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INTELLIGENT ZONE CONTROLLERS: A SCALABLE APPROACH TO SIMULATION-SUPPORTED BUILDING SYSTEMS CONTROL

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ABSTRACT

This paper describes the concept of an intelligent zone controller for the efficient operation of environmental systems in buildings. This controller deploys a predictive control methodology with embedded simulation capability. To address the scalability issue in realization of predictive simulation-assisted control systems, we explore the possibility to divide the target building into a number of well-formed sub-domains. Thus, control logic and the associated simulation routines can be distributed and enacted both autonomously and asynchronously. Toward this end, we deploy an original generative scheme for representation of buildings' systems control architecture that allows for a structured distribution of systems' control logic.

INTRODUCTION AND BACKGROUND

In previous publications, we have introduced the concept and various implementations of simulation-assisted building systems control (Mahdavi 1997, 2001a, 2001b, 2008). In contrast to the majority of conventional control algorithms (e.g., rule-based methods, PID), the simulation-based control approach is proactive, rather than reactive. Note that the simulation-based approach is to be distinguished from the model-predictive control (Mosca 1995), as it involves the explicit and run-time deployment of numeric in the control core of buildings' environmental systems (e.g., for window ventilation and shading controls). Thereby, candidate control options (i.e., alternative combinations of the possible states of different control devices) for a future time instance are proactively accessed via performance simulation. The simulation results for these alternative control constellations are compared with regard to the control objective. Thus, better performing control actions are identified and executed.

Previous work by the authors and associated small-scale implementations of the approach were shown to be promising (Mahdavi 2008, Schuß et al. 2011). However, certain questions and concerns persist regarding the feasibility of the simulation-based control method in terms of its scalability. Past implementations involved mostly smaller objects and modest numbers of control devices. In order to apply the simulation-based control strategy to larger multi-zone buildings with multiple environmental control systems, new creative solutions must be developed and tested.

In conceiving the intelligent zone controllers, we intend to address the scalability issue of the predictive simulation-assisted control methodology. Toward this end, we pursue a specific approach to building's control scheme involving the division of the target building into a number of well-formed sub-domains. Hence, locally applied control decisions do not require that the building's entire control state space is generated and virtually mapped all the time. Rather, control logic – and the associated simulation routines – can be distributed and enacted both autonomously and asynchronously. Accordingly, we deploy an original generative scheme for representation of buildings' systems control architecture that allows for a structured distribution of systems' control logic. The scheme is derived cogently from a limited set of initial relationships between two entity layers. The first entity layer comprises of building zones subject to environmental control actions. The second layer comprises of technical devices responsible for control functionality. The entire control scheme – including the zone controllers with embedded compartmentalized simulation routines – is derived in an automated fashion based on the relationships between the above two layers.

Besides supporting scalable implementations of the simulation-based control methods, the proposed generative control systems schema generation has the potential to address certain problems associated with environmental systems control, particularly in large and complex buildings. Such problems include, for example, the extensive initial periods of time necessary for system tuning and debugging, subpar energy performance, intensive maintenance requirements, and user dissatisfaction. Many measures and approaches have been proposed and implemented – with various level of success – to address these issues, including a well-conceived, highly structured, and properly documented building commissioning, delivery, and operation process that would involve integrated design, team decision making, proactive user involvement, continuous quality control and system performance monitoring, post occupancy analysis, and user feedback assessment. In this context, we argue that the design methods of systems control architecture in buildings have not kept pace with the integration requirements of increasingly complex technologies for heating, cooling, ventilation, and lighting of buildings. Decisions regarding the environmental control systems' type and devices, the number and extent of control zones, as well as the type, number, and position of sensors neither follow a structured approach, nor reflect a traceable reasoning. Rather, such decisions seem to be frequently made on an ad hoc basis. Moreover, decision processes in one domain (e.g. thermal control systems) are rarely coordinated with other domains (e.g. visual control systems). Such lack of structure and integration is likely to cause inefficiencies in design and operation of buildings and their systems. Specifically, implementations of innovative (e.g., predictive) building systems control strategies may be hampered in part due to a lack of transparent and systematic representations of the buildings' systems control architecture. Classical literature on control theory does not address this problem (CIBSE 2000; Franklin et al. 2006; Unbehauen 2008; Mosca 1995). More pertinent previous research work in this domain (Mahdavi 1997, 2001a, 2004; Mertz and Mahdavi 2003) has not affected the current state of practice.

