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AN AGENT-BASED SIMULATION-ASSISTED APPROACH TO BI-LATERAL BUILDING SYSTEMS CONTROL

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ABSTRACT

Conventional building control systems usually apply central control schemes that do not fully address individual occupancy differences in built environmental requirements. Recent application of personal control modules in commercial buildings presents a *bi-lateral control scheme*, in which a building operator and an occupant can both control the occupant's local environmental settings, e.g., lighting, heating, cooling, and ventilation, etc. While personal controls may enhance individual comfort, they may also neutralize operators' cost-saving efforts. The potential operational conflicts in the emerging bi-lateral scheme have not been sufficiently addressed. The paper presents an agent-based framework for building operators and individual occupants to negotiate their control activities. A prototype in the lighting controls domain was implemented and the simulation results showed that the framework effectively allowed for concurrent evaluation of energy consumption and individual comfort to achieve balanced control strategies.

INTRODUCTION

A high performance building must at least achieve two goals: maximize occupant comfort and minimize energy costs. In a central-controlled commercial office building that accommodates many employees, a building operator usually makes control decisions based on generalized occupant requirements. Guidelines for building operations usually set criteria based on acceptable response of 80% of the occupants (for example, ASHRAE Standard 62-1989 "Ventilation for Acceptable Indoor Air Quality").

Studies have shown that individual occupants could be highly dissatisfied with the work environment and lose their productivity even thought technical measurements indicated that standards were being met (Abdou et al. 1994). Individuals differ in age, sex, cultural background, living habits, physical and psychological conditions (Wyon 1992). There is currently no effective means for a building operator to capture individual requirements. On the other hand, energy costs are much easier to measure (e.g., gas, water and electricity bills). As a result, building control decisions are likely to favor cost savings at the expense of occupant comfort (Robertson 1988).

The emerging personal environmental control modules allow an occupant to personalize her work environment, and have shown some increase in occupancy satisfaction and self-reported productivity in office buildings (Kroner 1994, Littlefaire et al. 2001). The addition of personal control devices to existing central control systems presents a new control scheme, in which both a building operator and an occupant can control the occupant's local environment—hence we call it a *bi-lateral control scheme*. In the bi-lateral control scheme, a building operator and an individual occupant have different control perspectives (Table 1) that may lead to potential control conflicts—they may cancel each other's control efforts (Mo et al., 2002). While a building operator may effectively manage energy costs, an occupant knows better about her own preferences. To achieve both energy conservation and occupancy comfort, we suggest a *division of control responsibility* and *control negotiation* between operators and occupants.

Table 1. Conceptual illustration of control-relevant differences between operators and occupants

	Operators	Occupants
Motivation	Costs	Personal comfort
Perspective	Global view	Local view
Control scope	Entire building	Individual space
Decision style	Scheduled	Improvised
Execution	Delay	Instant
Granularity	Coarse	Fine-tune

The paper presents an agent-based negotiation environment to facilitate negotiation among building operators and individual occupants and to allow for concurrent evaluation of energy costs and individual comfort. A bi-lateral lighting control environment was implemented to evaluate several control strategies with respect to balancing energy costs and individual comfort.

AGENT-BASED FRAMEWORK

In a bi-lateral control system, occupants and building operators are self-reliant and interdependent. Each makes control decisions based on environmental information available to her. The negotiation of potential conflicts may be time consuming and ineffective. A group of software agents could potentially automate the negotiation on behalf of the participants.

According to Woodridge (1995), "An agent is a computer system that is situated in some environment, and is capable of autonomous action in this environment in order to meet its design objectives." Agents can be embedded into individual control interfaces, e.g., infrared controller, wireless hand-held, web-based control interface, etc., and they negotiate through the agent-based bi-lateral control framework. Figure 1 identifies five basic types of agents (Mo et al., 2002):

1. **Operator agent** incorporates a building operator's domain knowledge, receives environmental information from sensor agents, and sends control decisions to actuator agents.
2. **Occupant agent** is embedded in an individual control interface that receives control intentions from its occupant. It may have learning capability [8] to profile its owner's environmental preference.
3. **Actuator agent** is associated with an actuator to control the distribution of a resource. It accepts control command from both operator agents and occupant agents. Once conflicting control requests are received, a negotiation session is activated.
4. **Sensor agent** is associated with one or a group of sensors. It collects environmental information and sends it to related occupant and/or operator agents.
5. **Utility agent** interacts with external systems or legacy systems, such as an expert systems or a weather station.

