

A SIMULATION-BASED TESTING AND TRAINING ENVIRONMENT FOR BUILDING CONTROLS

Peng Xu¹, Philip Haves¹, Joe Deringer²
¹ Lawrence Berkeley National Laboratory
² The Deringer Group, Berkeley, CA

ABSTRACT

A hybrid simulation environment for controls testing and training is described. A real-time simulation of a building and HVAC system is coupled to a real building control system using a hardware interface. A prototype has been constructed and tested in which the dynamic performance of both the HVAC equipment and the building envelope is simulated using SPARK (Simulation Problem Analysis and Research Kernel). A low cost hardware interface between the simulation and the real control system is implemented using plug-in analog-to-digital and digital-to-analog cards in a personal computer. The design and implementation of the hardware interface in SPARK are described. The application of a variant of this environment that uses a derivative of EnergyPlus to test the implementation of a natural ventilation control strategy in real control hardware is briefly described.

The application to the education and training of building operators and HVAC service technicians is discussed, including the development of a community college curriculum that includes the use of the hybrid simulation environment to teach both control system configuration and HVAC troubleshooting.

INTRODUCTION

There are two different ways in which simulation can be used to assess the performance of building control systems. In the early stages of development, when the focus is on the design of the control strategy, the control algorithms can be implemented in simulation along with the models of the equipment being controlled. In the later stages of development, a hybrid system consisting of a real-time simulation of the building envelope and mechanical components connected to real control hardware can be used to study implementation issues. This 'hardware-in-the-loop' arrangement is commonly employed for product development and testing in other industries but is not commonly used

in the buildings industry. The first recorded application to HVAC systems was developed at the National Institute for Standards and Technology (Kelly and May 1990). A number of these hybrid environments (termed 'emulators') were developed in IEA Annex 17 (Lebrun, 1992, Vaezi-Nejad *et al.* 1991), primarily with a view to providing a repeatable method of comparative testing of building control systems, although some of the applications described in this paper were also envisaged.

A new prototype hybrid simulation environment for controls testing and training has been constructed at Lawrence Berkeley National Laboratory (LBNL). Application of this hybrid environment include:

- development of control algorithms and strategies
- control system product testing
- pre-commissioning of building control system installations
- education and training of engineers and technicians

In the LBNL hybrid environment, the building envelope and the HVAC system can either be simulated using SPARK (Sowell *et al.* 1986, Sowell and Haves 2001) or EnergyPlus (Crawley *et al.* 2004). SPARK is an object-oriented, equation-based, simulation program that allows continuous non-linear systems to be simulated at arbitrarily short time-steps. SPARK is well suited to the simulation of the dynamics of HVAC systems and is used in the first example described below. EnergyPlus is a whole building simulation program that treats the dynamics of the building fabric and uses steady state models to simulate HVAC systems. An example of the use of EnergyPlus to test the control system for a naturally ventilated building is described at the end of this paper. A coupling between EnergyPlus and SPARK is being implemented at LBNL in a separate project; this will allow detailed simulation of HVAC

components and subsystems, including local loop control, within a whole-building simulation.

When using simulation to test real control systems, the simulation is slowed down to run in real time and is connected to control system field panels via a hardware interface consisting of digital-to-analog (D/A) and analog-to-digital (A/D) cards that plug in to the PC running the simulation, as shown in Figure 1. The values of the sensor output signals from the simulation are converted to analog signals by the D/A card(s), which are then transmitted to the appropriate analog input ports of the control system. The control signals generated by the control system are transmitted from the analog output ports of the controllers to the input connectors of the A/D card(s), which then convert the signals into digital form for use as boundary conditions at the next simulation step time. The signals are transmitted by wires running between the cards and the control system hardware. The use of analog signals produces a generic interface between the simulation and the real control system, which facilitates coupling to control systems from different vendors.

