Summer 2011 Smart Lighting White Paper

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chandrayee: sensor placement/light tolerance (lux levels for standard activities-> 1000+ is daylight)

Implementation- Michael
-pix of platform

results- ryan
frequency of dropped packets, calibration curves+ Appendix

software
blip/ipv6- marlon
Data storage: mysql, html- marlon

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1. Project Background

Buildings consume more than one third of the primary energy generated in the U.S., and lighting accounts for approximately 30% of the energy usage in commercial buildings. Lighting harbors great potential for energy savings in the commercial sector, as the largest electricity consumer of all building electrical systems. More efficient lighting management strategies could reduce current energy consumption up to 50%

While commercial products do exist, they are poorly received due to exorbitant retrofitting cost and unsatisfactory performance. As a result, most commercial buildings, especially legacy buildings, have not attempted to generate savings from lighting. The emergence of wireless sensor and actuator network (WSAN) technologies presents an alternative that circumvents costly rewiring and promises better performance than existing commercial lighting through distributed control for each individual user.

An opportunity to explore this technology arose through a joint collaboration with NASA in summer 2011. Wireless sensor networks along with sensor fusion for prognostics, diagnostics and failure recovery is critical for space exploration and environmental/machine monitoring. Our group intends to build on NASA's experience with a domestic test bed in Sustainability Base that leverages the versatility of wireless sensor and actuator network technologies, to create a wireless networked lighting system for the green building that accounts for both energy efficiency and user satisfaction. This actuator/ sensor network platform can then be extended to new domains such as space vehicles or space-habitats.

2. Important Background Research and Implementations

See Appendix G for a complete list of Benchmarked sources.

- User Experience in Shared Spaces
    1. The US Green Building Council: (2010) advocates using volunteered geographic information from building occupants to evaluate the success of green buildings. This data will be incorporated into a requirement for LEED certification.
    2. Yozell-Epstain MS from BEST Lab lighting (2003) did studies on people who work in shared areas including a science lab, a cubicle room, a photography and design studio, a shared computer work area, and the BEST Laboratory. She determined that people preferred to deal with the default light level first. If there is a problem with these settings,

they would prefer personal control to automatic changing of the light levels.

- Daylight Harvesting
    1. Lbnl (1988) Uses ceiling mounted photosensors to determine lighting levels both subject to and independent from daylight. Then sends this information through 3 different control algorithms with success in maintaining constant light level on a task surface.
    2. EPFL (2003) Using genetic algorithms to take into account user wishes in an advanced building control system, this thesis from EPFL worked on developing an integrated blinds, artificial lighting and heat gain control system that adapts to user wishes. Genetic algorithm was used to perform the optimization of the control sequences for its better convergence performance as opposed to Gauss newton, Nelder Mead or simulated annealing method. They conducted randomized trial tests in 14 offices with 23 users. They found that users have higher propensity of rejected automatic control than manual or user adaptive automatic control. This research did not, however, deploy wireless sensor network for achieving higher visual comfort.

- Wireless sensor networks:
  1. Stanford Powernet (ongoing) Powernet is a hybrid network of hardware power meters and software sensors that monitor the energy consumption index of an entire building. Analysis of this data enables one to determine where the majority of the building's energy budget goes, and how much of the energy used could be saved.

- Fuzzy validation and fusion for wireless sensor networks
    1. BEST lab lighting (2004)

  Studied the use of sensor validation and fusion algorithms on a dimmable fluorescent lighting environment. The sensor network fuzzy algorithm demonstrated fast response to sudden operating condition changes in addition to faulty sensor readings. A fuzzy approach was used to fuse sensors, assign confidence values, and define the correlation of sensor readings.

- Market Research
  1. SBI energy: LED and Energy Efficient Lighting Worldwide Markets (August 2010)
  2. There are a number of research activities and emerging technologies in the lighting market relevant to our goals including LEDs, OLEDs, design of luminaries, daylighting and smart grids, and lighting controls. LEDs and OLEDs are still in development to create the kind of white light that is optimal for the human comfort zone while maintaining a low manufacturing cost and high yields. there are a few companies currently producing luminaries that fit older sockets, however, future luminaries will take advantage of LED features. Additionally, wireless sensor systems have proven to be an ideal platform for building controls, however, powering devices with batteries is time consuming and costly- EnOcean has created control systems that utilize energy harvesting to remove battery dependence.

