OR-10-006

The Virtual Cybernetic Building Testbed—A Building Emulator

Steven T. Bushby, MSc
Fellow ASHRAE

Michael A. Galler, MSc
Member ASHRAE

Natascha Milesi Ferretti, PE
Member ASHRAE

Cheol Park, PhD

ABSTRACT

Building emulators couple computer simulations to real control hardware, creating a useful tool for studying building control system performance. The National Institute of Standards and Technology's (NIST's) Virtual Cybernetic Building Testbed (VCBT) is a whole building emulator designed to support research in a variety of topics linked to the concept of a "cybernetic building", where numerous building control systems are integrated together and with outside entities such as utility providers. The design and use of the VCBT is described in the context of specific research projects involving building system commissioning, automated fault detection and diagnostics.

INTRODUCTION

The concept of developing building emulators, a simulated building shell and simulated heating, ventilation, and air-conditioning (HVAC) equipment combined with real building automation and control system hardware, as a tool for studying building control system performance emerged in the late 1980s. Early work led to an international collaborative effort to explore variations of building emulator designs and applications in Annex 17 of the International Energy Agency, Energy Conservation in Building and Community Systems program (Kelly and May 1990; Haves et al. 1991; Vaezi-Nejad et al. 1991; Karki 1993).

Building emulators have found limited use as research tools, training aids for control systems users, and for control system performance evaluation. (Liebecq et al. 1991) and (Kaerki and Lappalainen 1994) designed prototype emulators to test such aspects as accuracy, time-step, zone temperature control changes and tuning loop parameters. (Larech et al. 2002) developed a test method for evaluating HVAC controllers by emulation. (Brambley et al. 2005) discuss emulation for training, FDD, operational strategizing, and optimal control and state that "Computer emulation of building conditions that are fed into controllers will speed the adoption of new technologies by providing a resource for testing controller hardware under a complete range of conditions."

Building emulators vary in design details but common characteristics include real-time simulation linked to a hardware interface that couples the simulated building and simulated mechanical equipment to the controllers. Digital-to-analog converters are used to convert simulated sensor information such as temperatures, pressures, and flows into electrical signals that are wired to the sensor input terminals of the control hardware. Analog-to-digital converters are used to convert analog control signals into digital values that are fed into the simulation. Digital inputs and outputs are used for switching and status signals. The overall effect from the perspective of a building controller is that it "thinks" it is receiving real sensor input and controlling real building equipment; but, in reality, the sensor data and equipment are simulations. A building emulator combines the reproducibility and flexibility of simulations with the real performance constraints of actual control hardware.

The development and widespread use of the BACnet communication protocol standard (ASHRAE 2008; Bushby 1997) combined with rapid advancement in the capabilities of computer control hardware for building applications has made possible a new generation of "cybernetic building systems." Cybernetics is the science of communication and control theory that is concerned especially with the comparative study of automatic control systems (Webster's, 2009). A cybernetic building integrates building automation and control systems

Steven T. Bushby is leader, **Michael A. Galler** is an engineer, and **Natascha S. Castro** and **Cheol Park** (retired) are mechanical engineers of the Mechanical Systems and Controls Group at the Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD.

for comfort control, energy management, and fire detection, security, and transport systems. It also integrates the building systems with outside service providers and utilities. Cybernetic building systems offer the potential for significantly more energy efficient building operations, lower maintenance costs, and improved occupant comfort and safety.

The current generation of mechanical systems used for heating and cooing and their associated building automation and control systems almost never achieves their design efficiencies at any time during building operation and their performance typically degrades over time. For example, case studies indicate that energy consumption for HVAC systems can be reduced 20% just by detecting mechanical faults and ensuring that systems are operated correctly (TIAX LLC 2005). Additional case study examples can be found in Ardehali et al. (2003). The vision of cybernetic building systems involves a much more complicated web of potential building system interactions and interactions between building systems and external entities such as utility providers than is typically found in buildings today. In order to achieve the potential of cybernetic buildings there is a need to understand the failures of today's systems and ways to reliably take advantage of new opportunities that system integration provides.