Given this background, the present contribution focuses on a very specific part of the building systems control challenge, namely the formulation and realization of the systems control logic. Our effort concerns primarily the process of building systems control scheme generation via the decomposition of the target control domain in terms of a number of well-formed sub-domains. Toward this end, we have developed a generative scheme for representation of buildings' systems control architecture that allows for an integrated and structured (hierarchical and traceable) distribution of systems' control logic. The scheme is derived from a limited set of initial relationships between two entity layers. The first entity layer comprises of building zones subject to environmental control actions. The second layer comprises of projected devices responsible for control functionality. Once sub-domains are defined in a consistent manner, a network of communicating yet more or less independent zone controllers can be assigned to them. The proposed approach has thus the potential not only to benefit simulation-based control methods in view of scalability considerations, but also to improve the design practices of the systems control architecture in building automation systems toward integrating the requirements of increasingly complex technologies for heating, cooling, ventilation, and lighting of buildings.

CONTROLS TERMINOLOGY

There is a lack of a universally agreed-upon terminology in building systems control. Thus, to facilitate the present treatment, a few terms, definitions, and exemplary instances are adapted as per Table 1. Figure 1 illustrates a basic control loop: A device is assigned to control a certain parameter of a control zone. The controller (seat of the control algorithm) receives sensory information (S) concerning this parameter and manipulates the devices actuator (A). Consequently, the device delivers to (or extracts from) the control zone some amount of mass and/or energy via the device's terminal (T). The building systems control terminology of Table 1 works fairly well, if certain conditions, qualifications, and simplifications are applied. Two such qualifications are briefly discussed below.

First, "control zones" should be rather viewed as the physical targets of control actions and not necessarily as architectural entities such as rooms. To exemplify this point, Figure 2 illustrates a simple office space with multiple devices and multiple overlapping zones. As this Figure demonstrates, the devices may have different and overlapping intended impact areas (control zones). Thus, zones may be associated with parts, whole, or aggregations of architectural spaces.

Second, a control device is not necessarily a simple stand-alone technical component (such as window or luminaire) that has just one actuator with a simple set of distinct states. Rather, it is frequently a complex and nested (hierarchically organized) technical system. For example, a building's mechanical ventilation system consists of numerous components at multiple levels. Large amounts of conditioned air mass may be centrally prepared, distributed around the building over an extensive network of ducts, and finally delivered – via multiple terminals – to the building's multiple thermal zones. Terminals may in turn possess embedded, individually controllable, generative elements (such as reheat coils).

To simplify matters, we suggest viewing a complex device in terms of a black box, whose virtual actuator is realized in terms of the device's terminal (i.e., its interface with the control zone). The assumption is that the complex device's machinery within the black box is controlled in a way such that, upon request (i.e., upon manipulation of the device's virtual actuator) modulated amounts of mass and/or energy would be released to (or extracted from) the target control zone. In other words, the control device in the present discussion can be regarded as a zone-specific terminal of an overarching nested system, which is represented in the proposed generative control schema through its virtual actuator.

Table 1
Building control terminology (based on Mahdavi 2001a, 2004).

TERM	**DEFINITION**	**INSTANCE**
Controller	Agent that sets control actions	People, software
Control action	Induced change in the state of a control device's actuator	Opening a window, switching lights on/off
Actuator	Component of a device that changes the device state	Valve, dimmer, people
Control device	A component/system that delivers to (or remove from) a control zone mass and/or energy	Window, luminaire, HVAC
Control device terminal	The technical component of a control device that acts as its interface to the control zone	Radiator, diffuser
Control objective	To maintain a certain state in a control zone by keeping the respective control parameter in a certain range	Maintaining air temperature (or illuminance) in a control zone (a space, a task plane) within a certain range
Control parameter	Indicator of the control zone's relevant state	Air temperature, relative humidity, illuminance
Actuator state	Position of a control device's actuator	Open/close, dimming level, valve position
Control zone	Target domain of control action	Workstation, room, floor, building
Control state space	The logical space of all possible positions of all relevant actuators	All possible positions of windows, blinds, luminaires
Sensor	Reports the value of a zone's control parameter	Thermometer, photometer

