Co-simulation Based Building Controls Implementation with Networked Sensors and Actuators

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Abstract

The commercial building sector is one of the largest energy consumers in the U.S., and lighting, heating, ventilating and air conditioning contribute to more than half of the energy consumption and carbon emissions in buildings. Controls are the most effective way of increasing energy efficiency in building systems; however, the interdependencies among building subsystems must be taken into account to achieve deep energy savings. A networked sensing and actuation infrastructure shared among building systems is the key to optimal integrated control of the interdependent building elements in low energy and zero net energy buildings.

This paper presents a rapid-prototyping controls implementation platform based on the Building Controls Virtual Test Bed (BCVTB) framework that is capable of linking to building sensor and actuator networks for efficient controller design and testing. The platform creates a separation between the controls and the physical systems so that the controller can easily be implemented, tested and tuned with real performance feedback from a physical implementation. We realized an integrated lighting control algorithm using such a rapid-prototyping platform in a testing facility with networked sensors and actuators. This implementation has demonstrated an up to 57% savings in lighting electricity and 28% reduction in cooling demand.

Categories and Subject Descriptors

C.3 [**Special-purpose and Application-based Systems**]: *Real-time and embedded systems*; B.4.2 [**Input/Output and Data Communications**]: Data Communication Devices—*Processors*

General Terms

Measurement, experimentation.

Keywords

Integrated controls, lighting controls, sensor and actuator networks, energy efficiency, co-simulation, building controls virtual test bed.

1 Introduction

Commercial buildings account for 36% of the total electricity consumption in the U.S. in 2010 while lighting alone in buildings is responsible for 18% of site electricity usage and 14% of carbon dioxide emissions [5]. Together with heating, ventilating and air conditioning (HVAC), they contribute to more than half of the building energy consumption, expenditure as well as greenhouse gas emissions. Therefore, increasing the efficiency of lighting and HVAC systems is essential for realizing net zero energy buildings in the coming 15 years.

Successful and effective energy savings will only occur if user comfort and satisfaction are not compromised. Furthermore, truly deep savings can only result from controls that are backed up by rich sensor information to account for the interdependencies among building elements. A networked sensing infrastructure that is accessible and shared by all building control and management systems is critical to integrated controls.

The first objective of this paper is to present a novel rapid-prototyping controls implementation platform with networked sensors and actuators that facilitates efficient controls design and testing on physical systems. The second objective is to demonstrate the comfort and energy performances of the integrated lighting control algorithm realized on the rapid-prototyping platform.

The rest of the paper is organized as follows. Section 2 describes the needs for integrated controls and the role of sensor and actuator networks in this regime. Section 3 introduces the rapid-prototyping controls implementation platform for designing and testing control algorithms in physical facilities with sensor and actuator networks. Section 4 demonstrates a realization of such rapid-prototyping platform with integrated lighting controls. Section 5 analyzes the performance resulting from the demonstration. Section 6 concludes this paper with discussions and future applications.

2 Sensor and Actuator Networks and Integrated Controls

In order to properly account for the interdependencies among building elements, a building control system must be aware of the actions of other systems and rely on sensors to provide environmental conditions for making the best control decision. This is the essence of integrated controls. Consider, for example, that electric lighting and daylight can both be used for illumination. A photo-responsive lighting system can balance available daylight with dimmable electric lighting to maintain a target light level, thus optimizing the operation of the electric light and daylight with respect to the provision of illumination. However, the heat gain from electric lights and the solar heat gain from daylight are of different scale for the same amount of light, and these separate components impose different cooling loads on the HVAC system. Optimizing the energy performance operation of a single subsystem does not guarantee that total building energy performance will be optimized when the energy impacts of all systems are considered [3].

A networked sensing and actuation infrastructure that is accessible to all building systems and can monitor the state of the building elements, environmental variables (e.g. lighting, temperature, humidity, etc.), and actuator status is key to achieving deep energy savings. Furthermore, information carried in the sensor and actuator networks is also crucial from the standpoint of maintenance and diagnosis as well as gaining actionable insight into building system operation.

