A Fluorescent Lamp with Integral Proximity Sensor for Building Energy Management

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Abstract—**We have developed a proximity sensor that can be integrated with a fluorescent lamp ballast. This sensor measures disturbances in the electric field around the lamp in order to detect the presence and motion of people. Range test data from our preliminary experiments showed detection ranges of 11 ft. between the lamp and the closest edge of a human target. The detector enables fine-grain occupancy measurements in spaces, promising to improve energy efficiency by reducing wasted lighting of unoccupied spaces.**

I. INTRODUCTION

We have developed capacitive sensing circuitry to enable a fluorescent lamp fixture to serve "dual-use" as a proximity detector for occupants below the lamp. The lamp sensor measures changes in the electric fields produced by and surrounding the lamp with two electrodes on the luminaire cover. The lamp sensor has been demonstrated as a presence and motion detector in [1]–[3]. The lamp sensor has also been demonstrated as a proof of concept for metal detection and a vertical scanning capability in [2], [3]. The lamp sensor could be used as an occupancy sensor in any place illuminated by discharge lighting. Because the sensor detects changes in dielectric configuration around the lamp, it does not require motion or a thermal signature to detect a person. Fine-grain measurements of occupancy provided by the lamp could enable improved energy efficiency by eliminating lighting of unoccupied spaces. The lamp sensor could also be used for security applications (see [1], [2]).

There is a great interest in controlling lighting to optimize energy consumption. For example, in [9], the authors discuss the application of micro-electromechanical (MEMS) illuminance sensors spread around work spaces to measure daylight. The MEMS sensors would conceivably interface with dimming fluorescent lamp ballasts to adjust lighting levels. Other optimization schemes based on occupancy have also been proposed, again to conserve energy spent on illumination. Our approach can be deployed with additional sensing to adjust for background or "free" daylight illumination levels. It offers the possibility to adjust lighting based on occupancy without the need for a special occupancy sensor network, or a dependance on occupant motion. Our scheme can be integrated with the ballast, providing a "drop-in" capability in a luminaire for implementing occupancy based energy conservation schemes.

In section II, we consider the need for energy conservation through lighting control. In section III, we review the operating principles and theory behind our lamp-based occupancy sensor. In section IV, we discuss key lamp sensor parameters affecting detection sensitivity. Finally, in section V, we explore approaches for implementing lighting energy conservation using the lamp sensor.

II. FLUORESCENT LIGHTING ENERGY CONSUMPTION

Lighting in commercial and residential spaces consumes a significant portion of the end use demand for delivered energy in the United States. In 2005, lighting consumed 0.73 Quadrillion Btu (QBtu) in the residential sector and 1.18 QBtu in the commercial sector [16]. This accounts for 15.6% and 13.9% of the total electricity delivered in the residential and commercial sectors, respectively; approximately \$20.1 billion and \$29.7 billion spent by electricity consumers in the residential and commercial sectors respectively [16].

The U.S. Environmental Protection Agency (EPA) encourages reduction of energy consumption by improving efficiency of energy systems. The EPA's Energy Star program provides energy efficient solutions for reducing energy consumption while maintaining or improving the current standards of living [17]. The Energy Star program also recognizes businesses and organizations for reducing greenhouse gas emissions through energy efficiency. "In 2006 alone, Americans with the help of Energy Star saved \$14 billion on their energy bills and avoided greenhouse gas emissions equivalent to those of 25 million vehicles [17]."

A. Occupancy Detection Solutions

One implementation strategy for reducing energy consumption described by the Energy Star program is to reduce lighting in unoccupied spaces using motion sensors to detect occupants. Motion sensors monitor large spaces and turn lights on and off based on occupant motion. In principle, they reduce the energy consumed by lights in unoccupied spaces [18]–[23]. There are several disadvantages associated with detecting occupancy using motion sensors. First, the occupancy measurement is based on motion rather than presence. To turn on the lights, occupants must periodically move in view of the sensor.