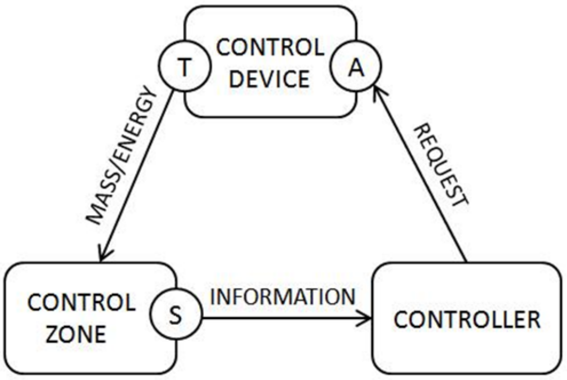

Figure 1 A basic control loop involving a control device, a control zone, and a controller ("T" and "A" : device's terminal and actuator; "S": sensor).

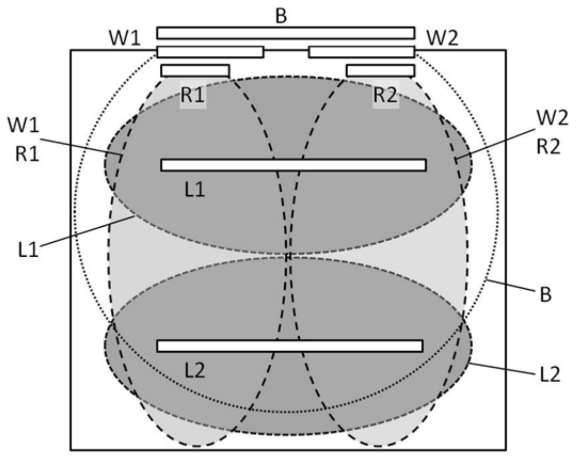

Figure 2 Illustrative depiction of a simple office space plan with multiple devices (B: external shade; W1, W2: windows, R1, R2: radiators; L1, L2: luminaires) and associated control zones.

CONTROL LOGIC SCHEMA

Defining the problem

In most practical cases, the assumption of a one-to-one mapping between devices and control zones does not apply. Rather, the control parameter (e.g., air temperature) in a target control zone may be influenced – intentionally or unintentionally – by the operation of multiple devices such as windows, radiators, and shading elements. Likewise, the operation of a single device such as shading element may influence two or more distinct control parameters representing different control zones (e.g., indoor temperature and task illuminance). In other words, devices and zones could maintain one-to-one, one-to-many, and many-to-one relationships. Thus, more often than not, the control task in a building must address a many-to-many pattern of relationships between control devices and control zones. The problem can now be framed as follows. On the one hand, a decentralized distribution of control logic appears attractive in view of considerations pertaining to system robustness, scalability, flexibility, adaptability, and security. On the other hand, the complex interplay of multiple devices in view of their implications for multiple control zones appears to favor a rather concentrated organization of control logic. In the extreme, where all devices can influence all zones, the control logic will have to be highly centralized. To address this problem, we have further advanced a previously introduced schema for the architecture of a building's systems control logic (Mahdavi 2004).

We envision a simple generative schema that allows for the high-level representation of a building's systems control logic. The starting point for schema generation is the unambiguous definition of two entity layers, namely control zones and control devices. Subsequently, the relationships between these layers must be established. A relationship denotes either a physical intervention involving mass and/or energy flows instantiated by the device controller and acting on the control zone, or zone state information flow via zone sensor to device controller. Note that the definition of two entity layers and their relationships typically involves some heuristically-based judgments and associated uncertainties. For instance, unintentional minor impact of a specific device such as heat emission of an energy efficient luminaire on a specific zone state indicator such as air temperature may be neglected, as the purpose of a luminaire is not to heat a zone, but to illuminate it. Moreover, the assumed impact zone of a device and its actual impact area may be different: The impact regions of control devices can be rarely defined in terms of sharp boundaries. Computational methods (simulation, sensitivity analysis) to support the design task in dealing with such uncertainties are conceivable and under development. However, we shall not deal with them in the present treatment.

