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Adaptive Building-Skin Components as Context-Aware Nodes in an Extended Cyber-Physical Network

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***Abstract*—This paper presents an adaptive building-skin system that attempts to establish the foundations for an intuitive and responsive interface between interior and exterior spaces with respect to environmental, thermal, acoustic, and user-comfort considerations. It does this by enabling each of its components to act as individual, context-aware, sensor-actuator nodes capable of differentiated—yet correlated—actions, reactions, and interactions. The proposal situates the system within an intelligent environment whose ecosystem's operational scope subsumes yet extends beyond interior environments to include exterior domains via wearable devices. Accordingly, as the sensed data of any device is accessible across all devices in a topology of meshed nodes, the computationally processed behavior of any node is potentially informed by and informing of the status of individual and/or sets of other nodes. In this manner, the building-skin is not construed as a mere envelope, but rather as a system comprised of agents that, in conjunction with all other embedded, ambulant, or wearable agents, actively promote the well-being, comfort, and spatial experience of users.**

***Index Terms*—Cyber-Physical Systems, Wireless Sensor Networks, Ambient Intelligence, Adaptive Architecture**

I. INTRODUCTION

The present work builds on the *Cyber-Physical System* (CPS) developed within an Adaptive Architecture discourse by Liu Cheng and Bier [1]. More specifically, it adds a swarm of context-aware and adaptive building-skin (i.e., skin) components to the extended *Ambient Intelligence* (AmI) framework. These components are treated as individual, independent, yet interrelated nodes in the CPS's underlying *Wireless Sensor Network* (WSN). That is to say, the skin nodes are subsumed into the WSN's topology consisting of location-specific embedded, ambulant, and wearable sensor/actuator nodes as well as location-unspecific wearable nodes expressed in terms of both *Information and Communication Technologies* (ICTs) and adaptive architectural devices. The structure of this topology explicitly ensures that the skin, as a system, becomes an active participant in the intelligent environment's decision-making process that continuously attempts to instantiate comfortable and adequate environmental states within the same space and for a variety of occupants.

The innovation of this work lies in (1) the autonomous intelligence of the skin nodes, (2) their causal relationships with respect to one another and to all other interior nodes in the WSN, (3) and their roles within the environment's decision-making processes. It does not lie in the nodes' mechanically adaptive character *per se*, as adaptive facades or architectural skins that react to or adapt towards environmental conditions are a mature technology (see Section II). However, in such mature cases, the skin as a system is deterministically reactive and often detached from the interior environment's ecosystem, which renders it a mere aesthetically affective and protective shell. Under this approach, the skin cannot effectively participate in the continuous and personalized regulation of interior environmental conditions, making it a poor interface between interior and exterior environments. This may be a salient reason why, for example, fifty-seven percent of the average energy consumption of commercial buildings in developed nations correspond to temperature regulation, lighting, and ventilation of interior environments [2].

Although one of the principal objectives of the proposed skin system is to demonstrate that it may reduce such energy consumption via an intelligent non-uniform behavior, the scope of the present paper is limited to developing a technical and technological *proof of concept* of its decentralized system architecture and effective operability (see Section III). This is achieved via two demonstrations (see Section IV and Section V), where the first establishes a causal relationship between skin components and an interior environment's sensor, and the second establishes a likewise relationship between skin components across different sides of the skin envelope. From this point onward, the CPS may be extended to feature a wider variety of sensors, and its optimal performance may be regulated primarily at a software level (see Section VI).

This paper consists of six sections. Section II provides a context by discussing the character and motivations behind the AmI discourse. Section III describes the skin system's architecture and Section IV the methods involved in its implementation as well as validation. Section V details the results of the demonstrations and discusses present limitations. Finally, Section VI concludes with the pertinence of said implementation with respect to the objective of this paper and discusses further work.

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II. BACKGROUND

In 1998 AmI was coined to describe a type of future dwelling space, a *digital living room*, where technological devices operated intuitively and without explicit user control to enhance the occupants' qualitative experience and comfort [3]. In nearly two decades of research and development, AmI's vision has informed and been informed by likewise technologically driven trends such as *Ubiquitous computing, Smart Environments, Internet of Things* (IoT), *Machin-to-Machine* (M2M) exchange, etc.

