integrated by ubiquitous computing and networking. The incorporation of such devices in public space is a central subject of a strategic Research Project that gathers a multidisciplinary team from architecture, product design, polymer science and ICT R&D units. This paper frames the key roles of public space and ICTs for UN Sustainable Development Goals and sustainable smart cities. It also reports the architecture R&D unit review on the relations between public space, community, environment and digital interfaces. This review was materialized in an Atlas that collects, classifies and relates a corpus of heterogeneous urban cyber-physical projects case studies. We expand on three main framing concepts (Digital Twin, Interface, Awareness) and identify trends on the devices' design and deployment strategies to counteract digitally hostile environments and early obsolescence. We also suggest the rising of new types of urban devices aiming at expanding the liveliness of urban places, the knowledge of urban life and the users' environmental consciousness. The lessons learned from the Atlas fed the design guidelines for a developing demonstrator of a new breed of environmentally sensible interactive urban devices.

1 INTRODUCTION

Throughout history, the role and meaning of public space in the city has evolved. Nonetheless, its infrastructural and social roles, remain fundamental components of inhabitants' wellbeing. Urban life has always been supported by the creation of devices that address human needs in those spaces, from street furniture to the architectonic artefacts of the cities' hidden infrastructures (Uslu & Bölükbaşı, 2019). With the widespread of internet and pervasive computing, most of the services are being digitalized and moved to a global networked virtual space, parallel to the physical one we inhabit (Castells, 2009). The evolving technology opened new possibilities of interaction between these two spaces, and from real to virtual, a gradient of mixed realities was created. Augmented Reality, Internet of Things (IoT), Big Data and Digital Twin are technologies and concepts that seem to be the sign under which Information and Communication Technology (ICT) is shaping our world. A new networked digital layer is correlating all aspects of the human life and identity, but also the built environment around us and the meaning of public space as a place (Cindio, 2008). Following this repositioning of public space, triggered by a new digitally mediated public realm and a pressing global sustainability crisis, the interlacing between digital and analogue, between *bits and atoms*, is pervading and redefining architecture and urban design disciplines (Ratti & Claudel, 2016).

1.1 Public Space and ICT, Key Factor for the SDGs

These two facets, Public space and ICTs, are key factors in reaching UN Sustainable Development

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Goals (SDG) and targets. Our main focus among SDGs is Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable; specifically, the target 11.7: To provide universal access to safe, inclusive and accessible, green and public spaces, particularly for women and children, older persons and persons with disabilities (*Goal 11 | Department of Economic and Social Affairs*, n.d.). Public spaces are an opportunity to achieve other SDGs, namely: SDG 3: Health and Well-Being – NCD prevention, access to healthy foods and local markets, physical activity, walkability and safe circulation; SDG 5: Gender Equality – public spaces safety for women and girls; SDG 8: Decent Work for All – public spaces are the “workplaces” for many informal workers; and SDG 13: Climate Change – green and public open spaces in cities addresses both climate change mitigation and resilience (Kristie, 2016).

Authors like (Tjoa & Tjoa, 2016) outline the enormous potential of ICTs to ensure quality and accountability, and to accelerate the accomplishment of the SDGs. The UN World Summit on Information Societies (WSIS) in 2003 and 2005 was devoted to the vision of “a people centred, inclusive and development-oriented information society”, which was synthetized in eleven WSIS Action lines (Cn) for ICT driven sustainable development. UN Action Line facilitators have produced a WSIS-SDG matrix linking WSIS Action lines with SDGs (www.wsis.org/sdg). ICTs are both identified as targets in the SDGs for education, gender equality, infrastructure (universal and affordable access to the internet) and as a cross cutting tool to be utilized for the achievement of all the SDGs (Table 1).

WSIS-SDG relations were further disaggregated into the SDG targets. There is no direct linking between WSIS ICT Action lines and our main focus SDG target 11.7, although we can say that the former are implicit in many solutions for a safe, inclusive and accessible public space. Also, Action line C9 (Media), related with information accessibility, user data security and the role of media in the Information and Knowledge Societies, is not directly referenced as related to SDG goal 11. The questions addressed by this Action line seem most relevant to cities as the natural relation between public space and media is historically acknowledged (McCarthy, 2003).

1.2 The Role of Urban Cyber-Physical Devices for Sustainable Smart Cities

A Cyber-Physical Device (CPD) is a device in which physical components and software are deeply intertwined. We consider CPD both as an individual device and a component of a broader Cyber-Physical System (CPS). These can process and define actions from data collected from their environment, being compliant to spatial and temporal contexts. Ongoing advances in science and engineering expand the link between computational and physical elements by intelligent mechanisms, increasing the adaptability, autonomy, efficiency, functionality, reliability, safety, and usability of cyber-physical systems

Table 1: WSIS Action lines - SDGs matrix, highlighting SDGs related to public space and Action lines related to SDGs 8 and 11 (adapted from https://www.itu.int/net4/wsis/sdg/).