Buildings are complex systems of interacting subsystems. Most commercial buildings are "one-off" designs with unique operating needs. Interactions between subsystems can be complex and are often not well understood. The industry is very sensitive to the first cost of new technologies and performance goals such as energy efficiency, indoor air quality, and comfort often conflict. There are no simulation tools that can realistically capture all of the necessary details of a complex cybernetic building system. An emulator is needed that can combine the strengths of simulations with the constraints of actual commercial control hardware and communication technology. A real controller has constraints in memory, processor speed, the number and size of the registers, the operating system features, and the design choices made when creating the control algorithms. These constraints are very important when trying to test and demonstrate the feasibility of algorithms that are intended to be embedded in the controllers.

THE NIST VIRTUAL CYBERNETIC BUILDING TESTBED

The NIST Virtual Cybernetic Building Testbed (VCBT) is a whole building emulator designed with enough flexibility to be capable of reproducibly simulating normal operation and a variety of faulty and hazardous conditions that might occur in a cybernetic building. It serves as a testbed for investigating the interactions between integrated building systems and a wide range of issues important to the development of cybernetic building technology including:

- Automated commissioning of building systems;
- Automated fault detection and diagnostics (FDD) of building systems and components;
- Optimization strategies for interacting building systems;
- Communication and interaction between building systems and utility providers to manage energy loads and respond to real-time price fluctuations;
- Development of communication standards for providing building system information to emergency responders;
- Development of decision support tools to aid emergency responders; and
- Extension of BACnet capabilities to new applications.

The VCBT control hardware consists of BACnet products from multiple companies that are used for HVAC control, lighting control, physical access control, and fire detection. The BACnet network topology is an internetwork of all network types commonly found in BACnet systems. Figure 1 is a photograph of the VCBT control hardware.

The interface between the control hardware and the building simulation permits the use of multiple simulation tools so that the simulation tool can be selected based on features that match the nature of the problem being investigated. For example, investigations of building system responses to fire events use a simulation tool whose primary strength is accurately representing fire physics, and investigation of fault detection in HVAC system components uses a simulation tool that provides detailed representation of HVAC system components where faults can be introduced.

The VCBT provides a way to emulate an entire building, including its various automation and control systems, in the laboratory. It provides a way to examine the interactions of the

Figure 1 *Virtual Cybernetic Building Testbed control hardware. Shown in the photo are the data acquisition unit in the lower left, a range of HVAC control products, a fire detection and alarm system, and on the far right some biometric devices that are part of an access control system. Not shown are other access control devices and a lighting control system.*

various systems and to see how the building reacts under adverse events, such as equipment failure or a fire. Tests can be conducted under reproducible, carefully controlled conditions, including weather, without endangering the safety or comfort of occupants in a real building. The VCBT can be used to test new concepts for control strategies and prototype products in a way that is economical, efficient, and convenient.

VCBT Architecture

The VCBT software components run in a real-time, distributed, multi-platform environment. Each component can potentially be run on a variety of computers, except for the data acquisition and control unit which requires special hardware. The software components can be distributed across different machines for operational convenience or, if needed, to increase parallelism in the processing to meet real-time synchronization constraints with the building controllers. The platform currently used is Windows XP, but past platforms used include Windows NT, Windows 95/98, and Sun Solaris[1]. The software components were designed to facilitate migration to alternative computing platforms. A variety of computer programming languages, including C, C++, Visual C++, FORTRAN, Java, and Virtual Reality Modeling Language (VRML) are used. Figure 2 depicts the logical interrelationships and data flows for the VCBT software components.

All of the component models communicate with the Center which serves as the heart of the distributed system and the main user interface. It serves as a repository for shared information that is used to couple the simulations, exchange information with the data acquisition unit, and control timing. Because real building controllers are used, each simulation must run in real time.

The Center manages the activation and deactivation of all component models used in a run, and coordinates all data flow to and from the models. It keeps time for the models and synchronizes the time on the BACnet controllers with the simulation time. Using the Center, an operator can choose which component models to use for a particular run, which of the available computers should be allocated to run each component, the weather data to be used for a particular run, and controls the initiation of any simulated faults. The operator can view data from any of the component models in real time, and view the status and any error messages from any of the component models used. When performing a run with a fire, the instruction to ignite the fire comes from the Center.