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Unfortunately, lights can turn off despite occupancy and stay on for some time after the occupants have left. Second, the motion detectors require custom installation distinct and in addition to the installation of luminaires. There is a premium on minimizing sensor hardware and installation expense, and measurement networks are often as coarse grain as possible to implement a basic level of functionality. Typical motion sensor implementations may allocate one motion sensor to an entire large room. If the rooms are sparsely occupied, there is still significant wasted energy on lighting unoccupied spaces. Finer grain lighting control increases sensor expense and installation effort.

The lamp sensor presented here and in [1]–[3] provides detection of motion and presence at ranges of up to 11 ft or more. In Section IV, we demonstrate how the detection range of this system can be adjusted for any given application. The lamp sensor is "dual-use" because it uses the electric fields and luminaire already present for discharge lighting to implement a detection capability. The detection electronics can be incorporated into the ballast and would "power up" with the ballast from the utility line. The lamp sensor ballast requires only two extra wires to connect to the electric field measurement electrodes. Therefore, retrofitting an entire public space with lamp sensors could be done essentially as a drop-in replacement of the old lamp ballasts with the lamp sensor ballasts, and the addition of two electrodes in the luminaire cover. It could also be "designed in" as part of a lamp fixture.

III. LAMP SENSOR DESIGN AND OPERATING PRINCIPLES

We have constructed two prototype proximity detectors. One is horizontally mounted and portable for quick experimentation. The other is a hanging sensor constructed in a two-bulb luminaire for testing in a real world configuration. Figure 2 shows the cart-mounted lamp sensor. The prototype consists of a two-bulb, 48-inch fluorescent fixture, the lamp sensor electronics, and two electrodes in front of the lamp. In the prototype lamp sensor, we use rectangular metallic electrodes placed in front of the lamp. In a production lamp sensor, the electrodes would be sprayed onto the inside of the lamp cover with Indium Tin-Oxide [24]. The lamp sensor ballast would require two extra wires to connect to the electrodes on the cover.

An example of the lamp sensor output is shown in Figure 2. The two electrodes have a differential effect on the sensor output. The output voltage from the lamp sensor deviates from zero as the occupant approaches one electrode. It returns to zero as the occupant approaches the center of the lamp. Finally, the output voltage deviates in the opposite direction as the occupant approaches the opposite electrode. More discussion of the lamp sensor output can be found in [1]–[3].

The proximity sensor design and associated signal conditioning circuitry have three key subsystems that provide the following features:

1) Balanced differential measurements
2) Current-mode detection
3) Synchronous detection

The next section describes the operation of these signal processing features to provide proximity detection capability.

A. Capacitive Bridge for Balanced Differential Measurements

Electric fields in front of the luminaire cover are measured through a bridge or balanced differential measurement. This approach offers several advantages. First, the differential measurement does not require a well-controlled reference potential for the signal source. This is important because the signal source is the alternating bulb surface potential, which does not have a well-controlled reference. Second, the differential measurement rejects common-mode interference from stray signals at the measurement electrodes. Rejection of common-mode stray signals improves the detection specificity, i.e., the response to people, in the presence of electromagnetic interference from other electronics in the environment. Third, in the absence of a detection, the differential output is zero or nulled. Therefore, the differential front-end amplifier can provide very high gain without saturating the output in the absence of a detection.

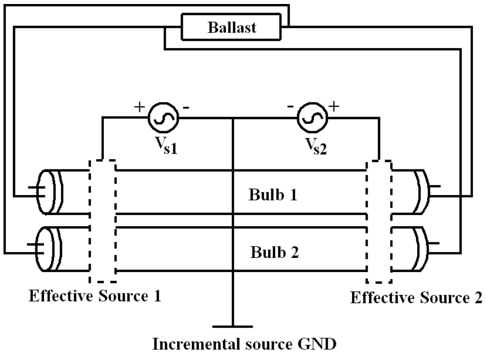

Fig. 1. Reversing the ballast connections to one bulb results in symmetric effective voltage sources referenced to the center of the lamp [2].

