Illumimote: Multi-Modal and High Fidelity Light Sensor Module for Wireless Sensor Networks

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***Abstract*— We describe the system requirements, design, system integration and performance evaluation of the Illumimote, a new light sensing module for wireless sensor networks. The Illumimote supports three different light sensing modalities: incident light intensity, color intensites and incident light angle (the angle of ray arrival from the strongest source), and two situational sensing modalities: attitude and temperature. The Illumimote achieves high performance, comparable to commercial light meters, while conforming to the size and energy constraints imposed by its application in wireless sensor networks. We evaluated the performance of our Illumimote for light intensity, color temperature and incident light angle measurements and verified the function of the attitude sensor. The Illumimote consumes about 90mW when all features on board are activated. We describe our design and the experiment design for the performance evaluation.**

***Index Terms*— Light Sensors, Wireless Sensor Networks, Embedded Systems.**

I. INTRODUCTION

Wireless sensor networks (WSN) composed of tiny embedded systems each with a processor, sensor, radio, and battery are already pervasively employed in many areas including target tracking and habitat monitoring [1], but they also have exciting applications in the arts, multimedia, and entertainment [2]. Poor sensing quality, fidelity, and diversity of currently available sensor modules have limited such expansion into these new areas like film, video production [3], [4], and lighting control applications [5]. To support research and development in these WSN areas, high-fidelity light sensing modules in a compact form factor are required.

The Illumimote was conceived in a joint effort by filmmakers and engineers to apply the evolving technologies of WSN to new purposes in art and entertainment. WSN offer many unique opportunities for improving the creative and business processes of entertainment. One example is the continuity management of lighting: the order in which an audience views a film's sequence of events is remarkably different from the order in which they are produced. Shots are filmed in the order that minimizes cost and makes best use of actors, crew, and locations. Footage captured at these different times must appear the same when shown consecutively, or differences must be controllable if they are required for creative purposes. Therefore, it is important to monitor and replicate the quality of light (illuminance and color) in each shot, so that footage captured at different times or in different locations doesn't show unexpected differences, which may not be perceived by the human eye but affect the film stock. The Lord of the Rings trilogy, for example, was filmed over a year and a half of production and required that footage be captured for use in three different movies with vastly differing release dates and schedules. Even with a staff of over 2400 people, maintaining continuity was remarkably difficult as notes had to be taken by hand and conditions were constantly changing. This is not uncommon and many large-budget feature films require significant post-production digital image manipulation prior to release, which is quite expensive. Continuity management is required for props, scenery, actor and camera information, as well as lighting, though the term is typically applied to management of non-technical elements. We have focused on lighting instrumentation as the first component of our Advanced Technology for Cinematography (ATC) [6] because of its vital role in the creative process of filmmaking.

ATC [6] is a joint project of UCLA's Henry Samueli School of Engineering and Applied Science and the School of Theater, Film and Television. The Illumimote is part of their larger vision to increase flexibility and creative control in media production using sensor networks and other emerging technologies. Deploying networks of tiny sensors adds a data acquisition layer to the film production environment that supports on-set decision making, such as the lighting adjustment described above, as well as post-production and asset management. Another component of the ATC project is UCLA's Augmented Recording System (ARS) [4]. In ARS, wireless sensors can be deployed onto a set to collect data in synchrony with the film or video frame rate. ARS provides a framework for establishing a correlation between the media footage and sensor data. Initial work with ARS has prompted the development of the Illumimote and other high-quality sensor platforms that can be deployed atop Mica motes [7], the de facto standard for WSN nodes. Their development addresses limitations of sensors currently available for this platform. For example, the light sensors on the MTS310 and MTS400 [7] are inadequate for high-fidelity applications, being too sensitive to infrared radiation, and lacking the necessary dynamic range. To our knowledge, the Illumimote is now the fastest, lowest-power, most accurate, and most replete light sensor available in the field of WSN.

The rest of this paper is organized as follows. Section II presents system requirements of the light sensing module for

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our application. In Section III, the implementation of the sensor module is described. Section IV presents calibration methods we used. Experimental setup and performance evaluation are presented in Section V and Section VI concludes.

