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Extension of a High-Resolution Intelligence Implementation via Design-to-Robotic-Production and -Operation strategies

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Abstract –

This paper extends the development of a responsive built-environment capable of expressing intelligence with respect to both ICTs and Adaptive Architecture. The present implementation is built with mutually informing *Design-to-Robotic-Production & -Operation* (D2RP&O) strategies and methods developed at *Delft University of Technology* (TUD). With respect to D2RP, a responsive stage built with deliberately differentiated and function-specific components is revisited and modified. With respect to D2RO, a partially meshed, self-healing, and highly heterogeneous *Wireless Sensor and Actuator Network* (WSAN) is expanded to integrate proprietary-yet-free cloud-based services. This WSAN is equipped with *Machine Learning* (ML) mechanisms based on *Support Vector Machine* (SVM) classifiers for *Human Activity Recognition* (HAR). The frequency and/or absence of certain activities, in conjunction with processed data streamed from environment-embedded sensing mechanisms, trigger actuations in the built-environment in order to mitigate fatigue, encourage activity / interactivity; and to promote general well-being in the user. A voice-enabled mechanism based on Amazon®'s *Alexa Voice Service* (AVS) is integrated into the ecosystem to connect the built-environment with services and resources in the *World Wide Web* (WWW). Furthermore, a notifications mechanism based on Google®'s Gmail® API as well as Twilio®'s REST® API enable instances of fatigue to be reported to third-parties. The present interdisciplinary development attempts to promote an alternative approach to existing *Ambient Intelligence* (Aml) and *Ambient Assisted Living* (AAL) frameworks.

Keywords –

Design-to-Robotic-Production & -Operation, Ambient Intelligence, Wireless Sensor and Actuator Networks, Adaptive Architecture.

1 Background and Introduction

This paper builds on the implementation presented in the *34th International Symposium on Automation and Robotics in Construction* (ISARC) 2017 [1]. As such, it continues to promote the concept of *high-resolution intelligence* in the built-environment driven by *Design-to-Robotic-Production & -Operation* (D2RP&O) [2] strategies and methods developed at *Delft University of Technology* (TUD). D2RP&O establishes an unprecedented direct link between design, robotic production, and operation. While D2RP is informed by variations of structural, programmatic, performative (both physically and computationally), and assembly considerations, D2RO operates as a distributed and decentralized system architecture, which is employed to serve as the nervous system of the building. The resulting built-environment is characterized by adaptiveness and interactivity with respect to ICTs as well as to *Adaptive Architecture*.

The present development continues to build on the responsive stage by combining the previously detailed features and scenarios (see [1]) with the following new features both with respect to the built-environment:

1. *Proof-of-concept* implementation of global and local ventilation systems in order to ascertain both optimal temperature and humidity ranges (as determined by the *Comité Européen de Normalisation* (CEN) Standard EN15251-2007 [3]; and air-quality via a variety of air pollution (see Figure 2, Section 3.1).

And with respect to *remote / cloud-based services*:

2. Integration of Amazon®'s *Alexa Voice Service* (AVS) [4] into the system (see Figure 3, Section 0);
3. Integration of (a) SMS notification capabilities via Twilio®'s REST® API [5] and Siemens®'s T35 GSM component/shield and standard prepaid SIM-card (see Figure 4, Section 3.3); (b) email notification capabilities via Google®'s Gmail® API [6].

As well as with respect to a new modified deployment scenario, where the adaptive stage invites the user to engage in activity if prolonged physical inactivity is detected (Figure 5, items 21 and 22).