SPARK

SPARK (Simulation Problem Analysis and Research Kernel) is an object-based software system that can be used to perform simulations of physical systems that can be modeled using sets of differential and algebraic equations. 'Object-based' means that components and subsystems are modeled as objects that can be interconnected to form a model of the entire system. Often the same component and subsystem models can be used in many different system models, reducing the cost of development.

SPARK models have a hierarchical structure. The most primitive element is an instance of a class consisting of an individual equation, called an atomic class. A macro class consists of several atomic classes (and possibly other macro classes) combined together into a higher level unit. The complete system to be simulated is then assembled

from instances of these atomic and macro classes. Classes serve as templates for creating any number of like objects that may be needed in a problem. The problem model is then completed by linking objects together, thus defining how they interact, specifying data values that specialize the model to represent the actual problem to be solved, and providing boundary values.

In previous versions of SPARK, a new C++ program is generated for each problem, which gets compiled, linked and executed to solve the problem for a particular set of boundary conditions specified at run-time. The latest version of SPARK (VisualSPARK Version 2.01, LBNL 2004) does not require separate compilation each time a new problem is generated.

Automatic classes that can write and read the voltage signals from the A/D and D/A cards have been developed for SPARK. The classes call driver functions supplied as object code by the manufacturer of the cards. Any virtual building simulation will use these two classes to interface with the cards. A similar approach is used in EnergyPlus.

Prototype hybrid environment

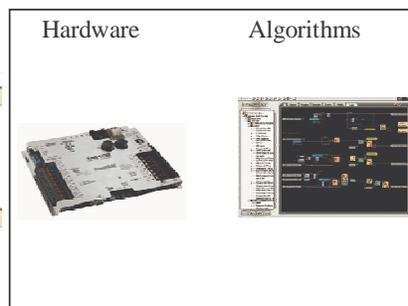
Figure 2 shows a simple, proof-of-control, example of the use of the hybrid environment to simulate temperature control in a zone with a pressure-dependent variable-air-volume (VAV) terminal box. The left side of the diagram is the virtual building, modeled using SPARK. The right side of the diagram shows the proportional, integral and differential (PID) controller in the real control system. To demonstrate the generic nature of the interface, control systems from two different manufacturers have been used in the hybrid environment.

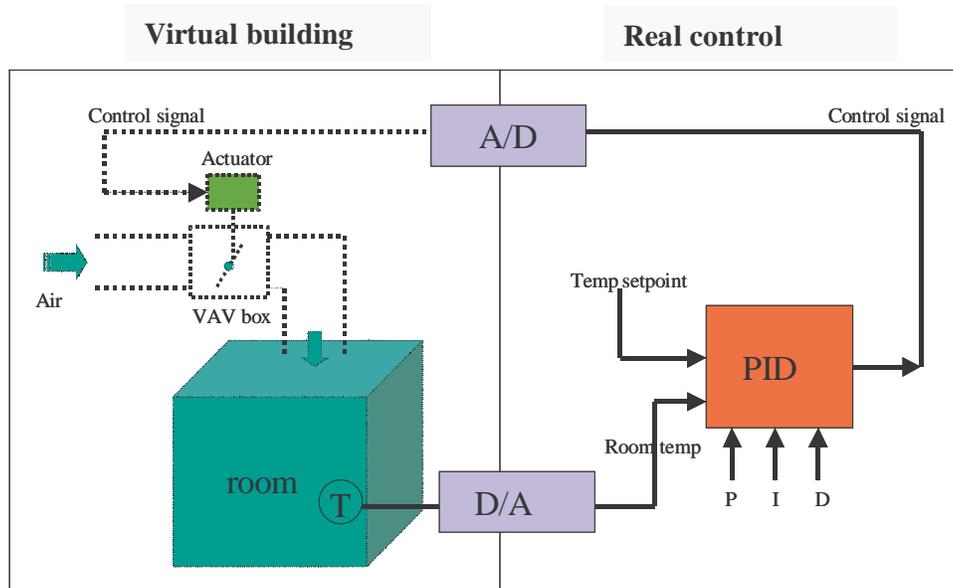
Two signals are transferred between the control system and virtual building. The simulated output of the room air temperature sensor is sent to the D/A card in the simulation computer, which generates an analog signal in the range 0-5 volts.

