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**DOI**

[10.7480/spool.2020.3.5490](https://doi.org/10.7480/spool.2020.3.5490)

**Publication date**

2020

**Document Version**

Final published version

**Published in**

Spool. Journal of Architecture and the Built Environment

**Citation (APA)**

Pavlovic, M., Bier, H. H., & Pillan, M. (2020). Ambient UX for Cyber-Physical Spaces. *Spool. Journal of Architecture and the Built Environment*, 7(3 #3), 27-36. <https://doi.org/10.7480/spool.2020.3.5490>

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# Ambient UX for Cyber-physical Spaces

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## Abstract

Ambient User Experience (Ambient UX) is a conceptual framework providing a strategy for design processes that target cyber-physical spaces. Such design processes interface Wireless Sensor-Actuator Networks (WSAN), Artificial Intelligence (AI), and physically built environments. For managing the complexity of such design processes and ensuring the development of a design facilitating users' satisfaction, design approaches focused on experience and user activities linked to bio-cyber-physical feedback loops are needed. This paper points out how Ambient UX supports decision-making in a design process. It outlines the importance of mapping user experiences for cyber-physically enhanced environments by discussing design practices that can support this activity and presenting a representative case study implemented with students at TU Delft.

## Keywords

Ambient UX, user journey, Wireless Sensor-Actuator Networks, Artificial Intelligence, Cyber-physical Systems and Spaces, design methods

## DOI

<https://doi.org/10.7480/spool.2020.3.5490>

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## Introduction

Current digital design and media architecture practice demonstrate the rich potential of interactive media for the built environment; however, the meaningful integration of interactive media in architecture remains challenging. Dalton et al. (2016) discuss Ubiquitous Computing (UC) embedded into the built environment as a way of creating environments that meet the dynamic challenges of future habitation. The integration of UC in the built environment requires envisioning the built environment as a Cyber-physical System (CPS) consisting of mutually informing computational and physical mechanisms that communicate and operate cooperatively (inter al. Rajkumar et al. 2010) through a Wireless Sensor and Actuator Network (WSAN) (inter al. Yang, 2014). These environments are sensitive and responsive to people; they integrate a variety of devices operating in concert to support human activities in an unobtrusive way, using intelligence that is hidden in the network connecting them. Such cyber-physically enhanced environments (Bier et al., 2018), build up on systems and approaches known as Ambient Intelligence (Aml) (Zelkha et al., 1998) and Interactive or Digitally-Driven Architecture, (inter al. Fox and Kemp, 2009; Bier and Knight, 2010; Bier et al. 2017). They involve Artificial Intelligence (AI) (inter al. Ferber & Weiss, 1999) and rely on the Internet of Things (IoT) (inter al. Atzori, Iera & Morabito, 2010), and UC (inter al. Lyytinen & Yoo, 2002).

Various interactive systems enhance today experiences and activities as, for instance, Google Home, a voice-activated virtual helper that is connected to the Internet and performs basic tasks like searching the web for travel options, or identifying the schedule of the day. It can be trained to recognize voices and customize its responses. Amazon Go makes shopping more efficient in physical stores, while HealWell improves moods of users, such as hospital patients, and dynamically adapts according to ongoing activities. The Concept-I vehicle automates driving activities and anticipates users' needs. Such systems respond to the contemporary shift from material-based activities to information-based actions; they impact cognitive walk-paths and mind-body ergonomic principles. In this context, architecture becomes cyber-physical in nature and is increasingly aware of users and their changing needs.

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## Designing for Experiences

The design of systems that are cyber-physical in nature requires the understanding of the complex tangle of physical and mental processes associated to human activities, including motivations, cognitive and emotional ways of involvement, etc. Designing for users' experiences (UX), implies to approach the design in a holistic manner, considering the diverse levels of influence the design solution might have on individual and societal level, together with their impacts on individual and collective lifestyles and freedom of action. Designing for interactive and therefore cyber-physically enhanced spaces imposes rethinking and reshaping design approaches from practices currently employed in the field, towards more hybrid approaches that lie at the intersection of diverse fields. This paper discusses a framework for a holistic UX approach, which appears to be missing in current UX practices as a structured design process. The framework is based on the merging of Architecture knowledge with those of UX Design and Interaction Design, and on the adaptation of conceptual models and of pragmatic tools typical of these disciplines for the project of such systems.