II. SYSTEM REQUIREMENTS

The Illumimote is designed to have equal or better performance to the class of commercial light intensity and color temperature meters used in the entertainment, film and video production industries. The initial design discussed in this paper will continue to be refined toward this goal. Such performance is required to provide confidence in the device for its target audience, allowing it to be used for basic metering tasks in real production.

The capabilities gained by the choice of a standard wireless sensor network platform and the Illumimote's high-fidelity sensing performance will allow us to explore new techniques and approaches to measuring light, one of the most practically and creatively important elements of media production. With these capabilities, we also expect the Illumimote may prove useful in industrial and commercial applications that require many physically distributed light measurements, such as construction and video projection calibration.

Design criteria for the Illumimote include the following capabilities. First, we list system requirements designed to match existing instruments in a significantly smaller form factor.

- **Light intensity and color temperature sensing:** The device should be capable of measuring both incident light intensity and color temperature in a single package, to simplify deployment and use.
- **Robustness against infrared energy:** Both sunlight and very high-power incandescent fixtures are common light sources in media production. The sensors must be band-limited so as not to be unexpectedly saturated by infrared energy.
- **Wide dynamic range:** Our final design target is for the Illumimote's dynamic range is to enable measurement in standard indoor production settings (up to 1,000 lux) through very bright outdoor environments (up to 100,000 lux). The first revision of the Illumimote provides a 2 lux to 18,500 lux dynamic range for light intensity, with color temperature measurements available throughout this range of incident intensities. This is sufficient for all indoor, high-intensity studio environments, and morning/evening outdoor conditions.
- **Fast response time:** The frame rate of NTSC television video is 29.97 frames per second (fps) and the duration of a television frame is approximately 33.37ms. (Film typically uses a slightly slower frame rate of 24 fps.) Therefore, the Illumimote should be able to capture and process the light information in 33.37ms to capture light changes within one video or film frame. (The ARS system discussed in the introduction allows these measurements to be synchronized with film and video capture.) Higher frame rates would support special effects photography and other specialized applications.
- **High accuracy:** The Illumimote is designed to match the accuracy of commercial meters, and exceed it if possible, to support novel future uses we hope to discover during deployment. This requirement is verified experimentally in later sections.

As the Illumimote has performance of commercial light meters in a wireless sensor network platform, there are additional requirements for the features beyond current commercial technologies of light meters.

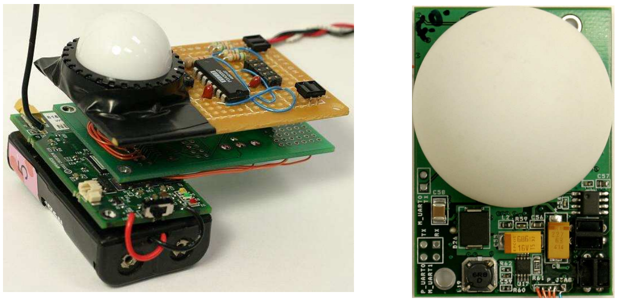
- **Wireless sensor network compatibility:** A primary design requirement was that the Illumimote be compatible with the Mica mote from Crossbow [7], a common platform in wireless sensor network research and development. This allows us to explore how the benefits of sensor networks—for example, low power consumption, small form factor, distributed computation and wireless communication—can support the target domain of media production.
- **Proprioceptive sensing:** Elsewhere, we suggest that proprioceptive sensing [2] is an important role of embedded devices in expressive applications like media production. This and other key roles of embedded devices requires them to have some knowledge of their own placement and area of observation or region of responsibility (RoR). Along with its incident light angle sensors, the Illumimote's situational sensors—a 2-axis accelerometer for orientation information and a temperature sensor—provide information in support of basic light measurements allowing for some knowledge of the sensor's RoR and surrounding environment.

III. DESIGN OF THE ILLUMIMOTE

A. Light Sensors

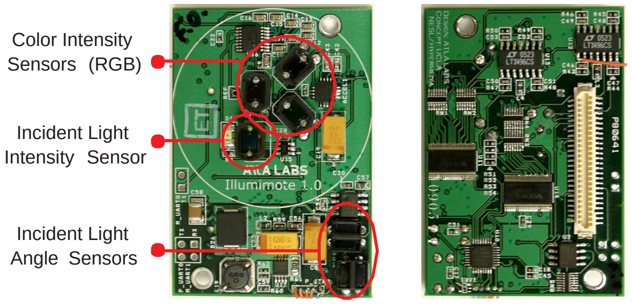
According to the different sensing modalities described in the Section II, the Illumimote's data acquisition capabilities cover the three principle attributes of illumination: Signal strength (intensity), frequency (color), and transmission vector (incident light angle and sensor attitude).

