Towards Embedded Wireless-Networked Intelligent Daylighting Systems for Commercial Buildings

Yao-Jung Wen
Dept. of Mechanical Eng.
UC Berkeley
rio@me.berkeley.edu

Jessica Granderson
Dept. of Mechanical Eng.
UC Berkeley
jgrander@me.berkeley.edu

Alice M. Agogino
Dept. of Mechanical Eng.
UC Berkeley
agogino@berkeley.edu

Abstract

Energy efficient office lighting systems can save 40% in electricity consumption in areas that receive significant amounts of daylight. In spite of the savings they can generate, daylighting systems are not widely used in the commercial office building. Barriers prohibiting adoption include high retrofitting costs, and difficulty estimating and maintaining worksurface illuminances.

In this paper, an intelligent control framework that utilizes MEMS-based (micro-electro-mechanical systems) 'Smart Dust motes' wireless platforms is explored. Due to their small size, they can be placed directly on the worksurface. As a result, illuminance estimation and maintenance is significantly improved. Furthermore, motes functioning as actuators can be interfaced with dimming ballasts without the need to rewire the building, enabling less expensive, less disruptive retrofitting of commercial buildings.

1. Introduction

Buildings account for 1/3 of primary energy, and 2/3 of the electricity generated in the US [3]. Roughly 40% of electricity consumption in commercial buildings is attributable to lighting. These numbers indicate that efficient commercial lighting has the potential to significantly impact energy efficiency in the US.

Commercial daylighting systems can save up to 40% in electricity consumption in offices that with significant amounts of daylight [7]. However, there remain several challenges preventing widespread adoption. Retrofitting buildings with traditional on/off lighting controls requires access to power lines located behind the walls or ceiling and hence is expensive and disruptive. Since they are hardwired, photosensors are placed on the ceiling, causing inaccurate measures of worksurface illuminance, and difficulty maintaining target illuminances. Finally, commissioning[1] existing daylighting systems requires a certain level of expertise, and a significant time investment [17].

Smart Dust motes are a novel wireless sensing and actuating technology with the potential to solve many of the problems associated with commercial daylighting systems. This research entails the development of intelligent algorithms for mote-based sensing and actuating for daylighting control. It is important to note that this research is tightly coupled with parallel work devoted to the development of an intelligent decision making algorithm. These complimentary research efforts will ultimately be combined to form an integrated intelligent daylighting control system.

The application of wireless sensor networks to daylight-responsive controls has recently been proposed as a promising energy conservation approach. O'Reilly et al. sketched a wireless platform that can be interfaced with DALI (Digital Addressable Lighting Interface) systems [15]. Singhvi et al. proposed a utility-based building control strategy that optimized the tradeoff between users' comfort and energy consumption [18]. However, this paper builds on the work in [6] and uniquely integrates wireless sensors and actuators into an "intelligent" decision-analytic framework. In this framework, the accuracy and robustness of the sensor readings are maximized, the sensors and actuators using the same platforms will cause no compatibility issues, and occupants' preference, managers' opinions and energy conservation are all taken into account.

The remainder of this paper details the design of the mote sensing and actuation components of the intelligent daylighting system. Results from three actuation and sensing experiments are presented to provide insight regarding the feasibility of wireless sensing and actuation for lighting control. Following a discussion of the

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[1] Commissioning refers to the process of calibrating photosensors under night and day conditions, setting photosensor field of view, and troubleshooting each component of the sensing and control system.

experimental results and implications, directions for future research are presented.

2. Distributed MEMS platforms: Smart Dust motes

Researchers at UC Berkeley first proposed ‘Smart Dust’ as a futuristic dust-sized processing and communication unit based on MEMS technology. While truly miniature platforms are still under development, millimeter-scale ‘motes’ are currently commercially available. Motes can be configured with a variety of onboard sensors for use in high-density, distributed sensor networks. The mote platform used in this research is the MICA2 manufactured by Crossbow Technology Inc. as shown in Figure 1.

