Designing smart product-service systems for smart cities with 5G technology: the Polaris case study

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Abstract

This paper explores the issue of the role of design and digital prototyping in the development of product-service systems in the smart cities, particularly concerning the spread of wireless connectivity technologies such as 5G and their use for innovative orientation and displacement purposes in urban contexts.

The first part of the paper reviews the technical and scientific literature to recount the main technological developments in smart cities with particular attention to the introduction of 5G to navigation systems. The second part analyzes a short collection of use cases to build smart systems for navigating, guiding, and orienting people in complex spaces. The collection and analysis of the cases help to identify the role of design (in the development of product-service systems for smart cities. The third part recounts Polaris, an interdisciplinary project involving design and computer science to develop an indoor navigation system designed for a smart university campus and smart cities. The project aims to realize tangible outputs that demonstrate the great potential offered by 5G, an intangible technology, which needs appropriate communication to future users. To do this, an advanced product/service has been designed, developed, and implemented capable of fitting into citizens' living spaces and environments, adapting, and supporting the end users who "inhabit" them. The conclusions present a critical discussion on the opportunities and limitations encountered when the design is faced with the conception and implementation of project outputs to foster the acceptance of technology.

Keywords

5G Technology; Smart Cities; Smart Direction; Internet of Things; Prototyping; Digital Fabrication

Introduction

Old-world cities are urban conglomerates, resulting from the stratification over time of cultures and inhabiting structures of various types and natures. Over time, the general needs have changed, evolved, and reconfigured, but only since the last century, at the end of the great world conflicts and thanks to the spread of large-scale self-aware medicalization, the implementation of security systems, and the creation of social, artistic, and cultural networks (Li et al., 2016), it's unimaginable that there should be large empty spaces to be designed and built from scratch to respond to the new modern demands. An estimated 70 percent of the global population would be urbanized by 2050 (Lierow, 2014); a percentage that rises to 80 percent when considering just the European scale, which faces a prediction that 97 percent of buildings will have to undergo extraordinary maintenance or heavy renovation within the next 30 years (Beson et al., 2020). A transformation of this magnitude can be supported by the Internet of Things (IoT), which allows us to modify and transform the way we interact with our surroundings. Through the appropriate use of IoT, indoor and private spaces in homes already have acquired *smart* characteristics due to a multitude of small, low-cost, connected computing devices that can detect, process and report environmental data to cloud/internet services. However, this enabling dimension offered by technology (meant in its more confined digital dimension) when scaled in the urban dimension, clashes with a reality oversaturated by buildings and infrastructure built according to logics no longer in line with the needs of the present and even less with the ones aimed at for a more sustainable future. Hence the need to create demonstrators of possible smart solutions for Smart Cities, which are places where traditional networks and services are made more efficient with the use of digital solutions for the benefit of its inhabitants and business (European Commission, 2023).

Smart Direction in a Smart Campus

University campuses can offer a functional response to this kind of need, as they appear to be of particular interest for simulating and testing the effectiveness of projects aimed at scaling in Smart Cities (Min-Allah & Alrashed, 2020). Indeed, university campuses imitate cities in many ways: they generally extend over a large urban area, are composed of many different types of buildings (administrative buildings, laboratories, classrooms, residences, bars/restaurants) and populated by different types of people/users (Longo et al., 2021). At the same time, they turn out to be more controllable and manageable places at the level of actors involved and from the point of view of readiness for technology adoption, even when not fully mature. For this reason, recent studies and test-level applications have already been carried out to transform these places into Smart Campuses, particularly with: smart parking systems (Mohandes et al., 2019; Nagowah et al, 2019), microgrids (Alrashed, 2020), smart libraries (Antevski et al., 2016; Chan & Chan, 2018), classroom monitoring and occupancy estimation systems (Longo et al., 2020; Tse et al., 2021), and other sustainable solutions (Villegas-Ch et al., 2019; Ceccarini et al., 2021). To infuse these places with intelligence, it isn't enough to equip them with advanced technology, but it is necessary to develop a meaningful design around its use. This is where the service dimension plays a crucial role, not least in making the technology usable (Brettle et al., 2020), because the more it evolves and becomes performant, the less comprehensible it is if not linked to concrete and tangible results that demonstrate its effectiveness. This is especially relevant when it comes to 5G technology (Pujol et al., 2020), on which the main innovations in Smart Cities are expected to be based; however, its markedly intangible dimension makes 5G difficult to understand for the general public, which often sees it as an invisible enemy to be opposed. This widespread idea is difficult to eradicate, despite its lack of support from any scientific evidence, which on the contrary fights to prove exactly the opposite with analyses and reports commissioned by the governments (Camera dei Deputati, 2020). In particular, in the Italian landscape, evidence-based arguments do not turn out to be effective, where a large segment of the population (and therefore of the potential 5G users) does not place trust in this type of narrative stage. Thus, the demonstration of possible applications of 5G, through *use cases* of related services and products, assumes a relevant role in promoting faster and more functional technological development, as well as in countering the latest social resistance to this technology.

