

Design Techniques for Sensor Appliances: Foundations and Light Compass Case Study

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ABSTRACT

We propose the first systematic, sensor-centric approach for quantitative design of sensor network appliances. We demonstrate its use by designing light appliance devices and the associated middleware. We have developed five models which are required to make this problem tractable and to undertake the challenging task of designing light sensor appliances: (i) physical world, (ii) light sensor, (iii) physical phenomenon, (iv) appliance design, and (v) computational model. With these models in place, we present the new design methodology that consists of two main steps: (1) a procedure for placement of individual sensors of the appliance, and (2) error minimization-based sensor data interpretation middleware. We have developed new optimization techniques for both tasks. A portable light sensor system was designed using the optimization intensive procedure, and its effectiveness demonstrated.

Categories and Subject Descriptors

C.0 [GENERAL]: System architectures; C.3 [SPECIAL-PURPOSE AND APPLICATION-BASED SYSTEMS]: Real-time and embedded systems.

General Terms

Algorithms, Design, Experimentation, Verification.

Keywords: Sensor Networks, Sensor Appliances.

1. INTRODUCTION

Sensor appliances are sensor equipped devices capable of monitoring and capturing essential aspects of an environment such as temperature, humidity, odor, and sound, in order to form a basis for scientific, economic and military applications. Some examples of these applications include habitat monitoring, contaminant monitoring, seismic activity monitoring in buildings, and military surveillance [3],[4],[7]. Our goal is to develop a Light Appliance (LA) that is equipped with light sensors which uses gathered light data to enable a multitude of practical applications. There are at least three key broad LA application areas for light monitoring: environment control, energy conservation, and visual security and privacy. A light appliance will enable a variety of environment control possibilities, from the office or workplace to museums and parking lots. People often

have different preferences for lighting schemes, which in many cases is dependent on their current task. For example, when working on a computer, many prefer a minimal amount of light shining directly into their screen, minimizing glare. At the same time they may prefer significant illumination of their workspace and desk.

The technical challenges associated with the design and operation of LAs can be classified in three groups: (i) related to the field nature of light, (ii) related to the limitations of the sensing device and its sensors, and (iii) associated with optimization problems related to the interaction between combinatorial explosion and the need to solve complex systems of interacting non-linear equations. Unlike temperature which can be defined at each point as a single scalar value, light is a function of not only location, but also direction. Furthermore, even with respect to electronic processes, changes in light intensity and directions are essentially instantaneous. Light interacts in complex ways with the environment. There are two main difficulties with respect to the components of a sensing device. The first is that all measurements are intrinsically noisy. A new layer of additional complexity is introduced when these errors start to propagate through numerical software used to establish the location of the light sources.

One of the goals of the LA is to be capable of operating well in a variety of environments. Each environment has a number of parameters and they can interact and give rise to the combinatorial explosion of the number of scenarios which need to be considered. For example, there can be a different number of light sources in each room and they can have a variety of different relative positions and intensities. Finally, location and orientation of a LA in the room is possible in a great variety of angles (two spherical angular components) and 3-D positions. Each of the specific points in this combinatorial space must be considered for a variety of error scenarios.

In the last several years, a large number of sensor appliances have been designed such as Cricket [7], Active Badge [9], and a 3-D odor compass [4]. The emphasis of the previous efforts has been on minimizing form factors, energy consumption, and communication. Furthermore, many of these devices were equipped with a single sensor of a particular. Although the Cricket compass utilizes more than one sensor on a single device, it still targets the measurement of scalar values (distances) and its application is restricted to fully instrumented environments. When the goal is to locate sources of light or to calculate the intensity of light at a particular location and direction, simultaneous multiple non-correlated measurements of light and sophisticated ways to extract relevant information from noisy data are required. This leads to a need for quantitative optimization intensive sensor-centric design of the LA, where multiple sensors are placed facing

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DAC 2003, June 2-6, 2003, Anaheim, California, USA.
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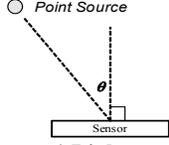


Figure 1 Light sensor

$$I = \frac{I_{src}}{d^2} \cos(\theta) \quad (1)$$

different directions, enabling the measurement of data sufficient to calculate the locations and intensities of sources of light.