2 Concept and Approach

The present implementation expands on a previously developed WSN [1] to include four main subsystems, briefly summarized as follows:

1. **Local System:** A variety of Microcontroller Units (MCUs) and development platforms (e.g., Raspberri Pi 3 (RPi3) and Zero W (RPiZW)) serve as nodes dependent on a local structured environment. More powerful nodes may be clustered dynamically to yield a single node with higher computational power depending on load-requirements. All nodes exchange data in a combination of wired (e.g., Ethernet, USB, Serial) and wireless (WiFi, BLE, and ZigBee) protocols, depending on latency and frequency requirements.
2. **Wearable devices:** A set of three LightBlue Beans™ (LBBs) conform the location-dependent wearables while a Fitbit® Charge HR™ activity tracker represents the location-independent wearable. The LBBs detect movement in the upper-body, upper- and lower-extremities and advises the system to listen for *Open Sound Control* (OSC) packets corresponding to accelerometer data sent from a smartphone for *Human Activity Recognition* (HAR). The activity tracker enables a constant feed of physiological data while the user is outside of the structured environment.
3. **Ad hoc Support devices:** In the last five years, smartphones have become convenient and ubiquitous tools for HAR via *Machine Learning* (ML) [7, 8], which in conjunction with their battery life and rechargeability render them a preferred means of accelerometer-data gathering in intelligent built-environment implementations.
4. **Remote / Cloud Services:** Six cloud-based services conform this subsystem: (I) external ML mechanism via MATLAB® (in case the local ML mechanism fails); (II) data exchange with Fitbit®'s servers via its API [9]; (III) cloud data-storage and -plotting via Plotly®'s API [10]; (IV) Amazon®'s *Alexa Voice Service* [4]; (V) automated SMS notifications, both via Twilio®'s API [5] as well as via a T35 GSM module; and (VI) automated email notifications via Gmail®'s API [6].

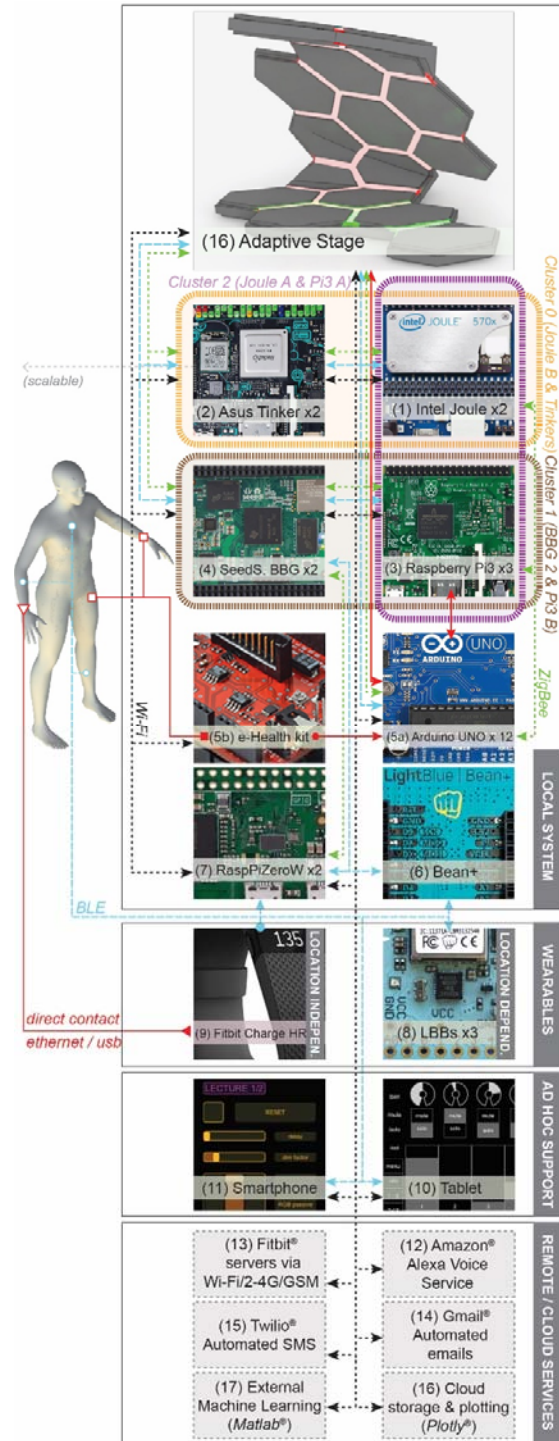


Figure 1. Heterogeneous System Architecture.