- **Incident Light Intensity Sensor:** The Illumimote acquires incident light intensity with the precision of a commercial light meter (Sekonic L-558Cine [8] light meter 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 [9] 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 are used to calculate color temperature [10]. We adopted Hamamatsu S6428-01 (red), S6429-01 (green) and S6430-01 (blue) [9], for similar reasons as the S1133. Calculation of color temperature



(a) Prototype of Illumimote

(b) Fabricated Illumimote with attachment of lumisphere



(c) Front side of Illumimote

(d) Back side of Illumimote

Fig. 1. Photos of the Illumimote [11]

and calibration of RGB sensors are discussed in Section IV.

- **Incident Light Angle Sensors:** The determination of the angle to the strongest incident light source involves a pair of Hamamatsu S6560 sensors [9]. 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:** Additional sensors are included onboard to provide richer proprioceptive information [2] 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. System Architecture and Implementation

Our Illumimote has evolved from an early prototype shown in Fig. 1 (a), which adopted a simple pull-down resistor photodiode bias circuit and instrumentation amplifier architecture to the recently fabricated version shown in Fig. 1 (b). The latter employs a two-stage active suppression power supply, dynamically configurable photodiode bias (sensitivity control), and a situational sensor unit. The overall system 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 10-bit digital signal. This resultant data is conveyed to the networked and embedded nodes (in our case, MicaZ 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 onboard Atmel Atmega48 microprocessor. Employing the local processor relieves the network interface (mote) of any real-time constraints associated with frame-rate-accurate sampling. The local processor also exposes interrupt facilities both to and from the host-processor onboard the mote. 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).

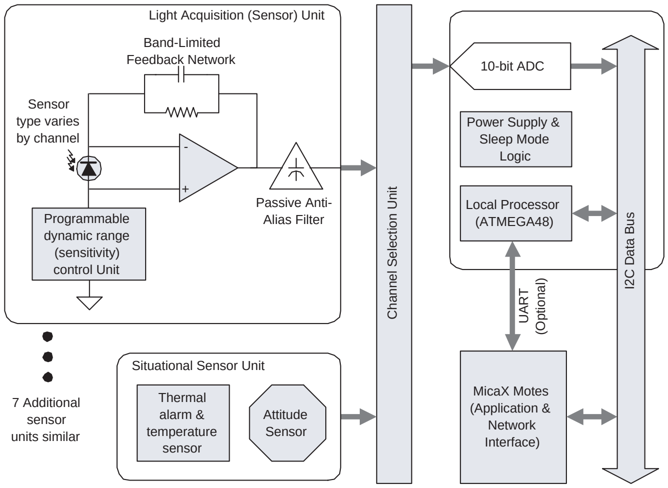


Fig. 2. Architecture of the Illumimote [11]

The assembled Illumimote with a lumisphere appears in Fig. 1 (b). The role of the lumisphere is to protect the sensors and to integrate incident light from all directions. On the bottom, Illumimote features a connector that is compatible with Mica-type sensor nodes (Mica2, MicaZ, Cricket etc).

C. Sensitivity Control

The sensitivity control unit (SCU) extends the dynamic range of the photodiodes by adjusting the bias current presented to each channel. Unlike more traditional gain control, which is applied at the amplifier, sensitivity control extends dynamic range without suffering the limitations of the amplifier's SNR. For example, the SCU bias circuit may present a larger bias resistance to the sensor when necessary to produce larger input voltages to the amplifier at low light levels. This avoids the additional amplification of the amplifier's internal thermal and coupled noise that occurs in the traditional model when the low-light conditions require a higher gain setting.