1. Full system:

    1. Best Lab (2001-2008) http://best.berkeley.edu/research/smartLighting/support/IESNA2008.pdf

   Uses modules interfaced with dimming ballasts to enable individual, dimable lighting control. Users are able to set preferences and interact with the system through a dedicated webpage. The pilot implementation in a shared office space with 19 luminaries demonstrated 46% energy savings.

2. Canada (2007) http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc49498/nrcc49498.pdf

Performed a study on luminaires centrally located in 86 workstations over one year. Light savings from the technologies implemented could be attributed as follows: occupancy sensors(35%), light sensors; daylight harvesting(20%), and individual dimming(11%). Higher occupant satisfaction was determined, although it was mainly attributed to the individual dimming control, which was only used once, to set the default light level.

3. Lutron (current) http://www.lutron.com/Products/WholeBuildingSystems/EcoSystem/Pages/Overview.aspx

EcoSystem from Lutron is a commercial lighting control system with digitally addressable dimming ballasts, controls, and environmental sensors. These components provide businesses with energy savings from 40 to 70%, while increasing space flexibility, improving occupant comfort and productivity, and reducing maintenance costs. It has two options for control; automatic control of lights and shades from a single device, and the option for wired control with two or three button interfaces.

4.

Our benchmarking process has guided our current research. Most of the technology for setting up a smart lighting system is well established. However, there has been little development into how one could use a prototyping platform for plug-and-play sensor data acquisition to quickly understand building control strategies.

3. Project description

Implement parallel wireless sensor networks in the CITRIS building at UC Berkeley and NASA Ames Sustainability Base that will allow for greater energy savings and increased user satisfaction. The synergy between these technologies will give a platform for conducting cutting edge research in green technologies and sensor fusion consistent will the goals of NASA and UC.

We aim to develop a plug-and-play platform capable of performing daylight harvesting in a variety of different areas. Features of our product currently include:

- self configuring sensor network for daylight harvesting
- data collection, storage, and remote realtime access.
- extreme modularity and flexibility
- sensor callibration and circuit implementation for human eye light spectrum
- developed framework for future developers using the tinyos programming environment on the TelosB mote platform.

4. Project Goals

Our key goal for summer 2011 was to research and implement daylight harvesting for commercial building spaces, as a plug-and-play prototyping platform. This includes setting up wireless motes with sensors in the CITRIS 4th floor and NASA Ames pilot building for data acquisition and interfacing. Data will be collected and analyzed for lowering energy use in naturally lit spaces.

The plug-and-play sensor platform will implementable in a variety of spaces. The motivation for such a platform stems from NASA's desire to increase sensing capabilities, along with the potential market share available for retrofitting existing buildings.

5. Collaboration/Stakeholders

Forged collaboration with CITRIS 4th floor on user studies, LOCal/Green Millenium for data collection,understanding who is in charge of Berkeley and Nasa sustainability research initiatives. contacting campus and Nasa groups to facilitate our work.

5.1 CITRIS

Our objective in CITRIS is to use this space to acquire light sensor data in an area conducive to daylight harvesting. More specifically we are implementing the plug-and-play light research platform at the west end of CITRIS's 4th floor. This area includes natural daylighting and an open plan office space.

We collaborated with a number of CITRIS's inhabitants in our time. Domenico Caregamino, the CITRIS building manager, was our initial point of contact for understanding re-design opportunity in CITRIS. He helped us implement the system through integration with the BACnet building management system. Mia Hermine, a lab researcher on the floor in charge of social organization helped facilitate interaction with floor members. Jason, who manages the CITRIS sustainability efforts, did baseline surveys on occupant reactions to the Green Millenium system (another prototype lighting control system currently installed on the 4th floor).

5.2 LoCal

Much of the work we have done setting up the hardware infrastructure has its roots in the work done by professor David Culler's research group. This includes wireless sensor networks and the affiliated TinyOS programming environment.