Typical interactions among the agents are illustrated in Figure 2. The detailed description of the framework can be found in (Mo et al. 2002). This paper focuses on a prototypical simulation and evaluation.

SIMULATION MODEL

As a proof of concept, the lighting environment in a test bay of the Robert L. Preger Intelligent Workplace at Carnegie Mellon University, Pittsburgh, Pennsylvania, was modeled with an implementation of the agent-based control framework.

Figure 3 shows the plan and the section of the test bay. The test bay had one west-facing double facade system, including a glazing facade and a set of three parallel movable louvers. The louvers were motorized and could be rotated. Four luminaires were installed, each with a continuous dimming ballast. The change of one luminaire affected the lighting levels in the other three cubicles.

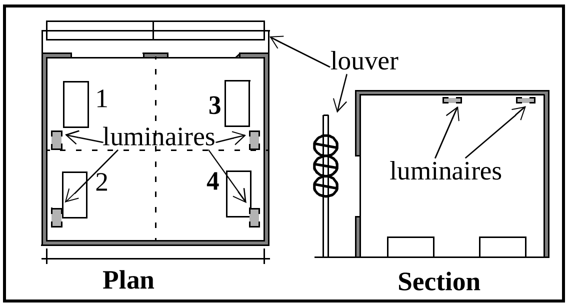

Figure 3. Test bay in the Intelligent Workplace

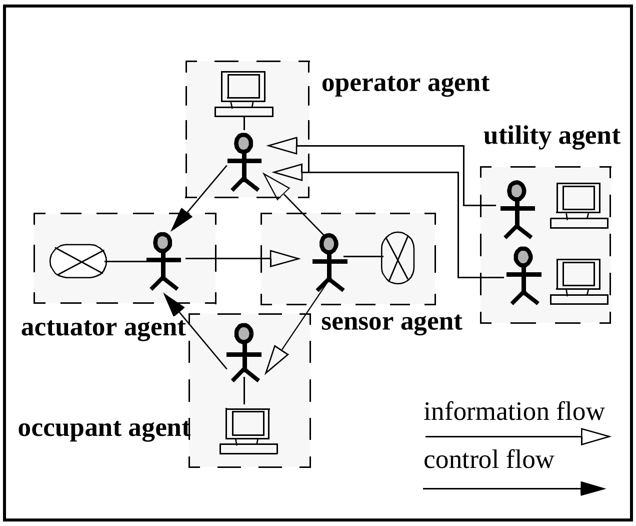

Figure 1. Agent types

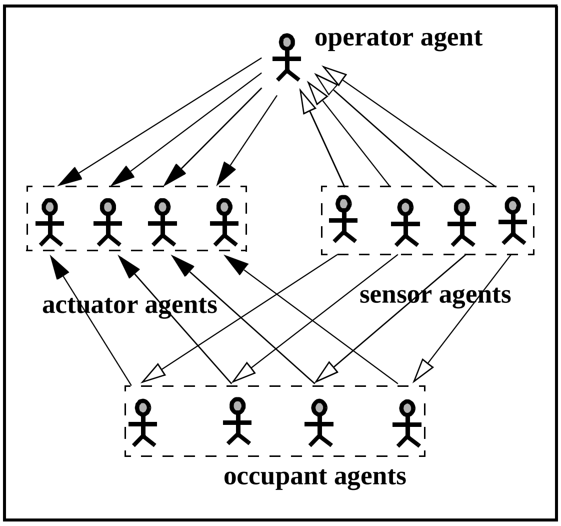

Figure 2. Agent interaction

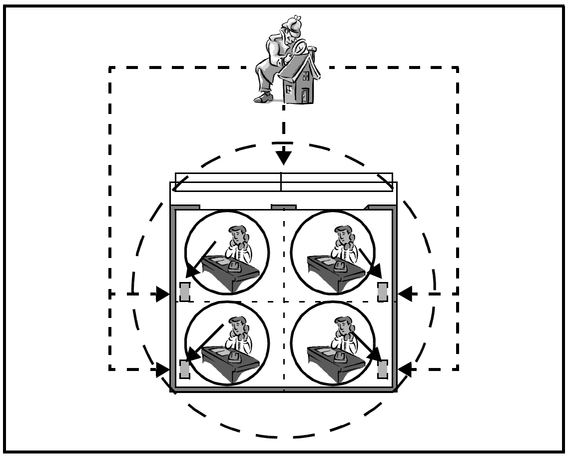

Figure 4. Control domains

Four occupants shared the test bay. Each occupant had a personal lighting control device only to control the luminaire above her cubicle. An operator could change the four luminaires as well as the louvers. The operator and the occupants had different control domains shown in Figure 4. In general, each represented a specific viewpoint and problem-solving entity and had partial control knowledge.

For simplification, the movement of the louvers was discretized into twelve angles, from 0^o up to 105^o; 0^o was the fully open position and 105^o the fully closed position. The continuous dimming system was also discretized into 10 output levels at 10% intervals, from 10% up to 100%.

To prepare data for simulation, the actual power consumptions of each luminaire at the ten output levels were measured. And at each output level, illuminance in the four cubicles and the center of the test bay were measured.

SIMULATED SCENARIOS AND CONTROL STRATEGIES

Three lighting control scenarios were evaluated and four lighting control strategies were simulated as shown in Table 2. The three control scenarios were:

A) centralized control only;
B) bi-lateral control without negotiation;
C) bi-lateral control with negotiation.

Though lighting environment closely relates to the thermal environment, the experiment only considered lighting controls. In the test bay, the lighting controls were to decide the angle of the louvers and the output level of each luminaire. An individual occupant tried to maintain the illuminance in her cubicle close to her preferred level. The operator tried to maintain the illuminance at the center of the test bay above a set point.