The balanced differential measurement requires a symmetrical signal source. We create a signal source which is symmetrical about the center of the lamp by reversing the ballast connections to one of two bulbs (see Figure 1). Details about the strength and characterization of the signal source are presented in [1]–[3].

Measuring electric field changes below the lamp in response to a conducting or dielectric target amounts to measuring changes in lumped capacitance values between conducting surfaces. References [1]–[3] present the full and simplified capacitive model of the lamp sensor and target system. The capacitive model is redrawn as the capacitive circuit in Figure 3. The measured signal is the differential current labeled i_{diff}. i_{diff} is the current that passes through the effectively low-impedance path from one electrode to the other created by our differential transimpedance amplifier shown in Figure 4.

This capacitive "circuit" (some elements are distributed in space around the lamp) is connected through shielded electrodes to an analog front-end amplifier. The electrodes are connected directly to the high-impedance inputs of a high-gain op-amp in closed-loop feedback. This transimpedance

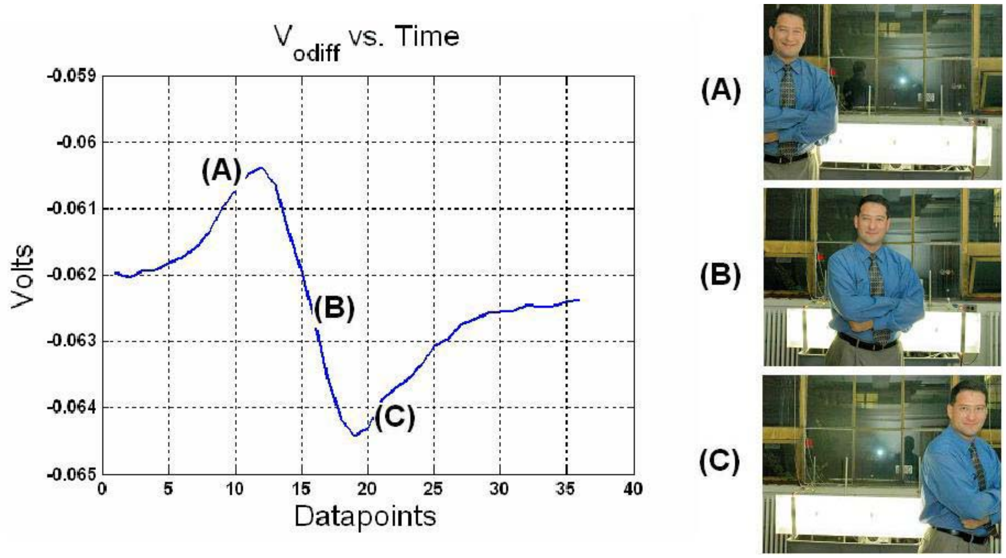

Fig. 2. The measured output response to a person moving under the lamp is shown in the plot. The position of the person under the lamp is represented by the person in the images standing in front of the cart-mounted lamp sensor.

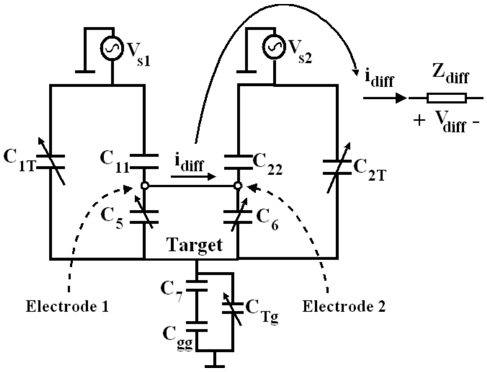

Fig. 3. The lumped element capacitive circuit consisting of the capacitances of interest shows a symmetrical and balanced bridge circuit for nullable differential measurement. The differential signal that will be measured is the differential current i_{diff} and it will be measured as the differential voltage v_{diff} at the output of a differential transimpedance amplifier with differential transimpedance Z_{diff} [2].