In these trends, *intelligence* has primarily expressed itself in terms of ICTs, which has inevitably rendered the built environment a passive or spectating host. In order for AmI environments to be effectively and adequately intelligent, the architectures involved must be conceived as dynamic entities capable of adapting to their likewise dynamic occupants, surrounding environments, and contained objects, informing and being informed by their ICT counterparts. Such desiderata lies at the core of the *Adaptive Architecture* discourse (see, for example, work by Kolarevic [4] and Schnädelbach [5]), which is why it is particularly suited to AmI.

AmI's vision involves all aspects of the built environment, both at architectural and urban scales. An overview of the literature suggests that, with respect to the former, it is primarily concerned with the intelligence of personal environments; and with respect to the latter, with the digital connections, corresponding services, and the group intelligence that potentially supervenes upon collective environments—e.g., city blocks, neighborhoods, open spaces, etc. (see, for example, work by Nakashima, Aghajan, and Augusto [6]). Broadly speaking, one may be said to reflect AmI's vested interest in private interior spaces, while the other in public exterior spaces. Façades or skins may be considered as general interfaces between these spaces.

There are numerous instances of deterministically automated façade systems, actuated both by virtue of mechanical mechanisms—e.g., Jean Nouvel's dilating façade components in his *Institut du Monde Arabe* [7]—and by virtue of material properties—e.g., Achim Menges's and Steffen Reichert's *HygroScope* and *HygroSkin* projects [8]. Similarly, deterministic mechatronic façade systems, consisting of mechanical as well as electronic mechanisms, are also available in industry—e.g., Aedas$^{®}$'s *Al Bahar Towers* [9]—and in academia—e.g., ETH Zürich's *Adaptive solar façade* [10]. But the domain of AmI-based façade and skin systems, especially ones with decentralized independent yet entangled components, remains to be expanded and explored. There are also instances, albeit scarce, of non-deterministically automated systems—e.g., Maria Eleni Skavara's *Adaptive Fa[CA]de* [11]—that showcase the potential of considering the façade and its constituents as agents of intelligence.

III. CONCEPT

Two IoT-ready skin fragments (A and B, see Figure 1) containing three components each (1-3 for A, 4-6 for B) are developed as part of the *proof of concept*. These components are formally similar to ones installed on Aedas$^{®}$'s *Al Bahar Towers* [9]. A variety of other skin components were also considered, but this one was chosen for its functional and aesthetic qualities. The architectural skin fragments are to be considered parts of a larger and unified whole, which will eventually be expressed in the form of a building-envelope. For the scope of this paper it is not relevant to detail the design considerations behind the form of the overall structure; what is relevant is that the nodes behave in a swarm-like manner with respect to each other and to the interior environment's nodes within a distributed, decentralized, yet unified solution.