In this framework comes the Polaris project, developed by Polifactory and AntLab at Politecnico di Milano, which aims to propose an indoor navigation system capable of guiding users within complex buildings and structures, orienting them in horizontal and vertical movements in search of spaces located in different areas or levels. Polaris is the result of collaborative and interdisciplinary work, in which researchers with expertise in Design and Electronic and Information Engineering worked in synergy to create an efficient and functioning solution both at the level of system architecture and from the perspective of user interaction. The phases of conception, development, prototyping and verification, presented in the following sections, offered relevant insights identified in the final conclusions.

Smart Direction case studies toward bounding project requirements

This part presents the qualitative analysis of case studies as a strategy for State-of-the-art mapping and is used to support the designing part of the final solution. The case study method enabled the identification of "the "what" is being observed and the "how" it is being detected and the reasons why, in order to understand the role of design in the development of product-service systems for Smart Cities (Cohen, 2015). For their identification, desk research was conducted in order to collect tested product solutions or prototypes for navigation in the city. All projects stuck at the concept stage were not considered because the parameter of technical feasibility was given priority. The result are six case studies of projects that share a digital or service dimension, and sometimes have proprietary hardware that is functional in optimizing the use of the entire system. A summary of the six selected projects can be seen in Figure 1.

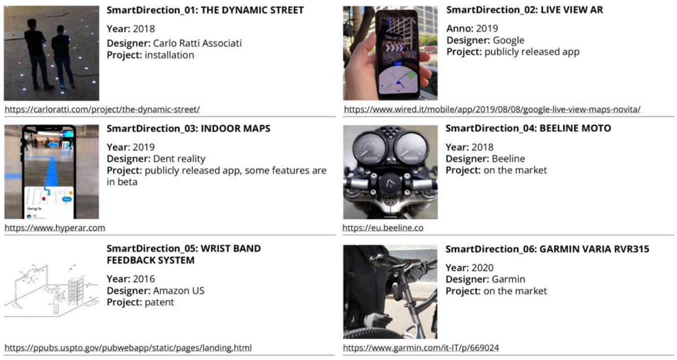

Figure 1. Chart summarizing information about the six case studies investigated.

More in detail, the first case is Dynamic Street (01), a signaling pavement made of hexagonal modules, equipped with light actuators. The grid modules can take different configurations and also host a plug and play element, i.e., a vertical structure equipped with accessory functions. This is an innovative project that, starting with a static non-wearable element, allows the spatial rearrangement. However, the lack of smart elements for transmitting and receiving data, does not allow the individual user to set customized paths to reach a specific touchpoint. The second example deals with the implementation through augmented reality of the Google Maps app (02) for outdoor walking navigation. To take advantage of this functionality, the user needs a smartphone compatible with Google's ARKit and ARCore, through which the association of the real environment with the digital one previously scanned by a Google Car takes place. The project is very interesting, especially in terms of reaching a touchpoint, but at the same time it has limitations in use because it only works outdoors and requires constant use of the smartphone with the camera on, which results in high battery consumption. Indoor Map (03), the third case study, enables the creation of detailed interactive and customized maps of interiors of public-use buildings to help visitors locate and reach points of interest. The interesting aspect revolves around the proprietary software that makes it possible to build a new map by following a few simple instructions, without the need for intervention by specialized technicians. Unlike the previous one, this case study works only in indoor environments; moreover, it works only after the user sets an itinerary. Beeline (04) is a navigation device for cyclists and motorcyclists, which displays a kind of compass that points to the destination previously set via a paired smartphone. While this solution promotes immediate directional readability, it doesn't optimize the navigation route, which in any case cannot be changed except via smartphone. The patent filed (05) by Amazon of a wearable device for identifying items inside the multinational corporation's warehouses is the fifth case study. Through haptic feedback, this solution lets the workers know if they are pointing their hand to the correct stall. The interesting aspect of this system is that it uses a series of sensors located in the warehouse to locate the picker, who can move without consulting a screen and thus have maximum prehensility. The latest example is Garmin Varia (06), which is a bicycle radar that can signal the rear approach of vehicles from 200 meters away. The product also has a function for group pedaling, in which it bypasses the presence of other cyclists in its slipstream. This last example is interesting because it combines spatial feedback with the promotion of road safety.