The SCU offers six bias current resistor values spanning four orders of magnitude from 1KΩ to 10MΩ. These final resistor values used on the Illumimote were obtained from experiments performed by the authors on a set of initial choices. Data from these early experiments was used to produce a model that predicted the final resistor values. These choices were then verified experimentally (See Fig. 6) and have been shown to achieve a comparably wide dynamic range of four orders of magnitude (in units of lux—lumens per meter squared).

IV. CALIBRATION

A. Light Intensity Sensor Calibration

Illumimote's current-mode architecture exhibits a vastly superior linear response than the MTS310 [7], [11]. Consequently, a linear data fitting method is appropriate for correlation with a reference light meter. In order to convert the digitized sensor values to light intensity (lux), linear transformation by two coefficients (i.e. $y = ax + b$, where y is the converted lux value, x is the ADC reading, and a and b are calibration coefficients) was used. The method to find the optimal coefficients involves three steps as follows. First, we plot the Illumimote's ADC readings with respect to reference lux values measured by a commercial light meter on 2-D plane. Second, a linear line (i.e. $y = a'x + b'$) that best represents the plot of the ADC values is found by the Matlab's `polyfit` command which estimates the coefficients by the least square method. Finally, the calibration coefficients a and b can be obtained by projecting the linear line ($y = a'x + b'$) onto $y = x$. The projection is done by $a = 1/a'$ and $b = -b'$. We collected the ADC output values and calibrated a and b for four of Illumimote's six sensitivity settings. For performance evaluation, the first half of the collected data was used to calculate the calibration coefficients, a and b.

B. Calibration of Color Temperature

Color temperature of a light source can be defined as the black-body radiator's temperature in Kevins that matches the hue of the light source [10], [12]. However, since many light sources except incandescent light do not emit radiation like black-body, we instead use Correlated Color Temperature (CCT) to represent the color temperature of the light source.

CCT is a simplified way to characterize the spectral properties of a light source by choosing the temperature of an ideal black body which has the best correlation in terms of predicting how the light's spectral curve contributes to its output. This may involve the image's capture and projection systems and the human eye's sensitivity.

The method used to calculate CCT requires sampling the light source with three silicon photodiodes, having red, green and blue sensitivities. These sensors are modeled while illuminated by an ideal black body in order to generate a theoretical locus that is later used to correlate the sampled light values, which finally gives the closest temperature match. Our calibration procedure adjusts the gains of each RGB values in order to match the model at a given color temperature.

Color temperature calibration is a procedure to set the factors that convert the RGB raw readouts into RGB relative light intensities. For color temperature computations, absolute intensity values are not necessary, so an arbitrary factor of one is applied to the green readout to normalize it, and for the red and blue proper factors are chosen to size them so they represent, in the model, the same color temperature that is measured with a commercial instrument during these readouts. As long as the sensitivity for all sensors remains the same, the raw values can be transformed with these factors effectively. If this is not the case, the factor should be divided by the sensitivity in order to make all samples comparable. These factors can be computed for more than one lighting condition and eventually, an average value of all of them could be considered.

Another option to get Correlated Color Temperature is using Robertson's method [10], but it requires to translate our RGB readings into the Human XYZ color space. Converting from RGB to XYZ is straightforward, but the equations will refer to an RGB light source, not an RGB light sensor, converted to perceived XYZ color. An option here is to consider an RGB light source with the same spectra of our RGB sensors, to represent them. Regardless of that, this method allows a level of spectral shift, depending on the sampled light source, so it was left as a second alternative.

The photodiodes we are using can be unequivocal to describe RGB light sources, but here we are exposing them to unknown light sources, and in our last method, asking them to represent them as emitting diodes. For spiky light sources the correlation can be critical, so a better knowledge of the possible spectra to be encounter in real film sets can help to predict results in worst cases.

The ideal filters to get accurate CCT are the XYZ tristimulus filters, which corresponds to the human eye's color perception. They can give unequivocal results, but they are not cheap or even accessible.

The key factor to improve this sub-system is to refine the model of the spectral response of the sensors, especially if any protective cover (e.g. lumisphere) is to be installed, and to include the human's eye perception sensitivities in the correlation process. Also the inclusion of a forth silicon diode sensor with a different sampling filter can enhance and make the matching capabilities more robust.

C. Calculation of Incident Light Angles

Calculation of incident light angle θ along an axis follows from (1) [9], where a and b represent the output current from active area a and b of a light angle sensor.