Andrew Kournikov, a member of David Culler's group, developed the Green Millenium system to allow for greater user control in the CITRIS 4th floor open-plan office space. Andrew gave energy usage data for the CITRIS building and Matlab code to grab readable data off of the sMAP interface. We gave him the occupancy readings we took over a week, so he could establish the validity of his system.

Stephen Daugherty developed the sMAP protocol to receive data from building management systems and sensor/metered data feeds throughout the buildings on campus. We worked with him to understand the python programming to set up a server that forwards data to sMAP. This will help us implement a parallel control system to the green millennium protocol.

5.3 NASA Sustainabilty Base test sites

The Platform for the Sustainability Base is in progress and currently relies on our successful implementation at the CITRIS building. With the CITRIS implementaiton in progress we are refining the platform and readying a secondary system for NASA. Meanwhile, as a group we have been meeting with Corey Ippolito to facilitate the transition of work from UC Berkeley to the Nasa Sustainability Base.

Corey has similar ambitions for the use of mote hardware. He is focused on the broader development of sensor data acquisition for lighting as well as humidity, pressure, and temperature. starting in the month of August we began our development of a NASA based plug-and-play system. We are also planning to set up our system in Corey Ippolito's lab at Nasa Ames before transferring the system over to the nearby Sustainability Base. Our implementations will include both temperature and humidity sensing, for Corey's research, as well as daylight harvesting, to build NASA's capabilities.

6. Hardware

6.1 Platform

We chose to use the TelosB platform running TinyOS purchased from the Memsic corporation.

Figure 1, TelosB platform

There were a number of suitable platforms to choose from, with varying factors including wireless communication protocol (zigbee vs 802.15.4), power usage, ADC and DAC capabilities, programming language, price, and open source capabilities. Reference Appendix A for a table detailing our choices. We chose to use the TelosB for its DAC actuation capabilities, and open source programming capabilities, which opened it up to a number of uses for rapid prototyping. The ADC ports on the TelosB are capable of taking in voltage ranges of 0-3V which translate to output ADC counts from 0-4096.

6.2 Battery Choice

The telosB requires a voltage input of 3V to run optimally. This is accomplished by the onboard package of 2AA batteries. One problem with our implementation was battery life. Using two standard AA batteries, we were able to achieve continuous sensing for approximately 1 week. Rechargeable batteries were also used, but had a significantly shorter lifespan (1-3 days), as they were only able to provide 1.2V each, causing them to drain significantly faster.

6.3 Server

We needed to choose a server computer in order to make our rapid prototyping system portable and modular for quick deployment in a variety of areas. Some criteria for our choice included low power consumption, processing power, and size. Our final choice was the ASUS Eee Box. [1]

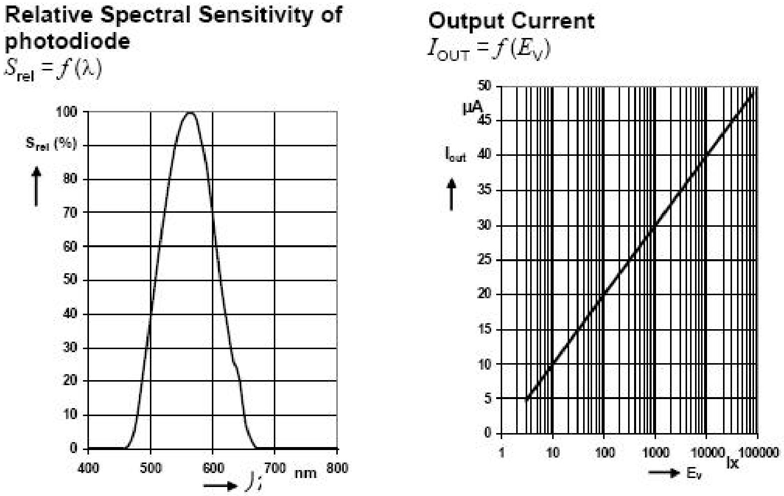
Figure 2, ASUS Eee Box

We chose to use a mini-computer rather than the traditional PC because it provides a form factor that enables easy transport and is well suited to an unobtrusive implementation of our sensor platform. The Eee Box runs off of 40W, versus traditional PCs which typically use over

131W. [2] However, the Eee Box is sufficient for our needs, with multiple USB ports, wireless card, 1GB of RAM, and 250 GB of hard drive for data storage.

