Demo — Luxapose: Indoor Positioning with Mobile Phones and Visible Light

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ABSTRACT

We explore the indoor positioning problem with unmodified smartphones and slightly-modified commercial LED luminaires. The luminaires—modified to allow rapid, on-off keying—transmit their identifiers and/or locations encoded in human-imperceptible optical pulses. A camera-equipped smartphone, using just a single image frame capture, can detect the presence of the luminaires in the image, decode their transmitted identifiers and/or locations, and determine the smartphone's location and orientation relative to the luminaires. Continuous image capture and processing enables continuous position updates. The key insights underlying this work are (i) the driver circuits of emerging LED lighting systems can be easily modified to transmit data through on-off keying; (ii) the rolling shutter effect of CMOS imagers can be leveraged to receive many bits of data encoded in the optical transmissions with just a single frame capture, (iii) a camera is intrinsically an angle-of-arrival sensor, so the projection of multiple nearby light sources with known positions onto a camera's image plane can be framed as an instance of a sufficiently-constrained angle-of-arrival localization problem, and (iv) this problem can be solved with optimization techniques.

1. INTRODUCTION

Accurate indoor positioning can enable a wide range of location-based services across many sectors. Retailers, supermarkets, and shopping malls, for example, are interested in indoor positioning because it can provide improved navigation which helps avoid unrealized sales when customers cannot find items they seek, and it increases revenues from incremental sales from targeted advertising [2]. Indeed, the desire to deploy indoor location-based services is one reason that the overall demand for mobile indoor positioning in the retail sector is projected to grow to $5 billion by 2018 [1]. However, despite the strong demand forecast, indoor positioning remains a "grand challenge," and no existing system offers accurate location and orientation using unmodified smartphones [3].

We propose a new approach to accurate indoor positioning that leverages trends in solid-state lighting, camera-enabled smartphones, and retailer-specific mobile applications. Our design consists of visible light beacons, smartphones, and a cloud/cloudlet server that work together to determine a phone's location and orientation, and support location-based services. Each beacon consists of a programmable oscillator or microcontroller that controls one or more LEDs in a luminaire. A beacon's identity is encoded in the modulation frequency and optically broadcast by the luminaire. The smartphone's camera takes pictures periodically and these pictures are processed to determine the beacon location and identity. Once beacon identities and coordinates are determined, an angle-of-arrival localization algorithm determines the phone's absolute position and orientation in the local coordinate system.

Our angle-of-arrival positioning principle assumes that three or more beacons with known 3-D coordinates have been detected and located in an image captured by a smartphone. When n modulated light source illuminates the camera, distinct light and dark bands appear in images. We employ an image processing pipeline to determine the extent of the beacons, estimate their centroids, and extract their embedded frequencies. Assuming that the camera geometry is known and the pixels onto which the beacons are projected is determined, we estimate the position and orientation of the smartphone with respect to the beacons' coordinate system through the geometry of similar triangles.

2. SYSTEM OVERVIEW

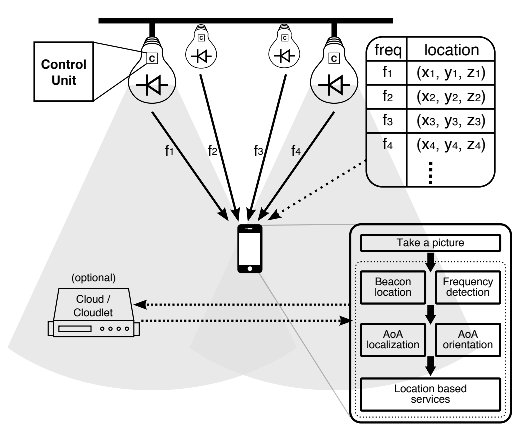

Figure 1: Luxapose indoor positioning system architecture. The system consists of visible light beacons, mobile phones, and a cloud/-cloudlet server. Beacons transmit their identities or coordinates using human-imperceptible visible light. A phone receives these transmissions using its camera and recruits a combination of local and cloud resources to determine its precise location and orientation relative to the beacons' coordinate system using an angle-of-arrival localization algorithm, thereby enabling location-based services.

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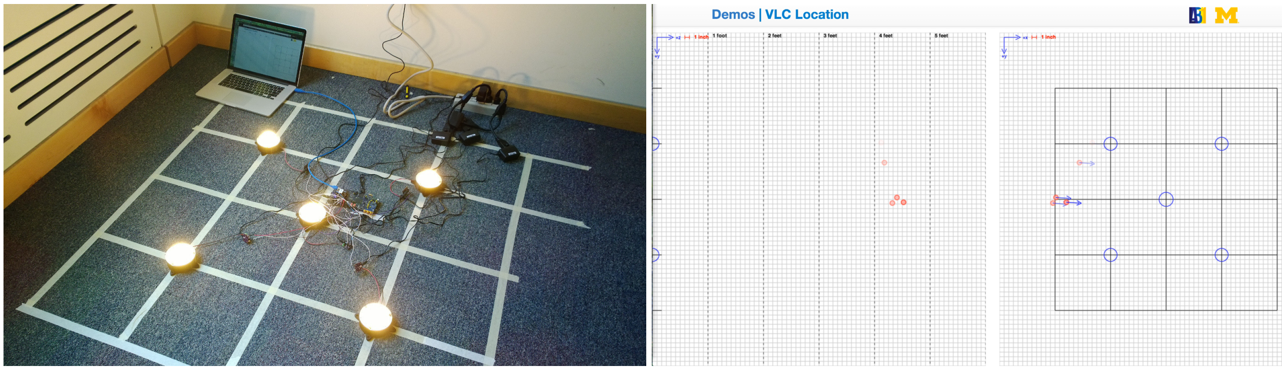

(a) Demo Setup.