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

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. 3). First, calculate the two angles θ_X and θ_Y along X and Y axes, respectively, using (1). The vectors of two planes that embed the line from the Illumimote to the light

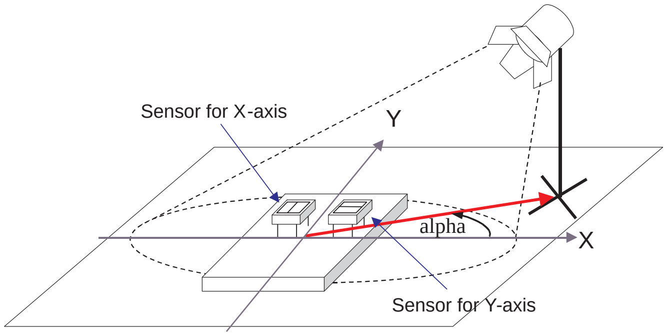


Fig. 3. Incident Light Angle Estimation [11]

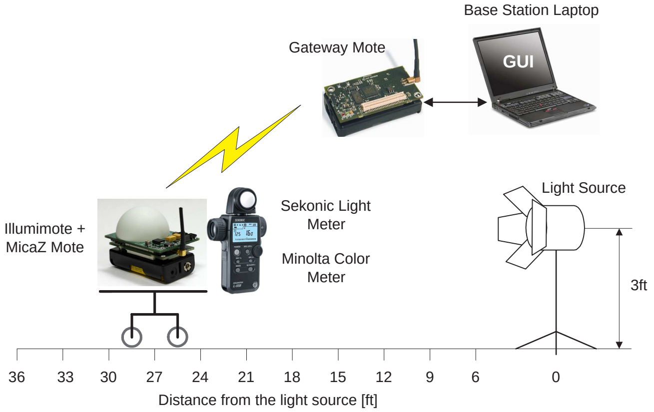


Fig. 4. Experimental System Setup

source and intersect X and Y axis can be obtained by (2).

$$\vec{v}_X = (\cos\theta_X, 0, \sin\theta_X), \vec{v}_Y = (0, \cos\theta_Y, \sin\theta_Y) \quad (2)$$

By calculating the cross product of the two vectors from (2), the vector of the line from the Illumimote to the light source can be calculated as in (3).

$$\vec{u} = (u_x, u_y, u_z) = \vec{v}_X \times \vec{v}_Y \quad (3)$$

Therefore, the angle α is calculated as follows:

$$\alpha = cos^{-1}\frac{u_x}{\sqrt{{u_x}^2 + {u_y}^2}} \quad (4)$$

V. EXPERIMENTAL RESULTS

A. *Experimental System Setup*

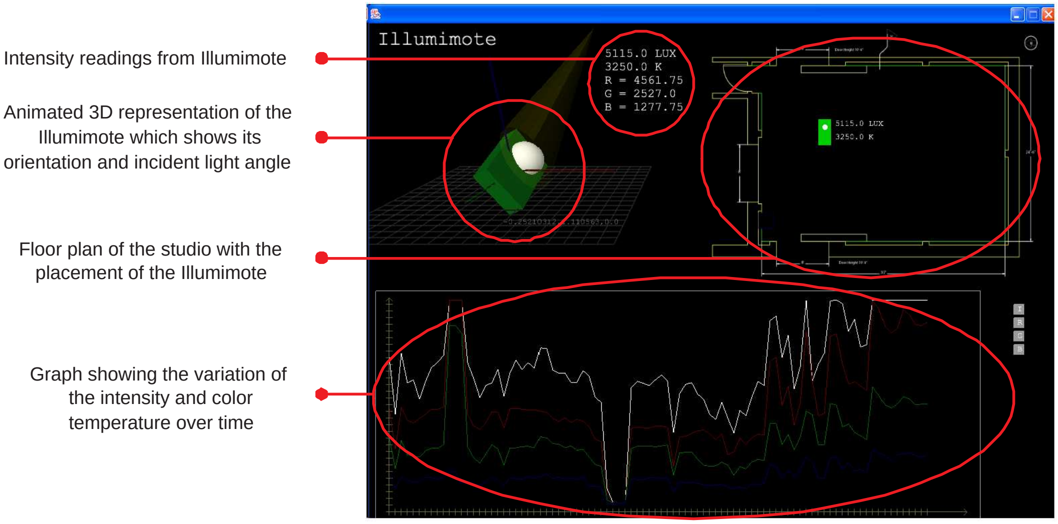
To evaluate the Illumimote, we integrated a wireless sensing system with the Illumimote. Experimental setup is shown in Fig. 4. For a light source, we used a tungsten-balanced incandescent lamp which generates a color temperature near 3200°K and can provide about 3,000 lux brightness at distance 6ft. This is a very common light source in film sets, and has a well defined and very specific color temperature. With this experimental setup, we compared the Illumimote for incident light intensity and color temperature measurements. To generate diverse brightness, we placed our Illumimote at 11 different points from 6ft through 36ft away from the light source in 3ft step. We set up two brightness settings for wide intensity ranges: one for bright light intensities from 100 lux up to 3,000 lux and the other for low intensities from 130 lux down to 4.7 lux. At each point, light intensities were measured wirelessly by our Illumimote. For reference lux value, a Sekonic L-558Cine [8] light meter was used. For the color temperature measurements, we fixed the location of the Illumimote at 6ft and applied different several kinds of color filters (gels) to generate lights that have sixteen different color temperatures. We used a Konica Minolta Color Meter IIIf [13] for measuring the ground truth color temperature for each light setting.