3 Methodology and Implementation

3.1 Global / local ventilation mechanism

This mechanism is first implemented and tested via an abstracted surrogate model equipped with twelve DHT-22 temperature and humidity sensors, twelve air-quality sensors (viz., three of each MQ-3 *Alcohol*, MQ-4 *Methane*, MQ-7 *Carbon Monoxide*, and MQ-8 *Hydrogen Gas*), and twelve small DC-motor fans connected to three RPiZWs and one RPi3 (see Figure 2, *Top*). Since the *General-purpose input/output* pins (GPIOs) of these devices are digital while the air-quality sensors are analog, 10-Bit MCP3008 ADCs are used to create a bridge.

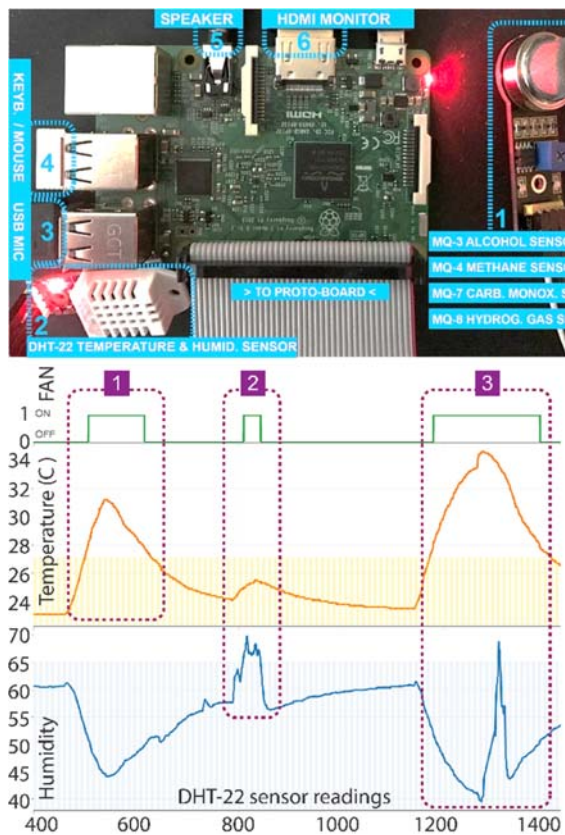


Figure 2. Top: Typical node: (1) Air-quality sensors: MQ-3 *Alcohol* or MQ-4 *Methane* or MQ-7 *Carbon Monoxide* or MQ-8 *Hydrogen Gas*; (2) Temp. & Hum. sensor; (3) USB Mic.; (4) Keyboard / Mouse (only necessary for config.); (5) Speaker; and (6) HDMI Monitor (optional). Bottom: Activation of ventilation fans in relation to temperature and relative humidity comfort thresholds (shaded).

As corroborated by the *Comité Européen de Normalisation* (CEN) Standard EN15251-2007 [3] as well as the *American Society of Heating, Refrigerating and Air-Conditioning Engineers* (ASHRAE) Standard 55-2013 and Standard 62.1-2013 [11], the *Thermal Environmental Conditions for Human Occupancy* with respect to comfort should be 67 to 82° F. ($\sim 19.5 - 27.8^{\circ}$ C.) [12], while relative humidity in occupied spaces be less than 65% in order to discourage microbial. Furthermore, independent of human comfort considerations, frequent and consistent ventilation reduces the concentration of toxins in the air as well as the prevalence of airborne diseases [13].

In this TRL-5 setup, if the collective temperature or humidity levels exceed said recommended limits for comfort, all the fans activate, thereby drawing fresh air into the inhabited space (i.e., Global ventilation concept). If, however, certain areas exceed either or both limits, only those fans within and surrounding them activate (i.e., Local ventilation concept) (see Figure 2, *Bottom*). The same concept holds for instances of air-pollution

3.2 Voice-control mechanism via *Alexa Voice Service*

This mechanism is implemented and tested (see Figure 3) via the same RPi3 mentioned in the previous section (see Figure 2, *Top*), an open-source repository using Amazon®'s API [14], and a generic microphone as well as repurposed speakers. A secondary device is also built based on an RPiZW node both to serve as backup and to instantiate an emphatically low-cost (i.e., USD $\sim$ \$15, as of writing) alternative to even the most affordable of Amazon®'s Echo™ product (viz., the Echo Dot™, at USD \$49.99 [15]). The flexibility of developing custom—and more affordable—Alexa-enabled Devices permits virtually any built-environment device, whether deployed in an architectural or an urban context, to capitalize from AVS.