We suggest that the distributed architecture of the building systems' control can be derived cogently from the aforementioned limited set of initial relationships between two entity layers, control zones and control devices, in an automated rule-based fashion (Mahdavi 2004; Mertz and Mahdavi 2003). This architecture can be seen as a template of distributed nodes, which can contain partial methods and algorithms for control decision making.

Generation rules

If a control task involves only one-to-one relationships between control devices and zones, the control logic architecture would be trivially distributed (maximally flat). At this basic level, every device can be thought as having a device controller (DC). The task of DC is to operate the Device's actuator autonomously, in the absence of higher-level requests. However, as previously argued, the real world building systems control tasks often involve many-to-many relationships. In the theoretical extreme case, where every one of p devices would influence every one of q zones, $p \times q$ relationships between devices and zones would have to be reckoned with. While real cases might not be nested as much, there is still a great deal of interdependency. Consequently, the design of a required complex control code structure could be supported, if it could be broken done into a manageable number of clearly defined segments or nodes. Generative rules could be applied to derive such nodes in the control schema for the accommodation of well-formed pieces of control logic in terms of rules, algorithms, and simulation code. We propose a set of such generative rules toward generating a multi-nodal control logic schema, i.e., a unique hierarchical multi-layered configuration of nodes for a specific control task:

- Step 1: Arrange distinct control zones as the basis layer of the schema. The state of these zones is captured via respective zone sensors.
- Step 2: Arrange device controllers (DCs) in the next layer. Every individually controllable device is assumed to have a DC.
- Step 3: Connect device controllers (DCs) to the zones, whose states are appreciably influenced by the operation of DCs.
- Step 4: Generate the zone controllers' layer as follows: If more than one DC influences the same zone, a respective zone controller is required to coordinate their operation. This layer accounts thus for the need for zone-specific coordination across multiple devices.
- Step 5: Generate the high-level controllers (HC) layer as needed: If a DC receives requests from more than one zone controller, a high-level controller (HC) is generated. This layer accounts thus for the need for device-specific coordination across multiple zones.
- Step 6: If high-level controllers overlap in terms of devices involved, merge them into one meta-controller.

Such a schema may be generated for an entire building or any part of a building that may be regarded as closed (well bounded) in terms of control actions and their implications.

An illustrative schema generation example

Consider the illustrative control task pertaining to a simple office space as depicted in Figure 3. The control task is to maintain a number of zone state indicators or control parameters within target values. These are in this case air temperature (θ), relative humidity (RH), carbon dioxide concentration (C), and illuminance (E_1, E_2). The control task is to be accomplished via the operation of windows (W1, W2), a shading device (B), radiators (R1, R2), and luminaires (L1, L2). Following the steps described in section 3.2, the distributed multi-layered multi-domain systems control schema of Figure 4 emerges. Layers 1 (zones) and 2 (device actuators) result from steps 1 to 3. Layers 3 (zone controllers) and 4 (high-level controllers) result from steps 4 and 5 respectively. Layer 5 (meta-controller) results from step 6. In this schema, the direction of control requests is downwards, whereas the sensor information flows upward.

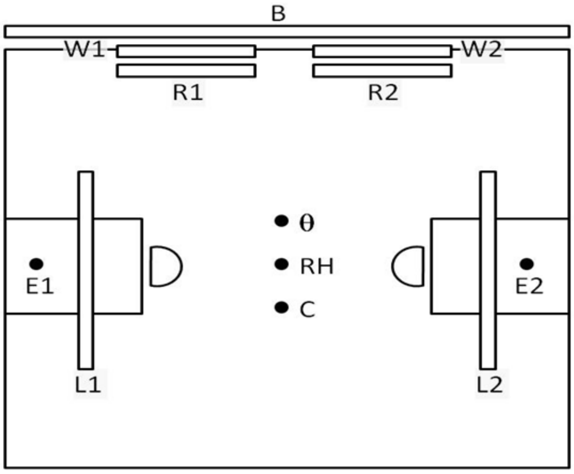

Figure 3 An office space with seven devices (windows W1 and W2, radiators R1 and R2, luminaires L1 and L2, external shade B) and five sensors (illuminance sensors E1 and E2, indoor temperature, relative humidity, and carbon dioxide sensors θ, RH, and C).