## Ambient UX

The Ambient User Experience (Ambient UX) approach provides a strategy for structured design processes that target the integration of Cyber-physical Systems (CPSs) in architecture (Pavlovic, 2020). The Ambient UX framework consists of Design Domains (DD) defining what is to be designed and User Values (UV), identifying why what is to be designed is designed. Ambient UX design in architecture implies consideration of various intersecting and sometimes overlapping DDs such as interaction design (focused on services, journeys of users, social organizations, interfaces and interactions between people and facilities) and architectural design (focused on the built environment) with the aim to achieve a continuous and cohesive user experience across devices, time, and space (Pavlovic, 2020). In projects focused on user experience, the overall design integrates the design of interactions – including macro and micro scale analysis and optimization of the activities of the users - with the design of physical environments.

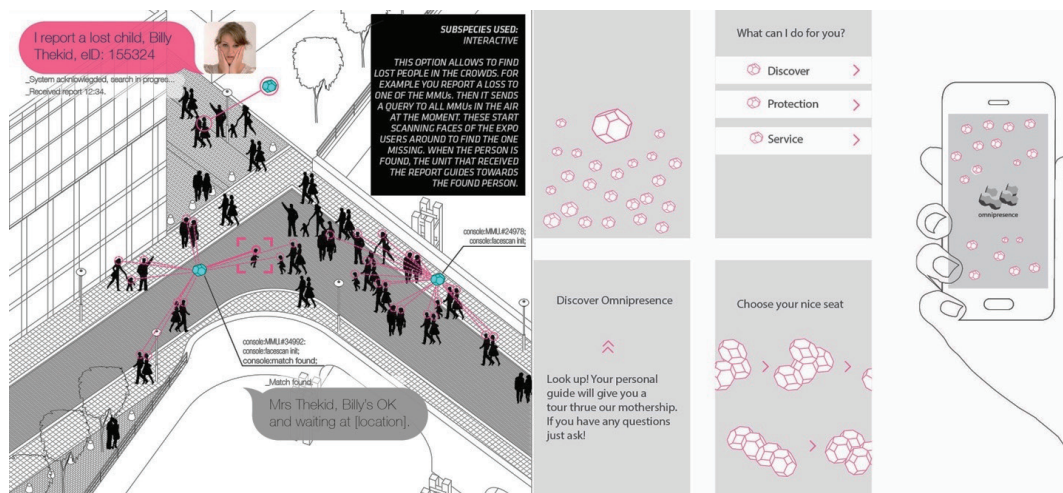


FIGURE 1 Mapping potential activities and interactions.

## Mapping Experiences

In order to manage the complexity of CPS solutions for the built environment and to orient design towards the optimal satisfaction of users, the project process includes both the physical facilities to be designed and the description of the non-tangible and non-material sources of value related to the CPSs to be designed, by mapping techniques focused on experience and user activities (inter al. Dalton et al., 2016; Kalbach, 2016) are explored through case scenarios.

The material features of the designed solutions imply natural constraints i.e. physical constraints that limit what can be done to the affordances, which convey possible uses, actions, and functions (Norman, 2013); the analysis of the interaction between users and solutions leads to the identification of a palette of constraints and enablers. These constraining/enabling points of activities together with the understanding of their impact on activities are starting points for designing user experiences. In a design approach fully focused on experience, the jobs and journeys of users in the context are fully investigated, together with the implicit and explicit motivations and meanings, while their envisioning make possible the political discussion on the convenience and desirability of the possibilities of actions by the subjects involved in the implementation and management of the CPS.

While the project and implementation of such systems requires the contribution of different disciplines – from Computer Sciences to Architecture, from Service Design to Robotics and more – the framework aims at an effective and efficient management of the project process.

The framework identifies three networks of interactions describing the independent dimensions experienced by the users in a CPS, which correspond to three diverse types of architectures to be implemented and made coherent in the project: spatial (interaction related to the physical environment and facilities), information (interaction related to manifest and hidden information flows), and relational (interaction related to human/ social relations and forms of social organization). The recognition of these different axes along which the project develops, but which require the capacity of holistic integration is the core of Ambient UX, and the conceptual reference for managing the complexity of CPSs.