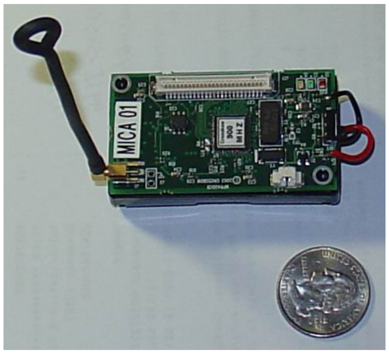

Figure 1. MICA2 mote by Crossbow Inc.

Several generations of smart motes exist, yet all consist of a microcontroller, a wireless communication unit and sensors to measure a number of physical or chemical stimuli [12]. Smart Dust mote platforms are unique in that they can be used for wireless actuation in addition to sensing. A further distinguishing feature of mote platforms is that they are self-powered with batteries.

2.1 Mote photosensors

The light sensor integrated onto the mote platforms used in this research is an analog silicon photodiode manufactured by Hamamatsu Phonotics. The photodiode is color-corrected to closely match the CIE curve[2]. This photosensor is connected to an onboard 10-bit analog-to-digital converter, and is calibrated such that unit changes in digital readings correspond to changes in illuminance of approximately 2 lux. As motes output digital sensor readings between 0 and 1023, the sensing range of the photodiode is 0 to 2046 lux. This is a suitable operation range and resolution for sunny offices, in which electric contributions to illuminance are on the order of hundreds of lux.

Sensing motes are programmed to periodically acquire readings, and send out data packets that contain the mote ID number and sensor values. The battery life of sensor motes using 2 AA 2300 mA-hr batteries is estimated at 13 months for general sensing and processing tasks [4].

2.2 Mote-based lighting actuation

The four-foot fluorescent lamps commonly used in commercial buildings can be dimmed through the use of electronic dimming ballasts. A 0-10VDC signal is used to regulate dimming between 5-100% of the maximum output. Mote platforms can be interfaced with dimmable ballasts with the addition of intermediate circuitry.

The architecture of the mote-based actuation used in this research is shown in Figure 2. The actuation mote is powered directly from the line electricity, circumventing the limitations of battery power. A voltage divider with a 100-stage digitally programmable potentiometer (DPP) is used to provide the 0-10VDC dimming signal. In this architecture, the DPP is controlled by the mote that accepts commands in terms of a specified ‘dimming amount’ and ‘dimming rate’ from the intelligent decision making system. The ‘dimming amount’ determines the amount to dim/lighten the light, while ‘dimming rate’ controls dimming speed as a function of the rate at which the mote moves the DPP wiper.

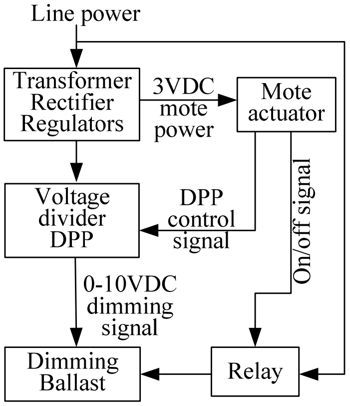

Figure 2. Mote-based actuation architecture

Unlike typical dynamic systems in which fast responses are usually desirable, high rates of dimming cause perceptible changes in illuminance that may disturb occupants, and are generally undesirable. Moreover, current research has shown that significant reductions in illuminance, and hence energy consumption, are undetectable to occupants, provided that the dimming rate is slow enough [2]. Finally, in addition to the two

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[2] The CIE curve is a color model based on human perception that was developed by the Commission Internationale de l’Eclairage (the International Commission on Illumination) committee.

dimming parameters, the actuators also recognize power on/off commands by switching a relay to turn the lamps on and off.