Bi-directional data exchange takes place through a Common Object Request Broker Architecture (CORBA) connection depicted in Figure 2 by thick green arrows. Most of the component models have a wrapper written in C and C++ (red shell) with the actual models written in FORTRAN and called from the C/C++ wrapper code. The Center also communicates directly with HVAC controllers via a BACnet connection (thin blue arrow).

The HVACSIM$^+$ component is used to simulate the HVAC mechanical systems. The Building Shell model, which is implemented using HVACSIM$^+$, is used to calculate heat transfer through the building surfaces, and to provide outdoor temperature and humidity information. ZFM-HVAC is used to simulate the effects of a fire in the virtual building, including interactions with the HVAC systems. The HVACSIM$^+$ and Building Shell model components are used when the purpose of the emulation is to study details of the HVAC control system performance. The ZFM-HVAC model is used when the purpose of the emulation is to study response to fires. These options are mutually exclusive. More details about HVACSIM$^+$ and ZFM-HVAC are provided below.

The Data Logger is the communication interface to the data acquisition system and, indirectly, the real building controllers. The simulated values that represent sensor inputs to the controllers are converted by the digital-to-analog converter of the data acquisition system into analog inputs represented by either DC voltages (0 V to 5 V) or DC currents (4 ma to 20 ma). The ranges for each input and output on the controllers are known to the Data Logger, so the input values can be converted from the value sent from the Center to the correct voltage. To the building controllers this input is indistinguishable from a real sensor. There is a capability to scale values to other ranges as needed. The output values of the BACnet controllers that represent inputs to the virtual building system component models are read by the digital voltmeter through multiplexers. The output voltage range of each controller is between 0 V and 10 V. The scaling for output values is handled similarly to scaling for input values.

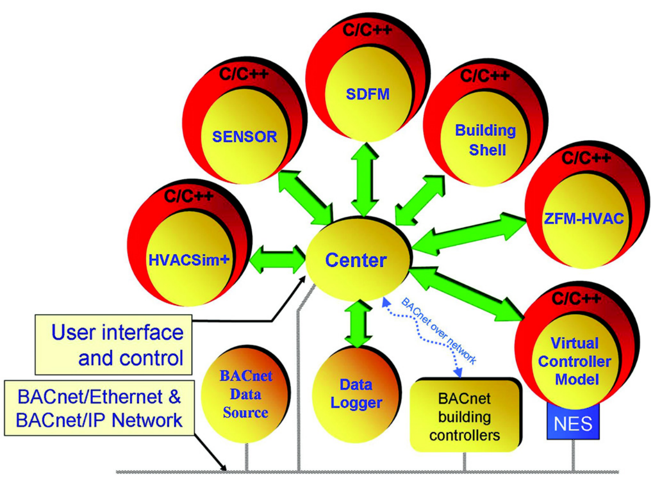

Figure 2 *Logical diagram of VCBT software and communications components.*

1. Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

The SENSOR model is specific to sensors used in fire detection and alarm systems. It converts simulation values for smoke and heat detectors from the ZFM-HVAC component into signals representative of real sensors that can be used for input to the Sensor Driven Fire Model (SDFM). The SDFM is a decision support tool for providing information to emergency responders about the presence and severity of hazardous conditions in the building and is described in more detail below. The Virtual Controller Model is a tool to enable emulation for virtual buildings that are larger than the physical building control hardware would permit. It provides a way to combine real control hardware in a portion of the building that is of particular interest with simulated control hardware in other portions of the building. There is also a Network Entity Simulator (NES) that can generate BACnet message traffic to simulate the load from the virtual controllers.

The BACnet Data Source (BDS) is a tool that uses BACnet/Ethernet or BACnet/IP messages to read and archive data from the BACnet controllers for post emulation analysis of the building systems performance. It also has the ability to write to BACnet object properties directly or through a predefined script. This feature can be used, for example, to command control actions for active tests performed as part of ongoing commissioning. Although the Center and other component models have access to sensor data from the simulations and the resulting control actions that are linked to the data acquisition system, they do not have access to other BACnet data. The BDS can access additional information, such as setpoints and occupancy status that are important for analysis.