6.4 Light Sensor and Circuit

Our main considerations when choosing a photodiode for our light sensor were to ensure that it matched up with the human eye's visibility range for light wavelength, and that it matched up with the standard lux range of office buildings (100-1000 lux) and had capacity to sense daylight (1000-100,000 lux) [3] We decided upon the Digikey SFH 5711 as it was able to satisfy all requirements. [4]


Relative Spectral Sensitivity of photodiode $S_{rel} = f(\lambda)$

Output Current $I_{OUT} = f(E_V)$

Figure 3, Digikey SFH 5711 Spectral Response and Output Current vs Lux

We designed a circuit to interface the output current from the SFH 5711 to the ADC port on the TelosB, which reads voltage.

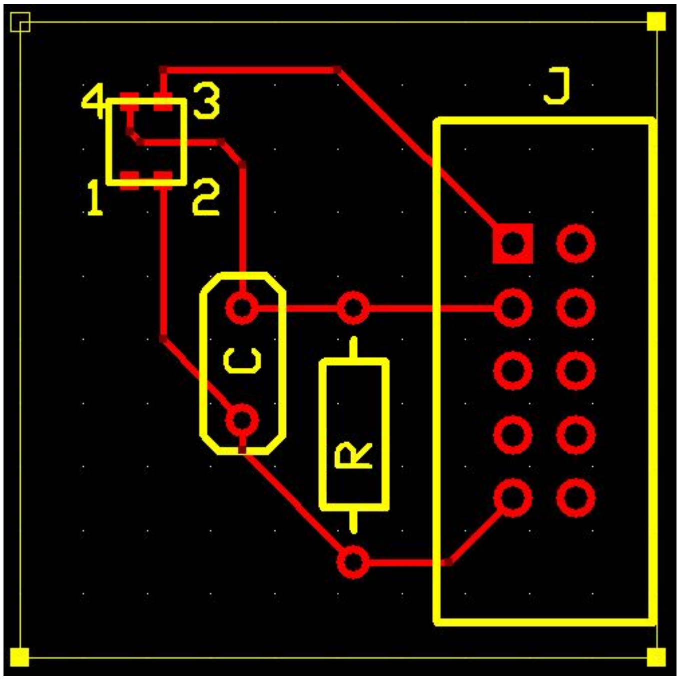


Figure 4, Printed Circuit Board layout Diagram

The current from the SFH 5711 is fed across a resistor and capacitor pair, and will then be read by the ADC input to the mote. Based on our testing, we were able to determine that resistor values of around 60,000Ω were suitable for indoor lighting levels from 0-2,000 lux. However, due to ADC saturation at higher light ranges, we designed an alternate circuit with resistor values of 5000-10,000Ω that is suitable for light levels over 100,000 lux. Further circuit design can be done by interested parties by simply substituting out resistor values to achieve the desired lux ranges.

6.5 Photodiode Calibration

We used Li-cor LI-210 photometric sensors borrowed from PG&E to perform calibration on the SFH 5711. [5] The LI-210 measures radiation as the human eye sees it, making it ideal for ensuring that the SFH 5711 properly met this quality. Additionally, as the LI-210 gave output in lux, we were able to calibrate our ADC outputs from the telosB to lux readings. We looked at a range of lux values between room lighting and outdoor lighting. The calibration curves may be found in Appendix F.

Figure 5, Li-210 Photometric Sensor

7. **Software**

7.1 Open Source Software

We are in the process of designing a series of tutorials to help interested parties use TinyOS in conjunction with the telosB motes to perform simple tasks such as data collection. Most of the provided support for TinyOS is for use with Linux, but we were able to determine several steps to provide plug-and-play capabilities for using TinyOS in conjunction with windows. These tutorials include direction on how to acquire the open-source software necessary to install TinyOS on the required motes, as well as run programs with Java and MySQL for data processing.