	C1	C2	C3	C4	C5	C6	e-gov	e-bus	e-lea	e-hea	e-emp	e-env	e-agr	e-sci	C8	C9	C10	C11
SDG 1 - No poverty	x	x	x	x	x			x		x			x	x			x	
SDG 2 - Zero hunger			x	x		x		x		x			x		x		x	
SDG 3 - Good health and well-being	x		x	x						x			x				x	
SDG 4 - Quality education			x	x	x	x			x		x		x	x	x		x	
SDG 5 - Gender equality	x		x	x	x	x		x		x			x			x	x	
SDG 6 - Clean water and sanitation			x	x										x	x			
SDG 7 - Affordable and clean energy			x		x									x				
SDG 8 - Decent work and economic growth		X	X		X	X		X			X		X		X		X	
SDG 9 - Industry, innovation and infrastructure		x	x		x	x	x	x				x	x			x	x	
SDG 10 - Reduced inequalities	x		x			x					x						x	
SDG 11 - Sustainable cities and communities		X	X		X	X						X			X		X	
SDG 12 - Responsible consumption and production			x	x							x		x		x	x	x	
SDG 13 - Climate action			x	x								x	x	x			x	
SDG 14 - Life below water			x	x								x		x				
SDG 15 - Life on land			x									x		x				
SDG 16 - Peace, justice and strong institutions	x		x	x	x	x	x									x	x	
SDG 17 - Partnership for the Goals	x		x	x	x	x	x	x		x	x		x	x			x	x

(Khaitan & McCalley, 2015).

Our approach to CPDs departs from the architecture and urban design disciplines. It targets CPDs developed to assist urban life in public spaces or to manage city infrastructures, which we termed: Urban Cyber-Physical Devices (UCPD) and Urban Cyber-Physical Systems (UCPS). In this perspective, both the object, its relations to user and impacts on the site and society, are as important as the technicalities of the system and ICT technologies. Urban Cyber-Physical Systems can be seen as a class of what has been labelled as Cyber-Physical-Social Systems (CPSSs): the extension of Cyber-Physical Systems to seamlessly integrate cyber space, physical space and social space (Pasandideh et al., 2022).

The combination and coordination between the physical public space, urban data and ICTs is tied to the concept of Smart City. A tentative definition of Smart City implies an approach to urbanization that uses innovative technologies to enhance community services and economic opportunities, improve city infrastructure, reduce costs and resource consumption, and increase civic engagement (Halegoua, 2020). They are the product of mass urbanization, the contemporary Society of Information and Knowledge and the fourth industrial revolution response to global problems that threaten our planet (Mitchell, 2000). UCPDs play a major role in all these fronts. As we shall see, UCPDs are (i) sensible hubs, collecting and broadcasting urban information; (ii) interactive interfaces between city, individuals and communities, raising awareness and engagement; (iii) gateway devices, bridging cyber, physical and social spaces; and (iv) adaptable devices, pushing for design and governance solutions that address both large-scale long-term societal emergences, and small-scale short-term daily life individuals concerns (Anwar et al., 2021).

1.3 The Research Project

The incorporation of UCPDs in public space is a central subject of an ongoing strategic Research Project that gathers expert teams from architecture and product design, polymer science and ICT R&D units. This paper reports the initial review on the relations between public space, community, environment and digital interfaces produced by the architecture R&D unit. This was materialized in an academic publication named *Atlas for the design of future e-cities* (Atlas from now on) (https://tinyurl.com/mrm5mnws) that collects, labels, relates and critiques a corpus of heterogeneous UCPDs case study projects deployed in public space around the world, which reflects the multidisciplinarity of the research team.

The scientific importance of this Atlas is trifold: (i) for the Research Project the lessons learned from the Atlas fed the design guidelines for a demonstrator of a new breed of environmentally sensible interactive urban devices, which integrates all the project's research lines; (ii) for the scientific community it is an updated state of the art in the subject, extending related work like the *Pool of Examples* of the *CyberParks* 2014-2018 project (CyberParks, 2014) or *Active Public Space* project publications (Markoupoulou et al., 2017); and (iii) for the non-experts it's a theoretical and monographic introduction to the subject, with an ample set of fully illustrated applied cases.

In the following sections we delve into the Atlas and use it as a leitmotif to expand on the subject of UCPDs, their public space incidence, user behaviour and societal transformation potentials into a more sustainable urban future. The paper continues as follows: first we present the Atlas and records structures, the set of case studies and the reading grid rationales; next we present results on case studies cross readings and relationship mappings; finally, in the discussion and conclusion section we comment on results, expand on their meaning to sustainability and on their importance to Research Project future work.

2 MATERIALS AND METHODS. THE ATLAS STRUCTURE

The Atlas is a compilation of UCPDs' case studies, presented as a set of records with a unified representation, meant to be used as an easy to consult state of the art document. It dives into aspects of devices' development and implementation and analyses public space transformations. It was methodologically devised after the definition of *Atlas* in Geography: a set of standardized thematic representations providing a comprehensive image of a *territory* (in our case: the *Interactive Urban Cyber-Physical Devices* subject). Because of the continuous emergence of new projects and technologies, the Atlas is designed with a chronological coded structure, receptive to new additions.

Table 2: List of recorded projects in the Atlas (please refer to links in the end of this paper).