Three embedded software components were developed for the experimental wireless sensing system. First, we programmed a sensor and sensitivity control software and downloaded it to the Illumimote board. We attached our Illumimote board on a MicaZ node that has a 7.37MHz 8-bit microprocessor and a 250kbps ZigBee radio [7]. Secondly, Illumimote driver and light sensing application were programmed at the MicaZ mote using SOS environment. SOS is an OS for mote-class wireless sensor networks developed by NESL at UCLA [14]. Finally, at the base station laptop, a Java program was used to monitor and log the light measurements, and a visualization interface was used for real-time debugging and analysis. We developed a GUI visualization interface as shown in Fig. 5 to display the status of the Illumimote in real time, that was used for testing, experimenting, and performing demonstrations. The interface was implemented in Java and Processing [15]. This GUI makes it easy to test and evaluate the Illumimotes visually and is a step towards designing the interface that could be used by a cinematographer in future.

B. *Performance Results*

First, the light angle sensors were evaluated by placing a tungsten-balanced incandescent lamp at all combinations of three angles (0°, 30° and 60°) and three distances (nine total points). The dual photodiodes (Hamamatsu S6560 [9]) on the Illumimote have same shape and are symmetrically placed with respect to vertical barricade in between them. So, the angle estimation performance would be symmetric with respect to X and Y axis. Therefore, only the first quadrant was tested as performance for the other three quadrants is similar. We measured and estimated the angle ten times for each point. The light-angle estimation results were well correlated with an average error of about 3°. This experimentation for the angle estimation was done with the prototype Illumimote board.

