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An Extended Ambient Intelligence Implementation for Enhanced Human-Space Interaction

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Abstract –

This paper proposes an extended *Ambient Intelligence* (AmI) solution that expresses intelligence with respect to both *Information and Communications Technologies* (ICTs) and spatial reconfiguration in the built-environment. With respect to the former, a solution based on a decentralized yet unified *Wireless Sensor Network* (WSN) is proposed. This is deployed across exterior, interior, and wearable domains, equipped with heterogeneous platforms across embedded and ambulant nodes, and open to a variety of proprietary and non-proprietary communication protocols. With respect to the latter, a corresponding functionally and physically reconfigurable built-environment pertinent to the Adaptive Architecture discourse is revisited. The ICTs component aims to demonstrate the advantages of a cohesive and interoperable heterogeneity distributed along local and web-based proprietary and non-proprietary services over a prevalent locally based homogeneity with respect to both development platforms and communication protocols in a WSN. The architectural component aims to demonstrate that a highly adaptive and transformable built-environment is better suited to complement and to sustain assistive as well as interventive services enabled by said WSN. As a unified solution, the proposal showcases that the merging of technological and architectural considerations in the design of an intelligent environment enables more intuitive solutions that actively adapt to, interact with, intervene on the user to promote comfort and well-being via computational as well as physical feedback-loops.

Keywords –

Ubiquitous Computing, Adaptive Architecture, Wireless Sensor Networks, Ambient Intelligence.

1 Introduction

Present *Ambient Intelligence* (AmI) solutions tend to be situated in discrete structured environments. The salient disadvantage of this tendency is that the functional scope of such solutions does not extend beyond their deployment domain, and can therefore neither extend their services to nor gather valuable physiological data from the user in his/her absence. This is particularly problematic to solutions with components that depend on aggregated human interaction (explicit and/or implicit) and/or physiological data to perform optimally. A brief overview of developing trends and themes in the AmI discourse—e.g., see [1]—is sufficient to suggest that a considerable segment of AmI-related solutions are developing with such considerations.

In order to extend the monitoring capabilities of a system, AmI solutions built on *Wireless Sensor Network*s (WSN) may integrate remote mobile sensor nodes to work in conjunction with local ones to ascertain uninterrupted monitoring [2]. While said remote sensors may be fundamentally developed as project-specific devices and from technologies similar to those employed within the local WSN, a more effective approach would be to render the AmI system interoperable with existing commercial products and solutions. Researchers and developers have typically favored technological homogeneity due to practical considerations, but such an approach limits the reach of the developed system, as no single standard supersedes all others in every aspect. Since some standards are more robust than others depending on particular tasks, heterogeneous solutions that capitalize on this distinction have an advantage over their homogeneous counterparts. However, interoperability among heterogeneous systems is an on-going challenge in the development of AmI solutions (see [3], for example). Researchers have noted that commercial equipment is often closed, making seamless integration with developing AmI systems unfeasible [2]. But in the last five years commercial manufacturers have acted on a vested interest in making their products interoperable with a variety of systems in order to broaden their market. As a result, proprietary *Application*

*Program Interface*s (APIs) have enabled the seamless integration of some commercial products with non-proprietary systems. The WSN discussed in this paper is heterogeneous not only with respect to devices but also to communication protocols, and it uses a proprietary API to extend its monitoring abilities to ascertain uninterrupted operation.

In conjunction with technological considerations, another imperative yet generally overlooked consideration pertains to the built-environment within which said WSN is to be deployed. Conventional models tend to labor on a retrofitting strategy, where new services and technologies are made to work within a setting whose built typologies were conceived without ICT-integration in mind. Such models are informed by the belief that the costs of retrofitting the new into the old are less than those associated with late-stage design consolidation of intelligent services and their corresponding production [4, 5]. But this is true insofar as said design consolidation is *late-stage*. Early-stage design consolidation of intelligent services in conjunction with robotically driven production [6], which considers the 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 [7, 8], do in fact instigate considerable cost reductions [9].