Code	Name	Year	Location	Development Team
P08.01	DIGITAL WATER PAVILION [1]	2008	Zaragoza, Spain	Carlo Ratti Associati and MIT
P09.01	COPENHAGEN WHEEL [2]	2009	Copenhagen, Denmark	MIT Senseable City Lab
P11.01	21 SWINGS [3]	2011	Montreal, Canada	Daily Tous les Jours
P12.01	SMART CITIZEN KIT 2.1 [4]	2012	Barcelona, Spain	Fab Lab Barcelona
P12.02	AIRFIELD [5]	2012	Atlanta, Georgia	Ueberall
P12.03	BIRLOKI [6]	2012	Bilbao, Spain	Nerei Emotional Intelligent SL
P13.01	ARRAY OF THINGS [7]	2013	Chicago, USA	Urban Center for Computation and Data
P13.02	RESPONSIVE PUBLIC SPACE [8]	2013	Graz, Austria	ORTLOS Space Engineering
P13.03	PUZZLE FAÇADE [9]	2013	Linz, Austria	Javier Lloret
P13.04	BEACONS [10]	2013	USA	Estimate (Apple)
P14.01	TETRABIN [11]	2014	Chicago, USA	Sencity
P14.02	ACTIWAIT [12]	2014	Hildesheim, Germany	Urban Invention
P15.01	UNDERWORLDS [13]	2015	Cambridge, USA	MIT Senseable City Lab
P15.02	THE HEART OF THE CITY [14]	2015	Sidney, Australia	Anaisa Franco Studio
P15.03	MURMUR WALL [15]	2015	San Francisco, USA	Future Cities Lab
P15.04	RESPONSIVE STREET FURNITURE [16]	2015	London, UK	Ross Atkin Associates
P15.05	FUTURE FOOD DISTRICT [17]	2015	Milan, Italy	Carlo Ratti Associati
P16.01	PROJECT BUS STOP [18]	2016	Singapore	DP Architects
P16.02	TREE.0 [19]	2016	Copenhagen, Denmark	Interactive Spaces Urban Studio
P17.01	BENCHMARK [20]	2017	Cambridge, USA	Civic Data Design Lab
P18.01	INTERACTIVE SCREEN [21]	2018	Barcelona, Spain	Trison
P18.02	ITECH DEMONSTRATOR [22]	2018	Stuttgart, Germany	University of Stuttgart (ICD, ITKE, ITFT)
P19.01	SMART POLE [23]	2019	Holesov, Czech Republic	INELS (ELKO EP)
P20.01	AUGMENTED SPACES [24]	2020	Wellington, New Zealand	Holly Chan, Victoria University of Wellington

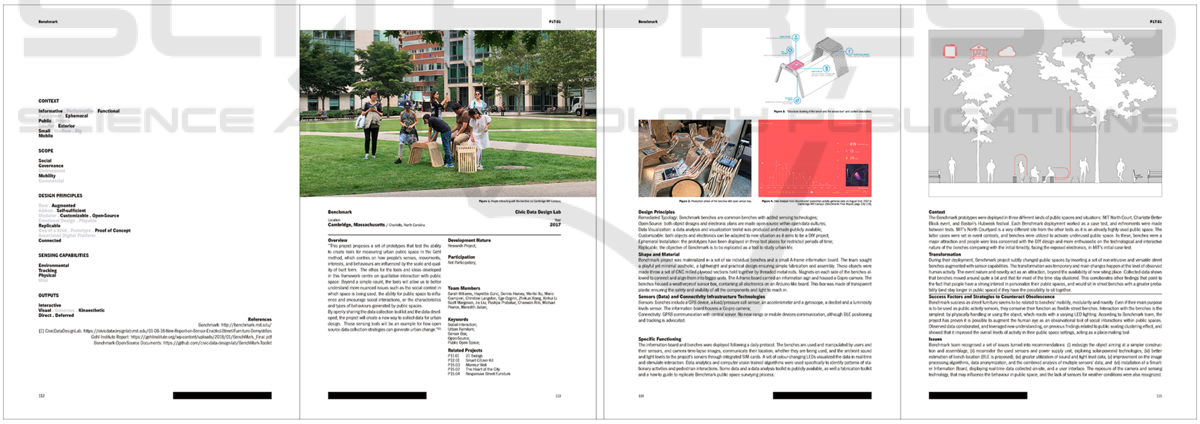

Figure 1: The four-page record's organization in Atlas' BENCHMARK case study (P17.01). Reading grid, from left to right: Preview; Datasheet; Object; Context (top) and Review (bottom). Images in pages 2 and 3 from [20].

2.1 Case Studies

The rationale behind the selection of examples followed a series of principles backing the main goal: to portrait the diversity of contexts and scales, and the several design and deployment strategies of innovative UCPDs. Priority was given to objects with a physical existence that support typical human needs (mobility, comfort, security, etc.), and to implemented or prototyped design objects over untested concepts, purely artistic interventions or digital-only initiatives. We've searched for examples that possess some sort of sensing, communication, interactivity or adaptability capacity that augments their physical performance and extends its existence into the virtual realm. The Atlas currently comprises 24 case studies (Table 2).

2.2 The Records Structure

Each project entry is bound to a four-page organization with two main foci: Object and Context (Figure 1).

The complete set of the records reading grid headings is: (i) Preview; (ii) Datasheet; (iii) Object; (iv) Context; and (v) Review.

(i) Preview. A bird's eye view of the project that summarizes its context and design concepts using highlighted tags that clearly make it easy to identify and situate. This information is divided into 5 topics as in Table 3.

(ii) Datasheet. Situates the example with general information: project's official name, code, development team, third-party participation, development nature (e.g. academic, independent), location, year, keywords, related projects and references. An Overview topic describes the project by the development team's own words.

(iii) Object. Under this heading, the main design features and functions of the objects are organized. Stress is in the relations between the physical and digital components of the device, and the functioning of its associated interface. Topics are as follows:

• Design Principles. Small description of the strategic, functional and implementation choices, considering modularity, customization, adaptability, associated digital platforms, etc.

• Shape and Material. Descriptive paragraph of the tangible scope of the object such as: dimensions, general shape, composition, materials, connections, structural design.

• Sensors and Connectivity Infrastructure Technologies. Detailed list of implemented sensors and type of collected data, as well as the connectivity infrastructure technology.