The data points that the BDS acquires can be configured by using a graphical user interface or through an imported settings file. Figure 3 illustrates the BDS user interface. The BDS can monitor up to 20,000 datapoints on up to 300 BACnet controllers, and can be configured to update data at intervals of 10 seconds or more. Subsets of the data can be saved in up to ten different files in CSV format. The BDS can find BACnet devices on the local network, allowing it to be used even if the operator has no information on the configuration of the HVAC controllers on the network.

HVACSIM$^+$ Program

HVACSIM$^+$ stands for "HVAC SIMulation PLUS other systems." It is a public domain computer simulation program developed by the National Institute of Standards and Technology for studying the dynamic interactions between building system components (Park et al. 1985). This program employs advanced equation solving techniques and a hierarchical, modular approach. The simulation of an entire building/HVAC/control system involves the simultaneous solution of a large number of nonlinear algebraic and differential equations over long time periods using time steps on the order of seconds or smaller. Variable time step and variable order integration techniques are also used to reduce the amount of computation time required for dynamic simulation. Stiff ordinary differential equations are solved using a method based upon the Gear algorithm (Gear 1971).

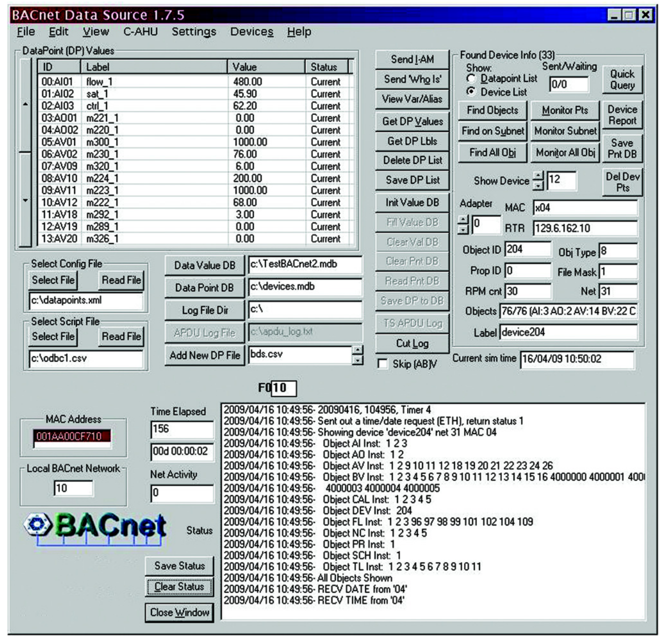

Figure 3 *The BACnet Data Source user interface. As shown, it is reading data from a controller on an MS/TP network through a BACnet/IP router.*

The HVACSIM$^+$ program consists of a main simulation routine, a library of HVAC system component models, a building shell model, an interactive front end program, and post processing routines. While most of the programs were originally written in Fortran 77, the program code has been updated to Fortran 90. Park (2008) provides details of the current version of HVACSIM$^+$ program.

The Building Shell model used in the VCBT dates to the original development of HVACSIM$^+$ and is based on even earlier work such as NBSLD (Kusuda 1976), BLAST (Hittle 1979), and TARP (Walton 1983). Simulation of building system components in the VCBT (sensors, air handling unit (AHU) dampers, valves, coils, actuators, ducts, and fans, and the variable air volume (VAV) box dampers, coils, and valves) are represented by HVACSIM$^+$ component models. Most component models (TYPE routines) used were originally developed or revised during the course of ASHRAE 825-RP (Haves and Norford 1997). Dynamic behavior of building systems are modeled in these component models. For instance, temperature, humidity, pressure, and flowrate sensor models are formulated in the first order differential equations which involve time constants. The drive shaft position of the motor-driven actuator model moves at a given amount based on the total travel distance each time step. The effective coil surface temperatures of cooling and heating coils are calculated by using the first order differential equations considering coil capacities based on fins, tubes, and water in the tubes. The flowrates in ducts and pipes are determined using pressure drops.

ZFM-HVAC Program

ZFM-HVAC is a fire simulation program derived by combining a Zone Fire Model (ZFM) with HVAC components extracted from HVACSIM$^+$ coupled to a single equation solver (Park et al. 2007). A building HVAC system delivers conditioned air to building zones. The virtual HVAC system determines pressures, flow rates, temperatures and humidity values. The HVAC-side equations of the ZFM-HVAC are solved sequentially. Treating the variables of HVAC-side as pseudo-steady state variables, the ZFM-side equation solver solves simultaneously only zone/room-related variables such as smoke layer temperature, pressure, density, and combustion product concentrations. Fire is modeled as a two-layer environment with a hot upper smoke layer and a cool lower layer. Currently, only smoke concentration is tracked within the HVAC system. No contaminants are tracked.