In order to address these challenges, we have developed the first LA which is capable of both locating sources of light and calculating light intensity in an arbitrary direction at an arbitrary location within a room. During the design process of this appliance, special emphasis was placed on handling error, both in measurements and data processing, and to make the appliance parameterizable. Maybe most importantly, the procedure is generic in the sense that it can be applied to not only different modalities of phenomena and sensors but also to phenomena which require measurements of a multi-modal nature. The foundation for quantitative sensor-centric design of appliances is provided by a newly developed system of abstractions and models for the physical world or environment, the phenomenon itself, each type of sensor, the sensor appliance, and the operational mode of the appliance. The complete procedure for the design, and use of LA involves three phases: deployment, design and optimization middleware. Here, we focus on the design and middleware phases.

2. PRELIMINARIES

Rapid advancements in VLSI, MEMS technology, and wireless communications have lead to the development of small and inexpensive sensor devices. These devices can be instrumented with a variety of sensors, such as thermal, optic, seismic, infrared, and acoustic transducers. A wide variety of applications have been developed. For example, utilizing such sensor nodes to form sensor networks [1],[2],[5]. One of the primary tasks in wireless sensor networks, especially those that are deployed in ad-hoc manners, is location discovery [6],[10]. The quantitative approach for calculating the sensing capabilities in sensor networks is presented in [6].

Among the sensor-based appliances, the Cricket compass and odor compass deserve special attention. The Cricket compass enables a mobile device to determine its orientation in the environment [7]. By carefully positioning five passive ultrasonic receivers on a device, the orientation is determined through the differential distance estimates of a beacon to each receiver. The 3-D odor compass is a navigational tool used to locate an odor source [4].

There are two main physical laws governing light and optics that are critical in our work: The inverse square law and Lambert's cosine law. The inverse square law is the basic principle that defines the relationship between the irradiance per unit area and the distance to a point source. Lambert's cosine law states that the irradiance falling on any surface varies as the cosine of the incident angle (Figure 1). In equation (1), d is the distance from the point source to the sensor, I is the light intensity per unit area (e.g. W/cm²) at the sensor surface, and I_{src} is the intensity of the point source.

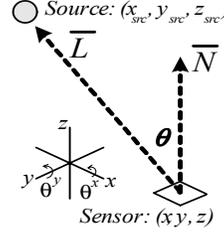


Figure 2. Angle of Incident

$$\cos(\theta) = \frac{\bar{N} \cdot \bar{L}}{\|\bar{N}\| \|\bar{L}\|} \quad (2)$$

$$\bar{L} = \langle x_{src} - x, y_{src} - y, z_{src} - z \rangle \quad (3)$$

$$\bar{N} = \langle \sin(\theta^y), -\sin(\theta^x) \cos(\theta^y), \cos(\theta^x) \cos(\theta^y) \rangle \quad (4)$$

We can express the incident angle θ as a function of the position of sensor, the light source, and the angle at which the sensor surface is rotated around its local x-axis (θ^x) and y-axis (θ^y). Consider the planar sensor shown in Figure 2. We assume that the center of the sensor surface is at position (x, y, z) . Equation (2) shows the relationship between the incident angle θ , the surface normal vector N , and the vector to the light source L . We assume that when both θ^x and θ^y are zero, $N = \langle 0, 0, 1 \rangle$ (i.e. the unit vector pointing in the positive z direction). Equations (3) and (4) show how to compute the vectors L and N , respectively.

Assumed angle and distance errors (and therefore location discovery errors) in measurement and calculation have a direct impact on the overall quality of results obtained by the LA. For angle and location error, we assume that they are directly measured and are modeled using the Gaussian distribution.

3. DESIGN METHODOLOGY

Abstractions are systems of rules used to create formalism in which the targeted synthesis and operation tasks can be treated tractably using formal mathematical analysis as well as in practical engineering terms. A good abstraction is one where one is able to capture all relevant properties of a wide range of phenomena, yet the created models are conceptually and computationally simple. Models are specific instantiations of abstractions used for a specific set of tasks.