Strategies 1 and 2 simulated centralized control scenario A, in which occupants had no control over their local environment. The operator could implement a number of control strategies.

The strategy 1 simulated a low-end strategy: the louvers stayed fully closed and functioned as a fixed blinds to prevent direct glare; and the four luminaires were always at the same output levels. There were only ten possible luminaire configurations.

Table 2. Simulated control strategies

	Operator Control		**Occupant Control**	**Negotiation**
	Louver	**Luminaire**	**Luminaire**	
1	closed	uniform	No	No
2	tracking	coupled	No	No
3	same as 2.		Yes	No
4	same as 2		Yes	Yes

The strategy 2 represented a more sophisticated level: the louvers tracked the sun's position in order to block direct glare while reflected indirect daylight into the bay to save electricity. To maximize the use of natural daylight, the output of the two outer luminaires (1 and 3) were always equal to or lower than that of the two inner luminaires (2 and 4). The operator relied on the center illuminance to monitor the test bay. The two outer luminaires were grouped together and had the same output, so were the two inner luminaires. There were totally 54 possible luminaire configurations, as partially illustrated in Table 3.

Table 3.
Examples of luminaire configurations in strategy 2

L1	L3	L2	L4
10%	10%	10%	10%
20%	20%	10%	10%
20%	20%	20%	20%
30%	30%	10%	10%
30%	30%	20%	20%
30%	30%	30%	30%
...			
100%	100%	100%	100%

The strategy 3 simulated the scenario B—centralized control with personal control devices. However, there were no coordination between the operator and the occupants. In this case, possible luminaire configurations were 10^4=10,000.

Presumably, the strategy 1 and 2 would result in lower energy costs but greater visual discomfort, because the operator could control the costs but did not know individual preferences. On the other hand, the strategy 3 might lower visual discomfort but consume more energy, because each occupant was allowed to customize her local environmental settings without necessarily being aware of the overall energy consumption and hence the energy costs.

The strategy 4 simulated the scenario C—the agent-based bi-lateral control framework. A group of agents were instantiated to communicate their owners' control intentions. It was hypothesized that, compared to the strategies 1 to 3, the strategy 4 would enhance occupant comfort without undue increase in energy costs.