Validation of HVAC Component Fault Models

In order to use the VCBT to test and evaluate automated FDD algorithms for HVAC systems and components, modified HVACSIM$^+$ component models were developed to represent a range of common system faults that are shown in Table 1. The fault models were designed to enable the user to vary the severity of the fault and to change the severity of the fault during a simulation representing a condition that is becoming worse with time. This capability has been used to investigate detection thresholds for FDD algorithms. The HVACSIM$^+$ implementation details for each of these fault models can be found in Bushby et al. (2001).

The HVACSIM$^+$ component fault models were validated by comparison of simulation results with experiments conducted at the Iowa Energy Center Energy Resource Station (ERS). Faults were manually introduced to the systems at the ERS and data was collected from system operation during both summer and winter weather conditions. The experimental data were compared with simulation results to confirm that system responses observed in the simulation data are representative of real systems. Only a subset of the faults listed in Table 1 was implemented at the ERS facility. The faults tested experimentally for air handlers were a supply air temperature sensor offset, a stuck open recirculation air damper, and a leaking heating coil valve. The faults tested experimentally for VAV boxes were a stuck open damper and a stuck open reheat valve. This set of experiments was considered to be representative of the entire set of faults listed in Table 1 because one fault of each type (sensor, damper, valve for the AHU; damper and valve for the VAV box) is examined and the implementation in HVACSIM$^+$ of the faults that are not validated are identical to those that are validated. Details of the validation experiments and comparison results can be found in Castro et al. (2003).

Table 1. HVAC Equipment Faults Implemented in HVACSIM$^+$

Supply air temperature sensor offset	Stuck recirculating air damper
Return air temperature sensor offset	Leaking recirculating air damper
Mixed air temperature sensor offset	Stuck cooling coil valve
Outdoor air temperature sensor offset	Leaking cooling coil valve
Stuck outdoor air damper	Stuck heating coil valve
Leaking outdoor air damper	Leaking heating coil valve

SUCCESSFUL APPLICATIONS

Due to its adaptability, the VCBT has been successfully used in a variety of projects including the development and testing of fault detection and diagnostic tools, commissioning tools, and tools to improve the actionable information available to emergency first responders. The building emulator has enabled researchers to test and validate implementations of these new technologies for the buildings industry. With each new application, the communication and emulation capabilities were expanded or enhanced to meet new requirements.

The VCBT was a valuable proving ground for two prototype FDD tools that were embedded in AHU and VAV box controllers, limiting the risk before the technology was evaluated in real buildings. AHU Performance Assessment Rules (APAR) is a diagnostic tool that uses a set of expert rules derived from mass and energy balances to detect common faults in air-handling units (Schein et al. 2006). Control signals are used to determine the mode of operation for the AHU. A subset of the expert rules corresponding to that mode of operation is then evaluated to determine if there is a mechanical fault or a control problem. VAV box Performance Assessment Control Charts (VPACC) is a diagnostic tool that uses statistical quality control measures to detect faults or control problems in VAV boxes (Schein and House 2003). The VCBT was used to determine the effectiveness of these tools in detecting commonly found mechanical faults and control problems.

The APAR and VPACC tools were both found to be successful at finding a wide variety of faults. It was also found that some faults could not be detected under certain operating conditions because the control system was able to mask the problem or because sensor data needed to detect the fault is not commonly available in commercial systems. Emulation results gave a high level of confidence that the FDD tools would perform well in real buildings. Subsequent field testing confirmed the laboratory results (Bushby et al. 2001; Castro et al. 2003).

