Methods for measuring work surface illuminance in adaptive solid-state lighting networks

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www.media.edu/resenv/lighting/

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Introduction

• MIT Media Lab
  – 25 years of multidisciplinary research: organized as 23 unique research groups, each with special research interest.

• Responsive Environments Group
  – Led by Prof. Joseph Paradiso
Solid-State Lighting and Control

1978

• What progress has been made in the general control and sensing methodology?
• How can LEDs and sensor networks be used to further research?

2011

Figure 20. Low voltage switch for operating luminaires from desk
The Lighting Control Problem

• Why is lighting control a difficult problem?
  – Designing lit environments that satisfy our basic lighting needs requires a deep understanding of the innate and automatic mechanisms related to satisfying our biological needs. [Lam, 1977]

• Balancing “measurement” and “interaction”
  – Constrained by approach (Human-Computer Interaction)
    • data-centered, expressive-movement, and space-centered [Dugar & Donn, 2011]
  – LEDs fit perfectly into this space because of switching speed and ease of control.
  – Simple question: What do I measure and how do I use it?
Our Current Approach

- Intelligent infrastructure for personal control of diverse light sources
- Measurement and interaction are confined to the sensor/specific location
Background

• Lighting Network Control
  ▪ Crisp and Hunt – Personal control, occupancy, and ambient light (1978)
  ▪ Singhvi et al. – Optimal dimming and prediction of lighting control (2005)
  ▪ Park et al. – Intelligent light control for entertainment and media (2007)
  ▪ Miki et al. – Balancing energy consumption with multiple users (2007)
  ▪ Caicedo et al. – Occupancy-based illumination control (2010)
  ▪ Aldrich et al. – Linear and nonlinear optimization of SSL networks (2010)
The Problem: Measurement

- First implemented early 2010, updated in 2011
- A sensor node samples the illuminance over a period of time
- Rapid sampling (>80 Hz) causes visual distraction
NIR-based Measurement

- First implemented in summer of 2010
- A linear transfer function describes the relationship between irradiance and illuminance
- Not necessarily ideal, the cones may not intersect the surface in the same way
Proposed Idea: Fourier Analysis

• In the ideal system, control and optimization happens seamlessly without distraction to the users – do we really need one more device to control?
• Fourier-based demodulation is a good place to start.

How do we go from this signal... ...to this signal (our answer)?
Graphical Illustration (1)

Fixture 1
50% duty cycle
120 Hz.

Fixture 2
50% duty cycle
240 Hz.

The illumination (1st order) is equivalent for both fixtures since the area defined by the PWM signals is the same for both fixtures.
Since the fundamental frequencies are not aliased, we can measure the attenuation in the 120 Hz band.
Formal Definition

\[
x(t) = \begin{cases} 
  E & nT \leq t < (n + d)T \\
  0 & \text{otherwise}
\end{cases}
\]

\[
a_1 = \frac{1}{T} \int_0^T x(t) e^{-j\frac{2\pi t}{T}} \, dt
\]

\[
= \frac{1}{2\pi} \int_{u_0}^{u_0+2\pi} x \left( \frac{T u}{2\pi} \right) e^{-j u} \, du 
\quad (u = \frac{2\pi t}{T})
\]

\[
= \frac{1}{2\pi} \int_0^{2\pi d} E e^{-j u} \, du
\]

\[
= \frac{j E}{2\pi} (e^{-j 2\pi d} - 1)
\]

\[
= -\frac{j E}{\pi} e^{-j \pi d} \sin(\pi d)
\]

\[\therefore \quad |a_1| = \frac{E}{\pi} \sin(\pi d)\]
The fixture to be measured must operate a different fundamental frequency than the other fixtures.
Implementation Details

• Tested with 4 Color Kinetics Adjustable White LED Fixtures

• A control computer implemented software-PWM (transmits on/off commands)
  – Limited in resolution, 120 Hz normal, 60 Hz measurement.
  – This limitation ultimately constrained possible brightness settings (0%, 20%, 40%, 60%, 80%, 100%).
Testing Details

• Due to duty-cycle constraints, we tested primarily using a 40% duty cycle signal.

• Measured at 3 different distances:
  – 145 cm, 150 cm, and 175 cm.

• We then compared a measurement of the 60 Hz signal with our algorithm.
  – Measure the test fixture at 60 Hz with other fixtures off. Then perform measurement with the other fixtures on at 120 Hz.
First, the ideal signal is measured by the receiver (left). Then, we measured the embedded signal (right). (a single example is presented above for readability)
Testing (2)

• The resulting Fourier transform of the demodulated signal from the previous slide (right).

• A table summarizing the results of testing at 3 distances (below).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Distance (cm)</th>
<th>$\Delta E_t$ (ADC Counts)</th>
<th>$\Delta \hat{E}_t$ (ADC Counts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>145</td>
<td>60</td>
<td>59</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>55</td>
<td>59</td>
</tr>
<tr>
<td>3</td>
<td>170</td>
<td>28</td>
<td>38</td>
</tr>
</tbody>
</table>
Conclusions

• **Contribution 1**: This technique enables remote monitoring of multiple luminaires with only a single receiver, and can be applied to more complicated systems of many wavelengths.

• **Contribution 2**: We derived a precise formula for Fourier-based sensing of a light fixture’s illuminance contribution intended for disturbance free measurement and optimization and provided empirical evidence of success.

• With infinite resolution, the measurement error is bounded by the receiver signal-to-noise ratio.

• The sampling frequency and power requirements of the sensor platform will impose limitations on the resolution of the luminaire dimming.

• More testing is needed (preferably with better resolution) to further explore if the system is truly unperceivable by humans.

• No DC-type signals, the fundamental (no harmonics) is assumed adequate.

• Data-driven lighting control offers simplified computer control over many parameters, yet sampling those parameters without user intervention remains a difficult problem.
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Further Reading