Given the complex nature of building physics, it is desirable to test and fine-tune a controller or a control algorithm directly in a physical setup to assess its performance in real environment. Therefore, a mechanism for rapid prototyping the implementation of controls will greatly accelerate the development of energy-efficient integrated controls.

3 Rapid-Prototyping Controls Implementation Platform

The main purpose of the rapid-prototyping controls implementation platform is to create a virtual separation between the facility and the controller such that changes in the controller, e.g. the control algorithm, can be taken online immediately to update system performance without affecting the physical setup in any way. This separation is realized using the Building Controls Virtual Test Bed (BCVTB) [1, 7].

3.1 Building Controls Virtual Test Bed

BCVTB is a tool capable of coupling multiple domain-specific application programs in a co-simulation environment, where each program updates its run-time status based on the information exchanged with others. In building science, there is no single tool that is powerful enough for simulating every aspect of the building behavior and condition. For instance, EnergyPlus is an advanced building energy modeling and simulation tool [6], but it does not generate adequate information on interior lighting distribution. BCVTB makes it possible to simultaneously study different aspects of the building condition via co-simulation as the example illustrated in Figure 1. BCVTB establishes communication channels to the coupled programs for data input/output and synchronizes them to the specified time step. Each connected program exchanges data through BCVTB at the beginning of a time step and incorporates the newly acquired data from other programs into the subsequent calculations. The graphical BCVTB configuration, as the centerpiece in Figure 1 illustrates, determines how the data are routed from one program to other programs. In addition, BCVTB allows synchronizing with the real time. In this case, the time step will be locked to the clock on the computer running BCVTB.

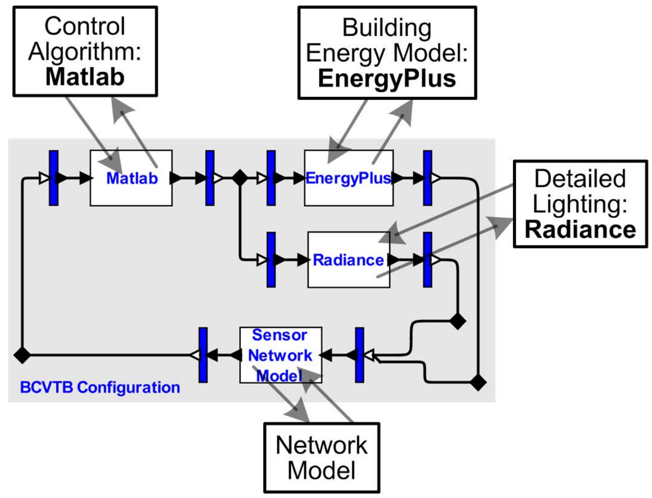

Figure 1. Architecture of BCVTB co-simulation.

Conceptually, BCVTB is able to establish a connection with any application tool as long as the program can input and output variables in the format recognizable to BCVTB. Along with the real-time synchronization feature, it opens the possibility of linking to a physical implementation.

3.2 Rapid-prototyping Controls Implementation Platform

In the rapid-prototyping controls implementation platform, the physical facility can be thought of as a virtual program that connects to BCVTB with its own inputs and outputs. As shown in Figure 2, the controller can be realized in any program that links to BCVTB. Meanwhile, the physical facility also establishes the connection to BCVTB through the gateway to the sensor and actuator networks. In other words, the sensor readings from the sensor network constitute the *outputs* of the facility while the control commands for actuating the corresponding building systems are treated as the *inputs*.

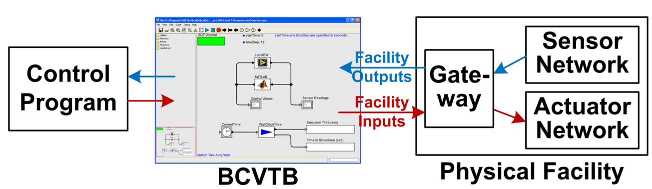

Figure 2. Rapid-prototyping controls implementation platform.