The VCBT has also been valuable in the testing and validation of building commissioning tools. Building commissioning is the quality control process that is needed to ensure that buildings are built and operated as designed and that they meet the owner's project requirements. Because buildings are complex and often involve the integration of multiple systems, building commissioning is challenging and requires expert knowledge. Commissioning agents and building operators need tools to facilitate the task of ensuring that the building is operating to meet the project requirements. Multiple automated commissioning tools were developed under the ECBCS Annex 40 and Annex 47 research projects, including CITE-AHU (Castro and Vaezi-Nejad 2005). In order to test some of these prototype tools that perform active testing (interacting with the building control system), added functionality was needed to bridge communications between an automated commissioning tool and the native BACnet controllers in the VCBT or in real buildings. This software extension, the BACnet Data Source, enables an operator or commissioning agent to initiate any of a number of automated test sequences in the Functional Test Library of the commissioning tool which would inject test signals and force particular modes of operation. The benefit is that this communications bridge can then be used to provide access to field sites having native BACnet controllers (Galler 2008). The VCBT provided the original platform for the development and testing of the BACnet Data Source, which was then transferable for real building sites.

Today, when first responders arrive at a building in response to an emergency they typically have very little information about what is happening beyond a high-level summary, such as a fire has been reported, a break-in has occurred, there is a medical emergency, etc. As a result valuable time must be spent determining the nature of the emergency, details of the building and its systems that are relevant to a response, and the number and type of emergency personnel who may be needed to carry out an effective response. Modern building automation systems increasingly involve integration of HVAC, fire, access control and other systems that contain a wealth of sensor data and other information that could be helpful to first responders. The VCBT is being used to conduct research on ways to tap into the potential wealth of information from building systems that emergency responders might need and present it to them in a timely and easy to use manner.

One aspect of that research is the development of a Sensor Driven Fire Model (SDFM), a decision support tool that can improve the response to fire events by identifying the present conditions such as fire size and location, smoke levels, and room temperatures. It also makes short-term predictions of how conditions will change and provides warnings about conditions that threaten the safety of the responding firefighters. The SDFM accomplishes these tasks by collecting data from the VCBT sensors and using that data as input to its fire model (Davis 2009; Davis et al. 2008).

The VCBT is also being used to investigate alternative ways for communicating a broader range of building information such as sensor data, floor plans, and incident alert messages to alarm call centers, emergency response operations centers and mobile units, and public safety officials. A prototype Building Information Services and Control System (BISACS) that interfaces with the VCBT has been developed. The intent is to establish a communication standards framework, consistent with existing public safety alert systems, which will allow authorized personnel to remotely monitor alerts and to do limited remote control of building devices or processes. The test environment of the VCBT provides a resource to develop and test communication methodology, data security and data integrity, network scalability, data content and encapsulation standards, interface protocol standards, and presentation standards (Vinh 2008).

VCBT LIMITATIONS

Although the VCBT has proven to be a flexible and valuable research tool there are some significant limitations to its use. An obvious limitation is scalability of the control hardware. Adding control hardware is a significant task that requires space for the control hardware, channels on the data acquisition system to connect sensor inputs and control outputs, and modification to the software tools that are used to configure and control emulations. A large building may have thousands of controllers and sensors that make up a cybernetic building system. It is impractical to duplicate that scale in an emulator. To mitigate this limitation the VCBT can be configured to combine real control hardware and simulated controllers.

Changing the design and floor plan of the emulated building is a significant task that requires changes in the configuration files of the Center and each component used. The simulation tools are flexible but complex. They do not have simple user interfaces that mask this complexity and therefore significant expertise is required to make and debug changes.

The control hardware used in the VCBT comes from several different manufacturers. This was done intentionally because of a desire to have a representative example of the operational strengths and constraints that result from the manufacturer's product design choices. A side effect of this design is that it is necessary to learn both the features of several different product lines and the programming and configuration tools that are specific to each manufacturer.

Emulations must run in real time because of the use of real building control hardware. That can make the time needed to conduct a test run very long. Features have been built into the Center to mitigate this problem for cases in which the emulated building has long unoccupied periods, e.g., nights and weekends. The Center can decouple the real control hardware and allow the simulation to proceed as fast as the computations allow for the unoccupied period and then recouple the hardware and reset the control system clocks to begin a new simulated day. This speeds up the process considerably but it does introduce the need for a period of time for the building control to settle from the disturbance caused by this discontinuity.