Yet the conventional model prevails due to either industry conservatism or lack of dialogue between researchers in the fields of ICTs and their counterparts in architecture and construction. As a result, contemporary discussions within the AmI discourse focus on ICT-based solutions while continuing to presuppose a static and conventional architecture. Such a tendency inadvertently hinders the development of the AmI discourse by neglecting considerations of consequence to both the pertinence and performance of said ICT-based solutions. For example, present conventional models are not able to accommodate situations where the very architecture of the built-environment altogether prevents or partially hinders the proper deployment and operation of ICT-based services. In order to facilitate a corresponding implementation and proper operation of heterogeneous ICT-based services, the architecture of the built-environment must be considered as part of the overall design strategy in order to express intelligence within it. In this manner, intangible computational services work in conjunction with tangible architectural transformations to mutually inform one another in order to enhance the quality and efficacy of both assistive and interventive services. Recent work in Adaptive Architecture has demonstrated that the immersed experience of built-environment transformations may inform and influence physiological responses—see [10], for example. The present work aims to showcase how ICT-based systems may work in conjunction with transformable architectural systems based on physiological phenomena in order to enhance the quality of living of the user.

2 Concept and Approach

The proposed solution establishes a justified link between sensed physiological user-data with actuated architectural transformations within a built-environment. It does this via a series of interrelated mechatronic devices and architectural mechanisms that conform the WSN (see Figure 1). The architectural transformations explored are intended to promote the well-being of the user as well as enhance his/her overall experience of the space. In order to do this, a set of decision-making criteria to justify the link between sensed input and actuated output is defined (see Section 3). In the present scope, a variety of simple actuation events corresponding to particular scenarios are triggered based on a rudimentary decision-making mechanism.

In the first scenario, the user is assumed to be in a seating position, and his/her heart rate, perspiration levels, temperature, and changes in posture are processed to gauge the period and extent of user-inactivity. Based on medical baselines, the user is tacitly encouraged to change position, stand and/or walk for a variable period of time by the actuating system's gradual shifting of the desk and seat positions. In the second scenario, the user is assumed to be in a standing position. The system gauges the period in which the user has been inactive in such a position and invites him/her to engage in exercises that are only possible with the appearance of specialized transformable components. Such components would tacitly shift to indicate that the activity levels are sufficient while leaving the user the option to continue through expressed persistence. In the third and final scenario, the user is assumed to be absent from the structured environment for the majority of the day. The configuration of the interior environment adjusts itself in preparation for the arrival of its occupant into different combinations depending on the heart rate, and activity averages gathered remotely throughout the day. As a result, the configuration of the space may be more open and ventilated or more enclosed and hermetic.

These basic scenarios are sufficient to demonstrate that transformations in the built-environment are capable of engaging the user in response to his/her physiological state in order to regulate it. Further work to showcase higher degrees of decision-making sophistication is presently under development (see Section 4).

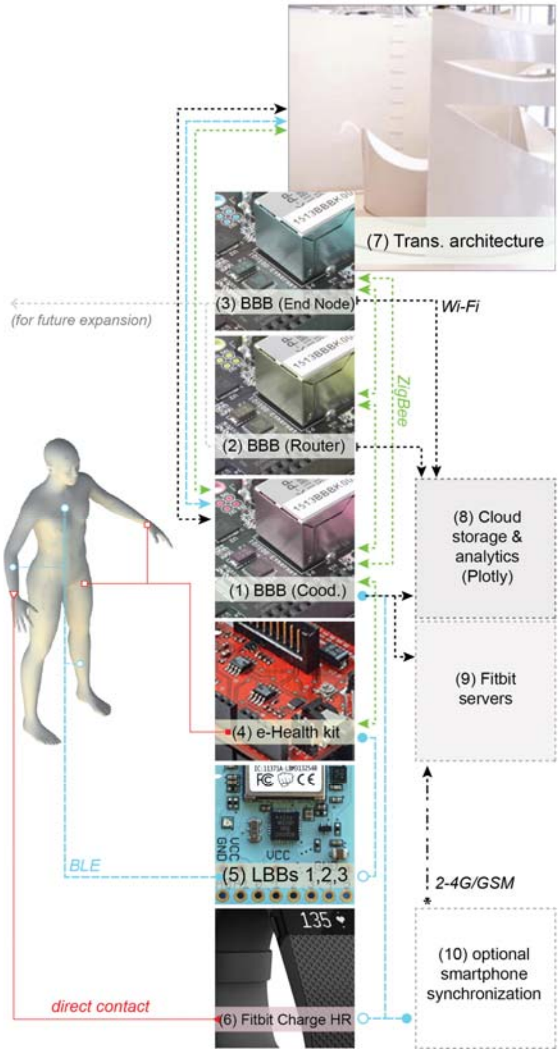

Figure 1: Proposed system architecture and organization.