AGENTIFICATION IN STRATEGY 4

The agent-based simulation environment was built on the RESTINA Agent Foundation Class [9] that provided building blocks and glues for multi-agent system development. The RESTINA was developed by the Intelligent Software Agents Laboratory in the Robotics Institute at Carnegie Mellon University. The semantic communications between agents applied the Knowledge Query and Manipulation Language (KQML), a protocol of exchanging information and knowledge between distributed agents. The programming language was C++. The daylight and lighting simulation engine was LUMINA (Pal 1999), an in-house application that computed indoor illuminance, given simulation date, time, test bay dimensions, and material information.

Based on the agent-based bi-lateral control framework, a group of agents were subclasses of the five basic agent types and formed an agent society, shown in Figure 5:

- **OperatorAgent** associated with the operator's control device.
- **OccupantAgents** embedded into the occupants' control devices.
- **IlluminanceAgents** to report lighting levels in the four cubicles, and CenIlluminanceAgent to report the center illuminance to the Operator-Agent.
- **LuminaireAgents** associated with the dimming system.
- **LouverAgent** associated with the louver actuator.
- **Negotiator**.

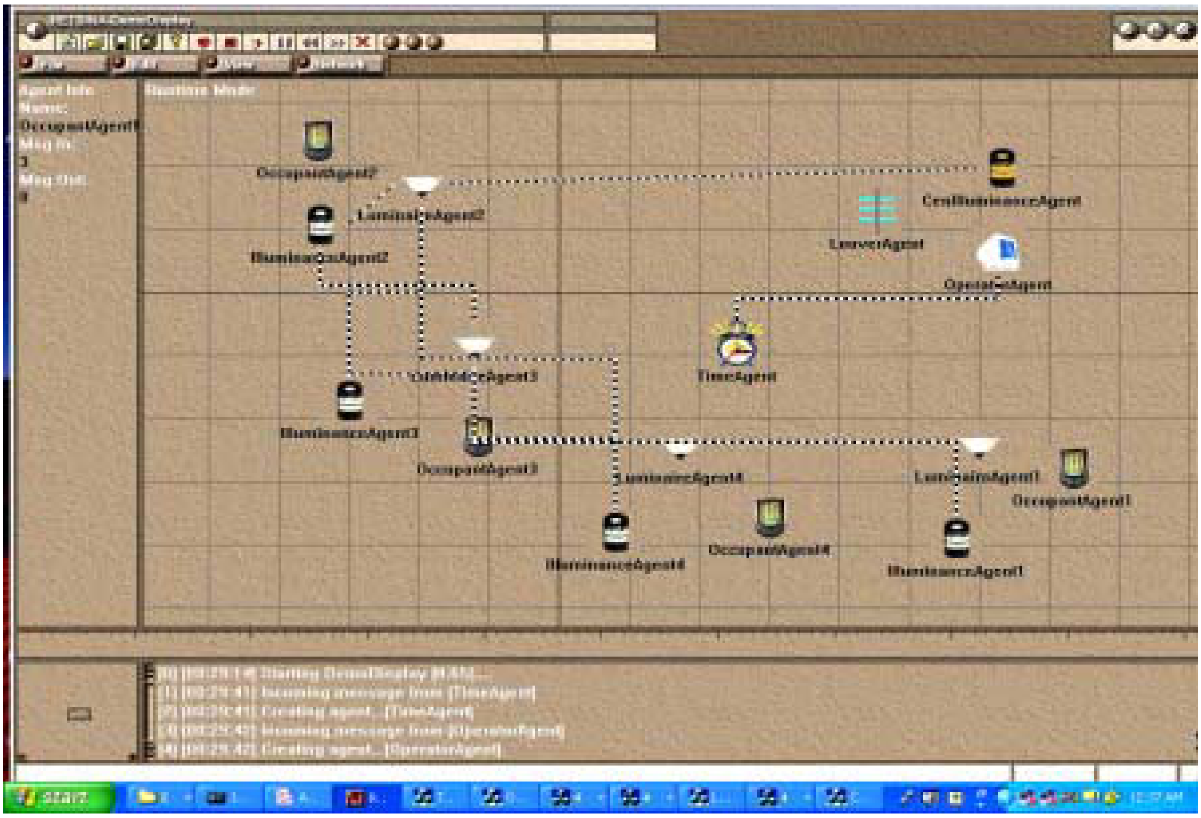

Figure 5. Agent Society and simulation environment

- **DaylightAgent** to report daylight changes over time.
- **TimeAgent** to synchronize agent interaction.
- **SystemAgent** to record energy costs and individual discomfort.