POTENTIAL FUTURE USES

The VCBT has already proven to be a valuable resource for developing and testing automated commissioning and FDD tools for a limited set of HVAC system components. Plans are underway to expand this work to enable the development of a comprehensive range of tools for both commissioning and FDD. Part of this work will involve expanding the VCBT to include central plant facilities such as boilers, chillers and cooling towers. In its present form the VCBT is not accessible to researchers from outside the NIST campus however NIST does provide opportunities for guest researchers to use our facilities.

Over the last twenty years, significant progress has been made in enabling the integration of building control systems and building services through the development of standard communication protocols, such as BACnet and BACnet/IP. Unfortunately, little or no progress has been made in actually making building systems more intelligent or in optimizing the performance of building systems. HVAC control systems are still basically proportional – integral (PI) or proportional – integral – derivative (PID) control at the lowest level, with one or two higher levels of heuristic supervisory control. The VCBT is a tool that can be used to explore new concepts for building control and optimization that have the potential to deliver significant improvement in building system performance.

Integration of building systems to date have been done in a superficial way. Emerging sensor technology has the potential to dramatically change the kind and quantity of information that will be available to building control systems. The VCBT can serve as a testbed to explore the implications and benefits of a ubiquitious sensor environment where data is available for use in a wide range of building systems.

The VCBT has already been used to test and demonstrate the potential benefits of providing appropriate and timely information to emergency responders at a “proof of concept” level. In order for this potential to be realized there is need to develop both communication standards and decision support tools that can help interpret and present the information available from a building during an emergency. A building emulator is an excellent tool for developing the needed science and technical basis for industry standards.

Programming and configuring building automation systems is a labor-intensive and error-prone process. Developing technology that would enable building automation systems to be self-configuring, including programming or selection of control sequences, has the potential to decrease installation costs and improve quality. For many years the building industry has been working to develop ways to capture and share building information electronically from early design, through construction and operation, and throughout the life of the building. However, this work has not been effectively applied to control systems. A building information model that is rich enough to capture details about instrumentation, control sequences, and supervisory control strategies at the design stage could provide input to automated configuration tools. A building emulator, such as the VCBT, would be a valuable tool for developing and testing this type of self-configuring system for a wide range of building types.

CONCLUSION

As the building industry strives for significant improvements in energy efficiency while maintaining or improving occupant comfort and safety, building emulators like the VCBT can play an important role in meeting the resulting technical challenges. Simulation tools are important and valuable but practical experience has shown that real buildings do not meet the performance expectations derived from simulation results. Building emulators, like the VCBT, provide a hybrid environment that combines the control and reproducibility of simulation with the operation of real control hardware. This combination is well suited for exploring a range of technology advances including better and more automated commissioning practices, automated fault detection and diagnosis, and performance optimization strategies. The VCBT also provides an environment to investigate the interactions of traditionally separate building systems as they become integrated into cybernetic buildings, and the response of those systems to stresses, failures and emergencies. The VCBT has also proven useful for developing and testing ways to make building system information available to emergency responders.

REFERENCES

Ardehali, M.M., T.F. Smith, J.M. House, and C.J. Klaassen. 2003. Building energy use and control problems: An assessment of case studies. *ASHRAE Transactions* 109(2):111-121.

ASHRAE. 2008. ANSI/ASHRAE Standard 135-1989, BACnet™—A data communication protocol for building automation and control networks. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Brambley, M.R., P. Haves, S.C. McDonald, P. Torcellini, D. Hansen, D.R. Holmberg, and K.W. Roth. 2005. Advanced sensors and controls for building applications: Market assessment and potential R&D Pathways; April 2005, USDoE Contract DE-ACO5-76RL0 1830 PNNL, Richland, WA.

Bushby, S.T. 1997. BACnet™—A standard communication infrastructure for intelligent buildings, automation in construction, vol. 6 no. 5-6, pp. 529-540.

Bushby, S.T., N.S. Castro, M.A. Galler, C. Park, and J.M. House. 2001. Using the cybernetic building testbed and FDD test shell for FDD tool development. NISTIR 6818.

Castro, N.S., J. Schein, C. Park, M.A. Galler, S.T. Bushby, and J.M. House. 2003. Results from simulation and laboratory testing of air handling unit and variable air volume box diagnostic tools. NISTIR 6964.

Castro, N.S. and H. Vaezi-Nejad. 2005. CITE-AHU, an automated commissioning tool for air-handling units. *Proceedings of the National Conference on Building Commissioning*, New York, NY.