When used with a 4-lamp luminaire positioned approximately 1.2m above an experimental worksurface, this configuration provided a resolution of 10lx/stage. Office lighting typically ranges from approximately 300-1000lx, and changes in illuminance of less than 50lx in this range are generally undetectable. Accordingly, an actuation resolution of 10lx/stage is deemed sufficient for lighting applications.

3. Intelligent daylighting system

The intelligent daylighting system and each of it's components is detailed in the following. System advantages and challenges, mote algorithms, and the decision engine and control algorithm are each described.

3.1 Intelligent system features

An image of an office with the proposed intelligent system is shown in Figure 3. The readings from each sensor are validated, aggregated and sent to a decision engine. Current mote platforms have a surface area less than the size of a matchbox as illustrated in Figure 1, permitting placement on the worksurface with minimal disturbance to the occupants. Moreover, ongoing research is devoted to further miniaturization [9].

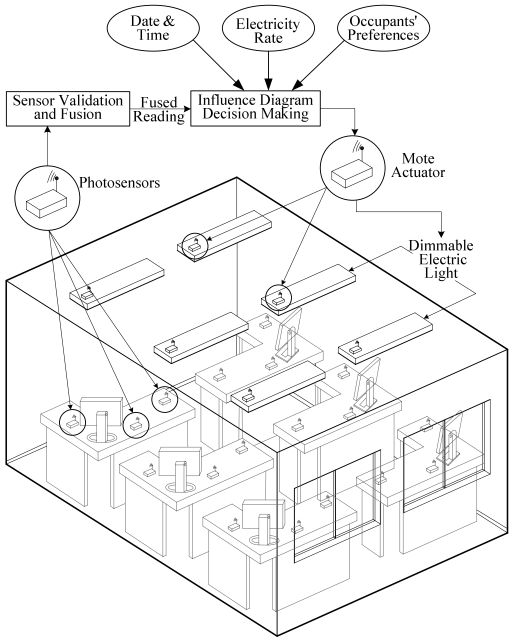

Figure 3. Intelligently lighted office space

In addition to hard-wired sensing and actuation, daylighting systems have been criticized for an inability to meet user needs. The diverse preferences of the occupants and building manager are not considered, nor is the price of electricity [14]. This results in unharnessed energy savings that could be gained by load shedding during times of high demand and price. The decision algorithm developed in this research addresses each of these limitations in decision making capabilities.

There exist two primary challenges in the application of mote sensors for intelligent lighting control. First, the one-year battery life does not meet the 3-5 year requirement typical in automated building applications [10]. In response, current research is devoted to the development of alternative sources of power. Solar power is especially appropriate for daylighting applications, where there is the potential to reduce the environmental impact of battery usage [8]. Concerns regarding safety and interference of radio transmission do not apply, as the motes use a different frequency range with far lower power than those used in wireless LANs, and cordless and cellular phones.

The second challenge is that sensors located on the desktop have a smaller view of the worksurface than ceiling-mounted sensors, and are more prone to interference from the user. Sensor reliability and accuracy can be effectively preserved by introducing appropriate redundancy with validation and fusion algorithms.

3.2 Sensor validation and fusion: The Mote-FVF algorithm

A fuzzy rule-based sensor validation and fusion algorithm named mote-FVF (mote-Fuzzy Validation and Fusion), was developed to verify and aggregate the data from desktop photosensors [19]. There are three components in the algorithm: validation, fusion and prediction.

