Thinking Ahead: Autonomic Buildings

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ABSTRACT

The time has come for the commercial buildings industries to reconsider the very nature of the systems installed in facilities today and to establish a vision for future buildings that differs from anything in the history of human shelter. Drivers for this examination include reductions in building operation staffs; uncertain costs and reliability of electric power; growing interest in energy-efficient and resource-conserving "green" and "high-performance" commercial buildings; and a dramatic increase in security concerns since the tragic events of September 11.

This paper introduces a new paradigm – autonomic buildings – which parallels the concept of autonomic computing, introduced by IBM as a fundamental change in the way computer networks work. Modeled after the human nervous system, *"autonomic systems"* themselves take responsibility for a large portion of their own operation and even maintenance. For commercial buildings, autonomic systems could provide environments that afford occupants greater opportunity to focus on the things we do in buildings rather than on operation of the building itself, while achieving higher performance levels, increased security, and better use of energy and other natural resources.

The author uses the human body and computer networking to introduce and illustrate this new paradigm for high-performance commercial buildings. He provides a vision for the future of commercial buildings based on autonomicity, identifies current research that could contribute to this future, and highlights research and technological gaps. The paper concludes with a set of issues and needs that are key to converting this idealized future into reality.

Introduction

Much has been written about creating intelligent capabilities in building equipment, systems, and controls (Brambley, Armstrong & Kintner-Meyer 2001; DOE 2001a, 2001b; Dexter 1996; Caffrey 1988), yet little true intelligence as measured by the Turing test (Turing 1950)[1] or the possession of consciousness by computers has been accomplished in buildings or other anthropomorphic devices (machines and computers). In fact, the focus on cognition and consciousness may have contributed to widespread disappointment in the field of artificial intelligence (AI) as it did not fulfill many of its claimed promises over the last 20 or so years. Artificial intelligence has subtly evolved from a highly visible field surrounded by enormous claims to a field that is providing "small" yet important capabilities based on the methods that have emerged from earlier investigations as they now appear as parts of software systems, some widely-used, others highly specialized (Hilzik 2002).

[1] The Turing test is a widely-referenced test for determining whether a digital computer possesses intelligence. It involves a game of imitation where an observer by asking questions tries to distinguish between answers given by a human and those provided by the computer.

Those of us employed in contributing to creating the future of buildings might benefit from modeling this change in future vision and deployment of new technologies for the control and operation of buildings and their component systems.

In 2001, IBM Corporation released a manifesto calling for a massive effort to develop, not intelligent systems, but rather *autonomic computing* (MetaGroup 2001; Scannell 2001; IBM 2001). These systems would be modeled after the autonomic capabilities of the human body, in particular the autonomic nervous system, and possess features such as self-configuration, self-healing, and self-protection. The primary purpose of this "call to arms" led by IBM was (and is) to address the incredible rate of growth and complexity of computer networking for which IBM estimates the number of administrators required to manage worldwide computer networks in 2010 will approximately equal just a little less than the current population of the United States (IBM 2001).

For buildings, the concept of *autonomic buildings* might provide a better vision and target for research and development focused on providing better built environments for the future.

This paper focuses on describing autonomic systems modeled roughly after the human autonomic nervous system, presenting the concept of autonomic buildings, describing some of the features of future technology for such buildings, and identifying research needs to realize this future.

Background--The Autonomic Nervous System (ANS)

The nervous system (Bakewell 1995; National Dysautonomia Research Foundation 2002; McGill University 2002) of humans and other mammals consists of the somatic nervous system, which provides voluntary muscle control and information from the senses, and the autonomic nervous system (ANS), which regulates the function of organs and ensures the body's homeostasis (i.e., a relatively stable state of equilibrium—such as body temperature, fluid content, and the pH of blood—under fluctuating environmental conditions). (Merriam Webster 1997) The somatic system conveys impulses from the sensory organs (e.g., eyes, nose, ears, and skin) to the cerebral cortex, where the sensed conditions (light, smells, heat, touch, sound) reach our awareness. It also enables us to voluntarily control body movements by sending impulses to our skeletal muscles. The ANS, in contrast, controls body functions such as heart rate and force of contraction, constriction and dilation of the vascular system, breathing rate and depth, constriction and relaxation of smooth muscles for organs, digestion, and visual accommodation, all without any awareness (cognition) of the human or animal.