Virtual Building/HVAC system



Real Controls System





This signal is read at an analog input port on the control system, converted to a digital signal by an A/D converter in the control system hardware and used as the measured value of the room temperature in a digital implementation of the PID control algorithm. The tuning parameters and the set-point for the PID controller are supplied by the control manufacturer's supervisor software running on the operator's 'head end' computer and so can be changed by the user. The output of the PID control is a digital value representing the demanded position of the damper in the terminal box, which is then converted to an analog signal by a D/A converter in the control system hardware. This 0-5 V signal is then transmitted to the A/D card in the simulation computer and the resulting digital value used as the demanded position of the actuator at the next simulation step time.

The room model in this simple example is the lumped parameter model developed by Laret (1988). The damper model is described, along with a number of other HVAC models for use in control simulation, in Haves *et al.* (1998) and Haves *et al.* (1996). Since the time constant for any real room is relatively large, for demonstration purposes, the simulation is speeded up by a factor of 100.

Application to Education and Training

One application of simulation, including the hybrid simulation environment described above is in education and training. The complexity of modern digital control systems, particularly in large commercial buildings, creates a requirement for new skills on the part of building operators and the technicians who install and service these control systems, many of whom were trained on pneumatic control systems. To address this need, a

partnership has been formed between the Peralta Community College District in Oakland, California, LBNL and The Deringer Group to develop a new community college curriculum that emphasizes controls and troubleshooting. A set of computer-based educational tools will be developed in this partnership that are based on SPARK and EnergyPlus and include user interfaces specially designed for the pedagogical needs of the students following the new curriculum.

Simulation tools can be the basis of a very effective, transportable method of education instruction. Retention is typically higher than for traditional teaching modes, and content can be mastered much faster. Simulation-based education tools are being developed based on the hybrid environment described above and on 'pure' simulation in which the control system is simulated along with the HVAC system and the building fabric ('virtual' mode). These tools will be used to support a broad range of curriculum objectives, encouraging students to:

- Understand the operating principles of HVAC system components
- Diagnose basic equipment problems at the component level
- Use goal-oriented, problem-solving methods at a systems level to find solutions to more complex equipment problems
- Focus on problem-solving methodologies in finding system-level solutions
- Focus on case-study exercises and 'project-based learning'

The tools being developed to support the new

community college curriculum have several key attributes:

- **Goal-oriented, problem-solving methodology:** The simulation-based tools will demonstrate and explain problem-solving methodologies in order to encourage students to use a consistent process to solve problems. Typical steps include: (1) identify potential problems, (2) select problems to analyze, (3) examine root causes, (4) identify possible solutions, (6) select, test, and implement solutions, and (7) monitor the effectiveness of the solutions (Carnevale *et al.* 1990). The tools will be structured so that this methodology can be applied to a series of case-study projects of varying complexity across a range of HVAC components and systems, climates and costs. Problem-solving situations to be addressed include commissioning of an HVAC system at the end of construction, diagnosing HVAC problems that occur during building operation, and improving the energy-efficiency of the HVAC system during building design or rehabilitation.
- **Highly-interactive, animation-oriented Graphic User Interface (GUI):** The GUI developed for the tools will provide animations and other graphics to explain concepts. It will allow (1) the user's focus to shift between component and system levels, (2) both structured exercises and open-ended exploration, and (3) open-ended solutions, where there is no single correct answer, but rather a range of possible acceptable solutions. The GUI will also be able to (1) provide feedback to students on the status of HVAC systems and components being examined, (2) track student progress toward exercise objectives, (3) provide or hide "Hints" and other assistance to support learning objectives, and (4) allow recording of student progress and test scores. The GUI will provide a consistent interactive environment for both Web and CD use. It will also hide the interface complexity of SPARK or other simulation programs used.
- **"Open-Source" Software:** Using an "open-source" software approach will facilitate the refinement and expansion of the tools, both by instructors and by other interested parties. To support this approach, the tools and the GUI will utilize widely available software platforms and languages.
- **HVAC Component Models:** Models already exist for essentially all the major HVAC components (e.g. Bourdouxhe *et al.* 1994a; Bourdouxhe *et al.* 1994b; Brandemuehl 1994; Haves *et al.* 1996) and a number have already been implemented in SPARK. Most of the remaining models will be implemented in the course of the development of

