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Towards embedding high-resolution intelligence into the built environment

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Abstract

Prevailing architectural design paradigms, identified as those informed by historically conservative positions and methods, are incompatible with the intelligent built-environment discourse. Two core considerations inform this assessment. The first asserts that such paradigms produce spaces and programmatic distributions in terms of discrete, precisely delimited, and artificially ordered static partitions. The second asserts that said paradigms preclude (at best) or exclude (at worst) discussions of technological intelligence from the early stages of the design process, thereby negating the possibility of imbuing the built-environment with inherent intelligence. The rigidity expressed in the first consideration, and the disregard for technological intelligence expressed in the second, produce very low-resolution and -adaptability architectures. As a result, occupants are compelled to conform to their built-environment rather than the expected vice versa, as it is fundamentally incapable of actively, reactively, and interactively promoting their well-being. In this paper, two key positions (i.e., high resolution space and high resolution intelligence) motivated by the above considerations are promoted as part of a fundamentally different design paradigm, one expressly geared towards personalization, interaction, and intelligence in a parametrically fluid and self-adapting built-environment capable of intuitive physical, spatial, and computational feedback-loops

Keywords

Robotically Augmented Environments; Cyber-Physical Systems; Wireless Sensor Networks; Interactive Architecture; Ambient Intelligence.

Introduction

Prevailing architectural design paradigms and their corresponding construction and fabrication methods subsume a historically and technically identifiable set of theoretical and technological positions that invariably produce buildings and structures with fundamentally similar shape grammars and typologies (e.g., standardized building blocks, prescriptive structural hierarchies, and clearly defined and delimited walls, floors, ceilings, etc.). These, in turn, yield as well as entail fundamentally similar spatial configurations and physical limitations that impose artificial static frameworks upon dynamic occupants, forcing the latter to conform to the former. Such paradigms and their resulting forms and spaces may have been, in their due time and in one expression or another, justified standard means of conceptualizing and realizing inhabited spaces. With the advent of the Information Age, however, the promise of new kinds of *soft* services as well as hybrid technologies consisting of both *hard* mechanical parts complemented or even driven by *soft* computational systems render such conforming unnecessary and indeed unjustifiable.

The feasibility of embedded *intelligence* in the built-environment is a relatively recent development. Although visions of such have been present for longer (see Cook, 1970, 1972; Eastman, 1972; Negroponte, 1969, 1975; Pask, 1975a, 1975b), it has not been until recently that the supporting components required to sustain the entailed systems and services have reached a level of reliable and affordable maturity—this is a necessary precondition for the present discourse, as no technologies (may these be tangible products or intangible processes) can flourish without a robust framework based on mutually complementary systems and/or services (both technical and market-oriented) to support them (Milgrom, 1990). It was at the end of the 20th century and the beginning of the 21st that robotically or otherwise enabled intelligent environments became demonstrably and functionally real—for example, *The Aware Home* (Kidd et al., 1999), *RoboticRoom* (Sato et al., 2004), *Wabot-House* (Sugano et al., 2006), etc. Such solutions, in conjunction with other similar yet experimental *proof-of-concept* implementations in practice and academia (for example, Fox and Kemp, 2009; Oosterhuis, 2003, 2011, 2012; Oosterhuis and Bier, 2013)—sometimes emphasizing material or formal, i.e., geometrical, intelligence over computational and vice versa—demonstrated that built-environments could express elementary forms of agency and intelligence in order to engage its users physically and informationally. This saw the proliferation of *Interactive Architecture* (IA) and *Ambient Intelligence* (Aml) from trends and tendencies to established discourse.