• Specific Functioning. A summary of the interface, hardware and software functioning

Table 3: Preview topics, subtopics, tags, and their description.

Topic	Subtopics	Tag	Description
Context	Role	*Informative*	Media content and knowledge to inform or educate the users
		Performative	Ludic nature, with motion, interaction and animation
		Functional	Tied to an operative use, as a utilitarian device
	Duration	*Permanent*	Permanently installed or intended to be a permanent addition to the public space
		Ephemeral	Limited time span or seasonal implementation
	Ownership and Use	*Public*	Relates to devices of public use and domain
		Private	Can be bought and owned by the common citizen
	Site	*Interior*	Indoor setting
		Exterior	Outdoor setting
	Scale (comparative to human)	*Small*	Up to an outdoor bench
		Medium	Up to an urban kiosk
		Big	Bigger than an urban kiosk
		Mobile	Designed to be moved easily
Scope		*Social*	Tackles Societal issues (e.g. inclusive designs, community gathering and cooperation)
		Governance	Data driven decision-making and management (e.g. institutions, smaller business)
		Environment	Sustainable habits incentives, ecologic concerns and environmental comfort
		Mobility	Mobility in the cities, both transportation and walkability
		Commercial	Indirect impact in the city's economical fabric
Design Principles	Typology	*New*	New concepts or object types added to the public space
		Augmented	New digital functionality added to already stablished types of urban objects
	Support	*Add-on*	Attaches to a host object for structural and/or infrastructural support
		Self-Sufficient	Independent power supply
	Tailoring	*Modular*	Composed of modular parts
		Customizable	Made to be customized in its physical or digital components
		Open-Source	DIY, open-source and open-data initiatives
	Attachment	*Emotional Design*	Empathy, engagement and appropriation through shape, software and interface design
		Playable	Gamification of the urban spaces or activities
		Replicable	Possible to be reproduced and applied to a different context with no major adaptations
	Oneness	*One of a Kind*	Designed to be unique, usually artistic expressions
		Prototype	Device in the first development phases, with intention of mass production
		Proof of Concept	Device showcasing a new technology or concept, with no direct intention of further development
		Associated App	Devices that have an associated app or e-service, interfacing with a website
		Connected	Connected to any kind of public or private communication network (intranet, extranet or internet)
Sensing Capabilities		*Environmental*	Temperature, humidity, chemical/gas, ambient light and sound sensors
		Tracking	Optical, position/proximity, movement/displacement or network-based tracking
		Physical	Force/load, vibration, torque...
		Vital	Heart rate, blood pressure...
Outputs		*Interactive*	Devices that have interactive user interfaces
	Sense	*Visual*	Lightscapes, screens or other data visualizations, also through associated apps
		Sonorous	Soundscapes
		Kinaesthetic	Induce user's movement or have moving parts that change the perception of space
	Immediacy	*Direct*	Immediate response to user's inputs and showcase of real-time data
		Deferred	Outputs takes effect in the future, e.g. data for governance or behavioural change

including connectivity infrastructure, technologies, interaction principles and data flow.

(iv) Context. Addresses the presence of cyber physical technologies and interactive devices in the public space. The focus is on the urban contexts in which they are deployed and their influence in the design and functioning of the spaces, and in the people who inhabit them. Topics are as follows:

- Context Diagram. A graphic diagram depicting (with relative fidelity) the urban context type and scale which the device is attached to, synthetizing its contextualized functioning.
- Context: Small description of the public space the system is applied to, including urban, cultural and geographical contexts.
- Induced Transformation. Analysis of the device's effects in the public space and the citizens (direct or indirect), as well as influence over contemporary pressing matters, namely urban sustainability.

(v) Review. A critique assessment of potential benefits and weaknesses of the project, both as an isolated and a contextualized object. Topics are as follows:

- Success Factors and Strategies to Counteract Obsolescence. Discussion about the project's characteristics and approaches that help make it a success.
- Issues. A speculative overview around what are the object's main issues considering possible obsolescence, dependencies and sustainability.

3 RESULTS. MAPPING THE RELATIONS BETWEEN CASE STUDIES

Keywords were assigned to projects empirically and ranked based on the specificity of the characterizing terms, from generic (lower rank) to particular (top rank). There are 40 distinct keywords, but 12 of them are only used once (e.g., Vital Signs, E-bicycle or Digital Water) and don't generate connections between projects.

In Figure 2 we represent the relations between Atlas records. Related projects are connected by edges via keywords sharing. Each record has five keywords, weighted by inverse ranking order, from lower (1) to higher (5), and the strength of the relation (edge weight) is determined by the sum of the keyword weights in source (left) and target (right) project. The disks size at right represent the number of times a project is referred to.

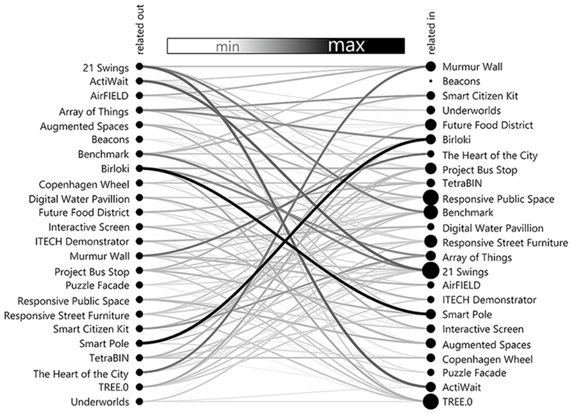

Figure 2: Diagram of the relations between Atlas records, via keywords.

