

A New Light Sensing Module for Mica Motes

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Abstract—We present the *Illumimote*, a new light sensing module for the Mica mote platform. The *Illumimote* achieves performance comparable to a commercial light intensity meter, while conforming to the size and energy constraints imposed by its application in wireless sensor networks. The *Illumimote* was developed to replace the Mica sensor board (MTS310) whose slow response time and narrow dynamic range in light intensity capture is unsuitable to many applications, including media production. The *Illumimote* features significantly improved SNR due to its adoption of high-end photo sensors, amplification and conversion circuits coupled with active noise suppression, application-tuned filter networks, and a noise-attentive manual layout. Unlike the MTS310, the *Illumimote* can capture RGB color intensity (for color temperature calculation) and incident light angle (which discerns the angle of ray arrival from the strongest source). Our prototype demonstrated significantly faster response time ($> 6x$) and a much wider dynamic range ($> 10x$) in light intensity measurement as compared with the MTS310. The light-angle estimation results were well correlated with an average error of just 2.63° .

I. INTRODUCTION

Sensor networks are already pervasively employed in areas including target tracking and habitat monitoring [6]. They also have exciting applications in the arts and entertainment [3]. Poor sensor quality, fidelity, and diversity have limited their expansion into new areas such as film and video production [1,10] and light control applications [7]. An early example that demonstrates the potential of sensor networks to be employed in media production, comes from Su et al.'s Augmented Recording System (ARS) [10]. In ARS, sensors are deployed onto film sets to collect data of interest in synchronized with film or video frame rate. As these authors discovered, in media production the incident light intensity and color temperature of each film or video frame are very important phenomena. Although the Mica motes [4] are the de facto standard for sensor nodes, the light sensors currently available for this platform, especially, MTS310 [4], are inadequate for high-fidelity application spaces. We have engineered the *Illumimote*, a form factor package for light sensing in sensor networks, to support research in these areas.

II. IMPLEMENTATION OF ILLUMIMOTE

A. Light Sensors

The *Illumimote*'s data acquisition capabilities cover the three principle attributes of illumination: Signal strength (intensity), frequency (color), and transmission vector (incident light angle and sensor attitude).

- **Incident Light Intensity Sensor:** The *Illumimote* acquires incident light intensity with the precision of a commercial light meter (a Spectra Professional IV-A [8] was used as the reference), for which both dynamic range as well as accuracy are of interest. The principal detector is a Hamamatsu silicon photodiode S1133 [5] chosen for its comparatively large active area. This type of diode increases the SNR for low-intensity measurements and allows for reduced power consumption under high-intensity conditions (when the sensitivity control unit, discussed later, is used). Further, it is surface coated with an IR-cut film so as to achieve a spectral response range from 320nm to 730nm (e.g. visible band-limited).
- **Color Intensity Sensors:** Color intensity sensors for red, green and blue colors can be used to calculate color temperature [11]. We adopted Hamamatsu S6428-01 (red), S6429-01 (green) and S6430-01 (blue), for similar reasons as the S1133. Calculation of color temperature using calibrated RGB sensors is part of our future work.
- **Incident Light Angle Sensors:** The determination of the angle to the strongest incident light source involves a pair of Hamamatsu S6560 sensors [5]. Each component includes dual photodiodes with a vertical barricade separating them. Consequently, the position of the light, relative to the shadow cast by the (differential illumination), implies the angle to the source along one axis. On the *Illumimote*, the pair of sensors are oriented orthogonally to create the X-Y basis vectors.
- **Situational sensors.** As outlined in [3], additional sensors are included on-board to provide richer

proprioceptive information on the operating status of the device. A gravity-based attitude sensor (accelerometer) is included to allow for Earth-plane relative transformation in the event that the sensor is not oriented parallel to the ground. A temperature sensor is also included to detect overheating conditions that might occur under high intensity lighting.