But there remains no corresponding proliferation of IA and Aml projects in industry. This is due to several factors such as: (1) costs typically associated with intelligent services (Andò et al., 2014; Wichert et al., 2012) and (2) with corresponding late-stage design consolidation of said services and their corresponding production (Isack and Gibb, 2003; Tam et al., 2007), as well as (3) innovation-hindering conservatism from the *Architecture*, *Engineering*, and *Construction* industries (Bock and Linner, 2015). Note that these factors are consequences of a mentality that hoists outdated methodologies upon innovative concepts. For example, costs corresponding to the *post hoc* installation of intelligent services in a conventional environment are admittedly high due to retrofitting—a reality that would be unnecessary if the consideration of said services had been conceived and conceptualized early in the design process. Similarly, the late-stage design of such services and their production cannot be conceived with a bottom-up approach, since the architecture in which these services are to be installed and deployed already prescribe limitations in size, scale, and scope. So service components are not necessarily produced with efficiency in mind, but with custom cohesion and compatibility restrictions, which increase costs—again, something that could be avoided via more appropriate early-stage design considerations.

In the last decade there has been an increase in the availability and accessibility of cost-effective intelligence-enabling technologies (Baronti et al., 2007)—robotic and otherwise—and their corresponding optimized fabrication methods (Bier, 2014; Bock and Linner, 2015; McGee and Ponce de Leon, 2014; Menges, 2015). By adopting a high-resolution paradigm prescriptive of early-stage design methodologies that subsume fundamental and analytical intelligence considerations, the detracting factors mentioned above may be mitigated or altogether avoided. For example, a number of recent Aml projects developed under a more progressive paradigm demonstrated that intelligent services—both in terms of architecture and of computation—may be implemented successfully and affordably (see, for example, Guettler, J., Linner, T., Georgoulas, C., and Bock, T., 2015; Linner et al., 2015; Liu Cheng et al., 2015) via Wireless Sensor Network (WSN) and Body Area Network (BAN) technologies. Moreover, early-stage design consolidation of intelligent services in conjunction with robotically driven production (Bier, 2014), which takes into account the fundamental changes in the structure and infrastructure of the architecture that must be adopted in order to enable robotic environments suitable for ubiquitous systems and service robots (Bier, 2011; Forlizzi and DiSalvo, 2006; Linner et al., 2015), have instigated considerable cost reductions (Bock and Linner, 2015).

The present discussion of high-resolution built-environments does not intend to prescribe an exhaustive list of identifying desiderata. Instead, it is limited to promoting two core characteristics that conform, in part, the common core characteristics of high-resolution strategies in general. These characteristics resolve the two identified disadvantages of prevailing architectural design paradigms—i.e., the predilection towards discreet and artificial spatial distribution that forces users to conform to static physical and spatial conditions as well as to the lack of fundamental intelligence. For detailed discussions of partial and/or full implementations of the positions promoted below, see Liu Cheng et al., 2015, 2016; Liu Cheng and Bier, 2016.

High-resolution Space

High-resolution built-environments conceive physical form as well as programmatic space as continuous and parametrically modifiable—both physically, spatially, and computationally—with respect to the physical behaviors and sensorial conditions of its occupants. Such environments may be most appropriately characterized as unified robotic systems with differentiated yet mutually supporting and complementing components, which mirrors Zappe's suggestion that robots may be viewed as scaled models of large-scale mobile buildings capable of changing their forms (2012) and—in the present case—functions. In order to conceptualize such fluidity of form and function, programmatic needs and user-requirements must be carefully analyzed and catalogued with respect to user-behavior across location and time. The resulting formal and spatial grammar would be a *de facto* dictionary of fuzzy typologies that correlate the occupant's physical and sensorial activities with geometrical and spatial transformations and function across time. Having done this, resulting programmatic spaces flow, merge, and ebb from and into one another, and complementing furnishings appear from and disappear into ambiguously identified floors, walls, and ceilings, depending on the presence or absence of its occupants as well as their necessities with respect to particular programs at specific moments in time.

In such environments, architectural systems, by virtue of their differentiated geometries and fuzzy typologies as well as supported by computational resources, become highly adaptable and transformable components that activate particular programs and services based on careful analysis of user-behavior over time via specific activation patterns. Consequently, a variety of programs may be instantiated in the same space, or a complementary overlap may be effectuated to suit user-needs. Furthermore, as the occupants and the habitat learn from and adapt to one another over time, the

built-environment develops a particular agency and non-deterministic behavior—Sanchez points out that a reactive approach is less interesting than a behavioral approach, where architectural elements could express their own ‘attitude’ to environmental stimuli (2014).