Control by the ANS is provided by sensory impulses transmitted from the controlled organ (e.g., the heart) via nerves that elicit mostly automatic or reflex responses causing appropriate reactions in the controlled organs. For example, if the need for more oxygen in the muscles is caused by exercise, the heart and lungs automatically respond to the appropriate rates to accommodate needs without any cognitive awareness or intentional control. The control impulses originate from many places in the nervous system, not all from the brain. Examples include: ganglions in the nervous system, the spinal cord, the brain stem, the midbrain, and to some degree the cerebral cortex.

The ANS consists of two major component subsystems, the sympathetic and the parasympathetic (PS) nervous systems. The function of the PS is primarily to control resting functions, such as digestion of food and energy storage. It detects conditions and instigates contraction of the pupil and changes in the curvature of the lens of the eye, stimulation of the salivary glands, stimulation of the digestive process in the stomach (secretion of digestive juices and mixing), sexual stimulation, and emptying of the rectum and bladder (which are only partially involuntary). As the result of limited branching of the PS nerves, most of the effects of this system are highly targeted and localized. The function of the sympathetic system, in contrast, is primarily to adapt the body systems to changes in external conditions. It controls the rate of secretion from the sweat glands, constriction and dilation of blood vessels, increase in the rate and strength of heart contractions, bronchial dilation, "goosebumps" and hair standing on end, and control of the metabolic system (mobilization of fat and glycogen).

The sympathetic nervous system also provides the "fight or flight" response of humans and animals, which prepares the body for threatening situations and includes responses such as increased heart rate, increased blood pressure, increased blood flow to the brain and skeletal muscles, dilation of the pupils, hair standing on end, and increased mental alertness (McGill University 2002). These responses occur very rapidly and without a cognitive decision to do so.

The autonomic nervous system, working in concert with the endocrine system, the immune system, and the somatic motor system, automatically provides for homeostatic control of the body and response to changes in our external environment (McGill University 2002). Together these systems provide maintenance of stable internal body composition and conditions (homeostasis), protection from outside intrusion and threats, and healing from disease or injury. Because these processes occur autonomically, we can concentrate (cognitively) on what we decide to do rather than on routinely operating and maintaining our body systems. Analogies with this automatic operation, maintenance, and control are the foundation upon which the concept of autonomic buildings is based.

Autonomic Buildings

Building from the discussion above, autonomic buildings would provide day-to-day functioning automatically. Building operators or occupants would not need to concern themselves with operation of the building, freeing them to focus on the things we do in buildings rather than the operation of the building itself. All but the most extraordinary events would be handled by the building systems themselves. The building itself would not necessarily need to possess intelligence (or more accurately cognitive awareness) but rather would be operated by systems like the ANS which responds without conscious thought. Some problems would be handled at a local level (e.g., a local device such as a valve or damper), others at a higher level of control (e.g., changing the set point for chilled water), and others at a building or facility level (e.g., implementation of pre-cooling of spaces prior to peak electric periods during hot days in response to a change in the electric rate structure or even price as a function of time). In addition to these direct adjustments, the systems would automatically correct for (or take advantage of) system interactions, much like the parasympathetic and sympathetic parts of the autonomic nervous system interact to produce the desired state in the body.

Isn't this exactly what we have today with direct digital control systems? Partially, and only partially. Direct digital control (DDC) provides the capability for both feed forward and feedback control. The body uses feedback control extensively to regulate its systems. For example, when you walk outside on a hot summer day, the body temperature begins to rise in response to decreased heat transfer from the skin to the environment by radiation and convection. This change is sensed by the hypothalamic center which automatically sends impulses via nerves in the sympathetic nervous system to sweat glands throughout the body, increasing the rate of perspiration, which enhances evaporative heat transfer. At the same time, the sympathetic system sends impulses to the blood vessels in the skin causing them to dilate and increase the flow of blood at the surface of the body, increasing skin temperature and, as a result, radiative and convective heat loss. When the body temperature decreases sufficiently, feedback from sensory inputs automatically causes a reduction in sweating and surface blood flow rate, again contributing to maintenance of relatively stable internal body temperature. No thought is required for these adjustments in body systems. They occur automatically. This is the primary model behind the concept of autonomic buildings.