In order to address the design and use of sensor appliances we have developed abstractions and corresponding models for the physical world (environment), phenomenon, sensors, appliance, and operational mode of the appliance. The physical world abstractions are mainly related to concepts of space and time. The space abstraction includes the concept of space as well as its dimension and how it is populated. One of the important aspects of space is that it can be used to describe either a single entity or to provide a summary for a multitude of spaces.

We assume 3-D Euclidean space. In order to simultaneously capture the essence of a number of different rooms where the appliance will potentially be deployed, we superimpose all rooms in such a way that their center of the ceiling is aligned to the origin of our 3-D Euclidean system of axis. For each point that belongs to at least one room, we define a weight factor which is equal to the number of rooms to which the point belongs. Essentially, the weights help us establish the relative importance of a particular point so that we can optimize our appliance to work well according to the likelihood the particular appliance is used at that point. Our current goal is to design an appliance which

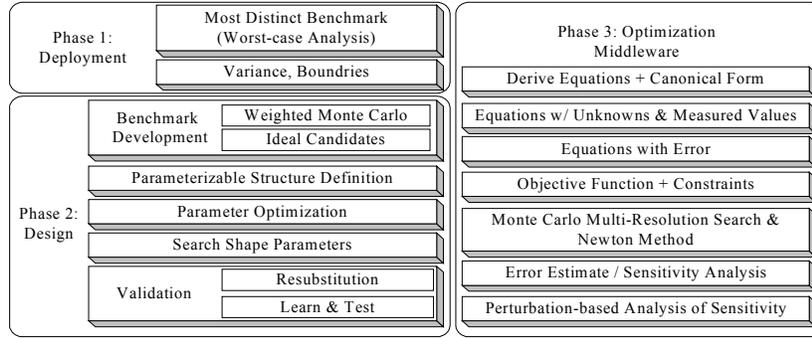


Figure 3. Overall Design Flow of a Sensor Appliance.

employs a single measurement of each sensor placed on the appliance. Therefore, there is no need to enforce any particular time model.

Phenomenon is characterized using two components sources and rules of its phenomenon propagation. Phenomena can range from simple data which do not require interpretation, such as in our case with light sensors, or could be as complex as for example, a speech recognizer which requires complex decision procedures. We assume two primary sources of light, artificial light sources and the Sun. We model all artificial light sources as point lights, and treat the Sun as a point light source that is infinitely far from all points in the room. Each point light has four attributes, intensity and three space coordinates. In addition to primary sources, we allow secondary sources which enable us to capture the effects of reflections. Complete specification of a sensor includes the physical properties of the sensor (position, size, shape), the accuracy, resolution, error, dynamic range, and latency. For our purposes, we adapted the assumptions that all light sensor have circular shape and finite dimensions.

The key characteristics of the light appliance itself are related to its physical dimensions and its rigidity. We assume that the appliance is relatively small compared to the room, specifically for a room which has the dimension of 10m we assume the appliance has dimension of 2 cm. It is mandatory to take into account the interference of the body of the appliance with the incoming light with respect to each of the sensors on the device. For example, two types of interference are blocking and shading.

In order to make the overall design problem tractable and suitable for treatment using classical optimization techniques, we divided the design process into three phases (shown in Figure 3): deployment, design, and optimization middleware. We focus on the design and optimization middleware phases.

The design phase is mainly dedicated to the quantitative derivation of the parameters of a LA that is targeting particular types of rooms with a particular upper limit on the number of light sources. The first step of the phase is the derivation of a set of scenarios each consisting of information about the light sources, rooms and their interior design, and the position and location of the LA. Inputs to this phase are the dimensions of the LA, error models for the distance, angle, and sensor readings, a set of parameterizable shapes for the LA, and the requested level of confidence for the results. The outputs of the phase are one of the proposed parameterized shapes with the values for the parameters which perform best on a set of benchmarks.