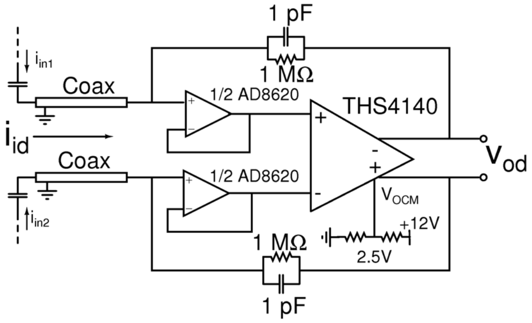

Fig. 4. Schematic of the low-noise analog front-end amplifier [2]

amplifier detects changes in current in the capacitive circuit of Figure 3. The schematic of the transimpedance front-end amplifier is shown in Figure 4. The JFET op-amps buffer the inputs of the fully-differential op-amp for low input-offset current and low input-referred current noise. Feedback capacitors stabilize the system using lead compensation in order to provide a stable closed-loop response despite the capacitive input elements.

B. Current-Mode Detection and Stray Capacitances

One advantage of using current-mode detection (by connecting the electrodes directly to the inputs of the front-end op-amp) is that stray capacitances from the electrodes to incremental ground can be neglected in the output response of the front-end amplifier. The fully-differential circuit consisting of the signal source and front-end amplifier can be separated into two identical half-circuits. The voltage reference for each half-circuit is the voltage about which the two halves of the differential voltages in the fully differential circuit are symmetric. Figure 5, shows the half-circuit in which the ground reference is labeled "differential ground reference." The stray capacitance, C_{stray}, shunts the op-amp input node to the differential ground [2].

In the closed-loop connection shown in Figure 5, the output voltage, V_{out}, of the half-circuit varies with respect to the differential ground reference. If the differential gain of the op-amp is $A(s)$, the input voltage variation relative to the ground reference is attenuated by $|A(j\omega)|$ from the output voltage. Because $|A(j\omega)|$ is large by design, the input voltage of the op-amp, V_{in}, varies very little relative to differential ground reference. Since the small variation in V_{in} appears across C_{stray}, the stray capacitance does not shunt much current from the input current, i_{in}. Therefore, the stray capacitance can be neglected. C_{stray} is "bootstrapped" because the voltage variation across it is small. The effective impedance, Z_{eff} of

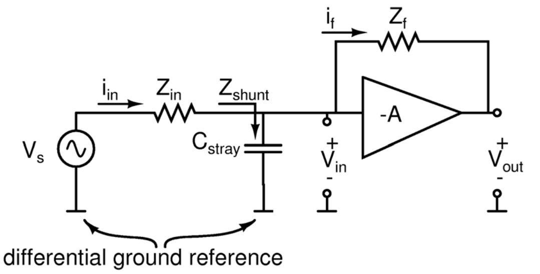

Fig. 5. The fully-differential circuit can be separated into two identical half-circuits. The half-circuit voltages vary with respect to the differential ground reference.

the bootstrapped stray capacitance is $Z_{shunt}/|A(j\omega)|$ [2], [7].

As an example, the relatively large (30 pF) shield capacitance of the coaxial cables connecting the electrodes to the amplifier can be conveniently neglected. The shield capacitances are connected to board ground which differs from the differential ground reference. However, we assume that the impedance from the input node to the differential ground reference through the shield capacitances is at least as large as the impedance from the input node to board ground [2].

Stray capacitances at the measurement nodes can be neglected due to the effective low-impedance looking into the input of the feedback connected op-amp. Similarly, stray capacitances at the signal source can be neglected because the signal source is also low-impedance (a voltage source). Therefore, the lamp sensor system presented here is insensitive to stray capacitances at the signal source and at the measurement nodes.

C. Synchronous Detection

The signal conditioning circuitry uses synchronous detection to isolate the effect of the symmetric alternating signal source on the capacitive system from other stray signals that differ either in frequency or in phase [2], [3]. In the synchronous detection scheme, the carrier signal is the alternating voltage source signal from the bulbs. The baseband signal results from the changes in the effective input capacitance due to the presence or movement of the target below the lamp. The carrier signal frequency is the ballast frequency. For our lamp sensor, the ballast frequency is 42 kHz. A modulated carrier signal results from the carrier signal driving current through the changing effective input capacitance. The signal is down-modulated back to the baseband after amplification. This is accomplished by multiplication with another copy of the carrier signal. A simplified block diagram of the synchronous detection system is shown in Figure 6.

