iTracking: Accurate Light-based Location-tracking in Wireless Sensor Networks

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***Abstract*—Most previous localization and tracking systems in wireless sensor networks are based on RF signals, ultrasounds, and UWB. However, systems using RF signals suffer accuracy fluctuations and systems using ultrasound or UWB need extra hardware. In our paper, we propose to utilize light, an easily accessible and pervasive resource in our daily life, and off-the-shelf TelosB Motes to achieve the goal of stability and high accuracy in localization and tracking. The iTracking[1] system is a mobile light source location-tracking system based on light intensity. Our main contribution is the first demonstration to track mobile light sources based on light intensity with high accuracy, which may provide an alternative method for localization and tracking or inspire game designers. We examine point light based tracking and flashlight based tracking in our demonstrations, which proves these two main sources of light in our daily life can achieve centimeter-level location-tracking requirements. Our future work will focus on enabling the iTracking system to writing Chinese characters in flashlight.**

***Index Terms*—Tracking, Localization, Light Intensity, Wireless Sensor Networks.**

I. Introduction

Localization and location-tracking are two of the most important applications in wireless sensor networks. One of essential parts for localization and tracking is the calculation of distances from the object to the given anchors or location-known sensors. Most previous works have used RF signals [1][2], ultrasounds [3][4] and UWB [5] to achieve such a purpose. However, RF-based systems have accuracy concerns due to multi-path fading effects, background noise interference, radio transmission fluctuations, etc. Ultrasound-based or UWB-based systems, although with better accuracy, need extra hardware. To the best of our knowledge, iLamp [6] is the first work to localize a static object based on light intensity. We step further and propose to use multiple light-aware sensors to localize and track different mobile light sources, including an ordinary electric bulb and an LED flashlight. In our demonstrations, firstly, we track a mobile point source of light, an ordinary electric bulb deployed on an automatic toy car, with four light-aware TelosB Motes [7], and secondly, we use a 5×5 sensor grid to track the movement of light from a LED flashlight. We show that both of these two main sources of light in our daily life can be used to achieve centimeter-level location-tracking.

[1] Video demonstration available at http://gps.nju.edu.cn/itracking/

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Fig. 1. Diverse artificial light sources

II. System Design

Our iTracking system is composed of three main parts: (1) distance mapping based on light intensity, (2) location calculation and (3) location updating and tracking. The goal of the first part is to obtain the distance from a light source to a light sensor based on the light intensity. The second part is to calculate the location of a light source by analyzing the distance information from multiple anchor sensors. Finally, we need to realize the real-time updates in the last part so as to track a mobile light source.

A. Distance Mapping based on Light Intensity

In photometry, we assume a point light source O has a total luminous flux of ϕ lumen in an ideal optical system, which means the light irradiates evenly in all directions. According to the definition of lux, the illuminance at any point P can be calculated as:

$$E = \frac{\phi}{4\pi d^2} \tag{1}$$

where $d = |OP|$.

However, this ideal model is impractical because ordinary artificial light sources are anisotropic, i.e., their luminous intensity is different in different directions, so that we can not use this theoretic model directly in our demonstrations. Therefore, we measure the light intensities of diverse light sources at different distances for different light sources, as depicted in Fig. 1. Then, we choose the most regular and suitable light sources and use linear or cubic spline interpolation to guarantee monotonicity and smoothness of the mapping from light intensity to distance. Fig. 2 shows the intensity-distance mapping for a 40w frosted bulb used in our point light source