In this manner, the relationship between architectural form and space and the user becomes intuitively intimate, decreasing the extent and degree of the negotiating medium or buffer between occupant and habitat. In this environment, architectural form (both positive and negative) and function would be engaged in a perpetual dynamic *dance* with the occupant, enhancing and capitalizing on the fact that architecture informs the way we move within a space—indeed, the formal language of a space could be interpreted as a script, a choreography for the body (Wortelkamp, 2012). According to Wortelkamp, dance transforms architectural space into movement, which consequently shapes and forms it (2012), making transitions throughout space feel as a natural extension of the body. As Schumacher pointed out, movement is characterized by a variety of acceleration and deceleration rates in displacing from one stationary condition to another, which entails that precisely and evenly defined sudden start-and-stop movements—implicitly involved in crossing imaginary programmatic boundaries under prevailing design paradigms—are unnatural (2012).

The systems subsumed by high-resolution built-environments would effortlessly facilitate an immediate and intimate version of what Oosterhuis has described as a *Society of Home*, where human and non-human objects / products endowed with a fair degree of sophisticated intelligence will communicate with one another, thereby instantiating a home of *Internet of Things and People*; as well as a *Society of Building Components*, where the environment’s components act and react informationally (i.e., exchange data) and physically (i.e., change shapes) towards one another and towards the users (2014).

High-resolution Intelligence

This high-resolution built-environment’s intelligence would supervene on WSNs, which are specialized autonomous sensors and actuators grouped (1) to monitor and/or to control environmental and physical conditions, and (2) to transmit the corresponding data to a base station and/or hand-over control to a specific actuator in the network (Yang, 2014; Yang and Cao, 2008). Data analysis and computation may be undertaken by one or more of the network nodes or by Internet-based analytics services, depending on data-volume, network scale, and service requirements. Since WSNs are decentralized solutions, they avoid the high-costs generally associated with highly integrated and centralized systems. Georgoulas et al. (2012) showed that a solution that seeks to reduce complexity of functions and cost should be one that does not have all services and functions centralized in a service robot or in a static location, but rather one that strategically distributes services along a decentralized and distributed controlled environment. These considerations also make WSNs particularly promising as enablers of intelligence, as distributed computing has been identified as a key foundation for applications and technologies involved in interactive architecture (Dulman, 2014), which is a principal reason why WSN technologies are currently used for the development of distributed and networked interactive environments and architectures that progressively converge physical and virtual space (Bier, 2012). In addition WSNs, which gather data from the user indirectly, BANs—a subset of WSNs that emerged in the last decade (see González-Valenzuela et al., 2013; Ruiz and Shimamoto, 2006)—would gather data directly, which makes them ideal for ambulatory monitoring solutions. With the combination of both indirect and direct user-observation, the intelligent system deployed as part of a fundamentally and analytically IA and Aml would be able to generate a higher-resolution profile for the user(s), which would increase learning fidelity and response accuracy. Furthermore, WSN nodes would be the primary source for interior / exterior environmental data, while BANs would be the primary source for user data. The IA/Aml system would be able to use this data difference to better understand the status of the user with respect to the interior / exterior environment and vice versa.

High-resolution built-environments are equipped with varying degrees of intelligence, ranging from computationally sophisticated physical and/or sensorial services based on heuristic decision-making processes to simple and reflexively reactionary ones (see figure 1). For example, a basic lighting