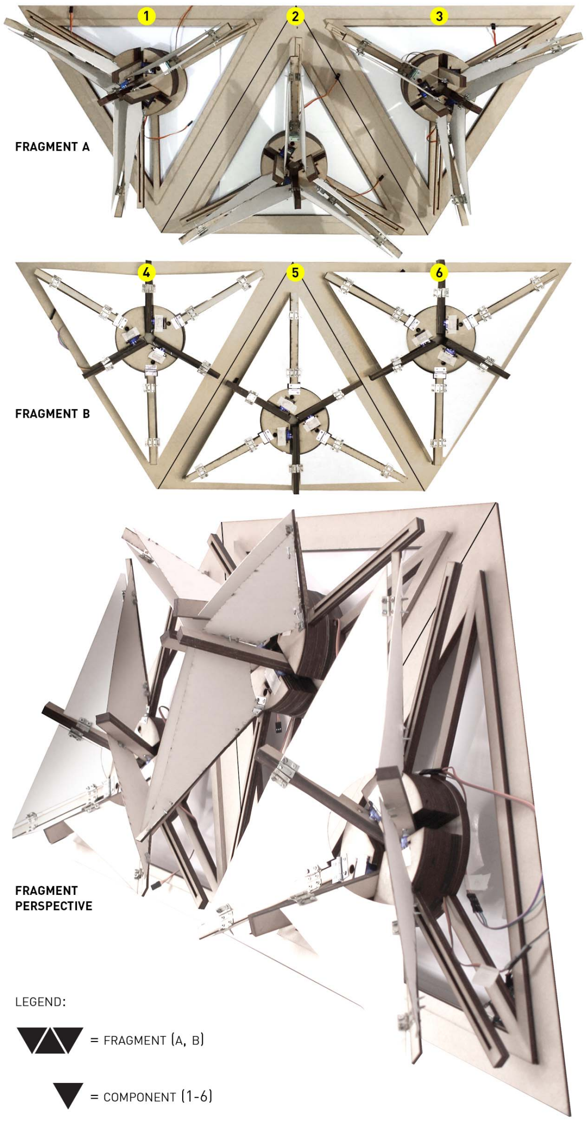

Figure 1. Top: Components 1-3, skin fragment A (fully open). Middle: Components 4-6, skin fragment B (fully shut). Bottom: Skin fragment perspective (with differing degrees of component openness).

In addition to their ability to operate as distributed systems, swarms are particularly pertinent to architectural applications due to their failure tolerances via self-healing mechanisms. Furthermore, while individual agents/nodes may be quite simple, the emergent behavior of swarms grows increasingly complex, where local interactions between agents/nodes lead to the emergence of a global behavior. In this context, local cooling/heating, ventilating, and/or shading/illuminating responds to indoor-outdoor conditions and users' needs by establishing changing global indoor climates.

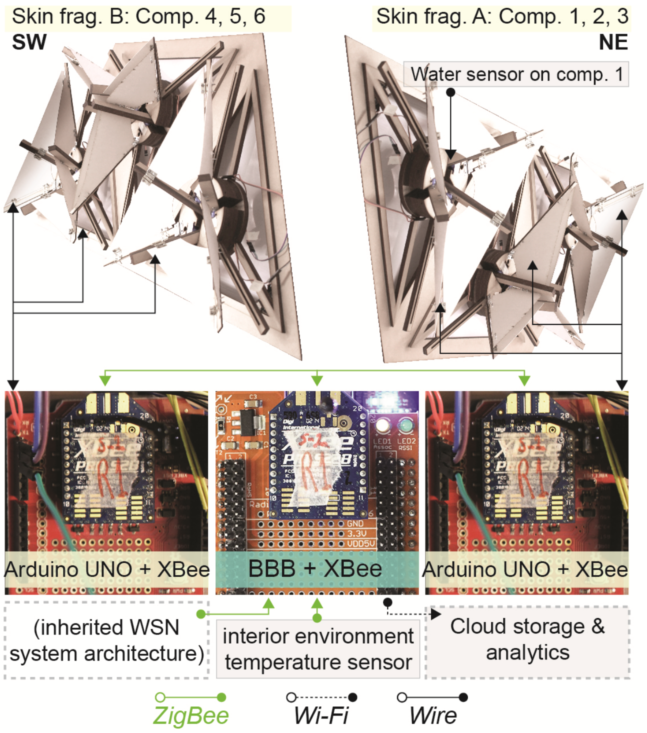

Figure 2. System Architecture (excluding inherited WSN components[1]).

The inherited WSN upon which the implementation builds consisted of a *BeagleBone Black* (BBB) development platform with corresponding XBee capes, an *Arduino UNO* microcontrollers (UNO MCUs) with a corresponding *e-Health Sensor Platform*, three *LightBlue Bean*s, and a *Fitbit HR* activity tracker. In this ecosystem, physiological data along with persistence of posture and lack of activity instigated interventive and preventive changes in the corresponding adaptive architecture (see Liu Cheng and Bier [1]). The present work expands this ecosystem by adding another BBB with a corresponding XBee cape, and two UNO MCUs with corresponding XBee shields. The new BBB serves as the *Router* node that links the new UNO MCUs to the original *Coordinator* node via *ZigBee*-enabled *XBee Pro Series 2B* antennae. Although the UNO MCUs could directly communicate with the *Coordinator* node, this setup was selected in order to extend the communication range between *Coordinator* and the skin nodes, which are controlled by the UNO MCUs. Each UNO MCU is connected to three skin nodes corresponding to each fragment of the skin. These fragments do not share a physical connection with each other, nor with any other node in the interior environment (see Figure 2).