The primary responsibility of the final phase, optimization middleware, is to calculate the locations and positions of up to k light sources from measurements taken from sensors placed on the LA. In addition, the procedure aims to provide a level of confidence for the reported results. The user's input to the procedure is the amount of maximally tolerated errors for each sensor measurement (either relative or absolute), the amount of maximally tolerated error for each inequality that describes each sensor measurement (or an arbitrary function of it), and the objective function, which is subject to minimization, which is a combination of all of these errors. In addition, for validation of the obtained locations and positions of the light sources, the user provides input data for perturbation analysis. The output of this phase is the number of light sources, 3-D location and intensity of each source, the value of the objective function, and the confidence level provided by the validation procedure.

4. DESIGN OF LIGHT APPLIANCE

Our goal is to design a light appliance - system of k sensors placed on a small dimension rigid body that is capable of identifying the number of light sources and their positions and intensities in a room. An alternative closely related goal is to design a light appliance that is capable of determining the intensity of light at an arbitrary point in the targeted space with respect to an arbitrary direction. The goals are closely related in the sense that once the location and intensities of all light sources are known, it is a straightforward calculation of the light intensity at an arbitrary location and direction.

We have two main objectives. The first is the design of an effective LA. By effective, we mean a LA that has a minimal number of light sensors and is still capable of being accurate (within user specified tolerances). The second is the development of a generic, quantitative technique for the design of sensor appliances, in such a way that only minimal conceptual and software alternations are needed for other types of sensors.

In the design phase, the first step is the development of a benchmark set that extracts the essential features of the positioning of light sources and places where the LA are to be placed. The role of the benchmark is to help us distinguish between different design options in a quantitative way, within a reasonably small amount of time. Once the benchmark is available, we specify specific families of shapes that are considered during the design of light sensor appliances. The next step in the design phase is to search through the space of design options in order to find a space that maximizes the accuracy of the

$$C_i : I_i d^2 - I_{src} \cos \theta_i = 0 \quad \forall i = \{1 \dots k\} \text{ where } k \text{ is the number of light sensors.} \quad (5)$$

$$I_i \left((x_{src} - x_i)^2 + (y_{src} - y_i)^2 + (z_{src} - z_i)^2 \right) - I_{src} \cos \theta_i = 0 \quad (6)$$

$$(I_i + \varepsilon_i^I) \left((x_{src} - (x_i^m + \varepsilon_i^x))^2 + (y_{src} - (y_i^m + \varepsilon_i^y))^2 + (z_{src} - (z_i^m + \varepsilon_i^z))^2 \right) - I_{src} \cos(\theta_i^m + \varepsilon_i^\theta) \leq E_i \quad (7)$$

light appliance for common case applications. Finally, we evaluate the proposed designs in terms of their accuracy.

The benchmark is a set of environments and LA deployment situations which is representative for future use of the appliance. Each benchmark example has the following components: the number, position, and intensity of the light sources, the number, location and dimensions of obstacles in the room, the dimensions of the room where the lights are active, and a position and direction of the appliance. The key question is how to select representative examples such that any non-selected situation is similar to one of the situations included in the benchmark. We have identified a set of relevant properties for a LA: distance from the lights sources, angle between the direction of the LA and the incident light, the correlation in errors, the number of light sources, and the existence of obstacles between the light sources and the LA. The first four properties are normalized against the highest possible value and the last property, which is binary, forms a 5-dimensional space for measurement of similarity. Similarity is inversely proportional to Euclidian distance in this space. The input to the benchmark selection process is a randomly selected pool of 25,000 instances. From these instances, we select 25 that are most representative for our target environment.

The basis for the ideal candidates procedure is a simulated annealing process with a geometric cooling schedule that minimizes the sum of maximal and average distances between the selected points and all other points. The move is a replacement of one point with another point. The proposed points are selected randomly. The points selected for elimination from the selected set are also selected randomly. Points that are similar to fewer points from the set of 25,000 test cases are proportionally more favored for exclusion. We define the stop-ping criteria for the procedure to stop if no improvement is observed at three consecutive temperatures.