At the beginning of each time step, BCVTB relays the outputs from the control program, i.e. the control commands, to the actuator network in the facility and also passes the information acquired from the facility sensor network to the control program. After the data exchange, the control program then proceeds to make the control decision based on the latest sensor readings. The new control decision will get transferred to the physical facility in the next time step. In the meantime, the actuator network implements the control commands on the corresponding building systems in the facility. Similarly, the resulting changes in the environmental conditions will be reflected in the sensor information and sent to the control program in next time step.

With this setup, the controller can be revised in real-time without the need of altering any physical hardware. Also, the controls may be prototyped in any program suitable for the tasks so long as it can establish a connection with BCVTB. This not only makes control algorithm development efficient but also enables real-time testing, tuning and revision of the controller.

In addition to creating a virtual separation between the controller and the hardware systems, it is also possible to establish a physical separation. For example, if the gateway is configured to communicate with BCVTB through the Internet, the control program as well as the BCVTB can be set up remotely from the physical facility. For the case of wireless sensor and actuator networks, even the gateway can be located at a different location as long as it is within the reach of the wireless signals.

4 Demonstration

An instance of the rapid-prototyping controls implementation platform was realized in the Advanced Windows Testbed Facility located at the Lawrence Berkeley National Laboratory. The sensor and actuator networks existing in the facility were connected to the platform for demonstrating the development and performance of an energy-efficient integrated lighting and daylighting control algorithm.

4.1 Testing Facility

The facility consists of three independent and identical testing chambers. Each of the three chambers is 10 ft wide by 15 ft deep with an 11 ft ceiling and a south-facing window. A dedicated HVAC system conditions the air in each chamber. The sensing infrastructure in each testing cell consists of a network of 18 light sensors, 15 temperature sensors and 11 power sensors at strategic locations. There are also sensors on the network for monitoring system status, including blind slat tilt, electric light dimming voltage, and so on. 16 global sensors located on the periphery of the facility measure external environmental conditions, such as solar irradiances, outdoor temperature, exterior illuminances, etc. The actuation network in each room is composed of a fully dimmable electric lighting system and a venetian blind system. Two chambers in the facility were utilized in this demonstration; one served as the baseline reference, and the other was implemented with the integrated control algorithm through the BCVTB platform. This side-by-side setup was particularly valuable for quantifying the benefits introduced solely by the controls, isolating other extraneous environmental factors.

4.2 Configuration and Implementation

The controlled chamber was set up as a realization of the rapid-prototyping controls implementation platform. The control algorithm was implemented in Matlab and linked to BCVTB. The gateway to the sensor and actuator networks in the testing cell was configured to be accessible via the Internet so that the sensor network could be queried and the actuator network could take commands over the Internet. An auxiliary Java program was dedicated to convert the data into recognizable formats, thereby interfacing the gateway and BCVTB over the Internet. Notice that the communication between the gateway and BCVTB described herein was only set up for the proof-of-concept demonstration. In practice, standardized protocols, such as BACnet, LonWorks, etc., is likely to be implemented in the gateway such that the building sensor and actuator network is accessible to other building systems for interoperability, and in this case, the connection to BCVTB should adapt accordingly.

The objective of the control algorithm was to provide 500 lux task lighting on the workplane between 6am and 6pm with integrated control of electric lights and the motorized blind as energy-efficiently as possible. An integrated feedback control algorithm was implemented as shown in Figure 3. The commercial-grade ceiling photosensor, one of the 18 light sensors on the network, was used to provide feedback to the controller. The control algorithm regulated the blind slat angle so as to provide the specified task light level of 500 lux with daylight. As long as daylight levels were less than 500 lux, the electric lights would just “top-off” the daylight to bring the total level to 500 lux. The global and diffuse exterior illuminance readings from two of the 16 periphery sensors were utilized to infer the occurrence of direct sun beam. The controller would drive the blind slat angle to block the detected direct solar radiation from penetrating the room.