Two main objectives inform the present integration. The first is to enable a powerful and scalable voice-control mechanism within the present development. The second is to demonstrate a cohesive technological heterogeneity between an open-source WSN and a proprietary commercial service without additional cost (with respect to Fitbit® and Gmail©) or with minimum cost (with respect to Twilio®). This latter consideration connects a local intelligent-built environment with vast resources in the WWW, enabling the user to engage in a variety of activities from streaming music to purchasing groceries via devices fundamentally embedded into the built-environment.

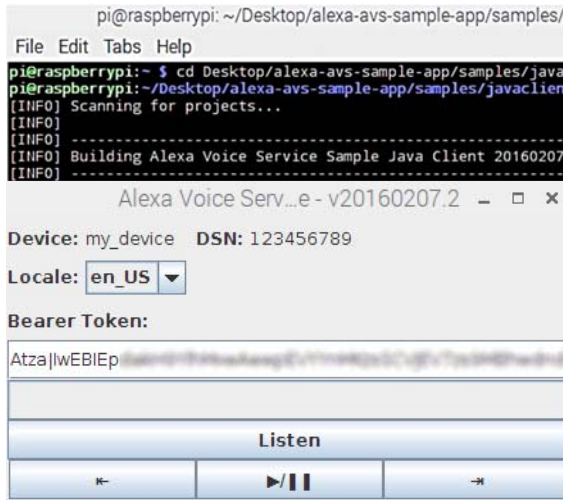


Figure 3. Top: Java Client service initialization. Bottom: AVS Java Client interface initialization.

3.3 Intervention via SMS and email notification mechanisms

This mechanism, inherited from an earlier implementation [16], is presently implemented and tested via a RPiZW node, a smartphone, and Twilio®'s as well as Gmail®'s APIs. Additionally, a non-web-based contingency device was developed using a Siemens® T35 GSM shield mounted on an Arduino® UNO™. The main objective with this implementation is to setup the foundations of an increasingly comprehensive intervention framework capable of reacting to emergency events, both with respect to the inhabitants of the built-environment and with this environment per se.

The Twilio® implementation represents a cost-effective SMS service, while the T35 GSM setup represents a standard prepaid SMS service. A scenario may be entertained where the built-environment's WiFi service is unavailable for a period of time, yet the integrity of the WSN's *Local System* remains uncompromised as its constituents remain networked via ZigBee and BLE. In such a scenario, an emergency event may be reported via the T35 GSM setup, as it relies on standard cellular communication. Conversely, another scenario may also be entertained, where cellular services are unavailable due to lack of coverage. In this scenario, emergency events may be reported via Twilio®'s SMS service to any location worldwide.

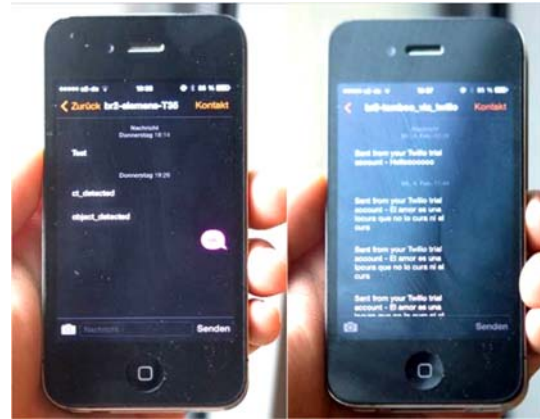


Figure 4. Left: SMS via WiFi (Twilio®). Right: SMS via Siemens T35 GSM module.