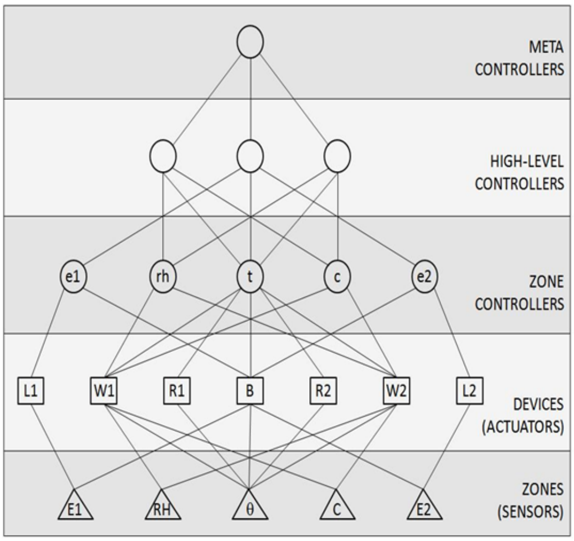

Figure 4 An Illustrative distributed multi-layer multi-domain systems control schema for the office space of Figure 3.

Populating the schema with semantics

The generated schemata for building systems control obviously does not predetermine what kind of control method or style is applied at each instance. Rather, the nodes in this schema represent containers or place-holders for pertinent parts (code segments) of the overall control logic. Consequently, the nodes can accommodate a variety of control rules and algorithms. A crucial benefit of the schema can be seen in its potential to provide a structured platform for a modular and distributed assembly of control code for large and complex buildings.

The manner in which the schema could be populated with control semantic could be further discussed with reference to the simulation-based control strategy (Mahdavi 1997, 2001b, 2008). This strategy frames the control task as navigation of the control state space. In case of multiple devices with a large number of possible states, the computational handling of the control state space may become infeasible. A circumstance that is further aggravated due to the necessity to conduct such computations on a recurrent basis: The control process is a dynamic one, given the changing nature of relevant boundary conditions such as weather, occupancy, as well as user preferences and priorities. Hence, the optimal combination of device actuator positions must be arrived at in an ongoing manner. To reduce the size of the control state space, various methods from operation research and optimization can be applied (Mahdavi 2008; Schuss et al. 2011).

To semantically populate the proposed generic system, the simulation-based control strategy could make good use of the nodal structure. Devices can be equipped with simple methods to either autonomously operate their actuators (e.g., in case of system communications break down), or to suggest, to the upper layers, preferable actuator positions. Zone controllers could merge the recommendations they receive by comparing the advantages of operating one device versus another. Alternatively, they could use partial system models to predict, compare, and evaluate the performance implications of recommendations from the lower layer. Similarly, meta-controllers could evaluate submitted options via some performance criteria (e.g., the pertinent devices' energy use), or they could independently conduct whole system simulations for all or a part of the recommendations they receive.

An attractive feature of the proposed schema is its capability to flexibly accommodate multiple evaluation criteria toward optimal control decision making. Thereby, evaluation criteria can be represented not only in terms of real sensors but also in terms of calculated, derived, simulated, aggregated, and virtual sensors. For example, performance indicators such as mean radiant temperature, PMV (predicted mean vote), and various glare indices could be computed in real-time and the results could be reported by the sensors to the higher levels of systems control hierarchy. Likewise, environmental performance criteria such as CO2 emissions attributable to consumption of a certain type of fuel as well as economic performance indicators such as energy-related expenditures could be effectively accommodated in the schema in terms of corresponding virtual sensors.

A prototypical implementation instance

Currently, an actual implementation of the proposed approach is being prepared within the framework of the EU-supported CAMPUS 21 project (CAMPUS 2011). Toward this end, the Environmental Research

Institute (ERI) Building of the University Collage Cork (UCC) is selected. An open office space in this building will be used for the prototypical implantation. The ERI Building (Figure 4) has an up to date building automation system and a fairly comprehensive monitoring infrastructure. The selected south-facing space (Figure 5) is located in the first floor (Figure 6).