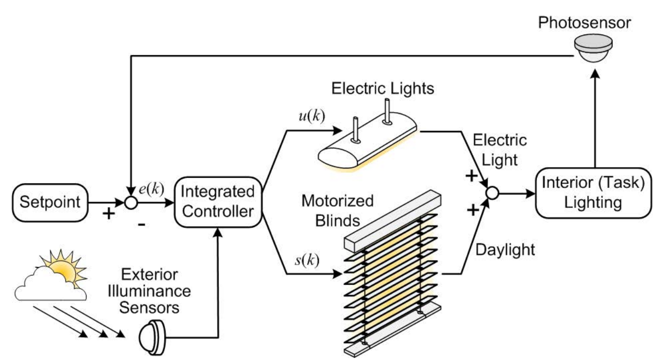

Figure 3. Integrated feedback control algorithm.

In this implementation, savings on lighting electricity was realized by dimming electric lights in response to available daylight to provide required task illumination. The blind slats were set to block glary direct sun beam when the ratio of global and diffuse exterior illuminance readings exceed a prescribed threshold. Meanwhile, the blind would be further closed to prevent discomfort glare due to strong daylight, and thus improving visual comfort. In addition, controlling admitted daylight level also helped regulate solar heat gain in the space, thereby generating energy savings on the HVAC system with reduced cooling demand.

During the testing period, the daylight responsive lighting control was implemented in the reference room to provide a task illuminance of at least 500 lux. The window treatment was a typical 1” venetian blind, which was always fully extended and with a slat angle fixed according to season. The blind slats were set to always block direct solar rays when the incoming angle’s altitude was at least 35° from June to mid August, 30° from late August to mid October and 0° from late October to December. In addition to the sensor readings used in the control algorithm, all other data from the sensor networks in both the controlled and reference testing chambers were collected and saved in a database for evaluating lighting and energy performance.

Table 1 summarizes the setups in the two testing chambers. The thermostat setpoints were set similarly (23.5°C) with minor differences to account for the intrinsic thermal discrepancies in each room.

Table 1. Setups in the testing chambers.

	Reference room	Controlled room
Lighting	Dimmable fluorescent	Dimmable fluorescent
Shading	Static blind	Motorized blind
Controls	Daylight dimming of electric lights for 500 lux task lighting.	Integrated control of dimmable electric lights and blind through BCVB for 500 lux task lighting.
	Fixed blind slats at seasonally prescribed angles.	
Remarks	Task lighting could exceed 500 lux when daylight alone contributed over 500 lux under the given static blind slat angle.	Task lighting could exceed 500 lux only under strong daylight when lights were off and blind was closed completely.

5 Performance Analysis

This section focuses the analysis on task illumination and energy by comparing the performance of the controlled and reference testing chambers. The test setup was cycled into the facility for a 4-day testing roughly every 2 weeks from summer solstice to winter solstice of 2010 (9 testing cycles for a total of 42 testing days) to sample across a wide range of different solar and weather conditions. The control algorithm was constantly under revision at the beginning few runs based on the performance feedback from the monitoring sensors. Thanks to the BCVTB-based rapid-prototyping platform, the improvements were able to be brought online immediately, greatly reducing testing time. After the control algorithm was operating satisfactorily, the data from 19 uninterrupted days between 6am and 6pm Pacific Standard Time were selected for analysis.

5.1 Task Illumination Performance

Task illumination is used as a surrogate for assessing visual comfort performance since a proper level of illumination on the workplane is a significant requirement for good lighting quality. The task illuminance of 500 lux in this demonstration is the recommendation for general office-type tasks [4].

The histogram in Figure 4 shows the distribution of the readings from the two out of the 16 light sensors in the controlled chamber acquired every minute over the course of study. These two sensors were at the workplane height close to the desks in the testing chamber, one towards the east and one towards the west of the north-south centerline, and thus best captured the task lighting conditions. Both sensors showed that 70% of the time the task illuminance was successfully maintained around 500 lux (500±50 lux) by the control algorithm. The other 30% was mostly caused by the fast-changing nature of the sky condition. Nonetheless, the task illuminance was regulated between 400-600 lux 93% of the time, and the control algorithm was able to restore the desired lighting condition once it was off-target. Also notice that the low task illuminance readings below 200 lux were those acquired around 6am when the system first came out of nighttime setback and began to turn on the lights for 500 lux task illuminance.