Stray signals in the detection environment include alternating signal sources created by other fluorescent lamps, and other uncontrolled signal sources in the lamp and fixtures. An illustrative example considers the effect of low-frequency 1/f noise from the front-end op-amp as the unwanted signal on the output in the synchronous detection system. Figure 7 outlines the frequency domain treatment of the carrier and baseband signals in the presence of the stray signal which in this case is 1/f noise from the op-amp in the front-end amplifier.

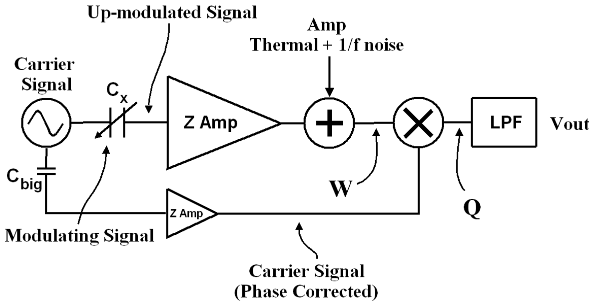

Fig. 6. A simplified block diagram of the synchronous detection system detects changes in the effective input capacitance C_x. Synchronous detection isolates signals of interest from unwanted signals [2].

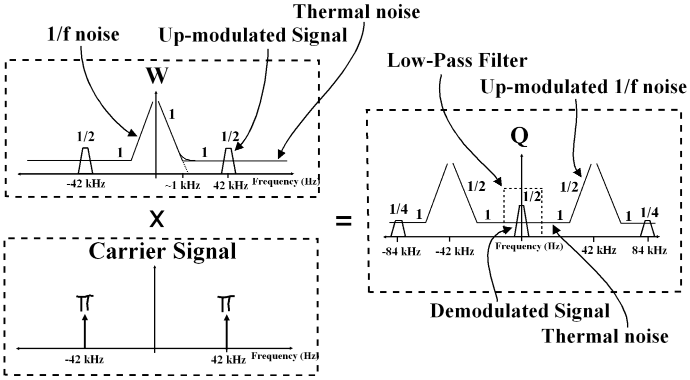

Fig. 7. Demodulation of the amplified up-modulated signal by multiplication with the carrier [2]. The labels correspond to the labels in the block diagram.

Because the amplification of the up-modulated signal takes place in the high frequency regime, the low-frequency or stray 1/f noise is left out of the final demodulated signal after low-pass filtering. Stray signals at the input of the lamp sensor are also treated like the 1/f noise from the amplifier; this example illustrates the specific advantage of using synchronous detection in the context of rejecting low-frequency noise from the electronics that would otherwise be overwhelming. This principle is similar to chopper-stabilization of amplifiers for low-frequency signal amplification [2]–[4]. The full schematic of the lamp sensor electronics is presented in [1]–[3].

IV. DESIGN VARIABLES AFFECTING DETECTION SENSITIVITY

From the perspective of a lighting designer, three key parameters affect the output sensitivity, e.g., detection range, of the proximity detector:

1) Electrode spacing
2) Electrode depth
3) Bulb power

The effects of the first two parameters, spacing and depth (electrode configuration) have been studied in our preliminary

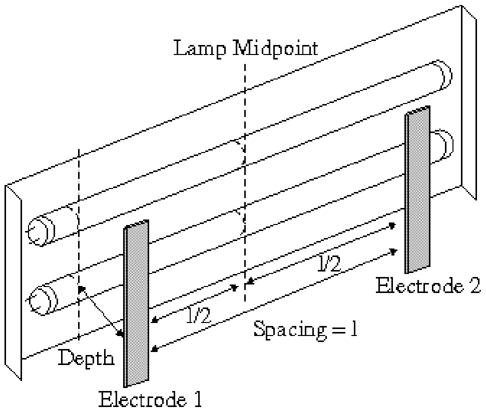

Fig. 8. A diagram of the two-bulb fluorescent lamp and electrodes. The spacing is the distance between the two electrodes. The depth is the distance between the bulb surface and the electrodes. The electrodes are spaced symmetrically about the center of the lamp.

