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.

Categories and Subject Descriptors

B.4.2 [**HARDWARE**]: Input/Output and Data Communications—*Input/Output Devices*; C.3 [**COMPUTER-COMMUNICATION NETWORKS**]: Special-Purpose and Application-Based Systems

General Terms

Design, Experimentation, Measurement, Performance

Keywords

Indoor localization; Mobile phones; Angle-of-arrival; Image processing

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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 [4]. 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 [3]. However, despite the strong demand forecast, indoor positioning remains a "grand challenge," and no existing system offers accurate location and orientation using unmodified smartphones [5].

WiFi and other RF-based approaches deliver accuracies measured in meters and no orientation information, making them a poor fit for many applications like retail navigation and shelf-level advertising [1, 2, 10]. Visible light-based approaches have shown some promise for indoor positioning, but recent systems offer landmarks with approximate room-level semantic localization [8], depend on custom hardware and received signal strength (RSS) techniques that are difficult to calibrate, or require phone attachments and user-in-the-loop gestures [5].

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 an OOK-modulated light source illuminates the camera, distinct light and dark bands appear in images. The width of the bands depend on the frequency of the light. We employ an image processing pipeline to determine the extent of the beacons, estimate their centroids, and extract their embedded frequencies, which yields the inputs needed for positioning. 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.

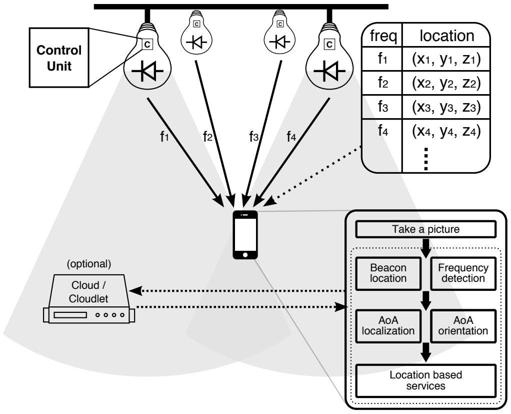


Figure 1: Luxapose indoor positioning system architecture. The system consists of visible light beacons, mobile phones, and a cloud/-cloudlet server. Beacons transmit their identities or coordinates using human-imperceptible visible light. A phone receives these transmissions using its camera and recruits 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.

2. SYSTEM OVERVIEW

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.

2.1 Optical Angle-of-Arrival Localization

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 2. Thus, a transmitter, the center of the lens, and the projection of transmitter onto the camera imager plane form a straight line.

2.2 Estimating Position and Orientation

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 ($(0,0,0)_R$ is center of lens), 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 and the unit of a_n, b_n, Z_f is pixels. By the geometry of 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:

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

where $\mathbf{R}$ is a 3-by-3 rotation matrix and $\mathbf{T}$ is a 3-by-1 translation

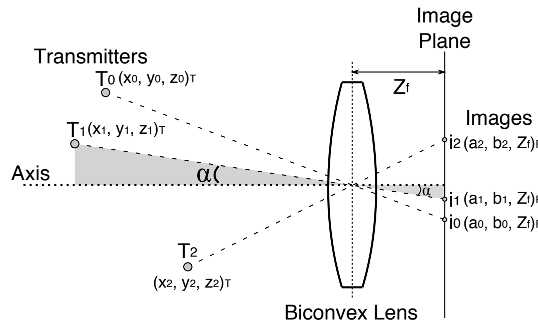


Figure 2: Optical AoA localization. When the scene is in focus, transmitters are distinctly projected onto the image plane. Knowing the transmitters' locations $T_j(x_j, y_j, z_j)_T$ in a global reference frame, and their image $i_j(a_j, b_j, Z_f)_R$ in the receiver's reference frame, allows us to estimate the receiver's global location and orientation.

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, $\vec{r_1}$, $\vec{r_2}$, and $\vec{r_3}$, as follows:

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

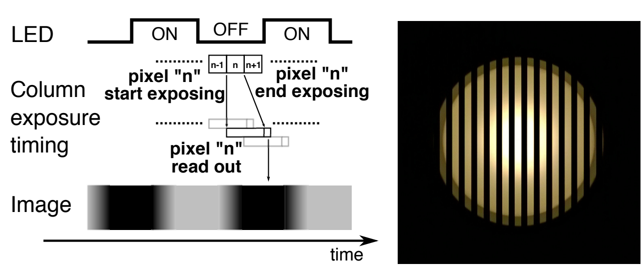
where the column vectors $\vec{r_1}$, $\vec{r_2}$ and $\vec{r_3}$ are the components of the unit vectors $\hat{x}'$, $\hat{y}'$, and $\hat{z}'$, respectively, projected onto the x, y, and z axes in the transmitters' frame of reference.