7.2 read data thru onboard sensors and ADC

1. Interpret data in ADC counts/ sensor data validation

7.4 Data Storage

We attempted and evaluated the efficiency of a wide variety of different options for data storage and accessibility including UDM, sMAP, MySQL, html, and .txt files.

UDm, or unified data management is a system currently being implemented by researchers at Lawrence Berkeley National Laboratory. It is a universal format for the sharing and storage of data. However, the system is currently still being developed, and thus was not a good choice for our project

sMAP, Simple Monitoring and Actuation profile, is a system that was developed by graduate students in Professor David Culler's wireless embedded systems laboratory to monitor building data. sMAP, as stated by the embedded systems website, "defines a data representation and a method of accessing the data over HTTP". While many devices are used to monitor physical data, most are an "integrated solution", and do not offer the capability of being represented on alternate data archives. Currently we have spent some time getting up to speed with the Python programming language which is the documented language for writing the sMAP data feed. However, the documentation for the building the sMAP data feed is user un-friendly and we are holding off on further work until we meet with Stephen Dawson-haggerty who manages the sMAP site for further instruction.

MYSQL
Html

Our actual choice of implementation, for our summer experiments, was to save the .txt files output by our java program to a folder in our group's dropbox. This enabled us to use our current software implementation to immediately begin gathering data. Additionally, it provided the advantage of public accessibility and real-time data updates. Finally, it also provides the .txt files to other computers, so that processing and control may be done immediately with the data collected. This method is conducive to our rapid prototyping efforts in CITIRS as it enables us to remotely monitor the status of our motes without having to physically check the server computer.

7.5 Power Consumption Issues

A major issue with our usage of motes is power consumption, as their default is to run off of 2x AA batteries and our application may require long-term installation of the motes. As indicated in the Hardware section, standard AA batteries were only able to provide 1 week of continuous sensing. We looked into several programming applications which would enable the motes to use less energy. One method, which is actually integrated into TinyOS 2.0, automatically turns off the power to the ADC ports until an explicit request is sent. We are also attempting to implement low-power sensing, whereby the mote will rest in a sleep mode until the basestation "pings" it, asking for a sensor reading. Another consideration is to only "ping" the mote for readings when necessary, i.e. when

7.6 Self-Configuring Networks

A major advantage of using TinyOS with the TelosB platform is that the motes are able to organize themselves into a self-configuring network, and are able to pass data in a chain across several nodes to the basestation, effectively increasing the radio range of the network. Additionally, the network will be able to reconfigure itself when any nodes go out, thus increasing the fidelity of the system.

7.7 IPv6

insert pictures of on-screen data feed

8. User studies

8.1 Occupancy Data

We took occupancy data on the 4th floor of CITRIS between the days of 6/13-6/17. The area was initially divided into 5 zones based on the lighting controls implemented upon the building's construction. Zones 1 and 5 corresponded to common areas on either side of the floor, while zones 2-4 corresponded to the work areas in the middle of the floor.

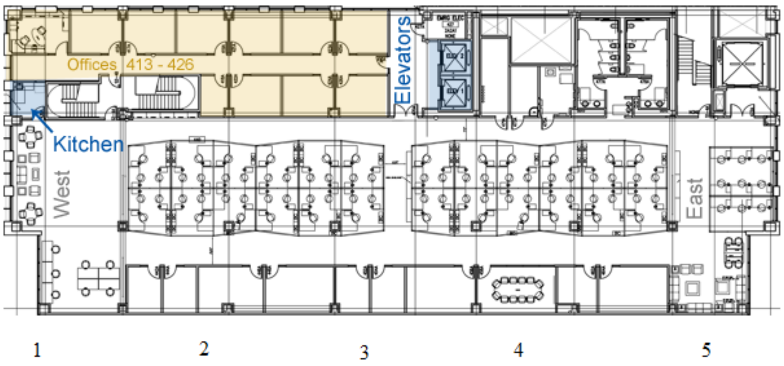


Figure 6, Map of 4th floor Zones

We further subdivided divided the area into 28 areas for further granularity, as shown in the floor-map below. Areas 2-13 and 15-26 correspond to single 4-person cubicles, while areas 1, 14, 27, and 28 correspond to different parts of the open spaces on either side of the floor.