The implemented simulation environment allowed for virtual experiment to validate different control strategies. Existing simulation applications (e.g., LUMINA) can be seamlessly agentified or packaged into an agent to help decision-making. Due to the space limit, the paper only introduces the OperatorAgent, the OccupantAgents and the Negotiator.

OperatorAgent

Figure 6 shows the sequence diagram of the OperatorAgent based on the UML standard. The OperatorAgent first decided the position of the louvers based on the sun's position and sky conditions, and then decided the output levels of the four luminaires to make up the difference between the set point and the daylight illuminance at the center position of the test bay. Figure 7 shows the control interface for building operators. The simulation date, time, central control strategy, and the set point for the center of the test bay were input to initiate a new round of simulation. The simulation engine LUMINA was packaged into the OperatorAgent to facilitate decision-making process.

OccupantAgent

An occupantAgent made control decisions on behalf of her owner. Each OccupantAgent received its owner's control intentions through a personal control interface (Figure 8). Most of the time, an OccupantAgent automated the control process based on "learned" (Mozer 1999) occupant preference or input profile. However, through the interface, an occupant could manually override its agent's control decisions. To simulate individual differences, each occupant had a different work schedule and lighting preference for a task. Table 4 shows assumed individual preferred lighting level for different tasks. Table 5 shows assumed different individual schedules in a work day.

Figure 7. OperatorAgent's interface

To evaluate an individual discomfort level, we used *deviation (D)*—the average difference between the desired illuminance level and the actual illuminance level over time,