the tools.

- **Simulating Control of HVAC Components:** The tools will contain models of generic control functions in order to simulate typical HVAC control loops (Haves *et al.* 1998). These control functions will be used in the pure simulation 'virtual' mode. The prototype hybrid simulator described above will be used as the starting point for the development of a compact hybrid simulator that can be implemented as a simple extension to the personal computers in a computer-teaching laboratory. Several HVAC control system manufacturers have agreed to donate equipment for use in developing the hybrid simulator.
- **Simulating System-level HVAC performance and control:** An HVAC simulation-based learning environment has the key advantage of offering a relatively low-cost, and low-risk, method of allowing students to explore and understand a range of behaviors of the large and complex HVAC systems typically found in commercial buildings. It is usually impractical and prohibitively expensive to provide students with either laboratory or real environments for studying such problems. The exercises will be structured to allow the student to handle progressively more complex problem situations as his/her learning and skills increase.
- **Diagnostics:** Testing and diagnosing building systems builds upon students' understanding of the behavior of both components and systems. Simulation-based exercises demonstrate the symptoms of faulty operation, ideally in relation to laboratory exercises using real equipment. Simulation-based exercises using blind faults can be used to develop and test students' diagnostic abilities. A number of such extended component models have previously been developed (Haves 1997) and these extended models will be implemented in SPARK and/or EnergyPlus in order to allow the component and system simulations described above to treat faulty operation.

Demonstration of Loop Tuning

The following example illustrates how the hybrid environment can be used to demonstrate tuning of control loops. The prototype hybrid environment shown in Figure 2 was used to demonstrate the tuning of a PI controller. The equation for the output of a PI controller is conventionally written as:

$$u = u_0 + K_p \left(e + \frac{1}{T_i} \int e dt \right)$$

where u is the control signal; u_0 is the bias; e is the control error (i.e. set-point – measured value), K_p is the proportional gain and T_i is the integral time. In practice, digital controllers operate in discrete time, so the integral is replaced by a summation, and a mechanism is introduced to limit the value of the ‘integral’ term (‘anti-windup’).

Figures 3 and 4 are screen shots captured directly from the simulation side before and after the tuning of the controller. Two variables are plotted on the graphs: room air temperature and damper position. If the room air temperature is higher (lower) than the set-point, the damper opens (closes) further, because the test bed is set up for summer conditions and so the supply air temperature is lower than the room air temperatures used in the test.

Figure 3 is a plot before the control loop was tuned. The gain of the controller is too high and so the response is under-damped when the set-point is changed from 77°F to 74°F. Figure 4 is the plot after the controller was tuned using the closed loop tuning method originally proposed by Ziegler and Nichols (1942) and both the proportional gain and the integral gain were decreased (as is usual in the HVAC industry, derivative action was not employed). The response is now over-damped, which is preferred because the danger of oscillation is reduced. A more comprehensive loop tuning exercise would repeat the tuning at different operating points since the damper characteristic is significantly non-linear.

