Luxapose: Indoor Positioning with Mobile Phones and Visible Light

Ye-Sheng Kuo, Pat Pannuto, Bradford Campbell, and Prabal Dutta
Electrical Engineering and Computer Science Department
University of Michigan
Ann Arbor, MI 48109
{samkuo,ppannuto,bradjc,prabal}@umich.edu

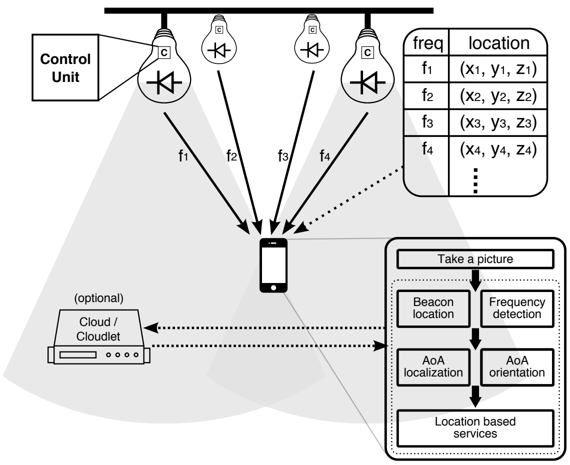

Figure 1: Luxapose indoor positioning system architecture. The system consists of visible light beacons, mobile phones, and a cloud/cloudlet server. Beacons transmit their identities using human-imperceptible visible light. A phone receives these transmissions using its camera and recruits a combination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

ABSTRACT

Luxapose addresses the indoor localization problem with unmodified smartphones and software controlled LED luminaires. Each luminaire, while providing normal lighting for a space, transmits an identifier by switching the luminaire on-and-off at a particular frequency. The pulses are imperceptible to humans, but smartphone cameras can detect the switching by exploiting the rolling shutter effect of CMOS cameras. Once the camera captures an image, the image is processed to find the luminaires, determine their identifiers, construct a sufficiently constrained angle-of-arrival localization problem, and ultimately calculate the smartphone's position and orientation in space.

Luxapose requires LED lighting infrastructure for localization, however, the LED lights can replace the current lighting in a building. Luxapose has virtually no cost to the end-users, requiring just an app on the smartphone they already carry. The system has demonstrated ninetieth percentile position error of 10 cm and orientation error of 10 degrees when the smartphone is held under the LED luminaires.

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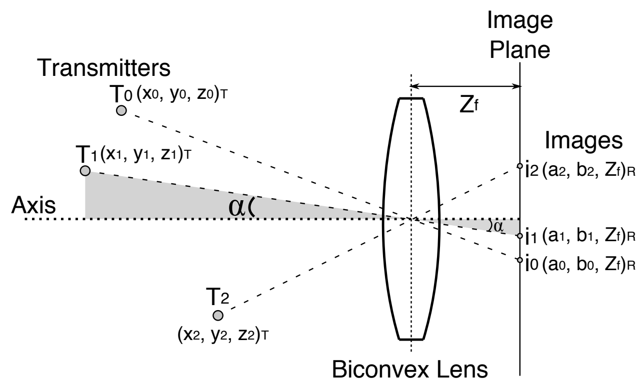


Figure 2: Optical AoA localization. When the scene is in focus, transmitters are distinctly projected onto the image plane. Knowing the transmitters' locations $T_j(x_j, y_j, z_j)_T$ in a global reference frame and their image $i_j(a_j, b_j, Z_f)_R$ in the receiver's reference frame allows us to estimate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

1. SYSTEM OVERVIEW

The Luxapose indoor positioning system shown in Figure 1 and first presented at *MobiCom '14* [1] consists of visible light beacons, smartphones, and a cloud/cloudlet server. These elements work together to determine a smartphone's location and orientation, and to support location-based services. A microcontroller modulates the power control signal to broadcast luminaire identities. The camera in a smartphone takes pictures of these luminaires periodically. These pictures are sent to a cloudlet server to determine luminaire locations in the image, extract their identities, and convert the identities into coordinates. With beacon identities and coordinates, an angle-of-arrival localization algorithm determines the phone's position and orientation in the luminaires' coordinate system.

1.1 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 the transmitter onto the camera imager plane form a straight line.

1.2 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:

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

where **R** is a 3-by-3 rotation matrix and **T** is a 3-by-1 translation matrix. The three elements of **T** (T_x, T_y, T_z) represent the receiver's location in the transmitters' frame of reference. The 3-by-3 rotation matrix **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.