Under this wireless ecosystem, whenever any skin node is affected by an environmental condition or a user-correlated action, the effects will propagate across all other skin nodes (in both fragments) as well as all interior-environment nodes. The distribution of the propagation's magnitude across the entire WSN will be correlated with the proximity as well as the relationship between the detecting skin node and its neighbors. For example, if a given interior environment sensor node (e.g., temperature sensor) is moved closer to either skin fragments, the immediacy and extent of the sensor readings' influence upon the behavior of corresponding components will vary (see Section IV.A and Section V.A, *First demonstration*). Similarly, if a skin fragment's component (e.g., Component 1 in fragment A) includes a moisture sensor that detects the presence of water, the extent to which the immediate neighbors (i.e., Components 2 and 3 in fragment A) react in an event of rain is more pronounced and immediate than that of more distant neighbors (i.e., Components 4, 5, and 6 in fragment B) (see Section IV.B and Section V.B, *Second demonstration*).

All the nodes are equipped with individual *Light Dependent Resistor*s (LDRs) in order to correlate light intensities to degrees of dilation / aperture (see Figure 3 and Figure 4). For simplicity, the normalized light intensity is inversely proportional to the normalized aperture extent. Additionally, one node (i.e., Component 1) in fragment A is also equipped with a water / moisture sensor in order to demonstrate how the sensed-data gathered from any one node affects the behavior of all other nodes. The setup is intended to illustrate that though all skin nodes are sensitive to exterior lighting conditions, some nodes may be specialized to account for other environmental conditions as well as user-dependent actions. This serves to enrich the capabilities of the skin as a unified system, as the specialized data sensed by one node is accessible by all others and vice versa.

IV. METHODS

The two demonstrations arranged in order to test the entangled functionality of the skin system specifically, and of the overall CPS generally, involve real-time sensed data and corresponding actuated reactions. One thousand sensor-state and actuator-state readings were taken per sample run. The experimental set-up involved installing fragment A as part of a skin facing North-East (NE), while fragment B as part of one facing South-West (SW), at 5:11 p.m. in the month of May in Quito, Ecuador. This meant that fragment B faced the late-afternoon sun while fragment A was exposed to diffused illumination characteristic of the late-afternoon sky. As the relationship between normalized LDR values and the aperture extent was inversely proportional, the components in skin fragment A were more open than those of skin fragment B, since the latter received more sun than the former. Figure 3 and Figure 4 represent the experiment’s baseline from which the force of external influencing factors was gauged.

In addition to this initial arrangement, the gathered data by each fragment’s node and the corresponding extents of actuation in both demonstrations were live-streamed to a cloud-based data plotting and analytics service, thereby establishing the possibility of future IoT expansion and M2M exchange within and without the CPS.

A. First demonstration: Interior sensor node influencing skin fragment A’s and B’s component behavior

In this demonstration, a temperature sensor was used to represent the class of sensors deployed in the interior environment. In the first sample run, the position of the sensor was set to an equidistant distance with respect to both skin fragments A and B. In the second sample run, the position was moved to be immediately next to fragment B, which is the sun-facing set of skin components. In this manner, it would be possible to gauge if all the nodes within the CPS’s underlying WSN were indeed taking relationship and proximity between acting nodes into consideration, as the varying of the sensor’s position would output different extents of influence and skin behavior variation (see Section V.A).

B. Second demonstration: Sensor data collected from a component in skin fragment A influencing both its immediate neighbors as well as distant neighbors in fragment B

In this demonstration, skin fragment A’s Component 1 was equipped with a water / moisture detection sensor in addition to the standard-issue LDR. Any detection of water in particular, and liquids in general, would affect the behavior of Components 2 and 3 explicitly, and of skin fragment B’s Components 4, 5, and 6 tacitly. Even within the broad influence of the moisture sensor across both skin fragments, the set-up would differentiate between the immediacy and extent of influence among components. For example, Component 1, being the node within which the moisture sensor is deployed, would trigger the most immediate and intense reaction to the possible event of rain. Similarly, Component 2, being closest to Component 1, would trigger a reaction more immediate and intense than would Component 3. This graduated influence would be subsequently experienced by more distant components with less immediacy and intensity.