3.4 Closed-loop Runtime Implementation

In order to describe how the above-detailed mechanisms integrate into the proposed development, a point-by-point runtime description is provided as follows:

1. The *Local System*, as the core of the WSN and backbone of the ICT ecosystem, initializes and establishes the network in multiple communication layers (WiFi, BLE, ZigBee). For security reasons, only registered MAC addresses are provided with IP addresses. Once the network is established, all *Linux*-running systems update and upgrade.
2. *Wearables* communications initialize. The WSN draws available data from Fitbit®'s servers and begins to listen for LBB notifications as well as to listen and record BLE / OSC accelerometer data.
3. *Remote / Cloud-based Services* communications initialize—i.e., *OAuth 2.0* tokens are provided, authentication and authorization are established. Received accelerometer data are streamed to and plotted by Plotly® used for local HAR, if a suitable classification model is present.
4. Since the deployment context is that of GSM3, the system checks if the responsive stage is being used by a lecturer.
5. If a lecturer is on-stage, the system checks if a suitable ML classification model is available.
6. If no ML models are available, local HAR considerations are omitted from subsequent decision-making processes—e.g., whether to activate ventilation systems if the lecturer is assumed to be agitated via Fitbit® data (see points 12 and 13).
7. Presupposing the availability of the SVM model

mentioned in point 3, the HAR mechanism is initialized—i.e., processed accelerometer data are set against the model and prediction begins in real-time.

8. All sensing systems—embedded, ambulant, and location dependent wearable—are initialized and verified.
9. Raw data are gathered, cleaned, processed, and made available across the entire network.
10. The data from point 9 are written into the (i) local ML and (ii) remote ML datasets (optional) for a subsequent model generation.
11. Similarly, said data are streamed, plotted online, and made available for remote monitoring.
12. When the system detects the presence of a lecturer on stage, it determines that the lecturer is probably physically agitated if (i) sweat sensors (see Figure 1, item 5b) detect perspiration; (ii) temperature and humidity sensors detect an increase in temperature and relative humidity in the overall environment in general, and in user-occupied areas in particular; (iii) the wearable LBBs detect an increase in body temperature; and (iv) the most recent Fitbit® data evidence existing and sustained physical activity.
13. Having determined a high probability of physical agitation, all the fans in the ventilation system activate until readings return to CEN recommendations. In the interest of time, this ventilation mechanism is developed and tested via a scaled surrogate setup. The ICT-configuration concept presented is asserted to function across a variety of physical forms within human scale.
14. After symptoms of agitation cease (e.g., heart-rate normalizes, body temperature falls within recommended levels, and perspiration is not detected), the system continues to check if the temperature and humidity readings of the environment comply with CEN recommendations.
15. As a strategy for responsible energy consumption, if the environment's temperature and humidity readings remain too elevated for comfort after a given period of global ventilation (in this runtime: two minutes), the ventilation system switches to ventilate only the areas surrounding the user. If external conditions raise temperatures across the entire environment, it is pointless to condition unoccupied areas.
16. In parallel to point 14, the system also checks for air-quality via its MQ-*n* sensors (see Figure 2, *Top*) independently of temperature and humidity readings.