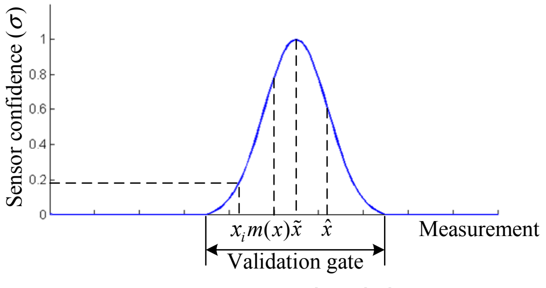

Figure 4. Fuzzy-centered validation curve

The validation portion of mote-FVF assigns each sensor reading a confidence value. The confidence value (σ) is determined with a fuzzy-centered validation curve, as illustrated in Figure 4. The curve is a Gaussian curve[3]

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[3] The validation curve is not necessarily Gaussian nor symmetric, but

centered at the previous prediction ($\hat{x}$), and shifted to the new center ($\tilde{x}$) by a set of fuzzy rules that takes into account the correlation among all sensor readings ($m(x)$). The correlation among sensor readings is represented with a majority-voting scheme, which is achieved by considering the median value.

In the sensor fusion step measurements (x_i) are averaged and weighted with corresponding confidence values ($\sigma(x_i)$). These averages are added to the predicted value ($\hat{x}$), which is weighted by α. The sensor fusion equation is:

$$x_f = \frac{\sum_{i=1}^{n} x_i \sigma(x_i) + \frac{\alpha \hat{x}}{\omega}}{\sum_{i=1}^{n} \sigma(x_i) + \frac{\alpha}{\omega}}.$$

ω is a scaling factor used to prevent system instability in the absence of valid readings. The adaptive parameter α, ranging from 0 to 1, carries information about the lighting state and is used in both the fusion and the prediction components. If the lighting is in steady state, any variation in measurements are likely due to noise, and α is set to a large value in order to weight the past history more heavily. On the other hand, if the lighting is in a transient state, α is set to a small value.

The predicted illuminance is generated with a time series predictor using the adaptive parameter α, and is of the form $\hat{x}(k+1) = \alpha\hat{x}(k) + (1-\alpha)x_f(k)$, where $\hat{x}(k+1)$ is the predicted value of next time step, $\hat{x}(k)$ is the predicted value of the current step, and $x_f(k)$ is the current upgraded fused value.

3.3 Influence diagram decision making

Influence diagrams are Bayes' nets with the addition of control and value nodes, that have been successfully applied to a range of sensor-based decision and control systems [1]. An influence diagram is an acyclic directed network with nodes representing variables or decisions/controls critical to the problem, with arcs to represent their interrelationships. A value function ranks the various decisions available to the controller in terms of critical variables in the model. Ultimately, the optimal decision is that which maximizes the expected value of the value function, given the values of the sensors.

Influence diagrams have been considered for the control of commercial environmental systems, although not specifically for lighting decisions [5]. The influence diagram developed for the intelligent lighting system is shown in Figure 5. In brief, sensor values are dependent upon the 'true' or actual states of the variables that they measure. The previous decision and solar state contribute to the work surface illuminance, and occupant perception is based on task type and illuminance.

The value function first balances occupant preferences with the building manager's desire to minimize energy consumption. Then, when electricity prices are elevated electricity consumption is reduced. This is referred to as demand responsive load shedding. Many utilities now offer time-of-use tariffs in which the price of electricity is dependent upon demand. It is generally recognized that demand response is a necessary capability of next-generation building controls.

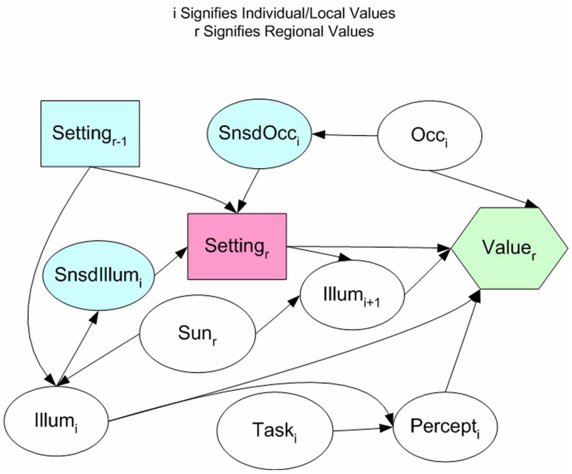

Figure 5. Daylighting influence diagram

4. Preliminary testing: mote sensing and actuation

The performance of the validation and fusion algorithm, and mote-based actuation was assessed in a set of experiments using a lighting fixture with four T-8 lamps suspended approximately 1.2 meters above the experimental worksurface. A high-fidelity light meter was used as a reference with which to compare mote sensing accuracy. A desktop PC was used for the mote base station, and for execution of mote-FVF and mote actuation. The experimental network comprised a network of six sensing motes and one actuating mote.