V. RESULTS AND DISCUSSION

Since each skin component possessed its own LDR, this entailed that every component aperture would be different—however slightly or emphatically—from one another (Figure 3 and Figure 4).

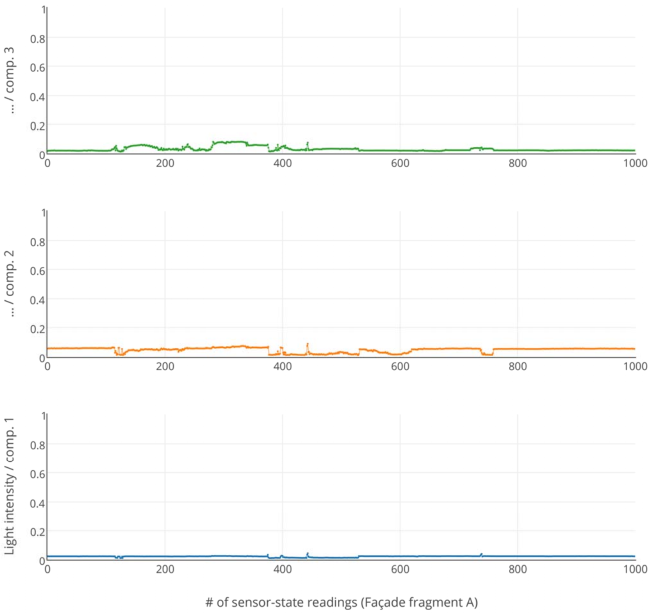

Figure 3. Components 1-3, Skin fragment A: Light intensity (normalized—0=lower-bound sensor threshold; 1=upper-bound threshold).

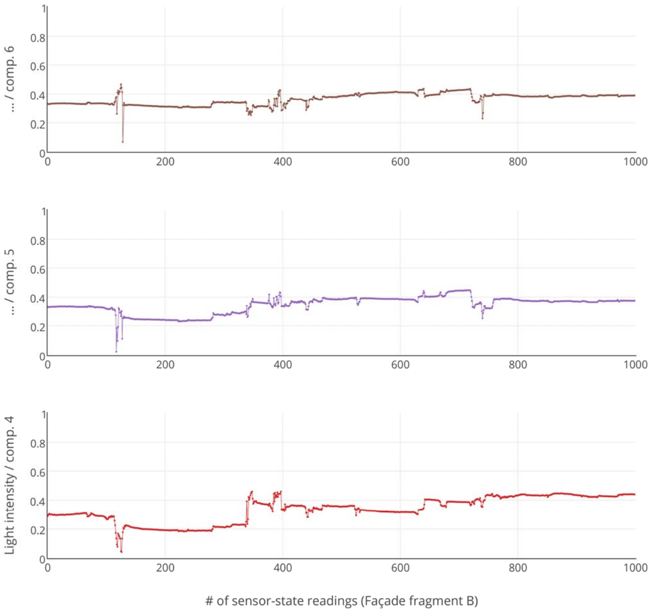

Figure 4. Components 4-6, Skin fragment B: Light intensity (normalized—0=lower-bound sensor threshold; 1=upper-bound threshold).

A. First demonstration: skin fragments A and B (and corresponding components) reacting to a temperature sensor situated in the interior environment.

For this demonstration, the *ideal temperature* constant was set to 22.5° C.—an average of the accepted human-comfort range of 21° C. – 24° C. [12]. If the sensed temperature exceeded this constant, skin fragment A was programmed to increase its aperture while fragment B to decrease it. That is, since fragment B received direct sunlight, if the interior temperature exceeded comfortable levels, the components in fragment B would reduce solar heat-gains by decreasing their aperture. Simultaneously, the components in fragment A would increase their aperture to contribute to the ventilation of the interior space. Alternatively, if the sensed temperature was below the ideal constant, skin fragment A was programmed to decrease its aperture while fragment B to increase it.