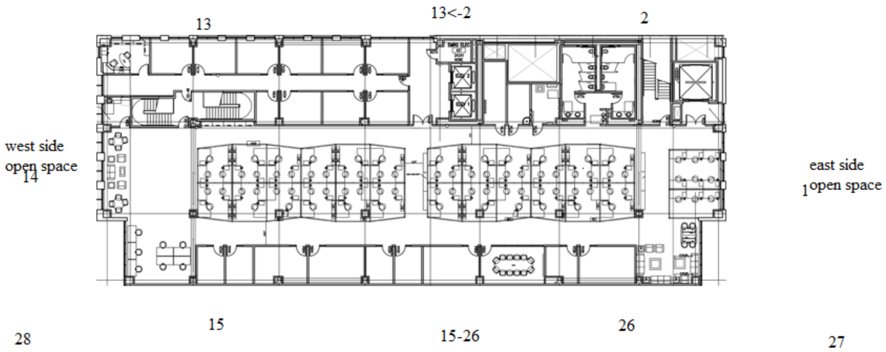
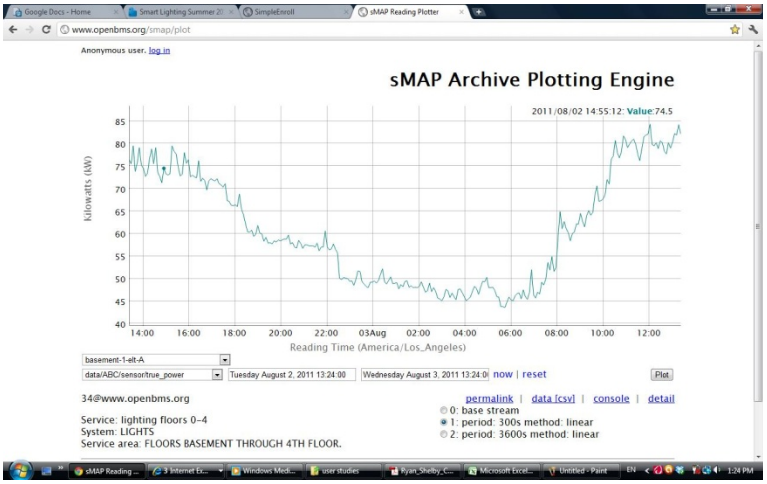


Figure 7, Further Subdivided CITRIS 4th floor

The data from our survey indicated that occupants of this open area would generally not come in until after 11AM. Trends indicated that most of the occupants occupied zones 2,3, or 4, while very few used the common areas: zones 1 and 5. Additionally, our data indicated that people would generally be clustered into a few cubicles, while many cubicles were left empty.

8.1 Comparison to energy usage from sMAP

Data was taken from sMAP, an online data repository used to display data stored in other databases.



basement-1-elt-A

data/ABC/sensor/true_power

Tuesday August 2, 2011 13:24:00

Wednesday August 3, 2011 13:24:0

34@www.openbms.org

Service: lighting floors 0-4
System: LIGHTS
Service area: FLOORS BASEMENT THROUGH 4TH FLOOR.

○ 0: base stream
● 1: period: 300s method: linear
○ 2: period: 3600s method: linear

Figure ___ Sample data from sMAP

The data was pulled off of sMAP and further processed using Matlab programs. The data will be correlated to the occupancy in each zone at each time in order to draw correlations.

9. Implementation

2. insert pictures of platform (i.e. the fancy new computer and motes installed throughout 4th floor of CITRIS)

On Friday August 5th, 2011, we installed a data collection server along with 6 motes equipped with light sensors into the 4th floor of the CITRIS building in UC Berkeley. The server was installed in a workstation, and the 6 motes were placed in areas exposed to different light levels. There was one pair of rechargeable/non-rechargeable battery powered motes placed in the same location. There was also a pair of motes at different angles placed in another location, wherein the