4.1 Mote-FVF performance

To test the mote-FVF algorithm the work surface illuminance was varied, and the output of the mote-FVF was compared to the high-fidelity reference meter. To ensure high data resolution, the motes were programmed to acquire readings from the sensors every 5 seconds.

The fused sensor value from the mote-FVF algorithm, individual mote sensor readings, and the reference

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should be chosen as appropriate based on the sensor characteristics.

illuminance are plotted in Figure 6. The cross signs indicate the raw readings from each mote, one for each color. The dashed line represents the reference illuminance measured by the light meter, and the solid line shows the value of the fused illuminance.

Upon analysis, the algorithm was found to match the reference illuminance with a maximum error of 3.36% regardless of the lag when the light was in transient. This error includes errors in mapping raw digital readings to units of lux, errors due to the spatial variation of illuminance on the worksurface, and errors resulting from hysteresis in the lamps themselves. Physically, the 3.36% error represents a variation of approximately 25 lux, which is undetectable to most occupants. These results confirm that the mote sensor validation and fusion algorithm works reliably, even under the most dramatic step changes in illuminance.

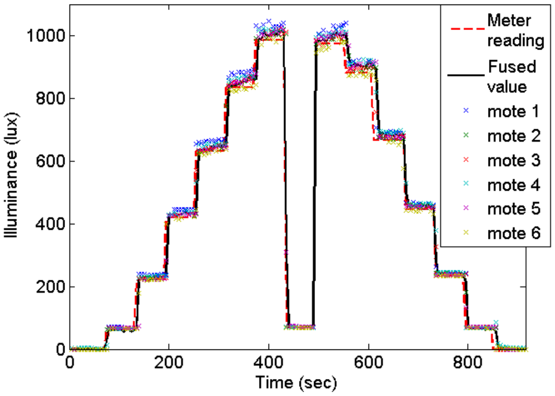

Figure 6. Performance of mote-FVF algorithm [19]

4.2 Mote actuator performance

To assess mote actuation, a test was conducted in which the goal was to maintain a given illuminance on the worksurface. Throughout the test the worksurface illuminance was continuously altered, the fused sensor value was compared to the setpoint, and an actuating command was transmitted to the actuating mote.

Towards the end of the test, two of the six sensors were deliberately covered to simulate inadvertent disturbance from occupants. The fused reading and the raw reading from one of the shaded sensors are plotted in Figure 7. Note that at time 33 minutes, the readings from the shaded sensor drop to approximately 150 lux, while the fused value remains at approximately 600 lux. These results confirm that the fused sensor data was not compromised by the shaded sensor. The illuminance on the experimental worksurface was kept to within 1% of the setpoint 95% of the time, with a maximum difference of 3%. This is promising evidence that the system can successfully regulate worksurface illuminance.

Figure 8 contains the results of a 17-hour illuminance maintenance test with a 550 lux setpoint. The line covering time 0-17 hours shows that the illuminance on the worksurface was kept to within 5% of the target during the entire 17-hour period. The increase in line thickness as compared to Figure 7 is due to an increase in the number of points plotted, and does not indicate increased fluctuation in worksurface luminance. The spikes in the plot indicate times at which the background lighting was toggled. The line from time 0-4 hours represents the readings from one of two sensors that lost power during the test. The unforeseen failure of one third of the sensors, and the corresponding success in maintaining the target illuminance demonstrated that the validation and fusion algorithm performs as designed, maintaining robust performance in the presence of individual sensor failures.