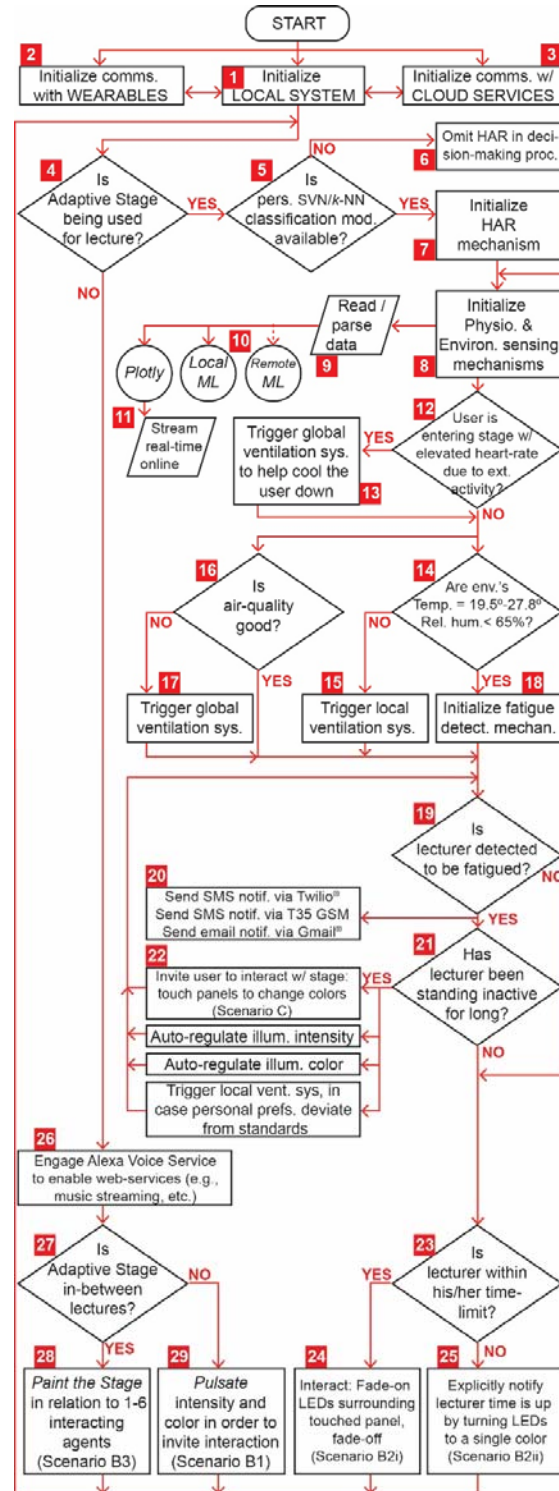


Figure 5. Runtime decision-tree.

17. The strategies for mitigating high-concentrations of toxins and reducing the prevalence of airborne diseases differ from the temperature and humidity strategies above in that global ventilation is engaged for the duration of detected poor air-quality. Even across unoccupied spaces, it remains in the occupant's interest to sustain air-quality.
18. Following point 14, if the lecturer is not agitated, and if the thermal conditions of the occupied space are optimal, the system begins to watch for potential symptoms of fatigue. In this development, fatigue is considered a possible consequence of sustained agitation and/or of normal wear while engaged in *Activities of Daily Living* (ADLs). That is to say, fatigue may be brought upon by concentrated and extraneous physical activity and/or simply by growing tired engaging in ADLs throughout the day. The fatigue-detection mechanism used in this development is inherited from ISARC 2017's implementation [1]—that is to say, it is a limited adaptation and modification of the *human state estimation system* developed by Nakaso *et al.* [17].
19. The fatigue-detection system relies on a camera—in this case a Microsoft® Kinect™ V2—and a face and eyelid-aperture detection classification model developed in MATLAB. If the lecturer is detected to be probably fatigued—e.g., his/her eyelids droop, activity levels decrease, acceleration in movement decreases—then the following two intervention mechanisms activate:
20. SMS notifications regarding the lecturer's state, including average heart-rate, temperature, acceleration, steps taken, and distance covered are sent via Twilio® and via T35 GSM. These notifications are shorter than the one sent via Gmail®, where an hour-by-hour overview of activity levels—in some predetermined period of time—are fully detailed. The degree of detail may vary depending on the purpose of the notification. In this development, these SMSs and email are triggered by detection of fatigue, yet these mechanisms serve as indicators of promising application potential.
21. In conjunction with triggering the above passive intervention mechanisms (i.e., such that notify yet do not mitigate or promote), the system considers activity data for the last hour to determine the amount and concentration of inactivity. If the lecturer has continuously stood still for longer than fifteen minutes, the system considers this inactivity as an exacerbating factor in the detected fatigue.



Figure 6. Interactive stage in action at GSM3 conference.