3 Methodology and Implementation

3.1 Sensor types with respect to scenarios

The WSN developed in this paper builds on the decentralized architecture implemented in [11]. In addition to three *BeagleBone Black*© [12] (BBB) development platforms, i.e., a (1) *Coordinator*, a (2) *Router*, and an (3) *End Node*; an (4) *Arduino UNO*© [13] microcontroller unit (MCU) coupled with *Libelium*®'s *e-Health Sensor Platform V2.0*© [14] (e-Health kit); (5) three *PunchThrough*®'s *LightBlue Bean*©s [15] (LBBs); and (6) *Fitbit*®'s *Charge HR*© [16], have also been integrated into the WSN. Only the *Coordinator* BBB node is used in the present implementation, while the remaining two will be used in subsequent development of the system. Furthermore, in addition to heterogeneity with respect to MCUs, the WSN operates across a variety of communication protocols, i.e., Bluetooth Low Energy (BLE), Wi-Fi, and ZigBee. The present combination of devices serves as a sampler of WSN functionality in exterior, interior, and wearable domains.

The BBB nodes represent the self-healing and meshed backbone of the WSN, while the Arduino UNO and e-Health sensors function as local embedded and principal sensors for the first scenario mentioned in Section 2; the LBB as the local ambulant and principal sensor corresponding to the second scenario; and the *Charge HR* as a remote ambulant and principal sensor corresponding to the third scenario. Although each scenario has a principal sensor system, it should be noted that all sensor systems play a role in each scenario. In the following subsections below a description for each corresponding system is detailed.

3.1.1 Local embedded sensing for scenario 1

The e-Health kit is used in conjunction with an Arduino UNO MCU to gather physiological data—i.e., pulse, peripheral capillary oxygen saturation (SpO2), sweat-levels, temperature—as well as pressure data as measured from a (7) transformable workstation consisting of a desk and a corresponding seat. The galvanic and pulse oximeter sensors are fixed directly unto the fingers of the user while temperature and pressure sensors are placed throughout the seat. These sensors are wired to the MCU. Simultaneously, the LBBs are used to track changes in acceleration, which occur whenever a change in posture takes place. The data gathered is transferred to the MCU via BLE, which is then relayed to the *Coordinator* BBB via ZigBee and made available to all other BBB nodes in case future subsystems require such data. The *Coordinator* node both analyses the data and streams it via Wi-Fi to a cloud-based plotting and analytics service, i.e., (8) *Plotly*® [17]. In this manner, long-term daily datasets are stored in *Plotly* and made accessible to any person and/or AmI system with the proper user-credentials; while short-term datasets are processed locally to trigger immediate corresponding actuation events. Over time, with the long-term statistical analysis, a personalized baseline may be ascertained. Short-term analysis would be set against this baseline to identify deviations from the user's *normal* state. Naturally, personalized baselines must also take into account prescribe medical baselines according to gender, age, weight range, etc.

The overall aim is to ensure well-being and encourage healthier living. According to the World Health Organization (WHO), physical inactivity is a leading risk factor for global mortality with approximately 3.2 million deaths each year [18]. In order to prevent, for instance, the formation of decubitus ulcers due to persistent applied pressure to a tissue region or to reduce the development of varicose veins [19] sensor-actuators embedded in the built environment will initiate physical movement or activity. Pressure and temperature datasets relative to time and extent may be sufficient to estimate the probabilities of ulcer formations [20]. With respect to varicose veins, when the user has been sitting on one muscle group and/or has remained inactive for extended periods of time, the *Coordinator* BBB will command the seat and the desk component to shift in different directions to tacitly encourage the user to shift his/her weight and/or to exercise his/her lower extremities. The duration and frequency of this interventive service vary and depend on inactivity levels considered against both short-term data as well as long-term personal statistical baselines.

3.1.2 Local ambulant sensing for scenario 2

A series of LBBs are used to provide the user with wearable devices operational within the structured environment. The redundancy in these devices is intended to enhance accuracy and regional coverage—i.e., one LBB represents a wearable attached to the lower extremities, another to the upper extremities, yet another to the core of the upper-body. As in the first scenario, the data is shared across the entire WSN as well as stored and analyzed in *Plotly*. When the extent and frequency of changes in acceleration from these three regions are minimal and scattered far between, the *Coordinator* BBB shifts exercise components towards the region of the user to tacitly invite him/her to increase in activity levels. In the present scope these exercise components are general and hypothetically assumed components, represented as attached to the shifting seat and desk/wall components (see Figure 2). At this stage it is not important to define particular types of exercises as long as the user is moving with frequency and consistency.