How then would autonomic buildings be different than intelligent buildings? The principal difference is not so much in the intent of "intelligent buildings" but a change in the ultimate technological target or objective and elimination of a misnomer. The term "intelligent buildings," has led to confusion regarding what exactly a building with intelligence is (Dexter 1996), much like the pursuit of "awareness" by machines muddled the perceptions and expectations of AI for many years. The characteristics of buildings and building systems that will provide a high level of performance are much better aligned with "autonomicity" than with intelligence. In fact, most features of highly advanced building control can probably be accomplished without adding any real intelligence to building systems (and definitely without giving them awareness). By focusing on providing autonomic behavior rather than intelligence to building systems, researchers and technology developers can avoid the trap of assuming that to operate at a high level of automation building systems and equipment require knowledge or intelligence. Providing the desired capabilities in building systems might actually be easier by developing systems that automatically respond to conditions without thought, compared to embedding the capacity to think (intelligence) in them. As a result, pursuit of autonomic buildings might lead to earlier technological improvements for buildings (if it is easier).

In addition, a model for future buildings based on the autonomic systems of the body may provide concepts for new systems, in addition to control, that are not as evident from (or inspired by) the concept of intelligence. Consider for example, buildings that would "perspire" onto their surfaces to increase evaporative heat transfer—somewhat like evaporative coolers, except using the entire exterior surface rather than isolated machines. Porous envelop skin could provide for "perspiration" by the building onto its surface. Or, maybe a commercial building that requires cooling year round that increases circulation of water through its "skin" during cold periods to pre-cool the water before sending it to a chiller (if additional chilling were required at all). Such as system might be modeled after the human circulatory system. Models based on the body might lead to technology not even envisioned today that meets our needs in buildings better.

Why is the concept of autonomic building needed? Isn't the concept of high-performance buildings sufficient? The U.S. Department of Energy in collaboration with a number of stakeholders has developed the concept and facilitated development of an industry roadmap for evolution of high-performance buildings through research, development, and market transformation over the next 20 years (DOE 2000, 2002). This work establishes qualitative (and ultimately quantitative) performance targets for buildings of the future with respect to energy performance, use of resources, and meeting the needs of building occupants. It also identifies many key activities needed to achieve increases in performance of the building stock. The high-performance concept, however, does not have embedded in a model for achieving high performance. It provides a target end point, but not an enabling vision. Much like IBM's use of the term "autonomic computing" (IBM 2001) which carries with it a model for achieving high performance computing systems (even a highly-integrated, high-performance, worldwide computing system) by focusing on the need for automatic operation and maintenance of computing devices and systems, "autonomic buildings" carries with it concepts at many levels from the human body that can serve as models for building systems and control of the future. The title itself provides an enabling vision, which will lead to high-performance buildings. These two concepts might be used together to establish a long-term vision that guides buildings technology development.

The next section of this paper discusses the key characteristics of autonomic buildings, paralleling the description of autonomic computing developed by IBM (IBM 2001).

Eight Key Characteristics of Autonomic Buildings

The eight key characteristics of autonomic buildings further develop the concept and explain the vision.

Infrastructure for Autonomic Reaction

An infrastructure is required to enable autonomic response to changes in the external environment, internal demands placed on the system (e.g., exercising for the human body or hosting a conference for a commercial building), or threats to the system (such as presence of an infectious bacterium for the body or failure of a sensor for an HVAC control system). This infrastructure must provide for acquiring necessary data and must possess the mechanisms by which to respond appropriately in many different situations, some which are unpredictable.

This is the one characteristic (or element) for which we deviate from the IBM manifesto for autonomic computing. The manifesto claims that "an autonomic system will need detailed knowledge of its components, current status, ultimate capacity, and all connections to other systems to govern itself," (IBM 2001) despite rejecting the need for machine intelligence elsewhere in the document and modeling autonomic computing after the autonomic nervous system. We characterize autonomic buildings as not requiring knowledge (which seems to imply cognitive ability) but instead requiring sensing, connections, and relationships, i.e., the infrastructure. This infrastructure provides connections among all components that affect one another directly or indirectly for the purposes of obtaining data (i.e., sensed conditions) and sending control signals to instigate (actuate) responses. It must also provide the ability to respond appropriately, i.e. to relate sensed conditions properly to instigated responses through control signals.