From the results of this analysis, we can observe that:

(i) The stronger aggregated sum edge is SMART POLE - BIRLOKI (weight: 24, via Smart City + Urban Furniture + Modular Design keywords), followed by edge 21 SWINGS - ACTIWAIT (weight: 21, via Playable + Social Interaction + Public Open Space keywords), and MURMUR WALL - THE HEART OF THE CITY (weight: 20, via Art Installation + Lightscape + Social Interaction keywords). This depicts some grouping of examples: first, UCPDs as smart city equipment; second, UCPDs as social and activity stimulators in public space; and, third, UCPDs as public art media;

(ii) The most referred project is 21 SWINGS (10 times), then RESPONSIVE PUBLIC SPACE and TREE.0 (9), and BENCHMARK (8). The fact highlights the importance of examples related to social interaction, design principles based on playable strategies and kinaesthetic interactions;

(iii) The project BEACON is never pointed out as a related project. As a technology it was deemed to generic, so relations to other projects are weak;

(iv) The most used keywords in the Atlas are Urban Furniture (10 times), Public Open Space (9), Human Tracking and Social Interaction (6). To some extent this reflects the bias in the designer's viewpoint and examples' selection;

(v) The keywords more often ranked on top (2 times) and producing the strongest simple edges between projects (weight = 10), are Smart City (associating SMART POLE – BIRLOKI), Sensor Box (SMART CITIZEN KIT - ARRAY OF THINGS), Big Screen (INTERACTIVE SCREEN - AUGMENTED SPACES), and Art Installation (MURMUR WALL - THE HEART OF THE CITY). This corroborates the results described in (i) and the importance of screens, yet the standard user interface.

3.1 Empirical Results from Cross Readings

In this section we do a summary of the Atlas' records cross readings, following the topics of the reading grid outlined above. We intend to give a clearer picture of the main problems, common solutions and affinities between projects.

In Table 4 a *case study project names – preview tags matrix* summarizes the tags highlighted in the *Preview* first page of each record. Tags description, and topic/subtopic grouping can be acquired from Table 3. Following the five topics classification, and by decreasing order of importance, the main used tags are: (i) Context: *Public* and *Exterior*, *Permanent*, *Functional*; (ii) Scope: *Social*, *Environment*, *Governance*; (iii) Design principles: *Replicable*, *Connected*, *Customizable*; (iv) Sensing capabilities: *Tracking*, *Environmental*, *Physical*; and (v) Outputs: *Visua*l and *Direct*, *Interactive*, *Deferred*.

3.1.1 Datasheet Overview

Selected examples are contemporary with the dissemination of internet and mobile digital technologies, spanning the last 13 years. The emphasis in this period reflects a bias towards the availability of information, but it also hints to the upwelling use of cyber components in urban devices. Development teams are mainly academic, and two organisations stand out: MIT (5 projects) and Gehl Architects (2 projects). While North America (USA) and Europe (Italy, Spain and Denmark) are the standout locations, this indicates a Eurocentric (or occidental) bias and the need for the diversification of origins in future work. Most cases are not participatory but most result from public institutions' support in the implementation of the devices in public space.

3.1.2 Design Principles

The incorporation of ICT technologies in the design of urban life assistance devices pushes to multidisciplinary and codesign processes. Multidisciplinary teams of specialists are necessary to address the increased complexity of the design task, and codesign approaches point to a new stage of hands-on participatory processes. This incorporation and design processes leave traces in new breeds of augmented types of standard urban objects, or give rise to new ones. Playfulness and Emotional Design

Table 4: Case study project names – preview tags matrix.

	Context													Scope				
	Informative	Performative	Functional	Permanent	Ephemeral	Public	Private	Interior	Exterior	Small	Medium	Big	Mobile	Social	Governance	Environment	Mobility	Commercial
Digital Water Pavilion P08.01			●	●		●			●			●			●	●		
Copenhagen Wheel P09.01			●	●			●		●	●			●		●	●	●	
21 Swings P11.01		●			●	●			●			●		●				
Smart Citizen Kit 2.1 P12.01	●		●	●			●	●	●	●			●		●	●		
AirFIELD P12.02	●			●		●		●				●		●				
Birloki P12.03	●		●	●		●		●	●		●			●	●	●	●	●
Array of Things P13.01			●	●		●			●	●					●	●	●	
Responsive Public Space P13.02		●			●	●			●		●			●				
Puzzle Facade P13.03		●			●	●			●			●		●				
Beacons P13.04	●		●	●		●	●	●	●	●					●		●	●
TetraBIN P14.01		●		●		●		●	●	●						●		
ActiWait P14.02		●		●		●			●	●				●				
Underworlds P15.01	●		●	●		●			●	●					●	●		
The Heart of the City P15.02	●	●			●	●			●		●			●				
Murmur Wall P15.03	●	●			●	●			●		●			●				
Responsive Street Furniture P15.04	●		●	●		●			●		●			●	●		●	
Future Food District P15.05	●		●	●			●	●				●				●		●
Project Bus Stop P16.01	●		●	●		●			●			●					●	
TREE.0 P16.02	●	●	●		●	●			●		●			●		●		
Benchmark P17.01	●		●		●	●			●	●			●	●	●		●	
Interactive Screen P18.01		●		●		●		●			●			●				
ITECH Research Demonstrator P18.02		●	●		●	●			●		●					●		
Smart Pole P19.01	●		●	●		●			●		●				●	●	●	●
Augmented Spaces P20.01		●		●		●			●		●			●				