$$D = (\Sigma(|E_p - E_a| \bullet T_i))/(\Sigma(T_i))$$

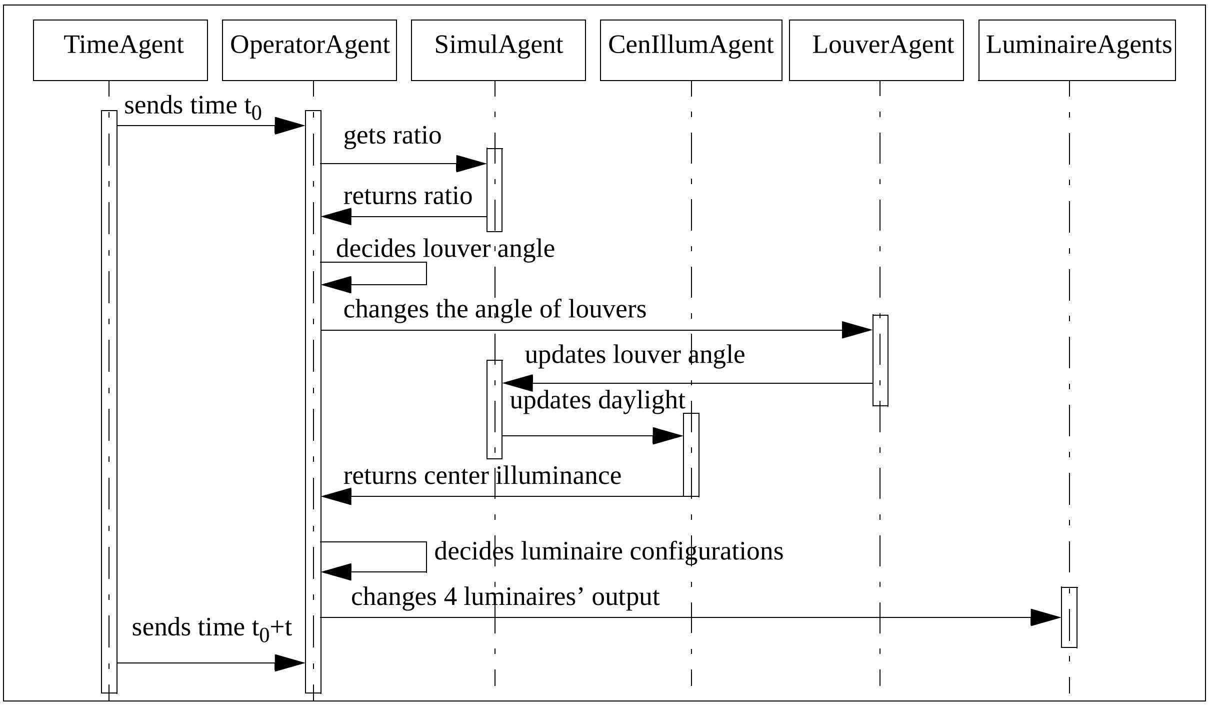

Figure 6. Sequence diagram of OperatorAgent control

where
Ep—preferred illuminance levels (lx);
Ea—actual illuminance levels (lx);
Ti— duration (h).

The smaller the deviation, the greater the occupant comfort during the simulation period.

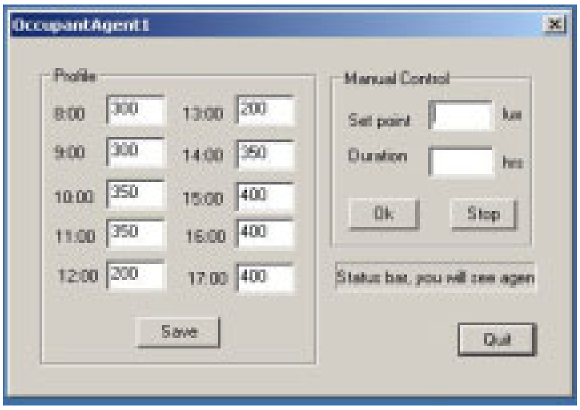

Figure 8. OccupantAgent's Interface

Table 4.
Individual preference by task (illuminance in lx)

	paper-based	**computer-based**	**meeting**	**away**
1	600	350	400	100
2	500	300	400	100
3	400	250	400	100
4	300	200	400	100

Table 5. Individual preference by work schedule (illuminance in lx)

	8:00-10:00	**10:00-12:00**	**12:00-14:00**	**14:00-16:00**	**16:00-18:00**
1	600		400	350	600
2	300		500		400
3	250	400			
4	100	200	400	300	

Negotiator

Figure 9 is the sequence diagram for the Negotiator. The negotiator remained idle until a conflict occurred. In a negotiation process, the negotiator evaluated energy costs and individual discomfort of each possible arrangement and chose one that yielded the greatest utility based on operational objectives. Research found (Probe 2002) that sometimes energy costs and occupant comfort were in conflict, sometimes they were in harmony, and sometimes they were independent. Three possible negotiation results were: 1) an agreement, 2) deadlock, or 3) a new round of negotiation involving more agents and objectives.

In different built environments, the operational objectives are different. In the present experiment, the objective was to apply the services of the negotiator agent to maximize light level desirability within the constraints of a given energy budget. The negotiation rule was therefore simply implemented as: if resulting energy use runs below a given limit, accept Occupant Agent's configuration; otherwise, accept Operator-Agent's configuration.