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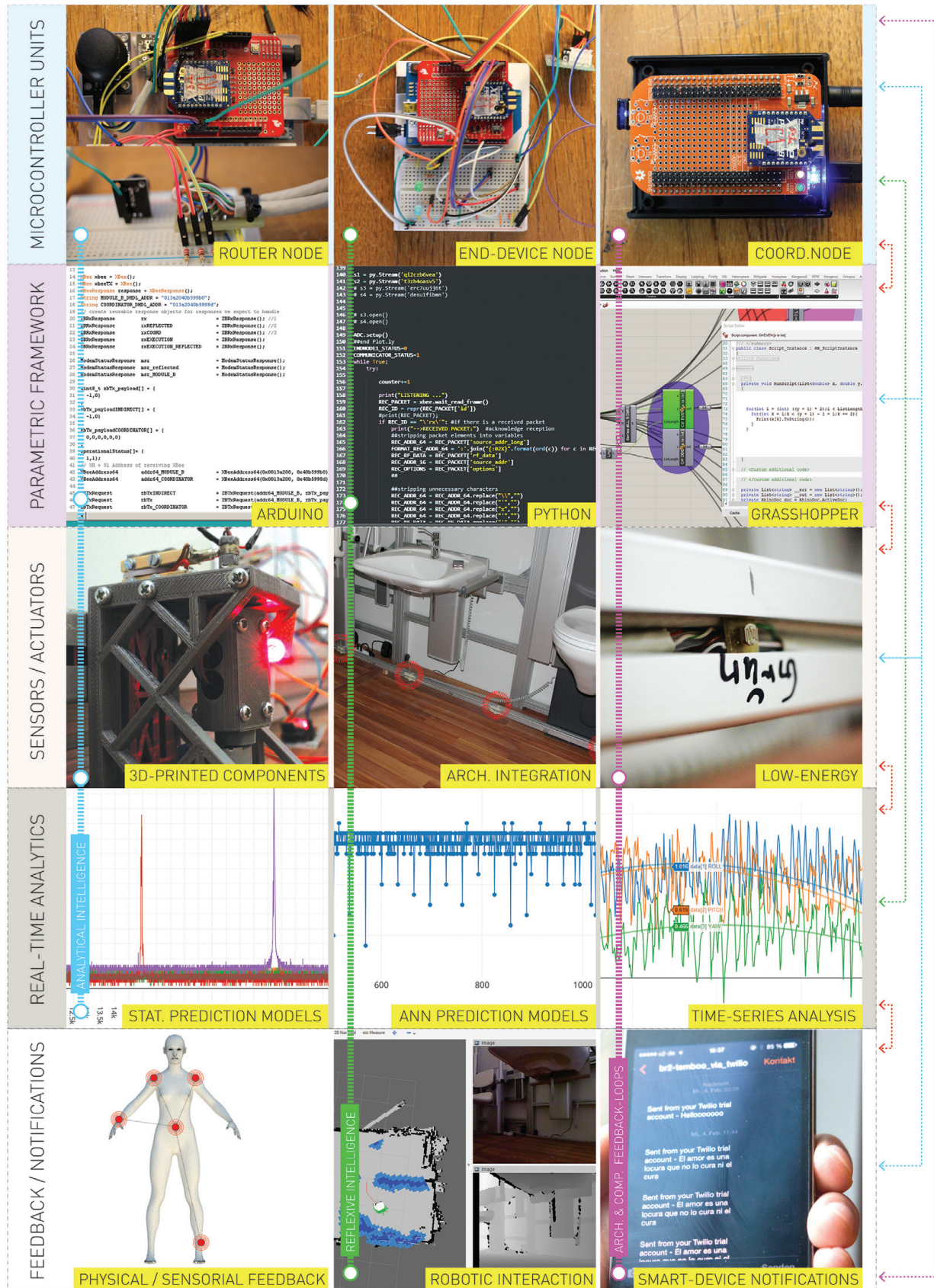


Figure 1.

A high-resolution intelligent built-environment's systems architecture. The general execution sequence is to be read top-down. However, due to its closed-loop character, routines may beckon one another without predetermined sequence.