The principal objectives in this scenario include the second objective of the previous scenario as well as the intention to proactively engage the muscular and circulatory systems. Aside from these considerations, there is also the intention to engage the user in entertaining tasks, as well-being is not confined strictly to medical concerns. The transformations instantiated in the geometry of the architecture may serve to engage the user in stimulating ways, some of which may have purely physical consequences while others may be both physically and mentally stimulating—for e.g., architecture-embedded Playware [21].

3.1.3 Remote ambulant sensing for scenario 3

A *Charge HR* activity tracker is used as the system's remote sensor node. This wearable device is designed to sense and record data pertaining to steps taken, heart rate, distance covered, calories burned, and floors climbed. The manufacturer's (9) API provides a means for the proposed WSN to connect to their servers in order to download user-specific datasets pertaining to the listed activities. This API is first installed in the *Coordinator* BBB, which is used in a *Python* script expressly written to fetch such datasets. As with the previous two scenarios, the downloaded time-series data is parsed for local analysis as well as *Plotly* storage and analytics. Inside of the structured environment, the Fitbit device synchronizes with the *Coordinator* BBB via BLE, and all collected data is subsequently relayed to Fitbit's servers via Wi-Fi. Outside of the structured environment, the device synchronizes with a smartphone with Fitbit's Application installed, and all collected data may be relayed to Fitbit's servers via (10) cellular communication technologies (e.g., 3G/4G). It should be noted that in the unlikely event that the *Charge HR* should malfunction, Fitbit's iOS / Android application is capable of turning the smartphone into an *ad hoc* tracker, thereby providing a level of justified redundancy.

The principal objective in this scenario is to maintain uninterrupted physiological data tracking with respect to the user even when he/she is outside of the structured environment. While he/she is within it, the Fitbit device may be used in conjunction with the e-Health kit to refine the heart rate analysis. But when he/she is outside the environment, it is in the interest of the WSN to keep gathering physiological data for the generation of a personalized long-term statistical profile. In addition to this objective, this scenario demonstrates how a remote agent may still be capable to influencing his/her home environment while absent. That is to say, depending on the currency of the gathered data *in absentia*, and relying on GPS-tracking services to ascertain user proximity to the structured environment, the WSN may adjust the built-environment's configuration in order to provide a more suitable welcome to the user. If the measured heart rate has been consistently elevated, and the activity levels have been construed as "intense" (under Fitbit's criteria) within a recent period, the built-environment may reconfigure itself to instantiate a more open and highly ventilated space to help balance the user's physiological status.

3.2 Transformable architectural systems

Local and remote sensing inform spatially reconfigurable architectural systems in order to facilitate adaptation and changing use. For instance, *Hyperbody*'s reconfigurable apartment is an experiment into designing a small apartment of 150 m^3 that has all the spatial qualities and functional performances of a standard 300 m^3 apartment. The initial assumption was that when a user is in the kitchen or living room, this user does not use the sleeping room at the same time implying that at one moment of the day large sections of the space could cater to only one or two functions.

Spatial transformation is exploiting material and geometrical properties in order to easily facilitate continuous change of use. Developed as a compliant mechanism the system transfers input force or displacement through elastic deformation. Consisting of a monolithic (single-piece) or jointless components, this adaptive architecture was envisioned to easily populate empty office buildings, which at the time corresponded to six million square meters and the number is—until now—still growing.

Such a reconfigurable apartment could employ WSN/BAN-enabled high-tech intelligence working in conjunction with architectural components in order to coordinate physical / geometrical rearrangements and/or spatial reconfigurations according to a set of conditions established in order to maximize the welfare of the user(s) (see Figure 2). The reconfigurable apartment is intended to cater to quotidian activities such as sleeping, eating, etc.; and the heterogeneous and decentralized WSN is envisioned to continuously gather interior environmental data specific to the respective activities via directly and indirectly attached sensors.

The apartment is envisioned to gradually *learn* that when the user is studying, s/he prefers a more private and intimate space, and accordingly walls, doors, ceiling heights, etc., may be adjusted in conjunction with temperature and illumination settings in order to instantiate just such space. Similarly, if s/he would prefer an open and welcoming space when socializing, the apartment would adapt its physical, geometrical, and spatial properties accordingly.

Furthermore, the apartment would encourage the user to adopt a healthier lifestyle by initiating spatial reconfiguration when physical activity is recommended. It would also adjust climate according to monitored needs. Heating, lighting, and ventilation would be distributed and locally deployed when needed and as needed, increasing levels of comfort while at the same time minimizing energy-waste.