Case study observations

The presented navigation systems are structured through three different needs, sometimes in combination: reaching a point, exploring an area or avoiding something. Remarkably, in terms of connectivity, none of the selected cases employ 5G technology, which, however, could be implemented to increase system stability and reduce data transmission latency times. Therefore, 5G should be considered as a concrete possibility for the scalability of the analyzed projects, as well as a solid base on which to structure proposals for new solutions useful for indoor navigation. Thanks to the outcomes of this reconnaissance, it was possible to conceive, design, prototype and test an indoor navigation system based on the use of 5G technology with the goal of simultaneously guiding multiple users to a customized touchpoint (unlike the 01 case), without the constant use of their smartphones (02 & 03 cases) as well as other personal (04 & 06) or corporate (05) devices.

Polaris: the Smart Direction System

Using the insights gathered from this reconnaissance, the Polaris indoor navigation system was designed and fabricated at Politecnico di Milano throughout "Base 5G" project, and then installed and tested on its Leonardo Campus, in order to provide a tangible demonstration of an intangible technology (Capdevila & Zarlenga, 2015). Polaris makes it possible to guide users within complex structures by orienting them in horizontal and vertical movements to search for spaces located in different areas or levels. This is possible thanks to a system consisting of a series of devices placed in the environment, the anchor nodes, capable of locating users as they move through the location. Such devices communicate via 5G technology with a control center that implements machine learning algorithms to continuously track users and, based on the users' location, controls beacons that guide them to their final destination. These beacons of light, the effector nodes, are also connected to the control center via 5G technology. Researchers from the area of Design and the area of Electrical and Information Engineering collaborated among themselves in the creation of the entire system, realizing: the logic at the control center, the technological infrastructure of the array devices (anchor and effector nodes), the study of their design according to versatility in different installation environments, the production by additive manufacturing of the necessary components, and the subsequent assembly.

Polaris system operation

Polaris is made up by a series of IoT devices spread throughout the indoor space interconnected through 5G technology. After an initialization phase in which the user signs in to the smart direction service, the system locates and tracks the user's position in indoor spaces through anchor nodes and returns navigation information to him/her through light indicators placed in the environment (effector nodes); hence, the person can be guided to his/her final destination without having to continuously observe a map on the smartphone. The anchor nodes operate through Raspberry PI4 equipped with BLE and WiFi communication interfaces to enable location and tracking of the user on the move. They scan Bluetooth Low Energy beacons sent by the user application, send messages to the control center through the communication system regarding the current location of the user(s). The effector nodes are composed of Raspberry PI0 and LED arrays, displaying navigation directions for users on the move. They receive commands from the control center to activate/deactivate the LED interfaces, on which specific indications are generated and recognizable by each user. The nodes are connected via WiFi technology with 5G CPEs. The 5G CPEs leverage 5G connectivity to connect the field network (anchors and effectors) with the control center. The control center receives messages from the anchor nodes notifying the current location of the users to be tracked, calculates the location of the users, works out the best path for each user based on his or her final destination and other context information, then commands the turn on/off of the effectors.

The service design part of Polaris

The architecture of the Polaris communication system is realized through a modular product to be placed in spaces, and an application through which to access the overall service. Polaris activation requires initialization through a user interface, which consists of an application installed on the personal smartphone.

The app allows users to register for the smart directions service by indicating their required destination and if needed other contextual information. The Polaris app can be integrated with the one for accessing university services (Figure) by then importing information from the associated database (calendars, exams, student/faculty profile, academic platform, floor plan of classrooms and common spaces, etc.) to which it then adds the smart indoor navigation system. The app allows the user to select his or her destination through three search modes: a *default* search (the user knows his or her destination), an *automatic* search (the user has an event saved on his/her calendar scheduled at a certain location), and finally a *suggested* search (when the user is looking for a particular type of service along the way).