Davis, W.D. 2009. A sensor-driven fire model, ver. 1.2. NIST Special Publication (to be published).

Davis, W.D., D. Holmberg, P. Reneke, L. Brassell, and R. Vettori. 2007. Demonstration of real-time tactical decision aid displays, NISTIR 7437, pp. 1-25.

Galler, M.A. 2008. Using the BACnet communications DLL v1.0. NIST TN 1607.

Gear, C.W. 1971. The automatic integration of ordinary differential equations. Comm, ACM, vol. 14, no. 3, pp. 176-179.

Haves, P., A.L. Dexter, D.R. Jorgensen, K.V. Ling, and G. Geng. 1991. Use of a building emulator to evaluate techniques for improved commissioning and control of HVAC systems. *ASHRAE Transactions* 97(1):684-688.

Haves, P. and L.K. Norford. 1997. A standard simulation testbed for the evaluation of control algorithms and strategies. ASHRAE 825-RP Final Report. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Hittle, D.C. 1979. The building loads analysis and system thermodynamics (BLAST) program, ver. 2.0: User Manual. Tech. Rep. E-153, Construction Engineering Research Laboratory.

Karki, S. (ed). 1993. Development of emulation methods. Finland, VTT, laboratory of heating and ventilation, Research Notes 1514. Available at www.ecbcs.org/annexes/annex17.htm.

Kaerki, S.H. and V.E. Lappalainen. 1994. A new emulator and a method for using it to evaluate BEMS. *ASHRAE Transactions* 100(1):22-26 Jan 1994; pp. 1494-1505.

Kelly, G.E. and W.B. May. 1990. The concept of an emulator/tester for building energy management system performance evaluation. *ASHRAE Transactions* 96(1): 1117-1126.

Kusuda, T. 1976. NBSLD, The computer program for heating and cooling loads in building. BSS 69, NBS.

Larech, R., P. Gruber, P. Riederer, P. Tessier, and J.C. Visier. 2002. Development of a testing method for control HVAC systems by emulation. *Energy and Buildings* Vol. 34, Issue 9, October, pp. 909-916.

Park, C., D.R. Clark, and G.E. Kelly. 1985. An overview of HVACSIM$^+$, A dynamic building/HVAC/control systems simulation program. *Proceedings of the 1st Annual Building Energy Simulation Conference*, Seattle, WA, August 21-22.

Park, C. 2008. HVACSIM$^+$ users guide update, NISTIR 7514. http://www.bfrl.nist.gov/863/HVAC/pubs/index.htm.

Park, C., P.A. Reneke, M.A. Galler, S.T. Bushby, and W.D. Davis. 2007. Enhancement of the Virtual Cybernetic Building Testbed to include a zone fire model with HVAC components, NISTIR 7414.

Schein, J., S.T. Bushby, N.S. Castro, and J.M. House. 2006. A rule-based fault detection method for air handling units. *Energy and Buildings* 38(2006):1485-1492.

Schein, J. and J.M. House. 2003. Application of control charts for detecting faults in variable-air-volume boxes. *ASHRAE Transactions* 109(2):671-682.

TIAX LLC. 2005. Energy impact of commercial building controls and performance diagnostics: Market characterization, energy impact of building faults and energy savings potential. Report no. D0180. Prepared for the DOE Building Technologies Program. www.eere.energy.gov/buildings/highperformance/pdfs/tiax_controls_diagnostics.pdf.

Walton, G.N. 1983. *Thermal analysis research program reference manual.* NBSIR 83-2655.

Webster's. 2009. Merriam-Webster online dictionary. www.merriam-webster.com/dictionary/cybernetics.

Vaezi-Nejad, H., E. Hutter, P. Haves, A.L. Dexter, G. Kelly, P. Nusgens, and S. Wang. 1991. The use of building emulators to evaluate the performance of building energy management systems. *Proceedings of Building Simulation 1991 Conference*, Nice, France.

Vinh, A.B. 2008. Computer-based monitoring for decision support systems and disaster preparedness in buildings. *International Multi-Conference on Engineering and Technological Innovation: IMETI 2008*, Orlando, FL, 06/29/2008 to 07/02/2008. vol. II:285-290.