Shape selection for the design of the LA is done manually. First possible shapes are evaluated with their potential to provide unblocked, out of shade access of light to a high percentage of points in space. We only consider symmetrical shapes. We mainly considered regular geometric shapes such as a cube and cut-top pyramids with a base which is a regular polygon with n -sides. For each sensor placed on each side of the LA, we defined relative distances from the center of the LA and two relative spherical angles. For each family of shapes, we defined the boundary cases. For example, for a four-sided cut pyramid, the boundary case is to place all sensors flat on each side, and the sides are 90° to the base (Figure 4).

Parameterizable shape selection is done using multiresolution search. For each proposed shape, we start from the boundary cases and calculate their suitability to serve as a LA by evaluating their performances on the selected benchmark sets: one selected using the ideal candidates methodology and one provided by a weighted Monte Carlo procedure. Next, we evaluate the performance value on k equally spaced points. In experimentation, we used a value of $k = 4$. We find the smallest difference S_D in qualities and keep increasing the resolution between any two points which are

different in their values for more than S_D . The procedure is repeated recursively on the better half of the current range as long as for each iteration the value for S_D is reduced by a factor of at least four. For the selected structure with the best obtained parameters, we establish the confidence intervals for a given set of assumptions. Essentially, we try 100 randomly selected test cases, and use the resubstitution technique. The final step of the design phase is to perform perturbation-based analysis of sensitivity of the set of instances for the system of equations which correspond to the selected structure.

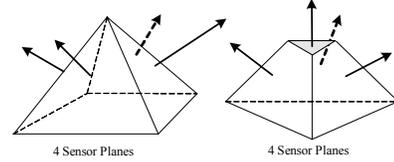


Figure 4. The 4-sensor pyramid and cut-pyramid

5. OPTIMIZATION MIDDLEWARE

In this section, we present our optimization approach for identifying the number of light sources in a room and calculating the location and intensity of these light sources from the measurements provided by the LA.

The first step is to identify how phenomenon and sources of excitation can be modeled. We begin with the physical laws for the specific sensor type and Euclidean laws for space. In the case of light, the physical law is available (Eq. 1). It is important to note that reflections and absorptions of light in the environment have a single consequence: scaling of the equation by an appropriate constant factor that can be experimentally found. We assume 3D Euclidean space with the origin at the center of the floor of the room. For each light sensor i , the Inverse Square Law can be written in canonical form (Equation (5)). Note that due to errors in measurement this equation can be fully satisfied by a number of different assignments and its left side should be replaced by the maximally allowed discrepancy after the equation sign is replaced with the less than sign. We refer to each such condition as a constraint, C_i .

The second step in the process is to determine the variables in the equation which are real unknowns and variables which one can measure. For our LA, the real unknowns are the location of the light source x_{src} , y_{src} , z_{src} , and its intensity, I_{src} . The variables in which we can measure are the position of each light sensor x_i , y_i , z_i , and the angles at which the sensor is positioned in the x and y -plane, θ_i^x , θ_i^y . The angle θ_i can not be measured directly, but is calculated using the measured values and Equation (2). The constraint for each sensor can be expressed with respect to the unknown variables and measured values as shown in Equation (6). The distance d , between the light source and the sensor, is replaced by the Euclidean distance formula.

Any measurement will have an error component. The goal is to identify the most consistent global picture by taking the errors into account. In this step, we introduce the notion of explicit

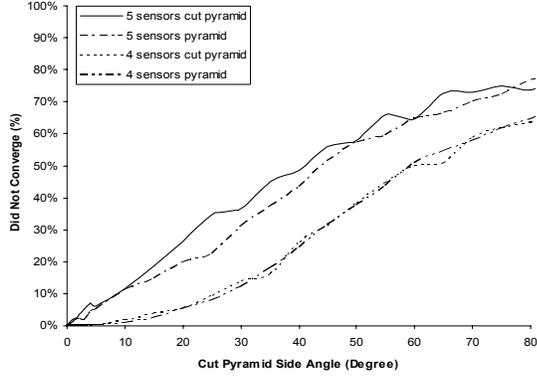


Figure 5. Comparison of 4- and 5-sensor structures: failure to converge vs. sensor angles