As evidenced by the real-time data collected in the first run of this demonstration, where the position of the temperature sensor was equidistant to both skin fragments A and B, the demonstration corresponded with the anticipated results. It may be observed in Figure 5 that the influence deviation was greater as the temperature increased. It was also observed that the change in fragment A[1] was less pronounced than that of fragment B. This was principally due to our baseline's experimental set-up, where the relationship between light intensity and aperture extent was inversely proportional.

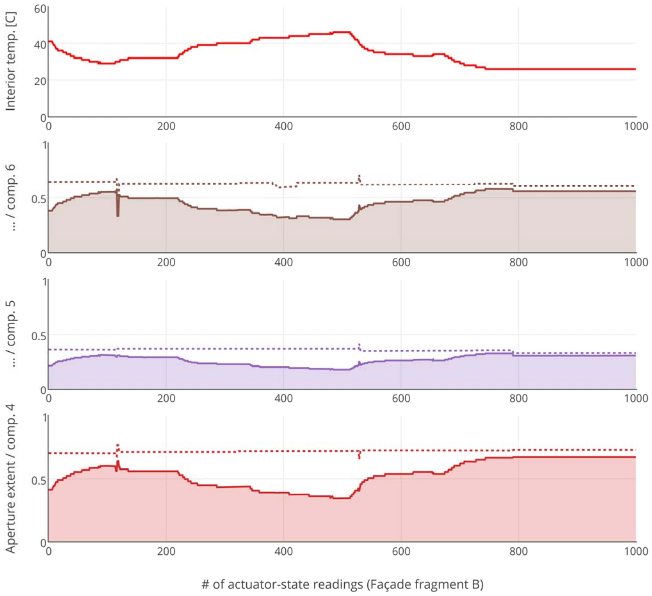

Figure 5. Components 4-6, Skin fragment B: Aperture extent (normalized) influenced by interior temperature sensor (equidistant between fragment A and B). Dotted lines: normal (uninfluenced) extent. Solid lines and fill: resulting deviations entailed by temperature fluctuations.

In the second run of the first demonstration, the temperature sensor was placed immediately next to fragment B's skin components. This informed the CPS whether the temperatures in the region immediately next to fragment B deviated from the established comfort range. Accordingly, and due to the proximity of the temperature sensor, the deviation affecting fragment B's components became more pronounced than before (see Figure 6).

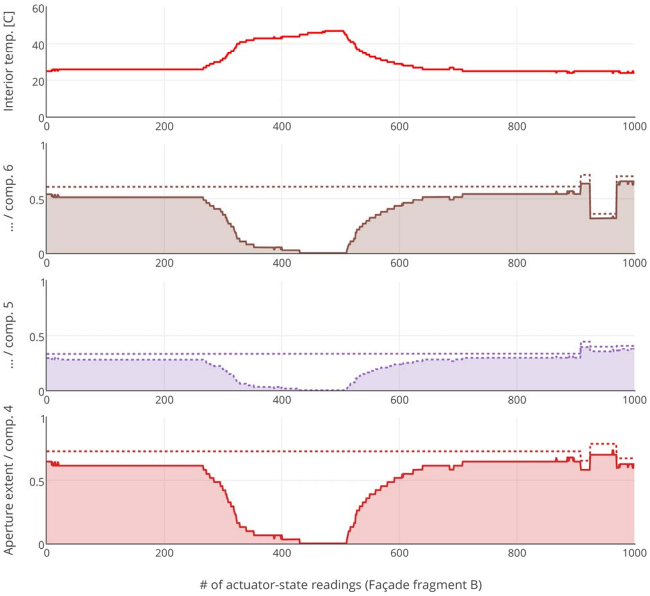

Figure 6. Components 4-6, Skin fragment B: Aperture extent (normalized) influenced by interior temperature sensor (positioned next to fragment B). Dotted lines: normal (uninfluenced) extent. Solid lines and fill: resulting deviations entailed by temperature fluctuations.

B. *Second demonstration: A water sensor attached to component 1 in skin fragment A affecting immediate neighboring components 2 and 3 as well as distant components 4, 5, and 6 in skin fragment B in a graduated manner.*

In the results of this demonstration, it was observed that the moisture content detected by fragment A's Component 1 influenced the behavior of the components in both fragments. However, the important phenomenon to highlight is that the extent of this influence was intelligently graduated. When the detected water / moisture levels were high, the deviation affecting Component 1 was more pronounced than that which affected Component 2, which in turn was also more pronounced than that which affected Component 3 (see Figure 7).