The fabricated Illumimote contains an experimental design for the two diodes comprising each channel of the light angle sensor. The sensor is packaged in a common-cathode configuration and it was hoped that by employing the design of Fig. 2, and thereby sharing the bias currents, we could accentuate the angle-to-voltage function and improve the resolution near apogee. Unfortunately, this approach proved highly unstable with the input tending to saturate in favor of one of the diodes as the source approached apogee. An alternative voltage-based prototype was developed separately for this sensor. We used data from the prototype for evaluation of the light angle experiments described in this paper. We will incorporate this architecture into the next revision of the Illumimote.



```
5115.0 LUX
3250.0 K
R = 4561.75
G = 2527.0
B = 1277.75
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5115.0 LUX
3250.0 K
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Fig. 5. Screen Shot of the Real-Time Visualization Interface

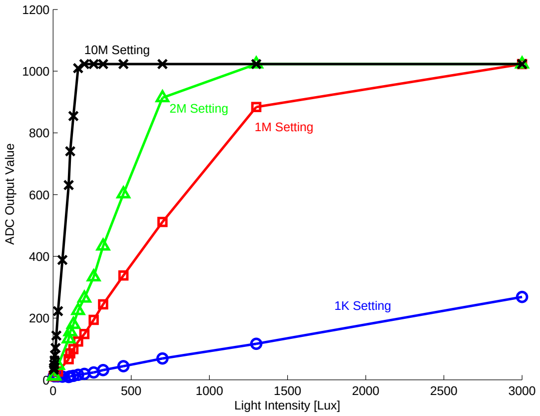
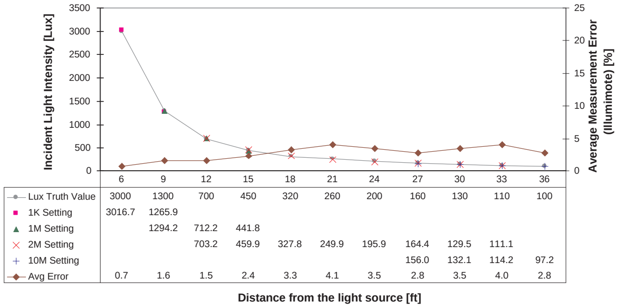
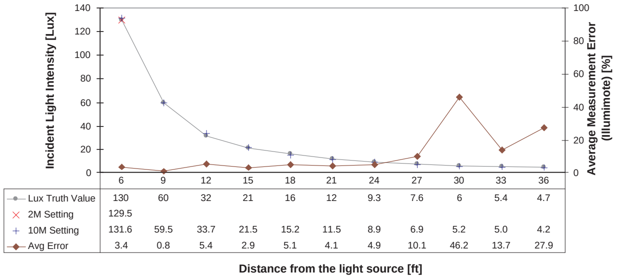


Fig. 6. ADC output of Four Sensing Sensitivity Settings



	6	9	12	15	18	21	24	27	30	33	36
Lux Truth Value	3000	1300	700	450	320	260	200	160	130	110	100
1K Setting	3016.7	1265.9									
1M Setting		1294.2	712.2	441.8							
2M Setting			703.2	459.9	327.8	249.9	195.9	164.4	129.5	111.1	
10M Setting								156.0	132.1	114.2	97.2
Avg Error	0.7	1.6	1.5	2.4	3.3	4.1	3.5	2.8	3.5	4.0	2.8

Fig. 7. Light Intensity Measurement for Bright Light Setting



	6	9	12	15	18	21	24	27	30	33	36
Lux Truth Value	130	60	32	21	16	12	9.3	7.6	6	5.4	4.7
2M Setting	129.5										
10M Setting	131.6	59.5	33.7	21.5	15.2	11.5	8.9	6.9	5.2	5.0	4.2
Avg Error	3.4	0.8	5.4	2.9	5.1	4.1	4.9	10.1	46.2	13.7	27.9

Fig. 8. Light Intensity Measurement for Low Light Setting

With the experimental setup shown in Fig. 4, we evaluated measurement accuracy and the dynamic range capability of incident light intensity sensor. With 11 measurement points and two brightness settings, we collected 41,318 light intensity measurements in total from the Illumimote and applied moving average filter with window size 20 to reduce random measurement noise. Then, calibration coefficients a and b for each sensitivity setting are calculated with the first half of the raw intensity measurement data. Once the calibration coefficients are obtained, any light intensity measurements (ADC values) can be converted into lux values by the methods in Section IV.

To increase dynamic range and sensing resolution, the Illumimote offers a 6-step sensitivity control: 1KΩ, 667KΩ, 1MΩ, 1.7Ω, 2MΩ, and 10MΩ setting. We evaluated four representative sensitivity settings among them with 1KΩ, 1MΩ, 2MΩ and 10MΩ bias resistances. Fig. 6 shows the ADC output with respect to light intensity in lux for these four sensitivity settings. As shown in Fig. 6, the output voltage of the light acquisition unit is linearly proportional to the light intensities and the ADC data revealed the sensitivity control unit (SCU) to have an effective and desirable response on the output. The light acquisition unit was confirmed to feature a rail-to-rail output range (0 – 1023 of 10-bit ADC output) 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 and Fig. 8 confirm that adjacent sensitivity settings have overlapping ranges 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.

Although we verified that the current fabricated Illumimote can measure up to 18,500 lux brightness [11], this experimen-

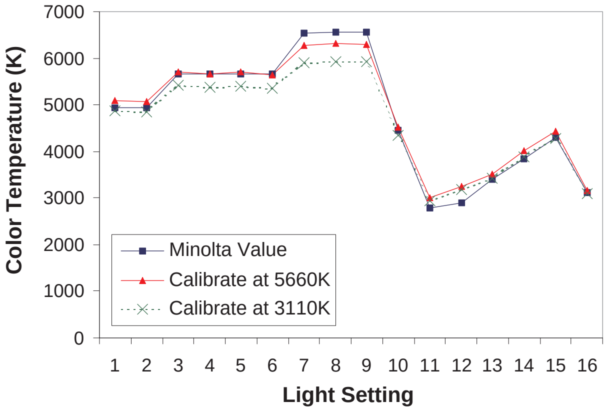


Fig. 9. Color Temperature Calculation Results