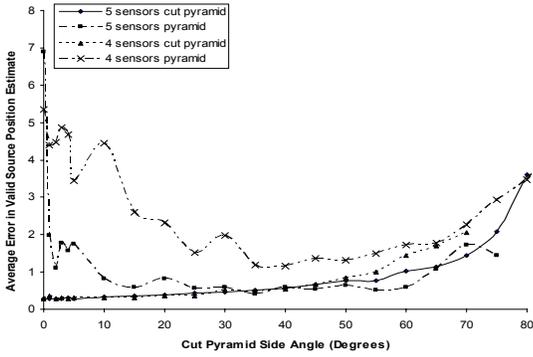


Figure 6. Comparison of 4- and 5-sensor structures: fraction of valid solutions vs. sensor angles

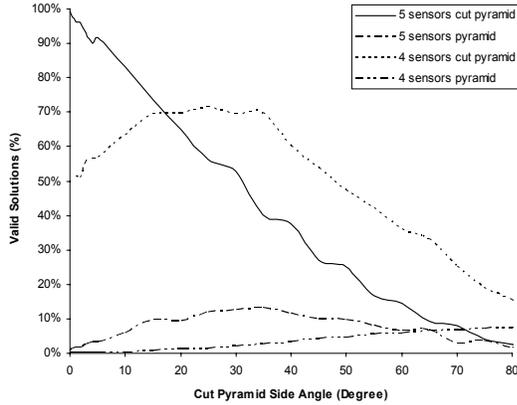


Figure 7. Comparison of 4- and 5-sensor structures: average source position error in valid solutions vs. sensor angles

measurement errors into consideration. We denote the errors of C_i by ε_i , with a superscript representing an individual measured component. Additionally, for each light sensor a maximum total amount of error, E_i , must be considered in order to ensure the accuracy of the intensity and location (Equation (7)). The maximum error for each light sensor is user specified.

The last step is to pose the entire problem using an objective function plus constraint format. This format directly corresponds

to the essence of the approach: to find minimal consistent corrections to all sensor measurements that provide overall high consistency. Specific relative magnitude of correction can be specified separately for each sensor. Also, the technique to measure the overall consistency using objective function is left to the user goals. We use a sum of all correction and equation discrepancies as our goal in experimentations.

The objective function for the light problem would be to minimize the error in the sensor measurements and the error of the real unknowns. We propose an objective function which is a function of the errors in the constraint equations. Weights for each of the error components may be applied. The constraints of the problem are the constraints presented in Step 3, one constraint for each light sensor.

$$\text{Min}(f(E_i, \varepsilon_i)) \text{ s.t. all constraints } C_i \text{ are satisfied.}$$

6. EXPERIMENTAL RESULTS

In order to gain a deeper understanding in to the behaviors of the non-linear system of equations inherent in the relationships between light sources, errors, and different light appliance structures, we have performed several simulation studies. We model device position errors as 0-mean Gaussian distributions with varying standard deviations, depending on the specified error levels for each case. The incident angle-dependent error component dI_k is a function of both the measured value I_k and the incident angle θ_k and is modeled as:

$$dI_k = \text{Gauss}(0,1) \cdot \frac{I_k \cdot \varepsilon}{100} \cdot \lambda(1 + \cos(90 - \theta_k))$$

where $\text{Gauss}(0,1)$ represents the current sample from a 0-mean Gaussian distribution with standard deviation of 1, the parameter λ indicates the strength of the angular component of the error, and ε is the specified error level (reported as % error in measurement). We present results for $\lambda=1$.

In all our following discussions, we restrict the “room” to $-500 \leq x \leq 500$, $-500 \leq y \leq 500$, and $0 \leq z \leq 500$. We assume that all sensors of the LA are placed at $(0,0,0)$, are circular and have negligible size, with the base of each LA device being in the x-y plane. We restrict the light source to the room, with $L_z \geq 100$.