5. Discussion and future research

The preliminary iteration of testing and evaluation of mote actuation and validation/fusion algorithms yielded compelling results that encourage further research. The proposed system for sensing and actuating in lighting control proved to be a feasible solution to selected problems confronting existing systems. Complicated expensive retrofits due to interfacing with building line electricity are relieved with wireless sensing and actuation. In addition, difficulty estimating and maintaining worksurface illuminance is overcome with desktop sensing capabilities. Finally, calibration and commissioning is simplified through automated procedures that are newly possible given motes' communication and processing capabilities.

There are however, open questions that must be answered before the intelligent mote-based actuation and sensing system can be used in commercial lighting controls. To offer a scalable alternative for sensing and actuation in commercial lighting, appropriate sensing, fusing and communication strategies are crucial. The mote-FVF algorithm is readily deployable to the mote platforms for decentralized sensor fusion in its current form. However challenges surrounding energy allocation in data collection algorithms, such as those found in the literature [11], confront attempts to implement mote networks for real-world applications. In short, identification of the optimal distribution of computational and communication energy loads for mote-FVF in a decentralized network is non-trivial.

Another open research question is how to best implement occupancy sensing within a mote sensing and actuation network. In addition to dimming, occupancy-based actuation comprises 40% of the total potential energy savings in daylighting systems [16]. Existing occupancy sensors are prone to false positives, and are not able to sense individual occupants in a shared space. Hence, alternative sensors or methods of detecting individual occupancy need to be further investigated and integrated to the intelligent lighting control system.

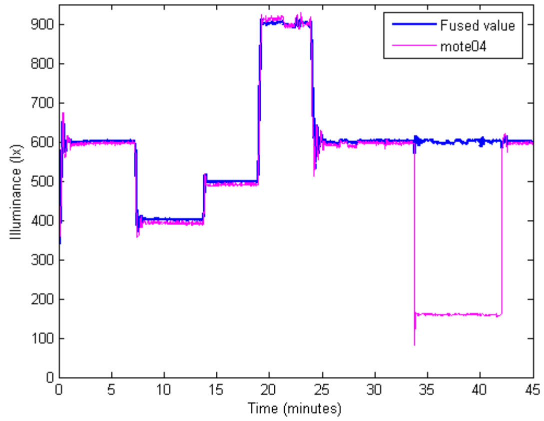

Figure 7. Setpoint maintenance result

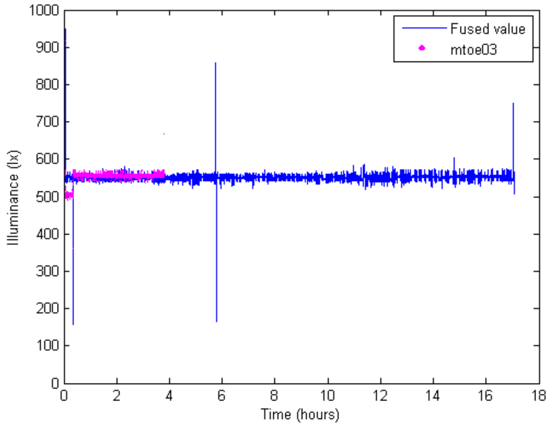

Figure 8. Extended illuminance regulation

Acknowledgement

The authors would like to acknowledge the Public Interest Energy Research (PIER) Program under the State of California's Energy Commission for their support of this research (Grant # CEC/SDSUF-53714A/0320-AG)-1/-6). We also wish to acknowledge the General Electric Corporation for its initial and ongoing support.

References

[1] Agogino, A.M. and Ramamurthi, K. "Real Time Influence Diagrams for Monitoring and Controlling Mechanical Systems", *Influence Diagrams, Belief Nets and Decision Analysis*, John Wiley & Sons, 1990, Chap. 9, pp. 199-228.