	Design Principles															Sensing Capabilities				Outputs					
	New	Augmented	Add-on	Self-Suffcient	Modular	Customizable	Open-Source	Emotional Design	Playable	Replicable	One of a Kind	Prototype	Proof of Concept	Associated Digital Platform	Connected	Environmental	Tracking	Physical	Vital	Interactive	Visual	Sonorous	Kinaesthetic	Direct	Deferred
Digital Water Pavilion P08.01		●				●			●	●			●	●	●		●			●	●		●	●	
Copenhagen Wheel P09.01	●		●	●		●				●				●	●	●	●				●		●	●	●
21 Swings P11.01		●	●						●		●							●		●		●	●	●	
Smart Citizen Kit 2.1 P12.01	●		●	●		●	●			●				●	●	●					●				●
AirFIELD P12.02											●			●	●						●			●	
Birloki P12.03		●			●	●		●		●		●		●	●	●				●	●	●		●	●
Array of Things P13.01	●		●		●	●				●					●	●	●	●							●
Responsive Public Space P13.02								●			●						●			●	●	●	●	●	
Puzzle Facade P13.03			●						●		●				●			●		●	●			●	
Beacons P13.04	●		●	●		●				●				●	●		●				●			●	●
TetraBIN P14.01		●				●			●	●					●		●			●	●			●	●
ActiWait P14.02	●		●						●	●		●			●					●	●			●	
Underworlds P15.01		●		●						●		●		●			●								●
The Heart of the City P15.02		●						●		●	●								●	●	●			●	
Murmur Wall P15.03								●			●			●	●					●	●			●	
Responsive Street Furniture P15.04		●				●				●		●		●	●		●			●	●	●		●	
Future Food District P15.05		●								●			●		●		●			●	●			●	●
Project Bus Stop P16.01		●			●	●				●		●			●						●				
TREE.0 P16.02	●								●	●	●			●	●	●		●		●	●		●	●	
Benchmark P17.01		●		●		●	●			●			●		●	●	●	●		●	●		●	●	●
Interactive Screen P18.01						●			●	●							●	●		●	●		●	●	
ITECH Research Demonstrator P18.02		●								●			●	●	●			●		●	●		●	●	
Smart Pole P19.01		●			●	●				●				●	●	●				●	●	●		●	●
Augmented Spaces P20.01						●		●		●			●				●			●	●		●	●	●

are two major design strategies to increase user interaction and engagement with the objects, the services or social goals. These strategies can be applied both to the object, the digital interface and media content that is presented by the devices. As sensing and interacting devices UCPDs may produce large quantities of data. Open-source, open-data but also data visualization, play a major role in the objective of the DIY Atlas' examples, and are the substrate for further artistic, design or commercial explorations by other devices.

3.1.3 Shape and Material

There is no typical size or scale for this kind of devices, nor implementation strategy, as they range from pocket-size sensor boxes to street scale interventions. Nonetheless, if most interfaces are designed for urban scale, interaction between user and the devices always happens in a human centred scale. Shapes tend to be simple and rectilinear. This trend can be related to the most used industrial materials and fabrication methods where the main concerns are cost-effectiveness and ease of fabrication. Nonetheless, there are a few organic and metaphorical shapes, such as trees, hearts or animal inspired.

3.1.4 Sensors and Connectivity

Most of the examples are equipped with sensors and can collect data in real-time. While some simulate a near real-time sensing capability by collecting online data, others have no sensing capabilities at all. The most used sensors are environmental sensors and user interface sensors. Geolocation, tracking, gesture and facial recognition are other major uses for sensors, which can be achieved in various ways (with predominance to computer vision). Interactive touch screens range from small tablet like screens, sensing the pressure of a finger, to very big floor screens, sensing the pressure of the users' body. Sensor data can be used locally and immediately discarded or recorded in a web server using pre-processed data if UCPDs' nodes have edge computing and long-range communication capabilities. In this case they can also be remotely managed and maintained. Devices may also work as a WI-FI Hotspot, nonetheless, connectivity between personal devices and UCPDs is mainly achieved by pairing Bluetooth/BLE wireless devices.

3.1.5 Specific Functioning

Interaction with UCPDs is, in most cases, stimulated by local soundscapes, lightscapes and personal device usage integration. This engagement happens through network facilitator systems such as QR codes, Beacons, Bluetooth or other means of wireless communication. Interfaces try to escape the common PC experience, there is a general trend of *gamifying* common actions in public space to increase attractiveness. These include synesthetic experiences that use the "body as interface" and alternative ways (other than screens) of displaying information. The data handling is carefully done to guarantee long-term sustainability in pressing matters such as: personal and site sensitive data security, legal usage, communication networks overload, data storage capacity and energy consumption of systems' maintenance.

3.1.6 Context

Most of the examples in the Atlas are deployed in developed countries' public open spaces (see Table 2) and address common global or characteristic urban problems: environmental sustainability, public participation, community resilience and security in public spaces. These devices are installed mostly in spaces seeking for high activity or pedestrian flow, such as squares, boulevards or important street intersections. Some cases are connected to indoor activities and entertainment, and others are mobile, therefore not site specific. Most devices are designed to interact directly with pedestrians instead of cars or traffic, notably a fruitful trend targets disabled people and assisted living in public space. However, some UCPDs are installed in segregated spaces, aiming at their activation. The urban scales of interventions vary from single interventions in small public spaces to citywide devise systems; their cyber contexts (network scale) also vary from direct physical interfacing, or in-place mobile device pairing, to global internet connectivity. The deployment time frame of research or artistic based interventions is short, while functional and industrialized products are designed to endure harsh outdoor conditions for long periods.