work. Figure 8 illustrates typical results associated with varying electrode spacing and depth. The output sensitivity is equal to the signal to noise ratio (SNR) at the output. The output response of the lamp sensor is compared to the noise floor in a detection range test in [1]–[3]. The detection data show that the noise floor does not vary dramatically with the electrode configuration. Therefore, we can simply view the magnitude of the output response as the output sensitivity when varying the electrode configuration.

Output data taken from the lamp sensor prototype for varying electrode depths is shown in Figure 9. The output voltage data is plotted as ac rms voltage for a passing target for ease of comparison with the noise floor of the lamp sensor. The output response increases for all ranges as the electrode depth increases. Therefore, one way to increase sensitivity and detection range is to increase electrode depth.

Because the electrodes might be sprayed onto the inside of the lamp cover, the cover needs to accommodate the electrode depth. A very deep lamp cover may be strange to the occupants below the lamp. However, deeper lamp covers are only necessary for longer detection ranges. Longer detection ranges are only necessary when the lamp is farther from the occupant. The farther the lamp is from the occupant, the less aesthetic impact will be caused by deeper covers.

Output data taken from the lamp sensor prototype for varying electrode spacing is shown in Figure 10. As the spacing between the electrodes increases, so does the difference measurement of the electric field between the two electrodes. Therefore, the output response increases as the electrode spacing increases.

We are currently studying the effect of the third parameter, bulb power, on the output sensitivity. It is discussed in Section VI because it is important for the "dimmed sensing" scheme in Section V.

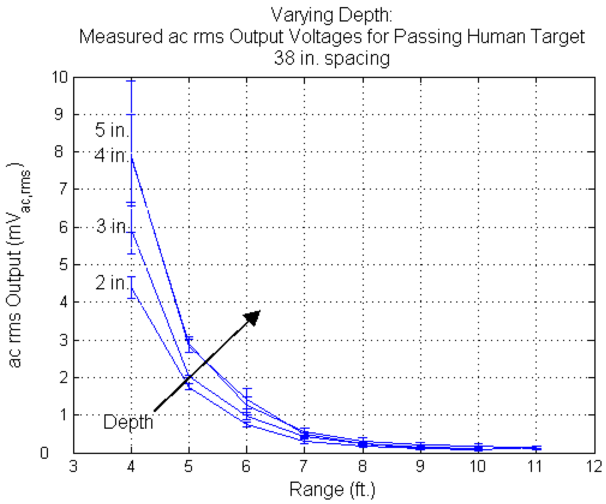

Fig. 9. Plots of the measured ac rms output response to a person walking below the lamp for varying electrode depths. In the plot, the output response increases for all ranges as the depth increases.

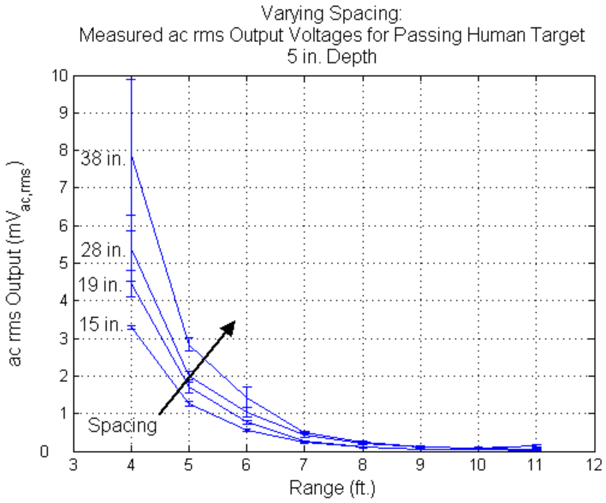

Fig. 10. Plots of the measured ac rms output response to a person walking below the lamp for varying electrode spacings. In the plot, the output response increases for all ranges as the spacing increases.