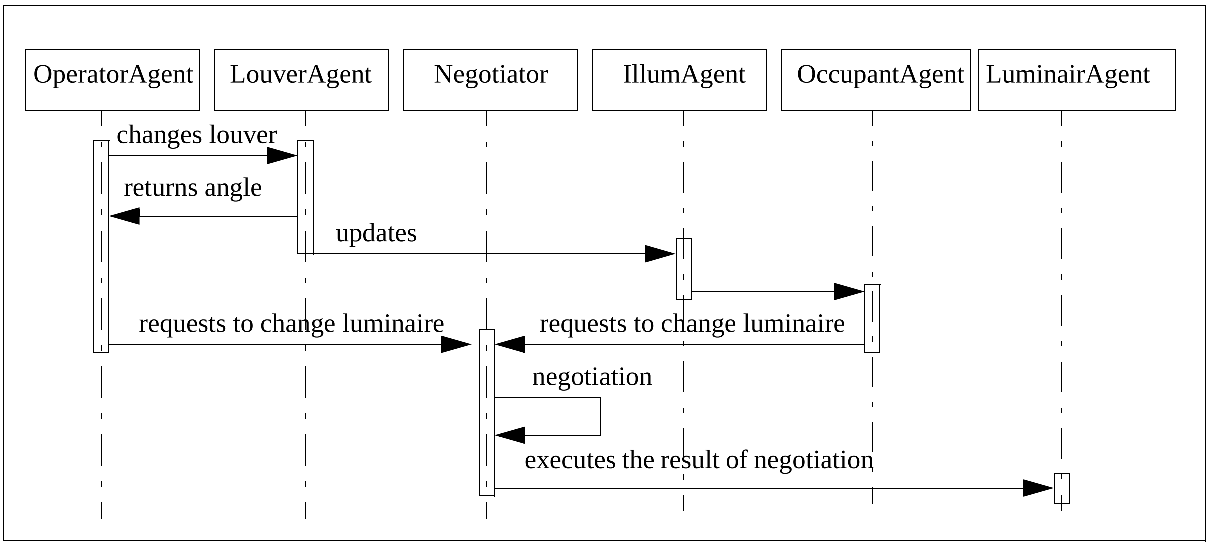

Figure 9. Sequence diagram of Negotiator

SIMULATION RESULTS

The four strategies were simulated on four typical days: March 15, June 15, September 15 and December 15, from 8:00 am to 6:00 pm. The OperatorAgent evaluated the lighting environment every 20 minutes. The OccupantAgents, however, took control actions at anytime to maintain the local lighting level close to its owner's preference. Two indicators were used to evaluate the four strategies:

1. discomfort: *deviation* D
2. energy use: *electricity consumption in kWh*

Figure 10 shows the luminaire configurations of the strategy 1 on March 15. All the four luminaires were at the same output level. The electricity use was 3.3 kWh.

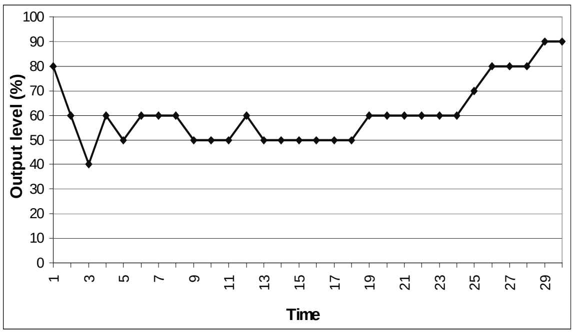

Figure 10. Luminaire configuration on March 15 in strategy 1

Figure 11 shows the luminaire configurations of the strategy 2 on March 15. The electricity use was 3.4 kWh. The coupled luminaire 1 and 3 always had lower output than coupled luminaire 2 and 4, because they were at the outer positions and took advantage of daylight.

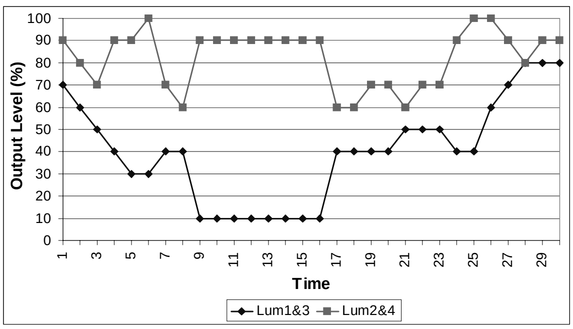

Figure 11. Luminaire configuration on March 15 in strategy 2

Figure 12 shows the luminaire configuration of the strategy 3 on March 15. Since the four OccupantAgents were able to control their local lighting environment based on their own preference, the four

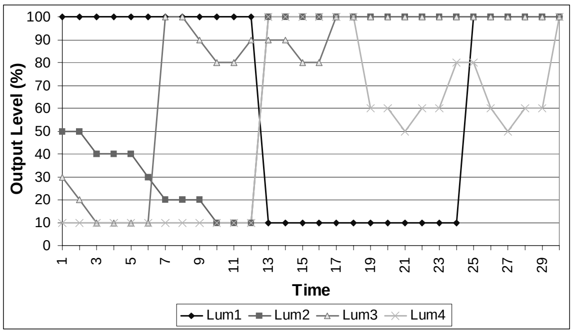

Figure 12. Luminaire configuration on March 15 in strategy 3

luminaires' output were unpredictable. The number of possible luminaire configurations in this strategy was virtually equal to the maximum number of possible luminaire configurations (10^4).