B. Calculation of Incident Light Angles

Calculation of incident light angle θ along an axis follows from (1) [5], where a and b represent the output current from active area a and b .

$$\theta = \frac{a-b}{a+b} \times 0.012^{\circ-1} \quad (1)$$

Utilizing the two orthogonal light angle sensors, we developed the following method to estimate the angle α of a light source projected onto the two-dimensional plane of the Illumimote (see Fig. 1). First, calculate the angles along each of the two axes using (2), where a_x, b_x, a_y, b_y are the light intensity measurements from the active areas a and b of each sensor.

$$\theta_x = \frac{a_x - b_x}{a_x + b_x} \times 0.012^{\circ-1}, \theta_y = \frac{a_y - b_y}{a_y + b_y} \times 0.012^{\circ-1} \quad (2)$$

The vectors of two planes that embed the line from the Illumimote to the light source and intersect X and Y axis can be obtained by (3).

$$\vec{v}_x = (\cos \theta_x, 0, \sin \theta_x), \vec{v}_y = (0, \cos \theta_y, \sin \theta_y) \quad (3)$$

By calculating the cross product of the two vectors from (3), the vector of the line from the Illumimote to the light source can be calculated as in (4)

$$\vec{u} = (u_x, u_y, u_z) = \vec{v}_x \times \vec{v}_y \quad (4)$$

Therefore, the angle α is calculated as follows:

$$\alpha = \cos^{-1} \frac{u_x}{\sqrt{u_x^2 + u_y^2}} \quad (5)$$

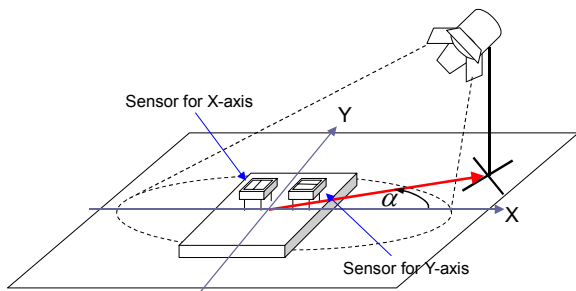


Figure 1. Incident Light Angle Estimation

C. Overall Architecture and Implementation

Our Illumimote has evolved from an early prototype (Fig. 3 (a)), which adopted a simple pull-down resistor photodiode bias circuit and instrumentation amplifier architecture to our commercially designed [2] and recently fabricated version shown in Fig. 3 (b). The latter employs a two-stage active suppression power supply, dynamically configurable photodiode bias (sensitivity control), and a situational sensor unit. The overall architecture diagram of the Illumimote appears in Fig. 2. In Fig. 2, only one light sensor channel is shown. There are eight light sensor channels allocated based on the number of detector circuits required to capture the illumination attribute. For example, the color temperature unit requires three channels – one for each of red, green, and blue luminosity. Signals from the eight light acquisition units and four situational units are multiplexed via the channel selection unit and presented to the ADC for conversion into a 12-bit digital signal. This resultant data is conveyed to the networked and embedded nodes (in our case, Mica2 motes) via either the I2C data bus or a direct 16550A-compatible UART link that uses line-level (rail-to-rail) output. The operation of the Illumimote's units may be controlled directly from the mote via the I2C bus or locally by an on-board Atmel Atmega48 microprocessor. Employing the local processor, which exposes interrupt facilities both to and from the host-processor onboard the mote, relieves the network interface (mote) of any real-time constraints associated with frame-rate-accurate sampling. When operating in this mode, the continuous I2C bus may be severed and reattached dynamically (hardware is bus-state aware) to create two isolated buses – one local to the Illumimote, and one local to the Mote – as needed. In addition to calibration functions, the embedded temperature sensor can wake a sleeping mote in the event of a dangerous thermal condition (risk of meltdown).

The assembled Illumimote appears in Fig. 3 (b). The roles of the lumisphere are to protect the sensors and to integrate incident light from all directions. On the bottom side, Illumimote mote has a connector that is compatible with Mica-type sensor nodes (Mica2, MicaZ, etc).

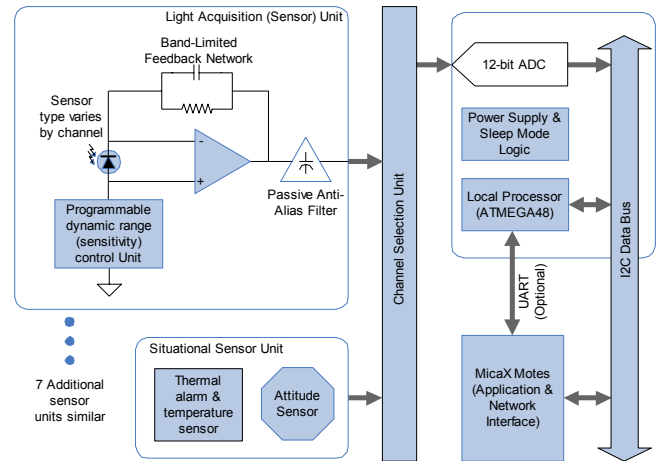
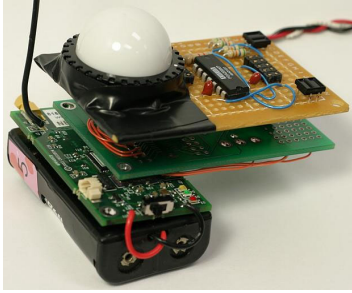