3.1.7 Induced Transformation

Public space transformation upon device implementation can be segmented into six groups. Although the device's (i) *Physical presence* is the only concrete direct transformation in the public space perception, data collection is the base of (ii) *governance informed decision-making*, which will, in turn, lead to more tangible and intangible transformations. (iii) *Behavioural change* is an exemplary indirect transformation where data communication and clever interface design are key aspects in the moulding of place and sustainability aware citizens. This also integrates (iv) *social interaction encouragement*, aiding in the rupture of bias and prejudice within different background social groups that share the same public spaces as well as (v) *urban setting activation* that foments social interaction and permanence in otherwise segregated spaces. The implementation of these devices can also be more operative, focused on (vi) *the facilitation of quotidian tasks* or even in the enhancement of city infrastructures that can improve safety and inclusion.

3.1.8 Success Factors and Strategies to Counteract Obsolescence

Successful interventions oftentimes rely on opportune timings and placement. These prospects on public space life renewal and good selection of deployment sites (where interaction is welcome by the users) are important aspects to consider. Apart from other direct object design parameters, such as safety, weatherproof, durability, anti-vandalism or even modularity to ensure long-lasting devices, its designed physical affordances are a safe fall-back in case of digital failure, and a way to avoid object's obsolescence as a whole. Providing enjoyable experiences as well as a sense of discovery through emotional design is also a strategy to create empathy, and therefore counteracting obsolescence. Perhaps even more important, is the perceived utility of the device and its inclusive goals (ethnographic, age groups and disabilities) through its formal design and intuitive user-friendly interface.

3.1.9 Issues

One of the main issues about applying ICT technology to the public space is implementation cost effectiveness. Although there are low-cost technology and DIY solutions, large scale implementations are yet too costly to produce and maintain. There are heavy counterproductive dependencies triggering obsolescence in UCPDs: high-end technology, high maintenance, third-party services, mandatory apps or even continuous service content feed. Also, heavy dependence on novelty, perceived usefulness and user attachment may become a trivialization issue. The inequality of access to ICTs, digital illiteracy or the bodily condition of users to operate physical interfaces, are another major issue from the perspective of users. User safety concerns go now beyond devices' ergonomic and placement concerns, extending into collected personal and site data security assurance, which conflicts with users' rights to privacy and anonymity in public space. Also, the ecological impact of the production of UCPDs we've studied is not a main consideration concerning recycled materials usage, sustainable fabrication processes or renewable energy sources.

4 THREE CYBER-PHYSICAL META CONCEPTS: DIGITAL TWIN, INTERFACE, AWARENESS

From a literature review on the design perspective on UCPDs, and the process of elaboration of the Atlas itself, a set of framing meta concepts were synthetized regarding UCPDs and their incidence in the public space. Without the objective of reaching closed concepts, we've identified the following: *digital twin*, *interface* and *awareness*.

From the engineering and CAD industries, *digital twin* is the real-time digital representation of a physical object or process integrating sensor data that can be used to manage the real world (Fuller et al., 2020). The responsive nature of UCPDs and their double physical and digital presence in the public space rekindles its use, counteracting a sense of alienation from place and architecture. Regardless of its complexity, the convergence between virtual and real worlds seems undeniable and it depends on the interface's conspicuity.

Interface is a fundamental concept in architecture and urban design, traditionally understood as the symbolic boundary between public and private realms or the physical surface that separates different spaces. With the introduction of cyber technologies, it could also mean the active control over building elements and adaptable spaces. Interface design is paramount in the engagement of people and UCPDs' success, becoming a synonym of functioning (Dade-Robertson, 2013). In the technological mediated realm of contemporary societies, UCPDs are regarded as the interface layer between a set of increasingly overlapping spaces and interconnected networks (Figure 3). Interface is the place where communication and interaction happens, therefore it is the place where awareness rises.

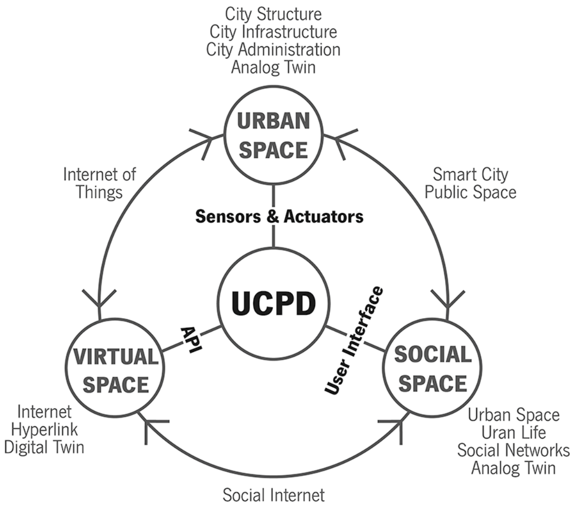

Figure 3: Conceptual diagram with UCPDs as the central interface node of a network of networks and as a gateway between social, virtual, and urban spaces.