system that activates when the environment's perceived lumens reach below a certain threshold may be considered *reflexively intelligent*, as it is driven by a simple *if-then* decision-making mechanism. We may contrast this with a highly sophisticated system that employs multi-layered, multi-dimensional, and heterogeneous mechanisms to recognize the mood of its occupant(s). Such a system could gather, for example, time series datasets on body-temperature, breathing and heart rates, blood-pressure, acceleration and spatial displacement patterns, volume and tone of voice, etc., and consider them against both a general pre-determined mood-categorizations baseline as well as the user's particular previously recorded datasets in a variety of contexts to ascertain correlations and probabilities associated with a variety of mood-profiles. Over time, and via Artificial Neural Networks (ANN), the system would learn to distinguish exhilaration from anger, even though both emotions are associated with elevated temperature and heart-rates, sudden and often erratic spatial displacement, etc., based on something as personal and subtle as the user's speech inflections.¹ During the initial stages of operation there would be frequent instances of inaccuracies. But the character of a self-learning system—assuming that the particular ANN model employed is appropriate to the learning task at hand²—is such that it becomes more accurate over time, learning from its own inaccuracies to approximate a high-resolution user-profile. The built-environment would thus be able to identify negative emotions and to attempt to mitigate their short- and long-term effects via sensorial stimulation by, for example, reconfiguring spaces to enhance particular spatial qualities and environmental conditions; or by regulating lighting and ventilation conditions to instantiate a perceptibly more tranquil atmosphere, and so on. Treur et al. have demonstrated via a computational model that strategic and targeted emotion regulation may mitigate depression in unstable people as well as mitigate the onset of depression in highly unstable people (2014). Accordingly, it would be pertinent for high-resolution solutions to integrate categorically similar preemptive strategies into their environments.

The built-environment's architecture would instantiate *spatial computing*, where computation and the local spatial properties become invariably entangled, and where distance, connectivity, and density become attributes that influence use of space (Dulman, 2014). In this architecture, intelligent systems would begin to infer and to correlate action to reaction (and vice versa), habit to phenomena (and vice versa), and to adapt accordingly, which is in line with Dulman's belief that such intelligent systems must be able to respond to change via self-adaptation, where the behavior of the system, and the way users interface and interact with them evolve over time (2014).

Conclusions

The scope of the present paper has been limited to discussing two core considerations of the high-resolution built-environment design paradigm. These, as well as other general high-resolution considerations, are motivated by the conviction that intelligent built-environments enhance the quality of user-experience within a space; and that they have the potential to promote the user's short- and long-term well-being. These considerations qualitatively and quantitatively contribute to an increase in quality of life. It may be argued against the first conviction that user-experience is by nature subjective, and that it may

1. For example, Malcangi (2015) has developed a biometric authentication system based on multiple ANN-models that is capable of identifying individual and distinct voiceprints. It may be conceivable that such a system—or an extension thereof—may be adapted to discriminate inflections, as it already factors a voice's *speed* and *stress*.

2. This is imperative. The indiscriminate application of ANN models to given tasks may not only result in inefficiency but also in an undesirable output.

be difficult to conceive of individually appealing high-resolution built-environments. It may be conceived, after all, that some will prefer their environments to remain static and unresponsive, even if such design paradigms can no longer be justified neither by functional nor economic considerations. However, the second conviction may prove more difficult to dismiss. According to Espinoza (2011), the *Organization for Economic Cooperation and Development* predicts that the health expenditure in the EU alone is expected to rise by 350% by the year 2050 compared to an economic expansion of only 180%. This reality alone serves to promote intelligent built-environments as potential promoters and extenders of health that would alleviate health-services from an unnecessarily premature burden.

Additionally, the thought of an environment replete with intelligent sensing-actuating devices with agency may seem chaotic, and indeed there is the risk that an interactive environment may be counterproductive if the user is bombarded by too many reacting systems at once. In such a scenario the user would become unnecessarily self-conscious of his/her actions triggering undesired ambiance reactions accidentally, which would compel the user to micromanage every feature in his/her environment, which may cause more problems than benefits (Jaskiewicz, 2014). This represents a challenge that cannot be overlooked, therefore, intelligent environments must be designed and implemented in such a way as to sustain a new kind of artificial ecosystem, where the environment's components are self-sustaining, and where their development, adaptation, and evolution occur in symbiosis with their corresponding users (Jaskiewicz, 2014). In such an ecosystem, interaction should be bi-directional, where the environment would not only react to a user's action, but where the user would react to the environment's action as well. Citing from Fox and Kemp (2009), Kolarevic points out that such systems do not merely 'react' but indeed 'interact' (2014) with an environment's variety of agents (human and robotic). The more a system and its user interact with each other, the more attuned to one another's agency, behavior, and corresponding effects.

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