2.3 Luxapose Photogrammetry

Our positioning scheme requires: i) identifying the location of the transmitter projections on the captured image (a_i, b_i, Z_f), and ii) labeling each of the transmitters, that is determining which (x_j, y_j, z_j) map to which (a_i, b_i, Z_f).

i) We convert the image to grayscale, blur it, and pass it through a binary OTSU filter [6] to find the minimum enclosing circle of the contours for each blob [9]. (a_i, b_i, Z_f) can be found and we examine the corresponding subregions to decode data.

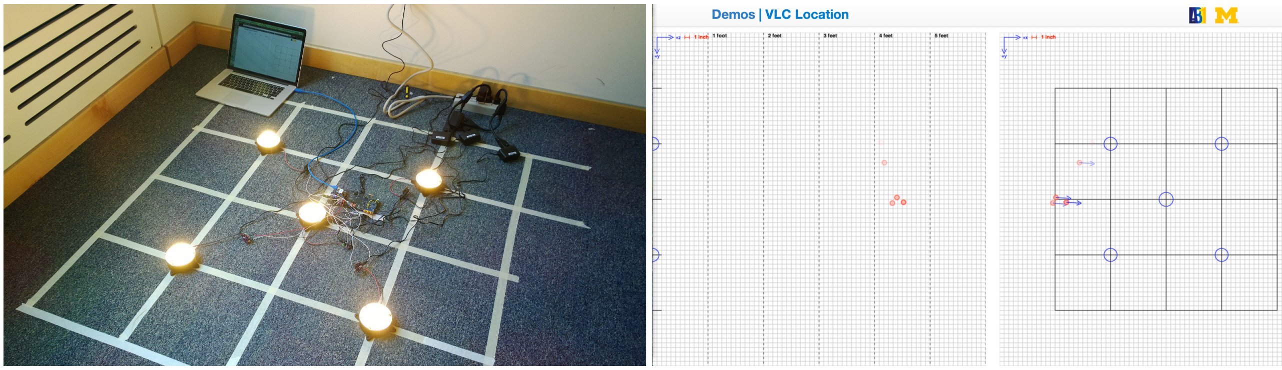
ii) We label transmitters by assigning each an unique frequency. CMOS imagers expose one column of pixels at a time, sweeping across the image creating a "rolling shutter". When capturing an image of an LED that is rapidly turning on and off, the result is a banding effect where some columns capture the LED when it is on and others when it is off, as seen Figure 3. One approach to decode the frequency is taking FFT on the subregions from (i).



(a) Distinctive banding pattern resulting from the rolling shutter effect of a CMOS camera capturing a rapidly flashing LED.

(b) 1 kHz pure tone with 50% duty cycle taken with a short exposure.

Figure 3: The effect of the CMOS rolling shutter and the image is taken by a Nokia Lumia 1020 of a modified Commercial Electric T66 10 cm ceiling LED with short exposure time (1/16667 s).



(a) Demo Setup. (b) Real-time Localization Results.

Figure 4: VLC Localization Demo. The demo setup as shown in (a) requires a reasonable floor area (minimum ~2×2 m). 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. Users will be able to use both the front and rear-facing camera of the phone to see the impact of imager quality on localization estimates. A live video of this demo is available at http://youtu.be/HSNY0XVXM1w.

3. DEMONSTRATION

Our demo, as seen in Figure 4 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.

The hardware (LEDs, control boards) and software (phone application, cloud service, image processing, localization solver) for our demo are available at https://github.com/lab11/vlc-localization. Location estimates are uploaded into our cloud data aggregation and streaming service, GATD [7] (available: https://github.com/lab11/gatd). Our visualization front-end runs as a browser application and is available at https://github.com/lab11/gatd-lab11/blob/master/web/work-in-progress/VLC_demo.jinja.

Since the location estimates run through GATD, users will be able to record their sessions and replay their traversal through the grid both during and after the demo (much like the "Replay Train Experiment" on http://inductor.eecs.umich.edu/VLC_localization.html). We will make an effort to provide a custom replay for each user, however we anticipate that this may prove challenging at scale.

4. MATERIALS AND SETUP

Our demo setup requires a resonable amount of open space for participants to walk around in. The smallest viable open space is about 7'×7' (~2×2 m). The demo also requires a screen to display real-time localization results. A larger screen is better, however something as small as a laptop will work if necessary. The demo will require access to AC power and WiFi.

The demo is relatively simple to setup and should only require a half an hour of preparation time at the most. The demo uses the grid as a frame of reference and should not require any local calibration, speeding and easing deployment. The demo is quick to tear down, requiring no more than 5 minutes.

5. RELATED PAPER

This work is a demonstration of the system proposed and presented in our paper *Luxapose: Indoor Positioning with Mobile Phones and Visible Light*, presented at MobiCom '14.

6. REFERENCES

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