Our bodies have five senses that we recognize plus the ability to detect conditions internally and intrusions from outside which we do not directly experience. The skin, as an example, besides serving many other functions provides a covering over the external surface of the body that is populated by nerve endings which serve as sensors. Similarly, the autonomic-building infrastructure will require much higher diversity and density of sensors than today's buildings. This will require development of smaller, more accurate, more stable, less costly sensors that can be deployed at high densities to provide the input for processing that leads to autonomic response. Besides sensing, the pathways for communicating sensed conditions and signals to instigate autonomic response will be required, much like our extensive nervous system provides the communication pathways for sensing and transmitting impulses that trigger responses by the body.

The evolution of the human body over millions of years has allowed its systems to develop sufficiently to possess the relationships for autonomic response. Operation of our internal systems requires no knowledge from us. It all happens automatically (for a healthy body). Buildings, being created by humans, require that we possess the knowledge necessary to make them autonomic, if we are to achieve this vision, but each building and its systems need not possess this knowledge and the ability to operate on it. No knowledge and no intelligence is required at the building, provided we create systems that mimic the automatic response to stimulus required to achieve high-performance automatic operation. Sufficient connectivity and the proper relationships between sensed conditions and proper responses are the keys. This represents a significant departure from "intelligent buildings."

Self-Configuration and Re-Configuration

An autonomic building should automatically set up itself for operation. This might include, discovering its components, specifying proper control algorithms, automatically ensuring that equipment and controls operate properly (self-commissioning), and dynamically adjusting the configuration to optimize performance in response to changing, even unpredictable, conditions. In the future, this may include calling on external resources (e.g., via the world wide web) to ensure proper operation, recovery from failures, or implementation of technological improvements.

Self-Optimization

An autonomic building will constantly optimize its operation and that of its components. It will monitor its state as well as external conditions (e.g., fuel and electricity prices) and adjust operations to optimize outcomes (e.g., minimum total life-cycle cost of operation consistent with healthy and comfortable indoor environmental conditions, security, and other concerns).

Such a building will require feedback control mechanisms beyond those available today. These controls will need to automatically control for indirect interactions among systems and equipment as well as those obviously and directly controlled. These systems will optimize across all building system interactions to achieve the specified optimal outcomes.

Self-Healing

Like healing provided by interactions of the immune system and ANS in humans by which injuries and damage to the body are automatically repaired, autonomic buildings should provide automated self-healing. Building systems should discover problems, anticipate potential future problems, and find alternate ways of providing their functions using other equipment or reconfiguring themselves temporarily or permanently. Some examples include:

1. Compensation through control for failed or degraded components by transferring some of the responsibility to other systems or components and optimizing performance of the entire building system in its current condition, until more complete repairs are made. Degradation of efficiency in a boiler might be compensated by temporarily transferring all or part of the load to another boiler temporarily.
2. Building materials that self repair damage or degradation resulting from aging or other events. This might include automatically fixing air and water leaks or damage causing structural weakening. Such materials might develop from technology similar to the autonomic healing polymer developed at the University of Illinois. (Wool 2001; White 2001)
3. Faults in control code might be self-discovered and automatically corrected or compensated for by the control system itself.

Self-Protection

The body protects itself by using a combination of physical/biological barriers (e.g., skin bathed in anti-bacterial substances) and the immune system. An autonomic building should protect itself against external attacks by detecting threats, identifying them, and taking protective action. Threats might include natural threats such as a severe storm with high winds or human acts to disrupt operation of the building, threaten its structural integrity, or threaten its occupants in other ways (e.g., by introducing a chemical or biological contaminant into the building ventilation system). Natural events might impede access to or egress from the building. An autonomic building could autonomically ensure that other routes are open and that occupants are directed to them, especially in emergencies. Other less significant events could include problems such an obstruction to a cooling tower fan introduced by severe wind. In this case, the system would automatically detect the presence of the obstruction before damage occurred to the fan motor or other components of the corresponding chiller plant, revise control to compensate for the temporarily disabled fan, and alert building-operation personnel of the problem.

Human attacks on the building or its occupants could take the form of cyber-attacks, attacks on the building structure, physical equipment and operation, or direct physical attacks intended to harm the occupants. Before the tragic events of September 11, 2001, direct attacks on the structure or occupants might have been considered absurd in the U.S. except for military facilities. This is no longer the case and many in the commercial building design and operation industries are now concerned about such attacks. An autonomic building should contribute to automatically detecting and thwarting such attacks.