Figures 5-7 depict the simulation results obtained from four different LA structures: a 4-sensor pyramid (square base), a 4-sensor cut pyramid (triangular base pyramid with a flat sensor on top), a 5-sensor pyramid (pentagonal base), and a 5-sensor cut pyramid (square base pyramid with a flat sensor on top). In each case, the objective was to estimate the positions of 5000 random light placement instances. In all cases, the measurement errors were set at 1%, and the standard deviation of the position errors at 4 units. The graphs show the performance of the system subject to varying the angles of the pyramidal LA structure. Note that the reported angles are the surface normal angles of each pyramid, with respect to the $z=0$ plane. Thus, angle=0 indicates a vertical sensor plane (in the z dimension). In each case, we accept a solution as a valid solution if the light source position estimate is within 10 units of the actual light location.

Figure 5 shows the fraction of instances where the optimization process failed to converge on a unique solution. Figure 6 shows the fraction of cases where a valid solution was found (among



Figure 8. (a) Light sensor components. (b) Light Appliance prototypes: 5-sensor cube and 5-sensor, 60°, cut-pyramid.

those that converged). Figure 6 shows, both regular pyramid their corresponding cut structures. In this case, the 0-degree 5-sensor cut-pyramid (i.e. a cube), has the best performance among all four structures. Figure 7 shows the average error in source position estimate, computed as the distance to the actual location, for the “valid solutions.”

Figure 8(a) shows a side-by-side comparison of two examples of the light sensors which we use in our experimentation. The smaller device on the left is a miniature silicon solar cell that

converts light impulses directly into electrical charges (photovoltaic). Unlike other conventional photo diodes or transistors, it generates its own power and does not require any external bias. The silicon cell is mounted on a 0.78cm x 0.58cm x 0.18cm thick plastic carrier and generates about 400 mV in moderate light (typical rooms). The significantly larger sensor on the right is a photoconductor measuring 2.54cm x 2.15cm in a

0.18cm thick plastic encapsulated ceramic package. Its resistance measures 20 Ω in strong light and 5K Ω in complete darkness. These components can easily be purchased in large quantities and are very inexpensive (they retail at roughly \$0.30 each). Figure 8(b) shows two prototypes of a 5-sensor LA. The cut-pyramid structure on the left has a base edge length of 3 cm and a top edge length of 1 cm with a 60 degree slope. The structure on the right is a cube with 2cm edges. They are both instrumented with 5 light sensors each.

At the heart of our experimentation platform is an 8-channel analog to digital converter (ADC) module, we use to read the sensor values through the parallel port of a standard PC laptop. The ADC component, pictured on the left in Figure 9, is comprised of a Maxim MAX186 ADC which has an internal analog multiplexer that can be configured for eight single-ended, or four differential inputs at a 12-bit resolution. The conversion time is under 10 μ s. The remaining components of the circuit are several resistors to protect the analog inputs, capacitors to filter power supply noise, an external 4.096V voltage regulator (external reference for the MAX186) and an 8-bit digital latch required for parallel port communications. Although the ADC chip is fast, we are limited by the serial nature of its interface. The ADC interface and other inherent PC parallel port limitations restrict our sampling frequency to less than 10Hz. Our goal was to have a very simple, reusable, and inexpensive platform which would allow for easily experimenting with a wide variety of different sensors.

The output of each sensor of our prototype designs pictured in Figure 8(b) is directly connected to a channel on the ADC module. This allows the connected notebook PC to read each sensor’s voltage output using standard C software. All calibrations are done in software, against an Extech model 407026 commercial digital light meter.

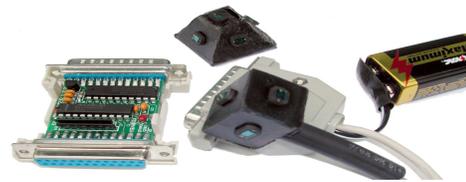


Figure 9. Light Appliance Platform

7. CONCLUSION

We proposed a systematic, sensor-centric approach for quantitative design of sensor network appliances. We have used the approach in the development of a light sensor appliance that can be used for the identification of light sources and calculation modeling at an arbitrary location in an arbitrary direction. Several prototypes are built and evaluated using our new quantitative design and evaluation methodology and tools.

8. ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. ANI-0085773. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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