V. APPROACHES TO REDUCED LIGHTING ENERGY CONSUMPTION

The lamp sensor does not work if the lamp is turned completely off. Therefore, we discuss two sensing schemes that reduce wasted lighting energy but retain lamp sensor detection capabilities: one in which every lamp is dimmed (dimmed sensing) and one in which most lamps are turned off but some are left on for detection (sparse sensing).

A. Dimmed Sensing

The dimmed sensing scheme for occupancy detection uses a dimming fluorescent lamp ballast in concert with the proximity sensing electronics in each lamp. If an occupant is detected below any lamp, that lamp brightens. Figure 11 shows an overhead view of the dimmed sensing scheme.

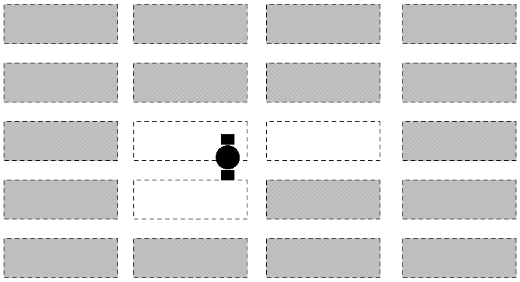

Fig. 11. An overhead view of the dimmed sensing scheme: all of the lights are left on but dimmed. When a lamp sensor detects an occupant, it turns full-on. Shaded boxes represent dimmed lamps and unshaded boxes represent full-on lamps.

In this approach, all of the lamps are left on, but they may be dimmed. When an occupant is detected below a lamp, the lamp increases its intensity to full brightness, or, alternatively, to a level appropriate based on time of day, lighting scene selection from a wall control, or background lighting (window light), as appropriate. The ballast can include other detectors, i.e., for photosensors for window or background lighting, to implement more sophisticated control schemes, as desired. That is, common lighting intensity and timing control schemes can, of course, be "mixed and matched" with the proximity sensor. For detecting an occupant below the lamp, the lamp sensor needs only to reliably detect the upper portion (e.g., the head) of an occupant. Therefore, the minimum useable detection range is determined by the distance between the lamp sensor and the top of the shortest occupant that we want to detect. The output sensitivity may change with the bulb power (see Section VI). Therefore, when designing a dimmed sensing occupancy detection system, the output sensitivity under dimmed conditions must be sufficient for the desired detection range.

This dimmed sensing scheme offers several advantages. First, by dimming the lamps rather than turning them off, the bulbs may last longer by avoiding unnecessary restarts [25]. Second, dimming all of the lights results in uniform lighting of unoccupied spaces. If we want to leave unoccupied spaces partially lit, uniform lighting of those spaces may be preferable.

B. Sparse Sensing

The sparse sensing scheme leaves one or a few lamps on in a cluster of many lamps that are turned completely off. Only those lamps that are left on ("sparse lamps") act as lamp sensors. The distance between sparse lamps is constrained by the detection range of the lamp sensor under full power. The lamp sensor detection field below the lamp is not necessarily directional, although the electrode configurations can be designed to make it so [2], [3]. Therefore, the detection field also generally includes space to the side of the vertical space below the lamp. In order to have no "blind spots" in the sparse lamp sensor array, the sparse lamps should be able to reliably detect the top surface of the shortest occupant. The detection field for each sparse lamp would typically, but not necessarily be designed to include the space below the lamp and the space under the adjoining turned-off lamps.

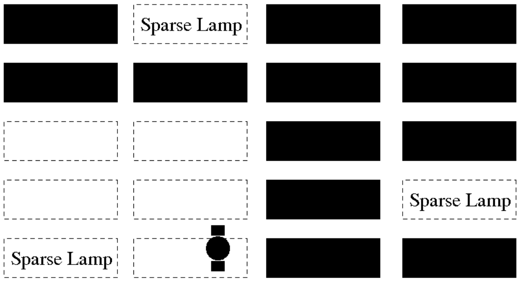

Fig. 12. An overhead view of the sparse sensing scheme: only some of the lights are left on for sensing. If a lamp sensor detects an occupant, it turns on the adjoining lights. Dark boxes are lights that are off and unshaded boxes are lights that are on.