(b) Real-time Localization Results.

Figure 2: VLC Localization Demo. The demo setup as shown in (a). A position grid is laid out using tape as a ground truth guide for demo participants. LED beacons are placed at periodic points throughout the grid. This simulates traditional ceiling-mounted lighting infrastructure in a much more portable form. Participants are given mobile phones pre-loaded with our localization app and allowed to wander the demo area. On a display as in (b), real-time location and orientation estimates for each user are shown.

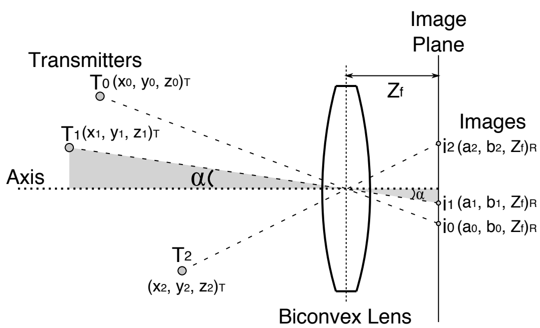

Figure 3: Optical AoA localization. When the scene is in focus, transmitters are distinctly projected onto the image plane. Knowing the transmitters' locations $T_j(x_j, y_j, z_j)_T$ in a global reference frame, and their image $i_j(a_j, b_j, Z_f)_R$ in the receiver's reference frame, allows us to estimate the receiver's global location and orientation.

The Luxapose indoor positioning system consists of visible light beacons, smartphones, and a cloud/cloudlet server, as Figure 1 shows. These elements work together to determine a smartphone's location and orientation, and support location-based services. An oscillator or microcontroller modulates LED lights to broadcast luminaire identities and/or coordinates. The camera in a smartphone takes pictures of these luminaires periodically. These pictures are sent to a cloudlet server to decode and to determine the beacon locations and extract identities. A lookup table may be consulted to convert identities into corresponding coordinates. With beacon identities and coordinates, an angle-of-arrival localization algorithm determines the phone's position and orientation in the venue's coordinate system.

Luxapose uses optical angle-of-arrival (AoA) localization principles based on an ideal camera with a biconvex lens. An important property of a simple biconvex lens is that a ray of light that passes through the center of the lens is not refracted, as shown in Figure 3. Thus, a transmitter, the center of the lens, and the projection of transmitter onto the camera imager plane form a straight line.

To begin, we assume transmitters' locations are known. For example, transmitters $T_0, T_1, \cdots T_{N-1}$ are at locations $(x_n, y_n, z_n)_T$, $n = 0, 1, \cdots N-1$. From the receiver's frame of reference their projection on the imager can be extracted and expressed as $(a_n, b_n, Z_f)_R$, where Z_f is the distance from lens to imager in pixels. By the similar triangles, we can find transmitter locations in receiver's frame of reference to be $(u_n, v_n, w_n)_R$. The relationship between two domains can be expressed as follows:

$$\begin{bmatrix} x_0 & x_1 & \dots & x_{N-1} \\ y_0 & y_1 & \dots & y_{N-1} \\ z_0 & y_1 & \dots & z_{N-1} \end{bmatrix} = \mathbf{R} \times \begin{bmatrix} u_0 & u_1 & \dots & u_{N-1} \\ v_0 & v_1 & \dots & v_{N-1} \\ w_0 & w_1 & \dots & w_{N-1} \end{bmatrix} + \mathbf{T},$$

where $\mathbf{R}$ is a 3-by-3 rotation matrix and $\mathbf{T}$ is a 3-by-1 translation matrix. The three elements of $\mathbf{T}$ (T_x, T_y, T_z) represent the receiver's location in the transmitters' frame of reference. The 3-by-3 rotation matrix $\mathbf{R}$ is represented using three column vectors, $\overrightarrow{r_1}$, $\overrightarrow{r_2}$, and $\overrightarrow{r_3}$, as follows:

$$\mathbf{R} = \begin{bmatrix} \overrightarrow{r_1} & \overrightarrow{r_2} & \overrightarrow{r_3} \end{bmatrix},$$

where the column vectors $\overrightarrow{r_1}$, $\overrightarrow{r_2}$ and $\overrightarrow{r_3}$ are the components of the unit vectors $\hat{x}'$, $\hat{y}'$, and $\hat{z}'$, respectively, projected onto the x, y, and z axes in the transmitters' frame of reference.

3. DEMONSTRATION

Our demo, as seen in Figure 2 and online at http://youtu.be/HSNY0XVXM1w, will perform real-time localization of multiple, independent users. Each demo participant will be given a Nokia Lumia 1020 smartphone pre-loaded with our localization application. The application features both single-frame mode, allowing participants to take carefully posed photos to see the results, and continuous mode, allowing participants to wander the space while the system tracks their location. Location estimates will be shown in real-time on a nearby display. As camera quality is important to Luxapose, participants will be able to use both the front- and rear-facing cameras, comparing the usuability, performance, and accuracy of each.

4. REFERENCES

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[3] L. Li, P. Hu, C. Peng, G. Shen, and F. Zhao. Epsilon: A visible light based positioning system. In *Proc. of the 11th USENIX Symposium on Networked Systems Design and Implementation (NSDI '14)*, 2014.