[2] Akashi, Y., Neches, J., "Detectability and Acceptability of Illuminance Reduction for Load Shedding", *Journal of the Illuminating Engineering Society 33(1)*, 2004, pp. 3-13.

[3] Brown, M.A., Levine, M.D., Short, W. and Koomey, J. G., "Scenarios for a Clean Energy Future," *Energy Policy*, Vol. 29, 2001, pp. 1179-1196.

[4] Crossbow Technology, *MPR/MIB User's Manual*, Rev. B, San Jose, CA., 2005.

[5] Dodier, R., and Kreider, J., "Detecting Whole-Building Energy Problems", *American Society of Heating Refrigerating Transactions*, Volume 105 Pt 1, 1999, CH-99-05.

[6] Granderson, J., Wen, Y.-J., Agogino, A.M., and Goebel, K., "Towards Demand-Responsive Intelligent Lighting with Wireless Sensing and Actuation", *Proc. IESNA (Illuminating Engineering Society of North America) Annual Conference*, Tampa, FL, 2004, pp. 265-274.

[7] Jennings, J., Rubinstein, F., DiBartolomeo, D., "Comparison of control options in private offices in an advanced lighting controls testbed", *Journal of the Illuminating Engineering Society*, 29 (2), 2000, pp. 63-85.

[8] Jordan, J.C., *Design and Implementation of a Stochastic Wireless Sensor Network*, Master's thesis, University of Illinois at Urbana-Champaign, Urbana-Champaign, IL., 2004.

[9] Kahn, J.M., Katz, R.H. and Pister, K.S.J., "Emerging Challenges: Mobile Networking for Smart Dust", *J. of Commun. and Networks*, 2(3), 2000, pp. 188-196.

[10] Kintner-Meyer, M. and Conant, R., "Opportunities of Wireless Sensors and Controls for Building Operation", *Proc. 2004 ACEEE Summer Study on Energy Efficiency in Buildings*, 2004, pp. 3-139 through 3-152.

[11] Lindsey, S., Raghavendra, C. and Sivalingam, K.M., "Data Gathering Algorithms in Sensor Networks Using Energy Metrics", *IEEE Trans. Parallel and Distributed Systems, special issue on Mobile Computing*, 2002.

[12] Maurer, W., *The Scientist and Engineer's Guide to TinyOS Programming*, DSP Labs, Livermore, CA, 2003.

[13] Mills, E., "Global Lighting: 1000 Power Plants", *Newsletter of the International Association fro Energy-Efficient Lighting (IAEEL)*, 2000, pp.1.

[14] Newsham, G.R. and Veitch, J.A., "A New Method of Deriving Illuminance Recommendations for VDT Offices", *IESNA Conference Proceedings*, 2000, pp. 211-217.

[15] O'Reilly F. and Buckley, J., "Use of Wireless Sensor Networks for Fluorescent Lighting Control with Daylight Substitution", *Proc. Workshop on Real-World Wireless Sensor Networks*, Stockholm, Sweden, 2005.

[16] "The Quest for the Ideal Office Control System," *Lighting Futures, Vol. 3, No. 3*, Rensselaer Polytechnic Institute, 1998.

[17] Rubinstein, F., Avery, D. and Jennings, J., "On the Calibration and Commissioning of Lighting Controls", *Proc. Right Light 4 Conference*, 1997.

[18] Singhvi, V., Krause, A., Guestrin, C., Garrett Jr., J.H. and Matthews, H.S., "Intelligent Light Control using Sensor Networks", *Proc. SenSys'05*, San Diego, CA, 2005, pp. 218-229.

[19] Wen, Y.-J., Agogino, A.M. and Goebel, K., "Fuzzy Validation and Fusion for Wireless Sensor Networks", *Proc. ASME IMECE*, Anaheim, CA, 2004.