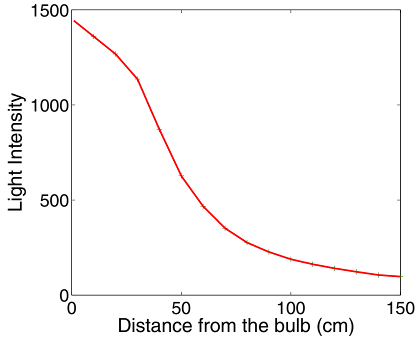

Fig. 2. Distance mapping for the 40w frosted bulb

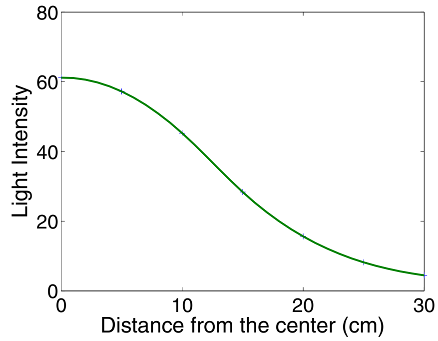

Fig. 3. Distance mapping for the LED flashlight

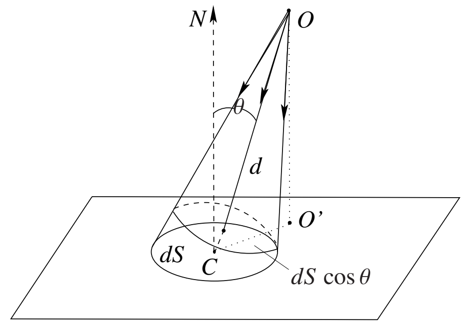

Fig. 4. Illuminance on unit area dS

tracking and Fig. 3 presents the intensity-distance mapping for the selected LED flashlight when it irradiates above a surface at a distance of 1m in the flashlight tracking. In Fig. 2, the distance is from the light source to a sensor, whereas the distance in Fig. 3 is from the center of illuminated area on the surface to a sensor.

In the flashlight tracking as depicted in Fig. 4, we assume a light source O directly casts over a unit area dS at a distance d with the angle θ between the axis of the light beam OC and the surface normal CN. Assuming the illuminance in direction OC is I, we have the illuminance on unit area dS [8]:

$$E = \frac{I \cos\theta}{d^2} \tag{2}$$

We suppose O is the position of the flashlight where $OO' \perp dS$ and $|OO'| = 1m$. Ideally, the beam of the flashlight is parallel to the surface normal CN, i.e., $\theta = 0$. But in practice, θ can be non-zero but small. Thus, we can neglect the impact of the angle between the surface normal and the beam of flashlight. Our intensity-distance mapping for flashlight tracking can be used in the cases of non-vertical irradiations.

B. Location Calculation

We aim to calculate the distance between the light source and anchors with high accuracy in a simple way.

In point light source tracking, as depicted in Fig. 5, based on distances from the source to four sensors at the corners, we calculate the mean of x from:

$$d_0^2 - d_1^2 = x^2 - (l-x)^2 \tag{3}$$
$$d_3^2 - d_2^2 = x^2 - (l-x)^2 \tag{4}$$

y can be obtained similarly.

In flashlight tracking, we have a 5×5 grid. We first make sure which sensor has been covered by the light disk and then use the aforementioned method in point light source tracking to obtain the location of the center of the disk. Based on measurements above, we know the LED flashlight can illuminate a disk with radius $r = 30cm$. According to the lower bound on the number of sensors covered by a disk [9], there are at least k sensors covered by a disk of radius r centered at an arbitrary point:

$$k \geq \frac{\pi(r - \frac{l}{\sqrt{2}})^2}{l^2}, \tag{5}$$

where l is the side-length of grid cell. Therefore, $l = 20cm$ ensures at least 3 sensors can be covered by the disk, which is necessary for localizing a point on any 2D surface.

C. Location Updating and Tracking

Obviously, tracking is harder than localization because it requires real-time location updates. On the one hand, to obtain the latest location information, time synchronization between the sink and sensors is indispensable; on the other hand, to achieve a high sensitivity, frequent sampling and data transmission may be inevitable. We also need to handle the interference among different nodes.

In order to realize time synchronization, in iTracking, the sink broadcasts a "start sampling" packet at the beginning of every round for updating. On receiving the packet, sensors start to sample. In the tracking of a bulb, the light intensity fluctuates seriously because of alternating current. So we sample 24 times in 240ms, and then send their mean to the sink. Quite differently, if all the sensors send their packets back in flashlight tracking, serious collision occurs at the sink and the sink cannot receive most important data in time or even lose them. To tackle this problem, sensors first estimate whether they are covered by the flashlight disk. We make sure that there are at most 9 sensors in a 3×3 grid which will send their packets in one turn so as to limit the consumption of communication. Second, we adopt a time slot method to avoid interference. We use a hash function to ensure every node in a 3×3 grid has a unique sequence number ranging from 0 to 8, which is shown in Fig. 6. We use i and j to indicate sensor's row number and column number respectively. Apparently, a node N_{ID} has $i = \lfloor ID / 5 \rfloor$ and $j = ID \, mod \, 5$. We define its sequence number as $sn = (3 \times i + j \, mod \, 3) \, mod \, 9$ which means a node with sequence number sn will send the packet at the sn-th time slot. In Fig. 6, bold numbers stand for nodes' IDs and italic numbers represent their sequence numbers. In the worst case, the flashlight disk, shown as a shadowed disk in the figure, may be detected by 9 nodes. However, by using our time slot method, interference can be avoided at the beginning.

