iLamp: A Sensor-Enhanced Lamp with Surface-Tracking Capability Based on Light Intensity

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Abstract—The iLamp\(^1\) system is a sensor-enhanced desk lamp with surface-tracking capability based on received light intensity. It consists of two components: lamp and bookmark. The bookmark is a ZigBee-enabled sensor node that can report its sensed light intensity to the lamp with a user-friendly interface and two-way communication capability. The lamp can use its LEDs to locate user's reading surface to which the bookmark is attached, move toward the surface, and further tune its luminous intensity to meet user's preference. We develop the geometrical model for surface tracking. iLamp demonstrates a new centimeter-level location-tracking system using light intensity alone without other extra media or devices.

Index Terms—LED, light control, location tracking, pervasive computing, sensor, wireless sensor network.

I. INTRODUCTION

The rapid progress of wireless communication and embedded micro-sensing MEMS technologies has made wireless sensor and actuator networks (WSAN) possible. A WSAN is a distributed system consisting of sensor nodes and actuator nodes interconnected by wireless links. Using the sensed data, actuators can perform actions accordingly. There are increasing applications of WSANs [7][13].

This paper presents a novel sensor/actuator application, called iLamp, a ZigBee-enabled, sensor-enhanced lamp with surface-tracking capability based on light intensity. Our goal is to provide a comfort while energy-efficient lighting source. There are two main components in iLamp: bookmark and lamp. While reading a book or a newspaper, the user can attach the bookmark to his/her reading surface. The bookmark has a light sensor, which will send periodical reports to the lamp via wireless communication. The lamp has a robot arm and some LEDs as light sources. When finding that the sensed light intensity is outside the comfort region, the lamp will compute its relative location to the bookmark and move, via its robot arm, to a better location and then adjust its LEDs to satisfy the bookmark's need.

Central to our design is the surface-tracking capability of the lamp. We design the underlying geometry model for this purpose. We believe that our main contribution is a new centimeter-level location-tracking model based on LEDs, which are “point-like” light sources, as opposed fluorescent lights, which are “line-like” light sources. It is expected that any light sources will be replaced by LEDs in the near future [3][4]. Previous works have used RF signals [9][11] and ultrasounds [8][12]. The former has accuracy concerns and cannot support our reading application. The latter, while more accurate, needs extra hardware. Our work uses the light source itself to achieve location tracking.

II. SYSTEM ARCHITECTURE

Fig. 1 shows the components of iLamp system. There are two main components: bookmark and lamp. The bookmark has a microprocessor, a ZigBee module, a light sensor, and a user-friendly interface. The lamp has a robot arm holding four sets of light sources. Each set contains several LEDs, which can support multiple luminous intensity. The microprocessor can communicate with the bookmark via its ZigBee module, track the bookmark’s current location by a light intensity model, give commands to the robot arm, and properly adjust its LEDs’ luminous intensity.

\(^1\)Video demonstration available at http://hscc.cs.nctu.edu.tw/~lwyeh/iLamp
In order to track the movement of the bookmark and adjust luminous intensity automatically, our lamp works as follows. There are four steps: (1) collecting light intensity from the bookmark, (2) calculating the location of the bookmark, (3) adjusting the position of the lamp, and (4) adjusting the luminous intensity of the lamp. Step 1 is executed periodically. Once it is found that the current illuminance intensity falls outside the expected region, steps 2, 3, and 4 will be triggered. Central to our scheme is step 2, so we will elaborate it in more details below.

Fig. 2(a) shows our geometry model. The lamp has four light sources located at points $S_i$, $i = 1\ldots4$ with coordinate $(x_i, y_i, z_i)$. Since the robot arm knows its current status, we assume that these coordinates are known. Without loss of generality, we regard the projection of $S_1$ to the ground as the origin $O(0, 0, 0)$, the projection of $S_1S_3$ on the ground as the y axis, the projection of $S_2S_4$ on the ground as the x axis, and the norm of the ground surface toward the sky as the z axis. Let the bookmark be at an unknown point $B = (x, y, z = 0)$. We will derive a scheme to find $B$ based on light intensity.