Cyber attacks might be made against the building control system and the computer infrastructure on which it runs or against computer systems supporting business or other activities in the building. An autonomic building will provide protection for these systems most likely using technology provided by the broader computer-networking field.

Adaptability

An autonomic building must adapt to changes in its environment. Simple adaptation would include changes in control strategy or "firing up" equipment to adapt to changes in season and the associated whether. Other adaptations could include responding to factors such as a significant shadow cast by a newly-built neighboring building, changes in energy and power rate structures, short-term drastic changes in occupancy levels (e.g., for a hotel during a major event), changes in equipment in the building, re-modeling of spaces in the building or expansion of the building. As an example of adaptability, consider a building in which a space used as a single large meeting room at a conference one day is divided into five smaller meeting rooms for the next day. The HVAC control system in an autonomic building would recognize this change and automatically adapt control of the HVAC systems to ensure adequate provision of space conditioning and ventilation in these spaces.

Open Standards for Communication and Integration

Control and other computer processing and network systems in autonomic buildings will need to exist in a highly heterogeneous environment. This will require that building control system components readily interconnect and communicate. Control system components from different vendors will require a high level of interchangeability. Building control systems will also need to interact automatically with a variety of computer systems external to the buildings such as those of: suppliers of materials and equipment, distributors of fuels and electric power, energy (and other) markets, and government regulatory agencies. The systems will require the ability to execute transactions with yet unforeseen information devices and services. This level of integration will require open standards at all levels in the computer/network systems architecture, including the building-specific application layer. Recent advancements in this direction specific to buildings include the BACnet Standard (ANSI/ASHRAE 2001) and the Industry Foundations Classes developed by the International Alliance for Interoperability (IAI 1997) Although these efforts are laudable, much greater development and widespread application of standards in products will be required to achieve significant autonomic behavior by buildings.

Hiding Complexity

Autonomic buildings and their components will meet building needs in an optimal way without human intervention in the details. This already is done, mostly on a subsystem by subsystem basis with control systems, but not across all systems and not without frequent intervention. Autonomic buildings would take this automatic reactive behavior to the next level of integration. It would provide self configuration, self optimization, self healing, self protection, adaptability, and communication among all component systems/equipment. Realizing this complete vision will require complex techniques, many yet to be developed. This complexity should be "hidden" from users. Users, whether a building manager or occupants, should have very simple interfaces with which to convey their needs, desires and objectives to the autonomic building system. Information should be provided in a form readily and easily understood by each user. Much like most automobile drivers have little comprehension of the details of how their anti-lock brakes operate and have a very small role in triggering operation of the anti-lock mechanism except to indicate their objective to stop by firmly and constantly applying the brake, there should be no need for humans to interact with building system(s) frequently or spend special time and effort learning the building systems. The system should conform to the needs of the humans and take over responsibility for implementation details. The systems should marshal the resources in anticipation of a need and be ready to operate when needed.

The next section expands on the required interaction of the systems in autonomic buildings to interact appropriately with humans.

Beyond Pure Autonomicity

The body, although a complex system with extraordinary automatic capabilities is not infallible. For example, although the immune system can in many cases detect intrusion by a bacterium or virus and successfully take action against the threat, it cannot always by itself adequately protect and heal the body sufficiently to prevent permanent damage, prolonged suffering, or death. Intelligent intervention by physicians is sometimes required to prevent infection, accelerate or manage healing, or relieve suffering. Similarly, autonomic buildings will require assistance from time to time to handle extraordinary events, even though the objective of autonomic buildings is to relieve humans of the requirements for "routine" operation and free the building systems of the limitations of human-controlled operation. Humans will also need to determine the objectives that the building systems must satisfy and somehow convey them to the building systems. These objectives may be governed by business needs, regulations, or other needs. The human-machine interfaces for autonomic buildings must provide easy access to information by specialists to intervene in extraordinary circumstances and for occupants or building managers to specify operation objectives for the building.

Because machines do not self-generate or replace themselves, yet fail or degrade over time due to wear, corrosion and other factors, they require physical repair or replacement occasionally. An autonomic building should provide information to human specialists regarding when such actions should optimally take place and automatically identify what should be done. Such capabilities might require knowledge and intelligence on the part of the building systems, taking them beyond purely autonomic systems into the realm of intelligence. These are topics currently under investigation in the field of fault detection, diagnostics, and prognostics.