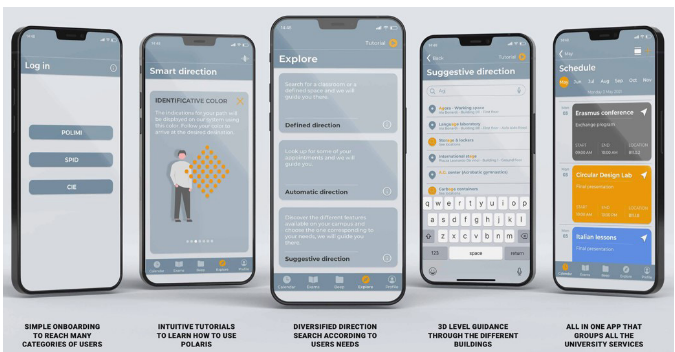

Figure 2. Some screenshots from Polaris' Smart Direction app.

The product design part of Polaris

As mentioned before, the hardware part of Polaris consists on a modular product to be installed within the spaces to be navigated. The final design of the installed object (Figure 3) was designed for maximum flexibility and adaptability to very different spaces as well. Indeed, instead of making different objects for the anchor and effector nodes, the choice was made to design a structure of interconnected tubulars via tetrapod-shaped hollow joints, at the ends of which to place and orient the number of anchors and effectors necessary for the system's operation. In this way, we designed a product capable of adapting to the different layouts of buildings, and of being able to be flexibly fixed according to the material and architectural constraints. Thus, the density and type of hardware nodes to be placed in the space can be optimized. All nodes are designed to allow maximum accessibility to internal electronic components for updating and maintenance. The use of interconnected tubular elements to make up the entire system occurred to facilitate the wiring of all elements and can be sized in length to suit specific space needs. The usage choice of a connection via tetrapod joints was guided by the need to be able to provide directions both in architectural interiors with orthogonal grids and with more organic layouts. Attachment of the structure can be to ceiling, wall, stand/ground, and in all cases by means of screws/dowels or clamps, depending on the characteristics of the support and whether or not irreversible action can be taken on it.

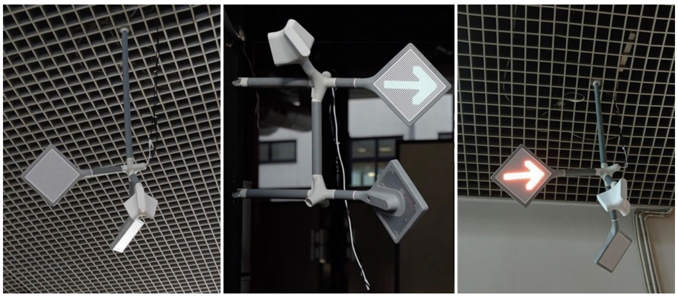

Figure 3. Polaris installed and tested at Building 11 of the Politecnico di Milano, Campus Leonardo, covering an indoor area of about 500 square meters on two floors.

All of these design choices were made with the clear goal in mind of making a working prototype through the technologies available in the university makerspace. Therefore, the product development phase was made by relying on the constraints of FDM and SLS 3D printing and laser cutting technologies. The design aspect, however, was developed to make the product also manufacturable by more traditional manufacturing technologies, such as injection molding, to facilitate the possible industrial scalability.

Figure 4. Polaris' prototyping phase.

The content of the pop-up indication on the LED matrix was also the subject of design, to ensure good readability of information, taking into account multi-user. The control center, recognizes the number of users searching for a different destination simultaneously and, thanks to machine learning, assigns a different color or symbol to each user upon login.

Conclusion

This project was positively evaluated by the grant committee as being able to comprehensively address and solve the challenges of both implementing a new technology in a working prototype and managing simultaneous multi-user navigation with a product/service that doesn't force users to use advanced information through a smartphone screen. During this experimentation, it was possible to see how, in the development of technologically advanced devices, a design-driven approach takes a central role due to the designer's ability to manage complexity and become an interpreter and translator of languages and processes. An advanced system architecture has taken a flexible and functional form to the needs of different indoor spaces and especially the users with whom it interacts. The developed service and app put usability at the center, as a technology must be immediately understandable and able to respond to user needs effectively through interactions that avoid slowing down people's lives in order to be accepted (Arthur, 2009). Hence, we can state that the outcomes of this challenge have shown how important is that the designers be recognized as a possible enabler of techno-innovation due to their distinctive interpretive ability and sensitivity.

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