tation focused more on practical light intensity region less than or equal to 3,000 lux. Illuminance by sunlight at the exterior is about from 32,000 to 100,000 lux; but illuminance for many film sets—especially indoor—is less than that. For example, brightness of the moonlight is about 1 lux, illuminance for bright office is about 400 to 500 lux and normal TV studios are lit at about 1,000 to 2,000 lux [16]. Fig. 7 and Fig. 8 show the results from the two brightness settings. In the figures, X axis represents the distance from the light source and left Y axis represents light intensity measurement in lux by our Illumimote. The tables below the figures show the average light intensity value and average of absolute error by the Illumimote for each point. Measurement regions for each sensitivity setting were determined by the ADC output shown in Fig. 6. For example, each sensitivity region can take the region that corresponds from 25 to 1000 of ADC output value. Measurement regions of our sensitivity settings are following; the 10MΩ setting covers from 0 lux to 160 lux, the 2MΩ setting covers from 110 lux to 700 lux, the 1MΩ setting covers from 450 lux to 1300 lux, and the 1KΩ setting covers more than 700 lux regions.

As shown in the figures, our Illumimote measurements were correlated to the Sekonic light meter readings within about 5% for most of points except very low intensities ($<$ 8 lux). We analyzed the reasons from followings. Experimental design was complicated by a number of factors: the exact same measurement position for the Illumimote and the Sekonic meter, angle of the lumisphere, hand posture when measuring light intensities with Sekonic meter (because of manual measurements) and light reflections from equipments in the environment. Measurements at very low intensities ($<$ 8 lux) appeared to be exacerbated by the complicated experimental design problems and have decreased the accuracy to more than 5% on average.

To evaluate color intensity sensors and our color temperature calibration methods, we collected 13,647 color intensity measurements from RGB sensor channels for light settings with different color temperatures ranging from 2900°K to 6560°K. Fig. 9 shows comparison results to the ground truth color temperature value by Minolta Color Meter IIIf [13]. Our color temperature calculation results by two calibration settings (3110°K and 5660°K) are shown. For both of the cases, our color temperature calibration methods correlated with the Minolta color meter within 5% in average. One of the key factors to improve this sub-system is to refine the model of the sensor's spectral response, especially if any protective cover is to be installed.

Throughout the experiments, we verified that the current wireless light sensing system with our Illumimote can collect light intensities at the speed of 340 measurements per second of which time for one measurement corresponds to about 3ms. Because one television video frame is captured over approximately 33.37ms [17], the Illumimote (at 3ms) is responsive enough to detect and process lighting changes that would impact a single video or film frame in real-time. Regarding power consumption of the sensor module, the Illumimote consumes approximately 90mW when all sensor channels are turned on.

VI. CONCLUSIONS

Our new light sensing module, the Illumimote, for the Mica mote platforms achieves performance comparable to a commercial light meter and color meter (as used by professional cinematographers) 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. The project website hosts the technical data (http://nesl.ee.ucla.edu/research/illumimote) and the Illumimote will soon be commercially available from Atla Labs (http://www.atlalabs.com) to allow other researchers access to the technology for their own experimentation. Our future work includes further enhancements to the general characteristics of the Illumimote (such as dynamic range), estimation of the vertical incident light angle, and further development of the software tools that support and integrate the Illumimote in support of its deployment on actual productions scheduled for the near future.

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