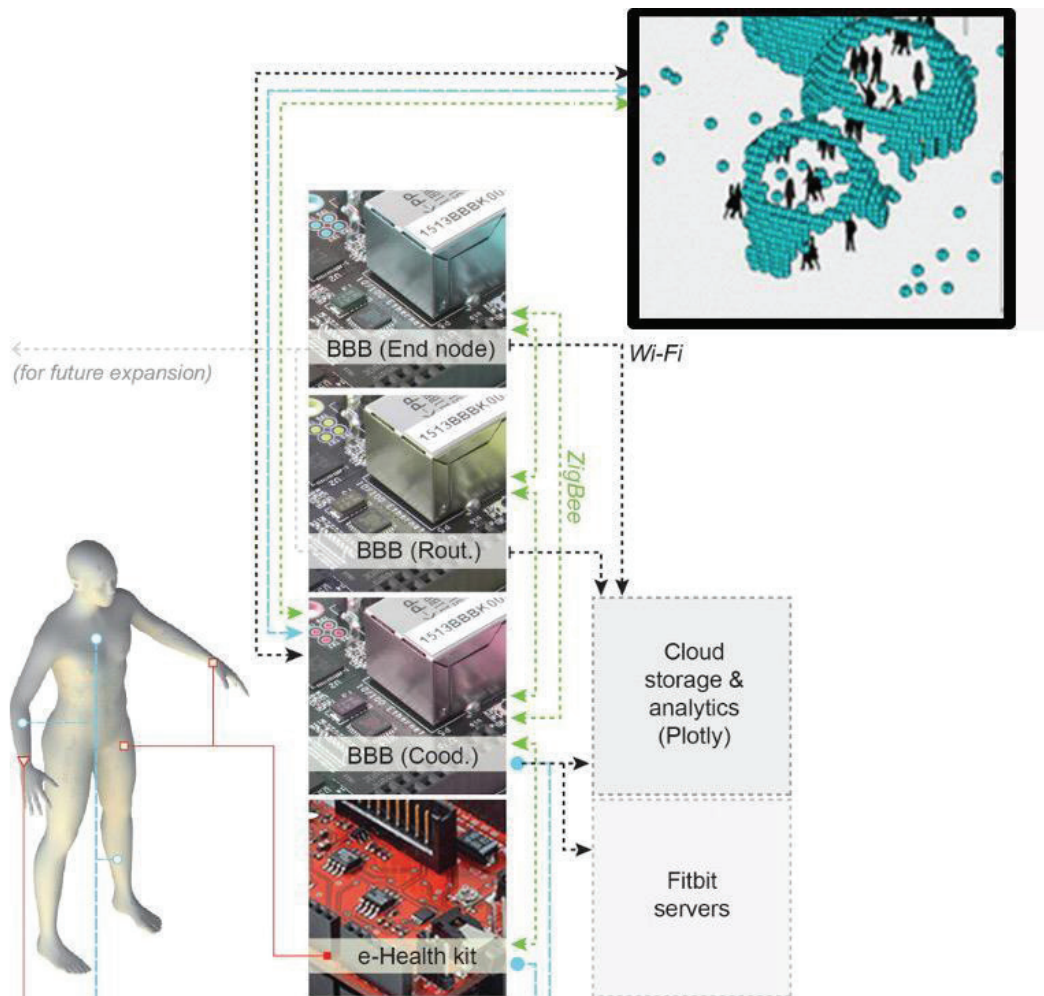


FIGURE 2 Bio-cyber-physical feedback loop established via AI supported WSN is detecting human needs and is actuating the swarm of drones accordingly.

Such spatial, informational, and relational aspects were considered in the Omnipresence project developed at TU Delft, wherein swarms of drones were introduced as means to guide visitors through a fictional world exhibit in Rotterdam (Fig. 1) as well as means to create temporary pavilions (Fig. 2 and 3) by anticipating potential activities and developing possible scenarios. The swarm of drones was then designed to respond to such scenarios by integrating cyber-physical features that would allow the swarm to operate semi-autonomously.