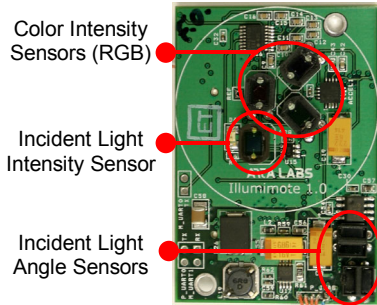
Figure 2. Architecture of the Illumimote



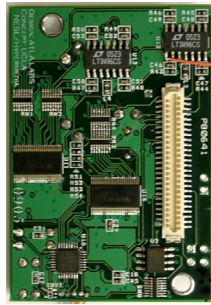
(a) Prototype of Illumimote



(b) Fabricated Illumimote with attachment of lumisphere



(c) Front side of Illumimote



(d) Back side of Illumimote

Figure 3. The Illumimote

III. EXPERIMENTAL RESULTS

In comparing the response time of our Illumimote prototype's incident light intensity sensor with that of the standard Mica sensor board (MTS310), a 0.5-second light pulse was generated and each photo sensor performed 200 light intensity measurements for two seconds as shown in Fig. 4. The Illumimote prototype took less than 10ms to reach 99% of the final light intensity value as compared to the MTS310, which took about 60ms (best case performance). Moreover, the MTS310's response time degrades significantly along the falling edge (scene getting darker), whereas the Illumimote does not. Because one television video frame is captured over approximately 33.37ms [9], the Illumimote (at 10ms) is responsive enough to detect in real-time applications lighting changes that would impact a single video or film frame.

The light angle sensors were evaluated by placing a 1000W tungsten-balanced incandescent lamp at all combinations of three angles (0°, 30° and 60°) and three distances (nine total points) as shown in Fig. 5. We measured and estimated the angle ten times for each point. Only the first quadrant was tested as performance for the other three quadrants is similar. The light-angle estimation results were well correlated with an average error of just 2.63°.

To stress the dynamic range capability of incident light intensity sensor, the 1000W tungsten-balanced incandescent lamp was employed to generate absolute incident intensities from 0 lux to about 15000 lux in a controlled environment.

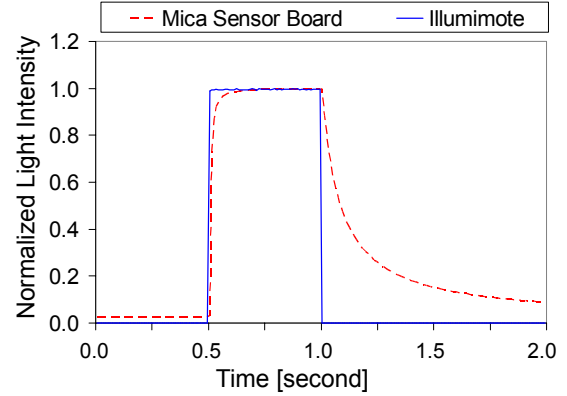


Figure 4. Response time comparison to a light pulse

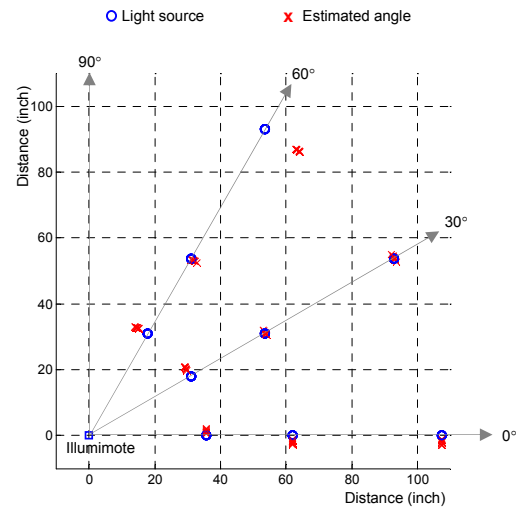


Figure 5. Incident Light Angle Estimation

A commercial light meter, the Spectra Professional IV-A [8], was used for reference.