Figure 12 shows an overhead view of the sparse sensing scheme. An occupant is in the detection field of one of the sparse lamps. The lamps adjoining the sparse lamp that has detected the occupant are turned on. The only other lamps that are turned on are the other sparse lamps. Figure 13 shows an overhead view of the detection fields in the sparse sensing scheme. Because each lamp sensor has a wide angle of detection, the detection field for each sparse lamp has been designed to span the space under adjoining lamps as indicated.

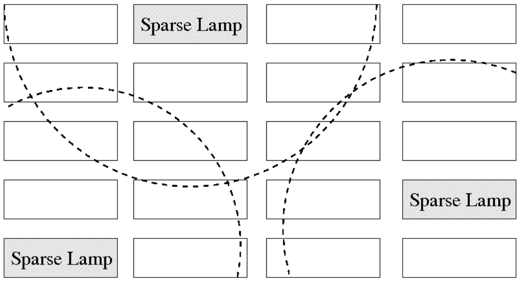

Fig. 13. An overhead view of the sparse sensing scheme with detection fields outlined below each of the sparse lamp sensors. Ideally, the union of the detection fields spans the entire 2-D space below the lamps leaving no "blind spots."

In the sparse sensing scheme, there is no need for dimming ballasts. The lamp sensor electronics can be interfaced with standard lamp ballasts. The sparse approach only requires lamp sensors in the sparse lamps rather than all of the lamps.

Some lighting control system must be provided to sequence or control the operation of the "non-sensing" lamps in the sparse configuration. In the dimmed sensing scheme, each lamp acted independently of the other lamps. In the sparse sensing scheme, the lamps would need to be interfaced with each other. The lamp interfacing could be achieved with lighting control technologies such as General Electric's Total Lighting Control® (TLC) or the Digital Addressable Lighting Interface® (DALI) [27] [26]. For autonomous operation, the non-proximity sensing lamps in the sparse configuration could detect a signal from the sparse lamp, e.g., an imperceptible optical flicker or other "triggering" signal such as an RF message.

VI. CONCLUSIONS AND FURTHER WORK

The lamp sensor shows potential as a built-in occupancy sensor for fine-grain lighting control. Three lamp sensor parameters affect the detection sensitivity. Electrode depth and spacing have been studied and their effects on the detection sensitivity were presented. We are currently quantifying the effect of bulb power on signal source amplitude and noise content. Further work will investigate the effect of varying bulb power on the detection sensitivity. These results will be important for the dimmed sensing scheme.

Two sensing schemes for reduced lighting energy consumption were presented. Both schemes use lamp sensors for fine-grain occupancy detection. One uses dimming lamp ballasts and operates the lamp sensors under dimmed conditions (dimmed sensing). The other uses sparsely populated lamp sensors and takes advantage of the wide angle of detection of the lamp sensors to detect nearby occupants (sparse sensing). Other schemes are also possible given reliable proximity detection.

The lamp sensor electronics have been designed so that they do not contribute significantly to the noise floor of the lamp sensor system. The dominant noise source is the signal source itself, i.e the bulbs and ballast. This noise source limits the robustness and resolution of the lamp sensor. Therefore, we are pursuing differential-mode feedforward compensation to actively cancel the signal source noise. Similar techniques are discussed in [10]–[13]. The implementation of feedforward compensation in the modulation scheme would require a division to eliminate intensity noise since it appears as random modulations of the carrier signal. Low-noise, high-frequency analog division may be achieved with current-mode translinear circuits. Examples of translinear design with current-mode circuits for synthesis of analog dividers can be found in [14], [15].

The lamp sensor has also shown potential as a security detection device; results and discussions of the lamp sensor as a security device can be found in [1]–[3].

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