The concept of *awareness* seems to frame the main goal for the implementation of cyber-physical devices in the city and the notion of Smart City itself. Awareness is synonymous of knowledge and perception, but also consciousness, sensitivity, and familiarity. This broad concept can be applied to people, machines, the relation between them, and between them and their environment. Public space users' increased awareness of global pressing issues is a key factor to participation and engagement and a main drive for the implementation of ICT technology. Awareness is the first step to behavioural change and social transformation which is arguably the very base of a sustainable future. Developments in ICT technologies also look to increase not only the machine's awareness of its users but also of other machines and its environment in (increasingly autonomous) automated networks of devices that keep alive a digitalised world that seems to dispense user's intervention (Pitt, 2015). The increasing dependency on ICTs may be seen as both an opportunity and a threat, but awareness is ultimately understood as human knowledge, literacy and conscious use of machine, and participation in a virtual world built to deal with real problems.

5 DISCUSSION AND CONCLUSION

Contrary to the idea that digital space deprives public space and collective life of its physical substrate, the Atlas reveals examples of how the dynamics between real and virtual, between physical and digital spaces, are allowing their reviving. In addition to the portrayal of current UCPDs, the Atlas provides a perspective on new ICT mediated relations between citizens and public space, that allow to pursue SGDs with innovative strategies for inclusion, local economic opportunity and sustainability awareness. UCPDs have the potential to open public space to the most vulnerable by means of increased security, assisted living, new forms of communication and simple human-centric playful interactions. Concurrently they develop digital literacy, community participation and environmental action, namely for those with fewer opportunities and education, by means of democratizing the public access to digital technologies, information and media. These devices also contribute to a reinvention and diversification of uses and activities in public space. Components of the public space or activities that are increasingly monofunctional or restricted get counteracted by devices that expand their possibilities and publics (e.g., working outdoors, virtual visits to museums). Diversity of uses and activities also means more people and longer occupancy, so more social and economic opportunities in a safer environment. As most of UCPDs are urban data sensors, they amplify an already data saturated digital space. This data, if shared as open-data and allied to open-source technologies and ingenuity, is a social and economic opportunity for local entrepreneurs.

Although it's too soon to establish the emergence of new typologies, UCPDs gave rise to new classes of objects deployed in public space with a distinct image and functioning. We've identified and named three instances: (i) *Sensor Boxes*, (ii) *Smart Trees*, and (iii) *Chargers*. (i) *Sensor Boxes* are small UCPDs devoted to sense the city, with the sole function of collecting urban data, mainly environmental. They range from institutional ICT infrastructures to simple DIY devices in the open-source and open-data spirit, merging ecological concerns with digitalization. (ii) *Smart Trees* are tree-like free-standing structures, devoted mainly to collect sun power, with their photovoltaic "leaves", for charging battery devices, usually acting as Wi-Fi hotspots. Placed isolated in urban squares they are also shading structures and meeting points with interactive features. With the multiplication of battery devices and electric mobility, the need for autonomous or integrated (iii) *Chargers* in the public space has increased. From electric car pole chargers to personal devices' USB chargers integrated in solar urban furniture, these devices are becoming pervasive. We notice that these new classes of objects are mainly sustainability oriented.

A significant part of the case studies in the Atlas depends on considerable financial, material and energy resources, and although sustainability problems are main design motivations, these concerns are not equally reflected in the production of the devices themselves. Nonetheless, it is notorious that this is an emergent and inescapable development. Urban objects residing outdoors are increasingly designed to ambient energy harvesting, becoming energetically self-sufficient, and the use of recycled materials and new fabrication methods that minimize waste, costs and promote circular economy (like additive manufacturing, is also a recent but growing trend. These developments in energetic, material and fabrication processes aren't currently highly intertwined with cyber components incorporation, nor large scale 3D printed objects are fully accepted as final products.

These challenges were the leitmotif for the developing Research Project's demonstrator for a new breed of environmentally sensible interactive urban devices, which integrates all the Project's research lines. It will be materialized in a family of augmented street furniture that incorporates: (i) cyber-components, (ii) renewable energy, (iii) recycled materials, and (iv) additive manufacturing in a full-scale outdoor-ready device, resorting to recycled plastic extrusion-based additive manufacturing by robotic arm. The lessons learned from the Atlas fed the demonstrators' requirements and design guidelines, balancing digital integration and physical affordances, as well as needed resources and expected results.

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List of links to Atlas projects' case studies in the web:
[1] https://carloratti.com/project/digital-water-pavilion/
[2] https://www.senseable.mit.edu/copenhagenwheel/
[3] https://www.dailytouslesjours.com/en/work/musical-swings/
[4] https://www.smartcitizen.me/
[5] https://ueberall.us/portfolio/airfield/
[6] https://www.juansadaba.com/projectbirloki/
[7] http://www.arrayofthings.github.io/
[8] https://www.ortlos.com/projects/responsive-public-space/
[9] http://www.puzzlefacade.info/
[10] https://developer.apple.com/ibeacon/
[11] http://www.tetrabin.com/
[12] http://www.urban-invention.com/
[13] http://www.underworlds.mit.edu/
[14] https://www.anaisafranco.com/heartofthecity/
[15] http://www.future-cities-lab.net/murmurwall/
[16] http://www.rossatkin.com/wp/?portfolio=responsive-street-furniture/
[17] https://carloratti.com/project/future-food-district/
[18] https://www.dpa.com.sg/projects/projectbusstop/
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[20] http://benchmark.mit.edu/
[21] https://www.trisonworld.com/en/projects/trison-digitalise-shopping-center-arenas-barcelona/
[22] https://www.itke.uni-stuttgart.de/research/icd-itke-research-pavilions/itech-research-demonstrator-2018-19/
[23] https://www.elkoep.com/smart-pole-in/
[24] http://www.ecaade2021.ftn.uns.ac.rs/session-16/