Since LED is a kind of point light source, it will dissipate identically in all directions. Our scheme consists of two symmetric processes. The first one is to use $S_2$ and $S_4$ to estimate two potential locations of $B$ and then use $S_1$ and $S_3$ to screen out one location. The second one is to use $S_1$ and $S_3$ to estimate two potential locations of $B$, and use $S_2$ and $S_4$ to screen out one locations. Finally, we will take the middle point of the above estimated points as the location of $B$.

1) For each LED at $S_i$, $i = 1\ldots4$, increase its luminous intensity $\Delta I_i$ candela and measure the change of illuminance intensity at $B$, denote by $\Delta L_i$. According to the definition of Lux, we have the equality:

$$\Delta L_i = \frac{\Delta I_i \times \cos \theta_i}{(\sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2})^2},$$

where

$$\cos \theta_i = \frac{z_i}{\sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2}}$$

This leads to

$$\Delta L_i = \frac{\Delta I_i \times z_i}{(\sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2})^2}. \quad (1)$$

2) Observe that the equations for $\Delta L_2$ and $\Delta L_4$ in Eq. (1) represent two balls centered at $S_2$ and $S_4$, respectively. Since it is known that $z = 0$, each of these two balls intersects with plane $z = 0$ at a circle. The above two circles will intersect at two points. Using any equation for $\Delta L_1$ and $\Delta L_3$, we can pick one point as the location of $B$, called $P_1$. (Refer to Fig. 2(b).)

3) Similarly, the equations for $\Delta L_1$ and $\Delta L_3$ represent two balls at $S_1$ and $S_3$, respectively, each intersecting with plane $z = 0$ at a circle. Again, these two circles intersect at two points, and we can pick one point, call $P_2$, with the assistance of $\Delta L_2$ as $\Delta L_4$.

4) Finally, the location of $B$ is predicted as the middle point between $P_1$ and $P_2$.

After calculating the location of $B$, the lamp will move toward the upper side of $B$ in two processes. First, it will calculate the angle $\alpha$ between y axis and $\overrightarrow{OB}$ and rotate along z axis so that $\overrightarrow{OB}$ is aligned to y axis. Next, it will move to the upper side of $B$. (In our implementation, the LEDs will be about 30 cm above $B$). Then the lamp will tune its LEDs’ luminous intensity to meet the user profile registered in the lamp.

Note that in practice, the estimated location of $B$ may have some degree of error. So the above process may be repeated several times to move the right position. In our experience, iLamp normally takes 1 or 2 rounds to move to its final destination.

III. SURFACE-TRACKING ALGORITHM

![Geometry model](image)

Fig. 2. The geometry model for surface tracking.
IV. IMPLEMENTATION AND DEMONSTRATION

Fig. 3 shows the components of iLamp. The wireless module is Jennic (JN5139) [2], a single-chip solution for IEEE 802.15.4 [10]. We use a six-axis robot arm consisting of six Dynamixel AX-12 actuator [1] as the lamp holder. The bookmark is equipped with a TFT LCD ILI9221 panel [6], a light sensor TSL230 [5], and several buttons as input devices. The front side, back side, and UI configuration of the bookmark are shown in Fig. 4(a), Fig. 4(b), and Fig. 4(c), respectively. The surface-tracking algorithm is implemented in the microprocessor of JN5139.

Our demonstration will include the following steps: (1) instant wireless link setup between the bookmark and the lamp, (2) illuminance requirement setup via our user-friendly GUI on the bookmark, (3) detection of illuminance intensity by the bookmark, (4) surface-tracking algorithm, and (5) luminous intensity adjustment. Demo videos of iLamp can be found in http://hscc.cs.nctu.edu.tw/~lwyeh/iLamp. A user scenario is shown in Fig. 5. In our experiments, the $\Delta I_i$ is set to 12.25 candela. The average time for executing the surface-tracking algorithm are about 3 seconds. (The steps 1 and 2 take about one second, and steps 3 and 4 take about two seconds.) Our experiments show that the amount of error of the angle pointing toward the bookmark is less than 15°.

V. SUMMARY

The iLamp system consists of a LED lamp and an electric bookmark attached on a book. The lamp contains four LED lighting sources and a robot arm with six axes, which compose of multi-axial driving motors. It can track the bookmark on the reading surface and move the lamp in order to provide the reader with sufficient illuminance intensity. The iLamp system tracks the bookmark and adjusts its luminous intensity based on light intensity. Perhaps future work of iLamp system could unfold a new era of localization research using light intensity.

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