In this context, sensor-actuated environments are not only customisable in order to provide healthier ambiance, but they may also offer solutions for managing the demands associated with rapid population growth, urban densification, and the contemporary inefficient use of built space by enabling multiple, changing uses within reduced timeframes.

Figure 2: Reconfigurable apartment developed with MSc 2 students and industry partners at *Hyperbody*, TU Delft (Pop-up Apartment, 2013)[6]

4 Discussion and Conclusions

The present proposal attempts to demonstrate the advantages of integrating considerations pertaining to both the ICT as well as the adaptive / transformable architecture discourse into AmI solutions. Such solutions would not be confined to delivering ICT services only, but their very design would enable the means via which to express such services in a tangible manner, thereby increasing effectiveness. On a personal level, users would benefit from the proactive, intuitive, and highly personalized suggestions provided with corresponding means of execution, particularly with respect to quotidian activities. On a societal level, public and private healthcare providers would be alleviated from unnecessary and premature cases of patients whose ailments were exacerbated by sedentary lifestyles. This latter consideration is particularly pressing. For example, according to Espinoza, 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% [22]. This reality alone serves to promote extended AmI environments capable of both servicing and providing the means of engaging users to counteract sedentary habits, thereby becoming effective promoters and extenders of health. Although the proposed system is designed to engage and to benefit all age-groups, foreseeable early adopters in the near future are likely to include people with early symptoms related to metabolic syndrome, which—if left untreated—may lead to more serious secondary diseases [23] such as heart attacks, cognitive impairment [25], and even vascular dementia [28]. It should be stressed that although the system does indeed potentially mitigate the extent of health degradation of such target group, it is not intended purely as a mitigating solution. The extended AmI proposal detailed in this paper intends to enhance user-experience, use space intelligently by shifting programmatic functions within the same space throughout the day, and increase meaningful engagement between users and their built-environment in order to promote well-being and health.

In order to more accurately meet the proposal's intended objectives, further work into the extent of spatial transformability and its appropriateness with respect to form, function, and users' needs has to be developed. Furthermore, limitations inherent in the present solution must be resolved. The following three salient limitations may be highlighted: (1) the BLE operational range with respect to the *Coordinator* BBB; (2) the resolution and reliability of low-cost sensors; and (3) the rudimentary character of the decision-making mechanisms.

With respect to the first consideration, a series of routing devices may be scattered throughout the built-environment to ascertain communication between the LBBs and the Arduino UNO MCU and/or any of the BBBs (provided these latter are equipped with pertinent BLE-enabling shields). The feasibility of this solution decreases as the structured environment's size increases. In a relatively extreme scenario, long-range communication protocols may be used instead of BLE. Alternatively, the system could rely on the smartphone's gyroscopic and accelerometer data, broadcasted via *User Datagram Protocol* (UDP) [24]—assuming Wi-Fi coverage throughout the structured environment—whenever the LBBs are out of range.

With respect to the second consideration, the implementation of higher quality and costly sensor systems may be justified if and only if the data resolution, reliability, and performance is considerably greater than that of the low-cost counterparts. If the difference is marginal, then the system should be alternatively configured to operate with lower levels of resolution. With respect to the long term statistical profiling, the loss of some datasets is tolerable. This, of course, depends on what the sensor is measuring and what the actuating mechanism is intended to respond to. Certain actuation events will require higher resolution and system fidelity, while others may tolerate a certain degree of simplification. Therefore, a solution to this consideration must involve a more robust definition and justification of sensed inputs and actuated outputs, which would help to ascertain tolerances as well as to gauge the appropriateness of low-cost sensors. With respect to the third and final consideration, it may be noted that decision-making mechanisms—and corresponding inputs / outputs—are simultaneously the most promising and limiting factor in the development of such cyber-physical AmI solutions. In order for such mechanisms to become the drivers of dynamic and adapting artificial agents, there must be a degree of machine learning involved. This is made manifest in the present literature with respect to the computational side of AmI.

Finally, it needs to be stressed that cyber-physical AmI solutions have to 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 [26]. In more sophisticated iterations of the present project, architectural components could begin to demonstrate basic yet explicit forms of agency based on and in response to processed user as well as environmental data [27]. The fundamentally and analytically intelligent built-environment effortlessly facilitates an immediate and intimate version of what Oosterhuis has described as a *Society of Building Components*, where the environment's components act and react computationally (i.e., exchange data) and physically (i.e., change forms) towards one another and towards the users [29].

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