3. pictures of platform in Nasa building

10. Results

1. Battery life of the motes (rechargeable vs. nonrechargeable)

Preliminary tests reveal that motes with rechargeable batteries experience a faster decrease in internal voltage compared to motes with nonrechargeable batteries. The rechargeable batteries also start with a lower maximum internal voltage. Each Ni-MH battery has a nominal voltage of 1.2V, compared to nonrechargeable alkaline batteries with a nominal voltage of 1.5V. The motes were loaded with identical programs and left to send their internal voltage over a period of a few days. The nonrechargeable batteries had a ratio of volt loss per hour of about 9mV loss/hr. The rechargeable batteries had a loss of about 15mV loss/hr. This loss is strictly tied to the program on the motes, but it is indicative of the tradeoffs that rechargeable batteries represent. Rechargeable batteries have the benefit of saving money on replacements,
they also have a lifespan of roughly half that of the nonrechargeable batteries.

2. Sensor placement and angle data

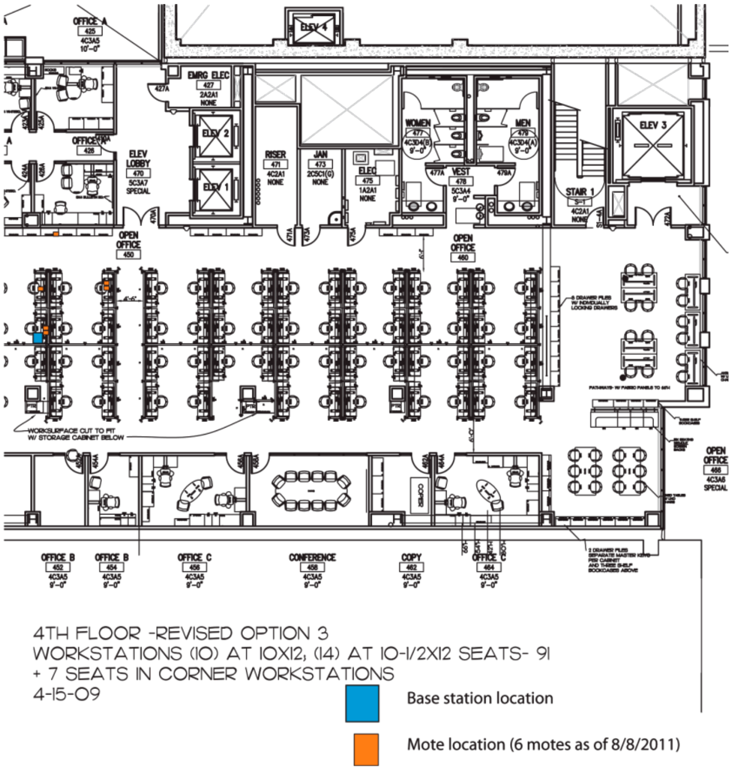


Figure ___: Initial sensor placement in CITRIS (8/8/2011)

The first instance of the wireless lighting sensor network in the CITRIS space consists of 6 motes and a base station, confined to two sets of cubicles, both under the same zone of lights. Three of the sensors were placed at desktops. Of those three, one was powered by rechargeable batteries. The rest of the motes were powered by nonrechargeable batteries. One mote was placed on a desk near the emergency lighting (which is always on). The final two motes were placed on a shelf above the desk. One of those two motes was oriented facing the ceiling, the other was oriented towards the windows, facing perpendicular to the ceiling. In this way, the network was optimized to test sensing conditions at the desktop, near the desktop facing the lights, near the desktop at an angle away from the lights, and far away from the desktops. The network also compared the performance of nonrechargeable to rechargeable batteries, as discussed in the previous section. Data from this system is currently being extracted.

3. network/mote reliability, frequency of dropped packets

4. normalizing the data between different motes/ making sense of the data

Normalizing the data between the motes will be implemented using the sensor validation/ fusion algorithms proposed by Yao-Jung Wen in his dissertation. The group will utilize these algorithms, taking into account the different space and lighting situation, especially the presence of daylight.

5. comparison of sensor data and building power usage

The sensor data is currently being extracted and when completed will be compared to the building power usage, captured via BACnet, to further validate the sensor readings.