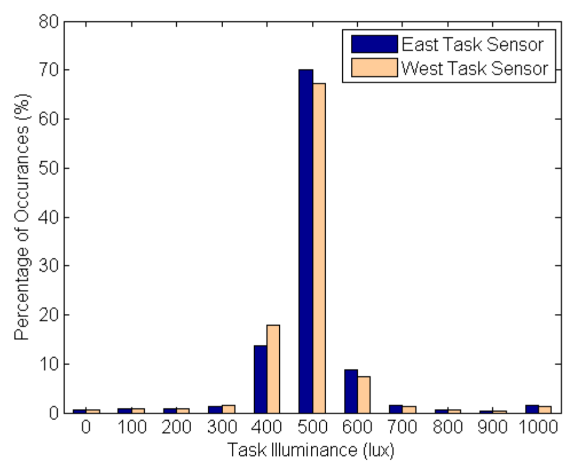

Figure 4. Task-level horizontal illuminance.

Figure 5 shows the comparison of average hourly task illuminance between the controlled and the reference testing chambers. The same sensors as those used to generate Figure 4 in both testing rooms were incorporated in this analysis. The crosses and triangles are the mean task illuminance in the controlled and reference rooms respectively, and the whiskers represent the corresponding standard deviations. The mean task illuminance in the controlled chamber was maintained within ±50 lux, a range that is in general unperceivable by most people at the targeted 500 lux light level. On the other hand, the task illuminance in the reference room was significantly higher on average with much larger variations. The high task light level in the reference room was caused by admitting excessive amounts of daylight, which not only implied high probability of discomfort daylight glare but would also result in higher cooling demand.

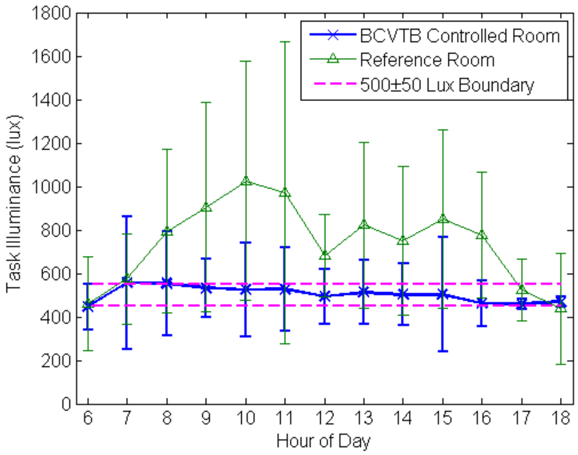

Figure 5. Task illumination comparison.

Scrutinizing the sensor data in the reference chamber revealed that 88% of the time the task lighting was higher than 550 lux, which roughly corresponded to the possible occurrence of discomfort glare 62% of the time (compared to 24% in the controlled chamber). The glare assessment was derived from the vertical illuminance measurements based on an earlier internal study, and the details were omitted here since it was not the focus of the analysis.

5.2 Energy Performance

The energy performance of the two testing chambers was compared from two aspects: lighting electricity consumption and cooling demand. Figure 6 shows the average hourly lighting loads aggregated in the same way as Figure 5 over the entire study period. With harmonized operation of the electric lights and the motorized blind, lighting demand in the controlled room was as much as 57% lower than in the reference room.

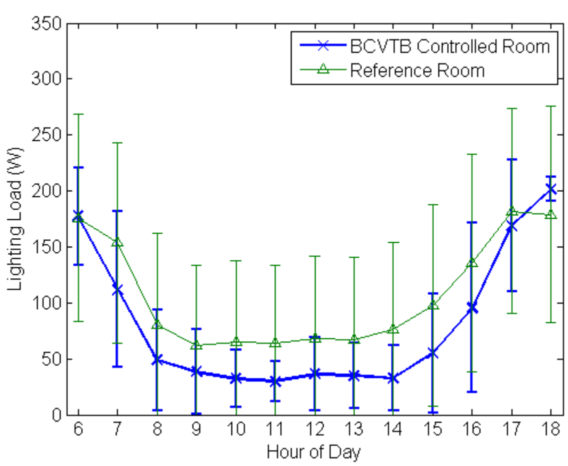

Figure 6. Lighting load comparison.