Autonomic systems would be supplemented by human and machine intelligence, but the objective of autonomic buildings remains to provide building needs in as automatically responsive a manner as possible.

Technology and Research Needs

Much of the technology for realizing autonomic buildings already exists in rudimentary forms such as automatic feedback control, sensor technology, computer networking technology, even standards for sharing data among control-system components. These technologies, however, are generally not sufficiently developed or adapted to meet the needs of autonomic buildings.

Sensors, for example, exist for measurement of most conditions and properties—temperature, pressure, humidity, flow rates, physical position—needed for control of autonomic building systems, but their installed costs are too high and reliability too low. To achieve the vision of autonomic buildings, sensors must become ubiquitous in buildings. This will require development of lower-cost, higher-reliability, longer-lived sensors, and lower cost means for transporting data from sensors to points where that data is processed. Wireless data transport technology shows promise for very significant reductions in cost in the future, yet its use for data collection in buildings may require specialization for this application and integration with sensors themselves to simplify sensor installation.

Automatic control also exists, but its use in most cases in buildings has been limited to control of individual equipment and systems. Integrated control, accounting for all building-system interactions, is limited and needed. The current trend toward integration of distributed electricity generation with sources and sinks of thermal energy to form combined heating, cooling, and power systems will increase the need for an even higher level of control among active systems.

In other areas, such as self-healing materials, research and development is just beginning to provide new technology. Fundamental research in this field, although focused on applications like defects in circuit board materials is likely to yield advancements that can be adapted to building materials (with additional development).

Self-configuring and adaptive control systems are also areas requiring significant advancements. Developments in the use of data in the architectural, engineering, and construction field today focus on creating the ability for software from different sources to share data. Although not yet fully developed and widely implemented, this is only an elementary step towards automatic discovery of other components and systems and self-configuration of systems.

The field of cyber-security is advancing quite rapidly. Some might question whether it exceeds the rate of development of methods for bypassing security, but significant resources are dedicated to advancements in this field, so that the need for special research for cyber-security for building operation and control is likely to be limited.

Physical security for buildings and their occupants is a field currently receiving significant attention as the result of the events of September 11. Knowledge, techniques, and technology are likely to advance rapidly in this area over the next several years and will have applications in autonomic buildings.

Optimization of building operations is an area with significant promise. Research needs in this field include model construction, computationally-economic optimization implementations, automated fault detection, diagnosis, and prognosis, and deployment of models, controls and diagnostics in distributed processing environments. Integration of building-operation optimization with automated energy procurement and load management is another area requiring research.

Some of the research required for autonomic buildings is specifically included in the technology development part of the industry roadmap for high-performance commercial buildings, which specifically identifies as one of three primary areas (DOE 2000):

> **Develop cost-effective, reliable monitoring and control technologies (e.g., indoor air quality sensors, wireless sensors and controls).** This will ensure that performance targets are met throughout building life.

- Promote "plug-and-play" simplicity and integration for monitoring and control technologies.
- Gauge the cost-effectiveness of sensor systems and increase the reliability of volumetric airflow sensors, self-diagnosing sensors, and self-calibrating sensors.
- Apply sensors technology to building cleaning and maintenance.

Other technology needs and research topics for realizing the complete vision for autonomic buildings complement or extend the ones identified in the roadmap and some probably extend beyond the 20-year horizon of the roadmap.

Conclusion

We have introduced the concept of autonomic buildings and shown conceptually and through examples that much of what we seek from intelligent buildings can be provided using autonomic systems, without the requirement of embedding intelligence in building systems and without the corresponding confusion frequently generated when attributing intelligence to inanimate objects.

Increased automation of routine building operation associated with autonomic building systems would help accommodate the impending shortage of building service technicians and operators, the pressure to reduce the number of facility operation staff, and the desire to reduce costs and improve energy efficiency.

The concept of autonomic buildings is compatible with high performance with respect to energy use, resource consumption, and providing indoor environmental quality. It captures both a target for performance as well as a set of mechanisms for achieving it.

The human autonomic nervous system provides several characteristics of value that might inspire new concepts for providing high-performance buildings of the future.

Acknowledgments

The work described in this paper was partially sponsored by the Office of Building Technology, State and Community Programs, U. S. Department of Energy as part of the Building Systems Program at Pacific Northwest National Laboratory. The Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under contract DE-AC06-76RLO 1830.

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