The documentation of the original control setup does not reveal an explicit analysis of the complex relationships between devices, actuators, zones, and sensors. The first step in the implementation of the control task is thus to capture and represent such relationships. As the schematic representation in Figure 7 shows, the space has the following individually controllable devices: 4 blinds (B1 to B4), 4 operable windows (W1 to W4), and 4 sets of 2 luminaires (L1A/L1B to L4A/L4B). Moreover, the space is supplied with a constant volume air system (V) and a floor heating system (H). The control objective is maintaining the values of a number of zone state indicators or control parameters within target values. In this case, the control scheme is based on the assumption of 4 lighting zones (represented by illuminance sensors E1 to E4), and two compound hygro-thermal and indoor quality zones represented by two sets of sensors for air temperature, relative humidity, and carbon dioxide concentration ($\theta1$, RH1, C1 and $\theta2$, RH2, C2). Following the previously described generative steps, the distributed multi-layered multi-domain systems control schema of Figure 8 emerges. In this schema, layers 1 (zones) and 2 (device actuators) result from steps 1 to 3. Layers 3 (zone controllers) and 4 (high-level controllers) result from steps 4 and 5 respectively. Layer 5 (meta-controller) results from step 6. Note that, for simplification purposes, secondary (relatively less essential) device influences on zones (dotted lines in Figure 8) were neglected in the scheme generation process. Hence, the resulting schema includes one meta-controller for the coordination of the two high level controllers for hygro-thermal and air quality zones.

Figure 4 The ERI Building.

Figure 5 Selected open office space.

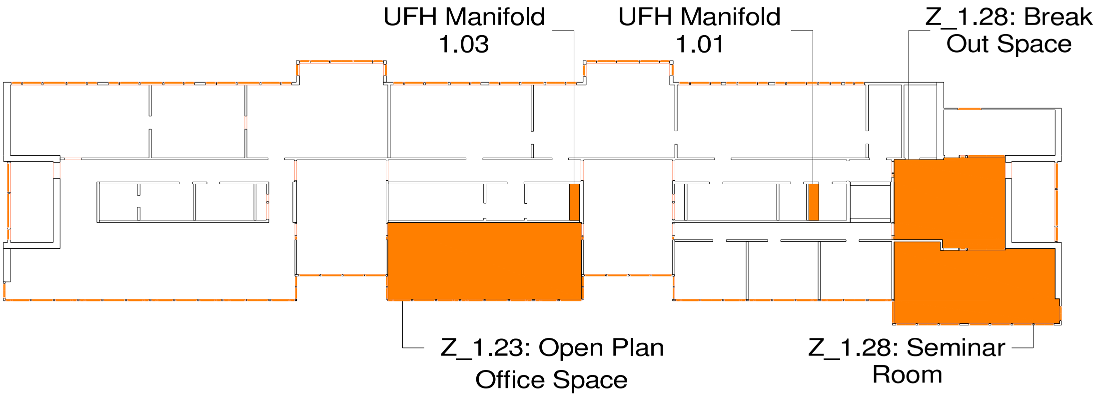

Figure 6 ERI Floor plan with demonstration room Z_1.23.