## Cyber-physically Enhanced Spaces

Designing interactive spaces where the built environment is enhanced cyber-physically implies thinking about architectural design in a different manner. Rather than designing for a range of functionalities the focus is on designing for human activities. This entails anticipating possible activities (the what, how and why for them) and designing dynamic responses accordingly. In this context, the development of multiple scenarios supports decision-making. The mapping of activities that might take place helps identifying most desirable scenarios the design should enable, as well as the possible problematic non-desirable scenarios the design should avoid.

Such cyber-physically enhanced spaces imply designing on the interface between Artificial Intelligence (AI), Wireless Sensor-Actuator Networks (WSAN) and architecture (Bier et al. 2018). The design calls upon definitions of AI that support computational as well as physical operation of the system.



FIGURE 3 Aggregation of drones for building temporary pavilions as adaptive systems.

## AI for CPSs

Even though AI has been developed for decades now (McCorduck et al., 1977), only in the recent years it has started to emerge as a significant new technology promising to have a large impact in diverse application fields in the industry, where the questions is not anymore if it will be implemented across industries but rather how it should be adopted efficiently (Brown, 2019; Ghosh et al., 2019). AI is embodied in many diverse forms, with capabilities that mimic cognitive functions such as learning and problem solving (Russell & Norvig, 2016). The design of the embodiment of AI has been explored in user experience (UX) and user interaction (UI) design, where the hardware of the system is tackled through product and spatial design, while the system values and performances are addressed through service and speculative design. In this context, various forms of AI may be combined. For instance, Swarm Intelligence (SI) targeted in the Omnipresence project for the autonomous flying of drones may improve in time through Machine Learning (ML), as a form of AI that improves automatically through experience and learning in time. Such AI forms are the backbone for user interaction flows within Aml and adaptive systems in architecture (Fig. 3). They rely on WSAN embedded into the physical environment.