Figure 13 shows the luminaire configuration of the strategy 4 on December 15. The negotiator agent was activated. The resulting luminaire configuration appeared as irregular as that in the scenario 3. However, individual discomfort and energy use were different from those in the strategy 3.

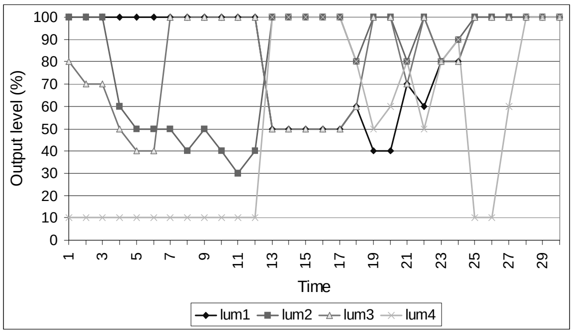

Figure 13. Luminaire configuration on December 15 in strategy 4

Table 6 summarizes the simulation results of the four control strategies. The annual energy use was projected based on the energy consumption on the four typical days for each strategy. The average deviation was the average of the four individual deviations.

Table 6. Simulation results of the four strategies

	Annual Energy Use (kWh/m^2)	**Avg. Deviation (lx)**
1	43	105
2	42	110
3	47	95
4	39	105

Figure 14 illustrates the energy use and individual discomfort in the four strategies. The strategies 1 and

2 were centralized controls, therefore, the operator could effectively control the energy use but led to higher individual discomfort.

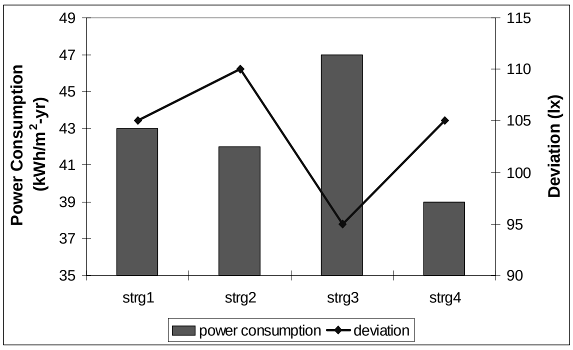

Figure 14. Comparison of energy use and occupant discomfort

The strategy 3 allowed individual occupants to customize their own environment. The individual discomfort was greatly reduced but much higher energy use resulted, because individuals were not aware of the entire building's performance and were only concerned about their own comfort.

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The strategy 4 implemented the agent-based control framework. As anticipated, the energy use was reduced without undue increase in occupant discomfort.

The negotiation rules and objective functions used in the simulation were rather primitive. It is possible that, by implementing more sophisticated negotiation algorithms and more comprehensive objective functions, higher individual comfort with lower energy use could be achieved.

CONCLUSIONS

The paper proposed an agent-based framework for bilateral control schemes. Simulation-based comparative studies showed that the framework effectively allows for concurrent evaluation of multiple control strategies with differences in:

- device control options (fixed shading vs. solar tracking, uniform dimming vs. individual dimming of luminaires)
- set point (universal vs. individually-based dynamic set points)
- control schemes (central controls vs. individual controls vs. negotiated controls)

The simulation results also generally suggest that it is possible for an agent-based simulation-assisted bi-lateral control strategy to improve occupancy requirements (e.g., desired light levels) without undue increase in energy use.

Future research work includes 1) testing different sets of individual preferences, 2) physical implementation of the framework in the test bay, and 3) multi-modal controls.

ACKNOWLEDGEMENTS

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