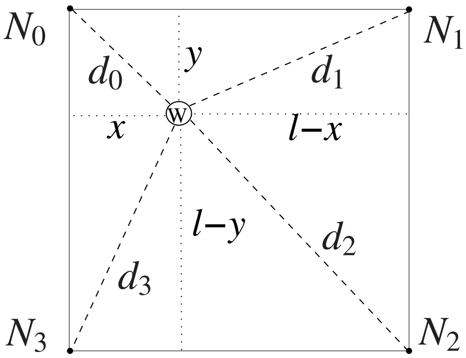

Fig. 5. Location calculation

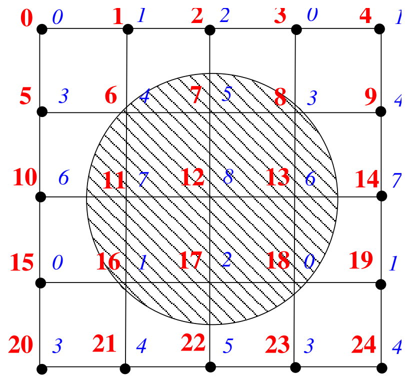

Fig. 6. Time slot

Fig. 7. Point light source tracking setup

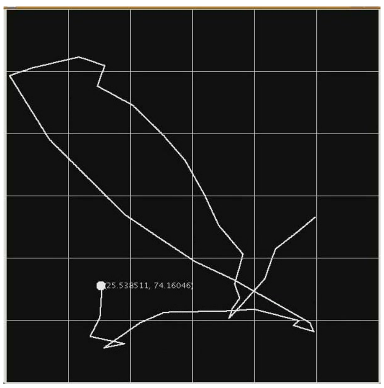

Fig. 8. Result of point light source tracking

Fig. 9. Flashlight tracking setup

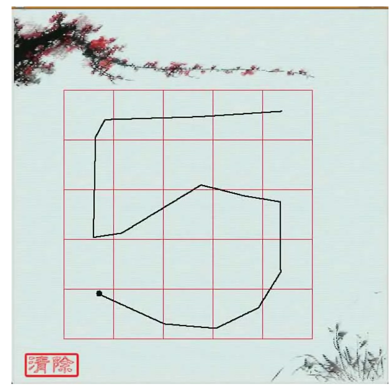

Fig. 10. Result of flashlight tracking

III. Demonstration

A. Point Light Source Tracking

We mount a 40w frosted lamp on a toy car, as shown in Fig. 7. We put the car in a $1m \times 1m$ square with four light-aware sensors deployed at the four corners. We use these sensors to collect the location information of the car and display the real-time trace, shown in Fig. 8. We have observed that the error of the calculated location is limited in 5cm.

B. Flashlight Tracking

We use a 5×5 sensor grid to track flashlight, which shown in Fig. 9. We require players to use our LED flashlight in front of the vertical grid board at a distance of 1m or above. We demonstrate how to use the flashlight to draw frame, circle, triangle and even Arabic numerals. Fig. 10 shows the flashlight trace when we write a number 5. In the future work, we will improve our iTracking system to write Chinese characters.

IV. Conclusion

The iTracking system can localize and track mobile light sources by multiple sensors based on light intensity. We demonstrate two cases including point light source tracking and flashlight tracking. In future, we attempt to realize writing Chinese characters based on flashlight tracking, which allows users to feel like using a Chinese writing brush. In addition, we attempt to improve the iTracking system so that it can adapt to various indoor and outdoor environments.

Acknowledgment

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