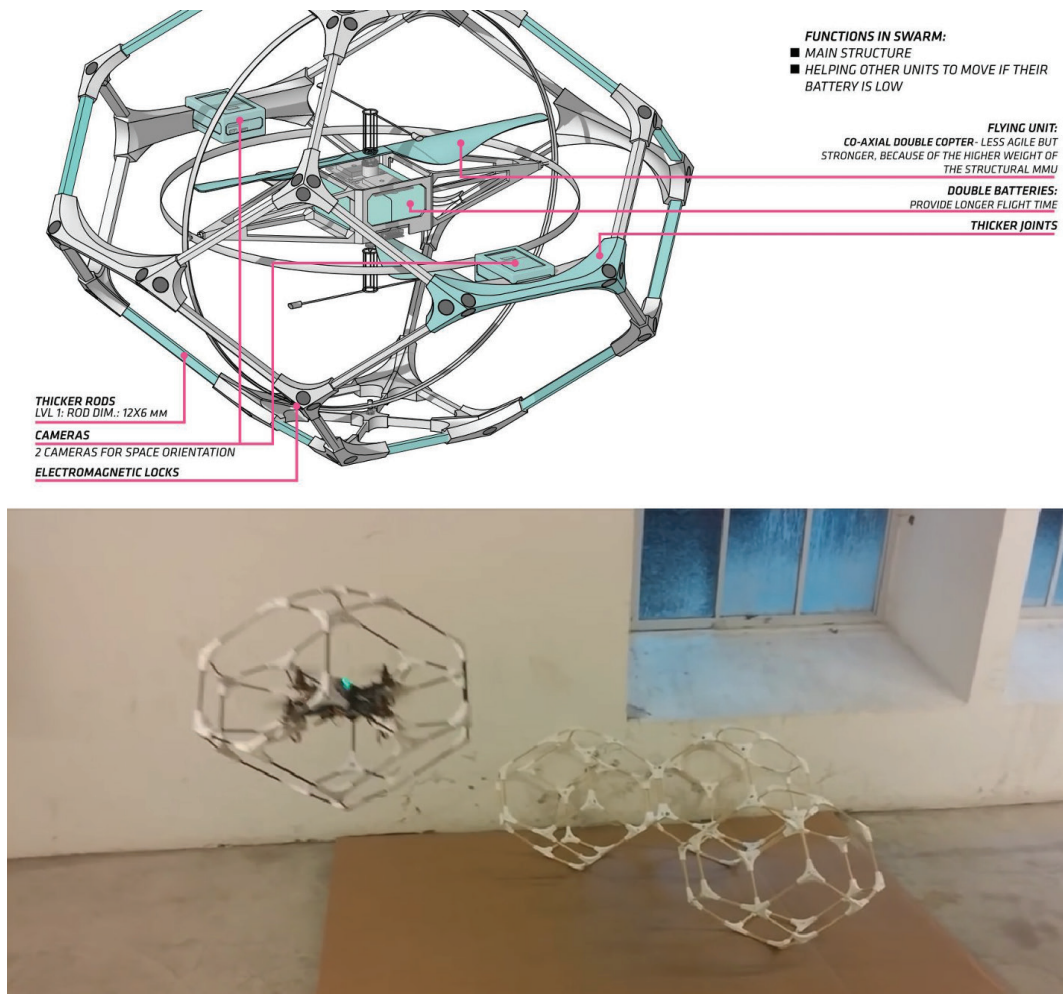


FIGURE 4 Drones design and testing of drones' aggregation of the Omnipresence project developed at TU Delft

## WSAN

WSAN are spatially dispersed and wirelessly networked sensors (for monitoring the physical environment) and actuators (such as servo motors for implementing various tasks) controlled by computer-based algorithms, which in this case are AI algorithms. The WSAN is embedded into the built environment, which facilitates tangible interactions and activity flows. In the Omnipresence project the WSAN is distributed in the drones (Fig. 2 and 3) and together with AI is detecting human needs for guidance or shelter and is actuating the swarm of drones accordingly. When designing such WSANs, the main challenge is to anticipate human activities, and plan for the responses of the interactive system.

An implicit Ambient UX approach for the design of cyber-physically enhanced built environments was employed in the development of the reconfigurable pavilions (Fig. 1-3). The temporary structures were emerging as aggregations of drones (Fig. 3) and demonstrated the potential of this technology for architectural purposes while responding to needs of dynamic reconfiguration. The drones act as a coordinated swarm communicating with each other and aware of the environment thus avoiding collisions and forming domes that shelter temporarily visitors of a fictive world expo in Rotterdam (Fig. 3).

After various activities were considered and several configurations were simulated, the aggregation of four drones was tested by building 1:1 prototypes (Fig. 4). The coordinated flight and aggregation behaviour was intended to rely on swarm intelligence (SI), which is the collective behaviour of (natural or) artificial self-organized systems and is a form of AI. SI systems consist typically of a population of simple agents, in this case drones, interacting with one another and with their environment. The agents interact locally following simple rules such as separation, alignment, and cohesion (Corne et al., 2012) leading to the emergence of intelligent global behaviour, which in this case manifests itself as domes. Specific flocking rules allow them to aggregate into domes by following structural requirements: As soon as a first row is in place, the second row and the next ones follow until the aggregation is complete. The SI relies on WSAAN involving spatially dispersed and dedicated sensors for monitoring the physical conditions of the environment and the people. The goal is that on request or self-initiated drone swarms create temporary shelters protecting people from sun or rain. This is implemented by SI allowing the drones to flock, on top of which ML is introduced to facilitate learning in time from the environment and users. While all these principles were considered, simulation, prototyping and testing has remained at proof of concept level.

## **Conclusion**

The presented paper highlights the challenges and opportunities of cyber-physically enhanced architecture. It discusses the design of such architecture involving inter al. consideration of DD, UX and UI, AI, and WSAAN requirements, which not only involve anticipation (by mapping activities) but also learning. If SI works with data collected within a short period of time, ML employs data collected from users and environment over a longer period of time in order to learn to respond to users' needs by establishing a bio-cyber-physical feedback. Such feedback involves AI ranging from basic intelligence level operating with if-then-else constructs to high levels of 'emotional intelligence', supported by learning processes that are tailoring actuation according to users' needs. While such feedback links the human with the cyber-physical space, the question of how to design an embodiment of intelligence that is human-like or if it should be human-like in the first place requires further definition.

While the case studies presented in the paper illustrate the potentials and the challenges of CPSs, Ambient UX and the framework proposed in the paper offer a conceptual reference for the definition of design methodologies for their design.

## **Acknowledgements**

This paper has profited from the input of TUD students and researchers involved in the described projects.



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