APPLICATION TO CONTROL SYSTEM PRE-COMMISSIONING

The variant of the hybrid environment that uses EnergyPlus instead of SPARK is to be used to test the implementation of the controls for the naturally ventilated part of the new San Francisco Federal Office Building (SFFOB), which is scheduled for occupancy at the end of 2005. The building design includes a narrow plan tower in which the open plan perimeter office space on floors 6-18 will be naturally ventilated, with no mechanical cooling or ventilation. Since natural ventilation in new commercial buildings is unconventional in the United States, there is concern that the associated control strategies will be unfamiliar to the contractors and that problems may arise with the initial operation of the building unless special measures are taken to test the implementation of the control strategy prior to occupancy.

The design of the naturally ventilated part of the building made extensive use of EnergyPlus, both to predict the performance of the natural ventilation system under peak conditions and to develop the strategy for the integrated control of the natural

ventilation system and the heating system. Since the control algorithm was developed in the simulation, the performance predicted when the control algorithm is included in the simulation is the intended performance of the building. The predicted performance obtained when the simulation is controlled by the real control equipment will be compared to the predicted performance when the control algorithm is included in the simulation. Any significant differences will indicate that the algorithm has not been implemented correctly and the nature of the differences will be used to identify the fault(s) in the programming of the controller. It is planned that this testing and debugging of the control program will be performed in the summer of 2004, during the construction of the building, so that a validated control program will be available as soon as testing in the real building becomes possible during 2005.

CONCLUSIONS

A hybrid simulation environment based on state-of-the-art simulation programs has been designed and a prototype constructed. The hybrid environment has a number of different applications and two of them – training and control system pre-commissioning – have been described. Tools based on this environment will be developed over the next few years for use in these and other applications.

ACKNOWLEDGEMENTS

This work was supported by the US General Services Administration and by the Assistant Secretary for Energy Efficiency and Renewable Energy, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

- Bourdouxhe, J-P.H., Grodent, M., Lebrun, J., Saavedra, C. 1994a. “A Toolkit for Primary HVAC System Energy Calculation - Part 1: Boiler Model”. *ASHRAE Transactions*. Vol.100, Part 2, 759-773.
- Bourdouxhe, J-P. H., Grodent, M., Lebrun, J.J., Saavedra, C., Silva, K.L. 1994b. “A Toolkit for Primary HVAC System Energy Calculation - Part 2: Reciprocating Chiller Models” *ASHRAE Transactions*. Vol.100, Part 2, 774-786.
- Brandemuehl, M.J. 1994. “Development of a Toolkit for Secondary HVAC System Energy Calculations,” *ASHRAE Transactions*., Vol.100, part 1, 21-32.