11. Future Goals and Research/ Benchmarking

1) Current lighting and HVAC (heating ventilation and air conditioning) building control strategies waste energy by blanketing areas rather than being optimized to serve inhabitants' needs. User needs continue to be neglected in building controls research. For green buildings, energy-related research received 36 times the federal funding of occupant experience research from 2002 to 2005. Lack of information on occupant preferences causes inefficiencies. Office lighting systems waste energy by lighting zones that do not correspond to occupied areas. High building thermal inertia and strict comfort requirements that do not reflect user preferences cause control algorithms for HVAC systems to be complex and wasteful.

2) Understand user needs with regards to lighting for large open office spaces. The user needs assessment includes determining an applicable methodology so that similar processes can be applied to related spaces. Research and develop user interface for 4th floor CITRIS Lighting system.

3) Light sensor fusion and optimization. Work toward a system that integrates daylight harvesting into the office space lighting control, optimizing user satisfaction and energy use. Future net zero energy buildings will be more reliant on smart facades and highly variable natural resources for optimum indoor lighting, heating, cooling, ventilation as well as power supply. Optimal energy efficient operation of such systems will be subject to complex integrated model based control, which can benefit highly from presence of dense, low cost and efficient multi-modal sensing for accurate monitoring and prediction of various influencing environmental parameters. The objective of this research is to develop a test bed for leveraging wireless sensor and actuator network technologies that enables model based control for energy efficient lighting and cooling systems, for example, LED and daylighting in phase I and mixed mode cooling in phase II, while optimizing for multiple user comfort preferences in shared environment. To accomplish this task a test bed building, already identified and equipped with the above mentioned technologies, will be provided with required wireless sensing and actuation capabilities. Sensor fusion algorithms for prognostics, diagnostics and failure recovery will be developed to account for sensor malfunction and inaccuracy, while maintaining the scalability of the concept by ensuring low implementation, operation and maintenance cost and energy consumption of the proposed technology. Wireless sensing and actuation will be used to develop integrated control algorithm for hitherto unconnected building systems, like artificial lights, façade and cooling systems to achieve unprecedented energy savings, while ensuring improved comfort to building users.

1. Benchmarking for future platform research* and HCD
2. HCD research: interaction with prototyping platform, user interface, individual control. Research and implement a suite of user control and interaction prototypes in line with the plug-and-play platform.
3. Prototyping (8/13+)
    - Actuate: shades, lighting, LED?
    - Balsamiq Website
    - Interviews
4. Sensor fusion and Control optimization for conflicting inputs from multiple users
5. We seek to improve performance in current buildings by more closely incorporating inhabitants' preferences into the building control strategy. My project also represents an opportunity to inform people about environmental sustainability.

6. Building retrofit potential
7. Ability to re-implement this technology for HVAC as well

Final goal: portable, human-centered commercial system for retrofitting existing buildings to improve energy efficiency.

References

1. Newegg.com, “ASUS Eee Box,” http://www.newegg.com/Product/Product.aspx?Item=N82E16883220066&nm_mc=OTC-Froogle&cm_mmc=OTC-Froogle-_-Desktop+PC-_-ASUS-_-83220066

2. Tom’s Hardware, “Calculating Power Consumption of the Entire PC,” http://www.newegg.com/Product/Product.aspx?Item=N82E16883220066&nm_mc=OTC-Froogle&cm_mmc=OTC-Froogle-_-Desktop+PC-_-ASUS-_-83220066

3. Engineering Toolbox: “Illuminance: Recommended Light Levels” http://www.engineeringtoolbox.com/light-level-rooms-d_708.html

4. Digikey, “SFH 5711 Datasheet,” http://catalog.osram-os.com/media/_en/Graphics/00042865_0.pdf

5. Li-cor, “Li-210 Support Page,” http://envsupport.licor.com/?Light_Meters_%26_Sensors&spec=LI-210

Appendix A Mote Selection

Appendix B. Occupancy Data

Appendix C. Results from motes

Appendix D Detailed Technical Readmes+ tutorial links

Appendix E Useful reference links

Appendix F lux calibration curves, etc

Appendices are located in Dropbox/Smart Lighting/Papers/Summer 2011 White Paper/Appendix