22. Accordingly, the responsive stage triggers four active intervention mechanisms (i.e., such that mitigate and/or promote) sequentially (see Figure 5, item 22). That is, upon detecting prolonged inactivity, components in the responsive stage fade-on varying colors and intensities to encourage the lecturer to touch them (see Figure 5, item 22, first row). This, along other scenarios (i.e., Figure 5, items 24, 25, 28, 29, and 26 assisting) turn the stage into *de facto* playware. The second and third active intervention mechanisms (see Figure 5, item 22, second and third rows) auto-regulate overall illumination intensity and color of the stage's LEDs in case these be exacerbating factors of the detected fatigue. Finally, the fourth active intervention mechanism triggers local ventilation in case the lecturer's preferences deviate from recommended thermal conditions, and this be an exacerbating factor of the detected fatigue (see Figure 5, item 22, fourth row). In order to avoid looping between points 19-22 indefinitely, a reconfigurable time-out mechanism is set in order for the system to move forward, if there are no indications of improvement within twenty minutes.
23. Assuming a time-out from the previous point, or a lack of fatigue detection from point 19, the system proceeds to check if the lecturer is within his/her allotted time-limit.
24. If the lecturer is within this time-limit, the stage enables the lecturer to activate instances of fade-on / fade-off by touching components for visual interaction. This scenario ends when the time-limit is reached.
25. If he/she is outside this time-limit, all LEDs turn on

- to a single color as a visual queue to the lecturer that time is up. This scenario ends when the moderator confirms this via OSC confirmation. Having concluded this or the preceding scenario, the system returns to point 4.
26. Returning to point 4, having explored the consequences of the reactive stage being occupied by a lecturer, the consequences of it not being occupied are now detailed. If the stage is empty, then AVS may be engaged for playful and/or entertainment purposes. That is, AVS is habilitated as soon as the WSA is conformed (back in point 3), but in this development, it is only engaged when the stage is empty. In practice, as was carried out in initial sample runs of this point-by-point outline, AVS was engaged in a lecturer scenario.
 27. At this point the system decides to engage one of two other inherited play / entertainment scenarios depending on whether it is in-between lectures or not. In this development, the state confirmation is provided via OSC confirmation.
 28. If the stage is in-between lectures, the scenario in item 28, Figure 5 activates. In this scenario, the audience is invited to interact with the stage by *painting it*. That is, depending on the position and movement of identified body-parts of up to six people (via Microsoft® Kinect™ V2), different regions of the stage will change in color and intensity in direct correlation with the articulation of said parts. This scenario ends when a lecturer wearing the LBBs returns to the stage.
 29. If, however, the stage is simply on a day off, the scenario in item 29, Figure 5 activates. In this scenario, the stage pulsates like a *beating heart* in order to invite interaction from anyone in a passive manner. This scenario ends via OSC confirmation. Having concluded this or the preceding scenario, the system returns to point 4.

4 Discussion and Conclusion

The detailed development attempts to promote D2RP&O strategies and methods as enablers of an alternative approach to intelligence in the built-environment, here identified as high-resolution intelligence. This approach merges ICTs as well as Adaptive Architecture considerations in order to yield a holistically and comprehensively adaptive, reactive, and interactive dwelling space capable of providing local and remote services. In this paper, these objectives were illustrated via the extension of a proof-of-concept implementation whose subsystems were developed to

high TRLs and tested in naturalistic scenarios. Particular to this paper, three new features or mechanisms are presented and described, each retaining promising potential for expansion. In particular, the first mechanism, viz., Amazon®'s AVS is an especially important complement to the system in that its scope of service is open-ended. Via *Amazon Skills Kit* [18], custom skills may be designed and developed to accommodate environment-specific and purpose-built cost-effective devices, each capable of independent Internet access, effectively turning the dwelling space into a society of IoTs and people [19]. Furthermore, the possibilities extend to the urban scale, where public spaces may be envisioned to possess service capabilities that promote security, provide guidance, and support comfortable lifestyles.

At present, and in addition to on-going work on AVS's customized skills as well as more sophisticated ML mechanisms, work is being conducted to design and to develop an enclosable and integrated environment where an integrated ventilation system may ascertain *Interior Environmental Quality* [20], which is an indicator of comfort. It depends on thermal, acoustic, illumination, ventilation, and related parameters [21], and thus far only illumination, ventilation, and partial thermal aspects have been considered. Although IEQ lacks a globally accepted index [21], it is known that when its parameters deviate from comfortable thresholds, stress mechanisms are occasioned in the human body that—if left unmitigated—may potentially cause or exacerbate disorders and diseases [22]. Such considerations prompt an urgent reassessment of prevalent architectural strategies, especially since people spend the majority of their time indoors [23].

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