It may likewise be observed that when the water / moisture content was high, the extent of aperture in the components in skin fragment B were affected by an increasing deviation, which sought to account for the loss of ventilation resulting from the reduction of aperture extents in fragment A. However, this deviation was considerably mild since the water / moisture sensor was far from the components in fragment B.

The results of these demonstrations validate the hypotheses and satisfy the objectives outlined at the beginning of this paper. Although the *proof of concept*'s service capabilities and scope are simplified, they demonstrate the potential of such decentralized, context-aware, adaptive skin components as actors in a CPS.

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[1] The corresponding figures for façade A in the first demonstration, and for façade B in the second, are omitted for brevity.

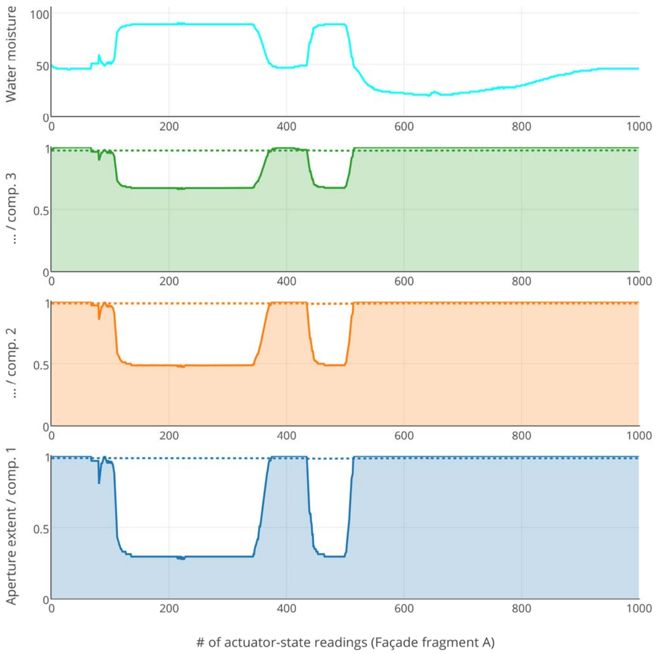

Figure 7. Components 1-3, Skin fragment A: Aperture extent (normalized) influenced by water sensor (installed in Component 1). Dotted lines: normal (uninfluenced) extent. Solid lines and fill: resulting deviations entailed by detected water.

VI. CONCLUSIONS

The general objective of the present work has been to promote the building-skin as a potential collection of context-aware IoT-sensor/actuator nodes in equal standing as all remaining nodes in a CPS's WSN. The advantage of this strategy lies in the resulting increase of intelligence resolution and scope in AmI environments, no longer confining intelligent services within the interior context. Furthermore, such a strategy also results in interior / exterior space interfaces that better accommodate or respond to both user comfort requirements as well as to environmental phenomena. The detailed demonstrations argue for the feasibility of such a strategy, however limited or simple their set-up may have been for the present scope.

There remain considerable limitations that should be overcome in order to develop the system. For example, the robustness and resolution of the sensors used should correspond to the real-time needs of the skin mechanisms. At present, the functions involved in the retrieval of temperature readings instantiated longer delays than real-time systems would tolerate. The constituents of a system should be mutually complementary to one another in order for it to be considered robust and to perform optimally. Regardless of how sophisticated a given constituent part may be, the conformed system will require mutually complementary parts in order to work [13]. But this raises a more important issue cum limitation, and one that calls into question whether reactions, adaptations, and interactions within a CPS should necessarily require *real-time* data exchange. A CPS similar to the one detailed in this paper may indeed use the best and newest of components, yet its sophistication could require computation resources and services that render it inaccessible to the majority of the population. Furthermore, perhaps the difference between using the best and newest of components over relatively modest counterparts is negligible depending on the function. The challenge is therefore not to find the means to use highly sophisticated devices, but to first understand what services may be achieved with which accessible components and still attain at the desired performance and results.

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