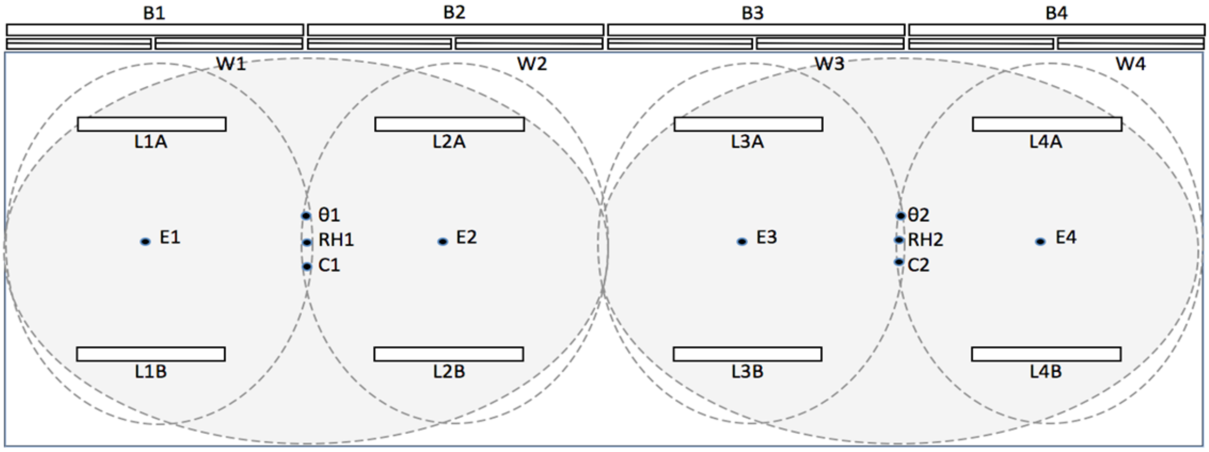

Figure 7 The ERI office space (Z_1.23) with devices (windows W1 to W4, luminaires L1 to L4, external shade B1 to B4) and sensors (illuminance sensors E1 to E4, indoor air temperature $\theta$and θ, relative humidity RH1 and RH2, and carbon dioxide sensors C1 and C2).

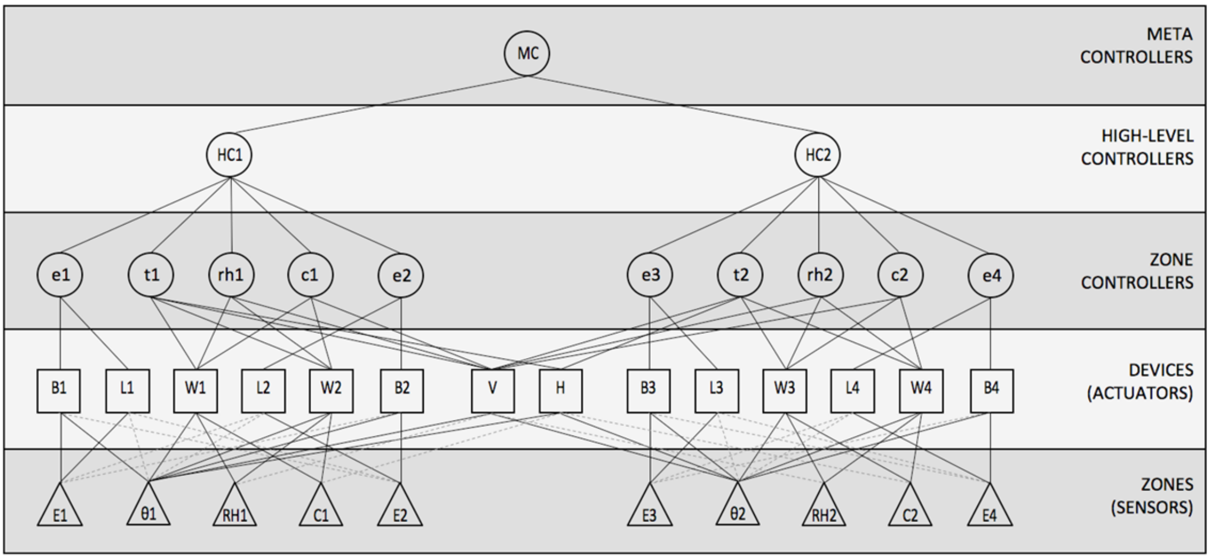

Figure 8 The distributed multi-layer multi-domain systems control schema for an office space (Figure 7).

CONCLUSION

This contribution described a method to generate a schema for the control architecture of multi-zonal multi-domain building systems control scenarios. The schema allows breaking down a complex control task into five layers (zones, devices, zone controllers, high-level controllers, and meta-controller). Zone controllers facilitate zone-specific coordination of multiple devices. Nodes in the high-level controller layer facilitate device-specific coordination across multiple zones. These nodes provide thus containers for the distributed encapsulation of the building systems control semantic. Specifically, predicitve control with embedded simulation can take advantage of the nodal structure of the schema, addressing thus the scalability challenge: The underlying simulation model and code can be distributed and enacted both autonomously and asynchronously.

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