The commercially designed [2] revision of the Illumimote, among other new features, offers a 16-step sensitivity control. We evaluated two of these sensitivity settings as shown in Figs. 6 and 7. As shown in Fig. 6, the data revealed the sensitivity control unit (SCU) to have an effective and desirable response on the output¹. The light acquisition unit was confirmed to feature a rail-to-rail output range (0 – 5V) that operates from a stable 5V reference regardless of the mote's operating voltage and battery state (assuming sufficient current drive – battery life remaining). Fig. 7 confirms that adjacent sensitivity settings have enough overlapping range to ensure reliable measurements across the transition points between SCU regions and to serve as margin in the implementation of hysteresis functions inside the SCU's control software.

In order to convert the digitized sensor values to light intensity (lux), a simple calibration method, involving multiplication of a constant value by the ADC readings, was used. The optimal constant multiplying value was found by

¹ We used 10-bit ADC in this experimentation.

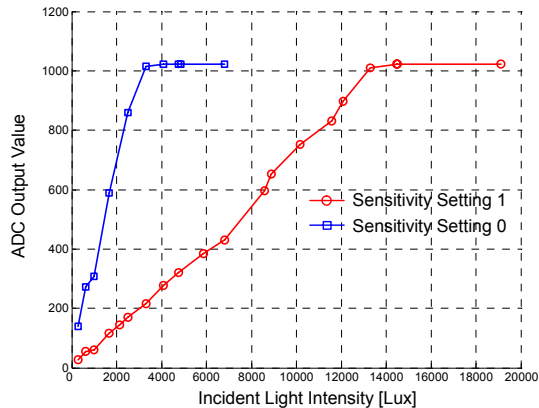


Figure 6. Two Sensing Sensitivity Settings

the `lsqnonlin` command in Matlab, which solves non-linear least-squares (non-linear data-fitting) problems.

As shown in Fig. 7, measurements by the MTS310 begin to experience significant non-linearity at 1000 lux and saturate by 2000 lux. The Illumimote, in contrast, has a fully linear response over the entire test range. The stability of the intensity readings, averaging $\pm 0.82\%$ for ten readings over 23 light intensities, was better than the Spectra meter, which averaged $\pm 0.86\%$ in repeat measurements for 30 light intensities.

Experimental design was complicated by a number of factors: the exact same measurement position for the Illumimote and the Spectra meter, angle of the lumisphere, hand posture when measuring light intensities (because of manual measurements) and light reflections from equipments in the environment. To evaluate the accuracy of light acquisition unit of Illumimote with the Spectra light meter, we measured the output voltage of light acquisition unit for 147 light intensities and converted into lux values. Measurements at lower intensities (< 150 lux) appeared to be exacerbated by the complicated experimental design problems and have decreased the accuracy to 5.2% on average. For light intensities above 150 lux, the Illumimote measurements were correlated to within 3.9%, on average, with the Spectra readings for overall measurements

IV. CONCLUSIONS

Our new light sensing module, the Illumimote, for the Mica mote platforms achieves performance comparable to a commercial light meter over the ranges indicated in our findings. It consists of incident light intensity, RGB intensity (for color temperature calculation capability), and incident light angle sensors as well as thermal and attitudinal sensors. We characterized its performance and verified its capabilities using both our prototype and our commercially designed Illumimote. The project website hosts the technical data (<http://nesl.ee.ucla.edu/research/illumimote>), while tested assembled units will soon be available from Atla Labs, LLC [2] for evaluation and deployment. Our future work includes development of methods for color temperature calculation from the RGB color intensity measurements, estimation of

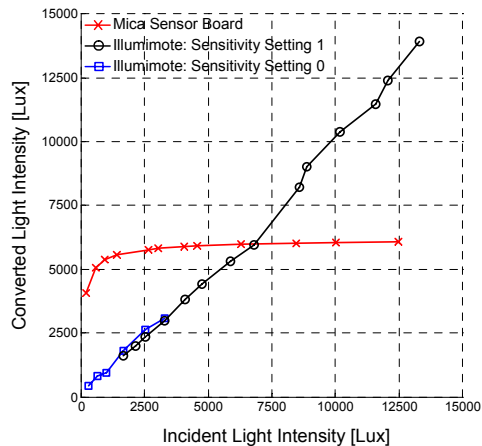


Figure 7. Dynamic Range Comparison with Mica Multi Sensor Board and Light Intensity Measurement with Two Sensitivity Settings

the vertical incident light angle as well as horizontal angle, and improvement of incident light intensity measurement accuracy through adjusting sensitivity settings and eliminating the experimental design problems.

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