This high demand savings of 57% might have occurred because the blind in the reference room was relatively closed for the majority of the study period (recall that the slat angle was set to block direct normal sun beam from late October to December, which corresponded to a slat angle of 60° from horizontal). Consequently, electric lights often had to be turned on to compensate for insufficient daylight.

The test facility was not designed to enable direct comparison of HVAC energy consumption. Instead, the cooling or heating demand due to the window and lighting systems was measured for each room. Measurements were corrected for thermal and room-to-room variations using a static thermal model. The resulting "dynamic net heat flow", or standardized cooling demand, is expected to represent, on average, only the effects of solar, thermal, and lighting heat gains (including internal solar storage) on a standardized room. Hourly cooling loads were determined by averaging 1-minute data over an hour, then computing the hourly net heat flow. A detailed description of the method can be found in [2].

The daily cooling demands due to window and lighting systems in both testing chambers are plotted in Figure 7. The cooling demand reductions introduced by the control algorithm were between 0.7 and 2.4 kWh (10-28% savings), depending on the specific weather and sky conditions each day. Note that the negative cooling demands in Figure 7 imply that the heat gains and heat flow through window resulted in a net heat loss. In these cases, it is difficult to directly compare the energy performances. Nonetheless, the 17% average cooling demand reduction shows the potential positive impact of integrated lighting controls on HVAC energy consumption.

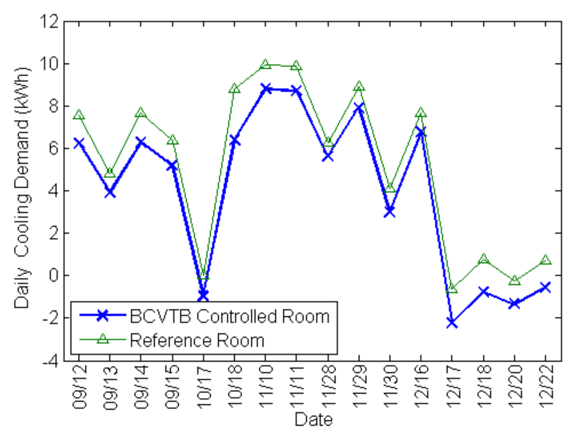

Figure 7. Comparison of daily cooling demand.

6 Discussion and Future Applications

Leveraging the rapid-prototyping controls implementation platform, the performance of an integrated lighting control algorithm has been demonstrated in a testing facility with a networked sensing and actuation infrastructure. Compared to the reference case, the task lighting in the controlled case was more consistently maintained at a desired level for visual comfort while the lighting and cooling demand were reduced by as much as 57% and 28%, respectively. The

BCVTB-based platform also enabled fast revision and testing of control algorithms, which could be implemented in any program, without interfering with the physical setups.

Integrated control of electric lights and venetian blinds has demonstrated a promising potential for deep energy savings. Exploiting the concept of a shared networked sensing and actuation infrastructure, controls integration can be extended to include other interdependent building elements, such as thermostat for indoor air temperature and thermal comfort. Incorporating wireless mesh networking technologies, wireless sensor and actuator network will afford more flexible and economical configuration for integrated controls both on the rapid-prototyping platform and in practical implementations.

Beyond prototyping, the BCVTB-based control platform may also be extended for practical implementations. Coupling other domain-specific building modeling tools, such as EnergyPlus, Radiance, etc., with the physical sensor and actuator networks as well as control sequences, building models can be calibrated in real time. The calibrated models are then useful for model-based retro-commissioning and fault detection that compare real measurements against simulated building behaviors for abnormalities. Failures and drifts in building systems over time usually are the primary causes of energy performance degradation. Therefore, model-based continuous commissioning and fault detection incorporating real-time sensing and controls information could potentially be an elegant solution for sustainable building operation.

7 Acknowledgments

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