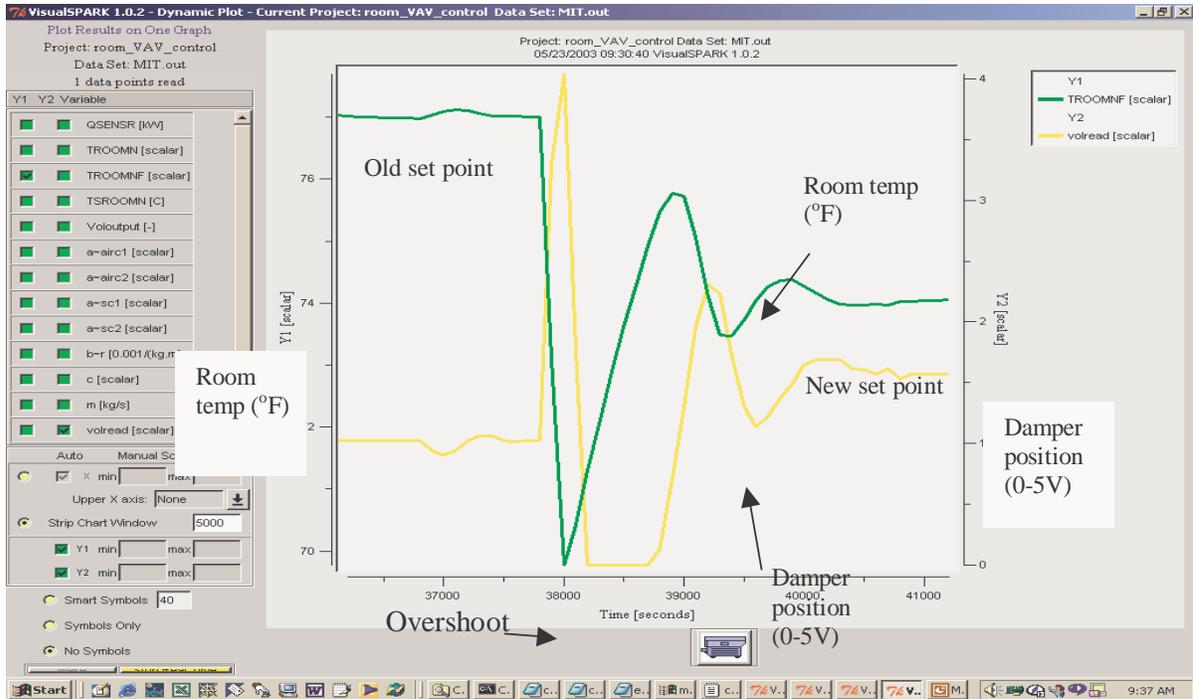


Figure 3 System response with poorly tuned controller



Figure 4 System response with tuned controller

Carnevale, A.P., L.J. Gainer, and A.S. Meltzer. 1990. *Workplace Basics: The Essential Skills Employers Want*, Jossey-Bass Publishers, San Francisco.

Crawley, D. 2004. "EnergyPlus Update", Proceedings of SimBuild 2004, Boulder, Colorado, August, IBPSA-USA.

- Haves, P. 1997. "Fault Modelling in Component-based HVAC Simulation," *Proceedings of Building Simulation '97*, Prague, Czech Republic.
- Haves, P., Dexter, A.L., Jorgensen, D.R., Ling, K.V. and Geng, G. 1991. "Use of a Building Emulator to Develop Techniques for Improved Commissioning and Control of HVAC Systems," *ASHRAE Transactions*, Vol. 97, Pt. 1.
- Haves, P., Norford, L.K. and DeSimone, M. 1998. "A Standard Simulation Testbed for the Evaluation of Control Algorithms & Strategies," *ASHRAE Transactions*, Vol. 104, Pt. 1.
- Haves, P., Norford, L.K., DeSimone, M. and Mei, L. 1996. *A Standard Simulation Testbed for the Evaluation of Control Algorithms & Strategies, 825-RP Final Report*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.
- Kelly, G.E. and May, W.B., 1990. "The concept of an emulator/tester for building energy management system performance evaluation," *ASHRAE Transactions*, Vol. 96, Pt. 1.
- Laret, L 1988. "Development of a Building Dynamic Multizone Model for Large Scale Simulations," *Proceedings of the USER-1 Building Simulation Conference*, September, Ostend, Belgium.
- Lebrun, J., 1992. *IEA Annex 17 Final Report*, University of Liège, Belgium.
- LBNL. 2004. *VisualSPARK Version 2.01*, free from <http://simulationresearch.lbl.gov/>
- Sowell, E.F, Buhl, W.F., Erdem, A.E. and Winkelmann, F.C. 1986. "A Prototype Object-based System for HVAC Simulation," *Proceedings of System Simulation in Buildings '86*. December, Liège, Belgium.
- Sowell, E.F., and Haves, P. 2001. "Efficient Solution Strategies for Building Energy System Simulation." *Energy and Buildings*, Vol. 33, 309-317.
- Vaezi-Nejad, H., Hutter, E., Haves, P., Dexter, A.L, Kelly, G., Nusgens, P. and Wang, S, 1991. "Use of Building Emulators to Evaluate the Performance of Building Energy Management Systems", *Proceedings of Building Simulation '91*, August, Nice, France. IBPSA.
- Ziegler, J.G. and Nichols, N.B. 1942. "Optimum Settings for Automatic Controllers," *ASME Transactions*, Vol. 64, 759-768