1.3 Luxapose Photogrammetry

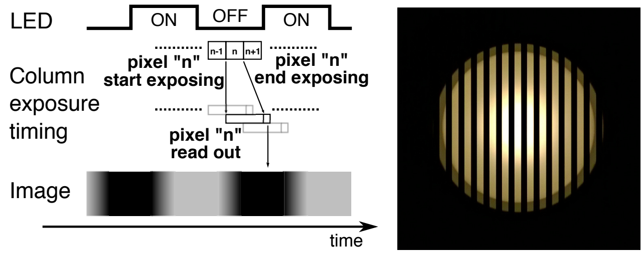
Our positioning scheme requires: i) identifying the location of the transmitter projections on the captured image (a_i, b_i, Z_f), and ii) labeling each of the transmitters, that is determining which (x_j, y_j, z_j) map to which (a_i, b_i, Z_f).

i) We convert the image to grayscale, blur it, and pass it through a binary OTSU filter, creating a blob per luminaire [2]. Next, for each blob we find the minimum enclosing circle of the blob contours [4]. This yields (a_i, b_i, Z_f) and defines image subregions for each transmitter.

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. Image processing allows recovery of the frequency, labelling the transmitter.

1.4 Localization Accuracy

Luxapose is highly accurate with sufficient luminaire coverage. As shown in Figure 4, when the smartphone is under the lights the ninetieth percentile location error is 10.5 cm. Performance suffers when the phone is outside of the grid of lights.



(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).

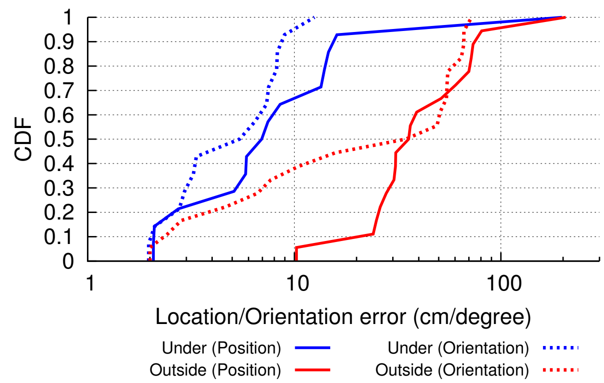


Figure 4: CDF of location and angular error. When the phone is under the lights the ninetieth percentile error is 10.5 cm for location and 8 degrees for orientation. When the phone is within line-of-sight but not directly beneath the lights, the error is much greater.

2. ENTRY DETAILS

Our system, as seen online at http://youtu.be/HSNY0XVXM1w, uses a Nokia Lumia 1020 or Apple iPhone 6 smartphone pre-loaded with our localization application. The application continuously captures and processes photos, allowing users to wander the space while the system tracks their location. Location estimates are shown in real-time on a nearby display and in the app.

The hardware (LEDs, control boards) and software (phone application, cloud service, image processing, localization solver) for our system are available at https://github.com/lab11/vlc-localization. Location estimates are uploaded into our cloud data aggregation and streaming service, GATD [3] (available: https://github.com/lab11/gatd). Our visualization front-end runs as a browser application and is available at https://gatd.eecs.umich.edu/.

3. MATERIALS AND SETUP

Our localization system requires the ability to install lights from the ceiling in the space to be localized. The lights are lightweight and can be mounted non-destructively. With some advance knowledge of the facility we can prepare a suitable mounting system. In the worst case, we could construct a free-standing structure to hang the lights from, but this is not ideal.

The ground truth location of the placed lights must be established. We are exploring an automated mechanism for this, however, in the worst case we will leverage laser range finders to establish installed light positions.

The smartphone being localized requires Wi-Fi to upload images for processing.

4. REFERENCES

[1] Y.-S. Kuo, P. Pannuto, K.-J. Hsiao, and P. Dutta. Luxapose: Indoor positioning with mobile phones and visible light. In *The 20th Annual International Conference on Mobile Computing and Networking*, MobiCom '14, September 2014.

[2] N. Otsu. A Threshold Selection Method from Gray-level Histograms. *IEEE Transactions on Systems, Man and Cybernetics*, 9(1), 1979.

[3] P. Pannuto, B. Campbell, and P. Dutta. GATD: A robust, extensible, versatile swarm dataplane. In *The First International Workshop on the Swarm at the Edge of the Cloud*, SEC '13, 2013.

[4] S. Suzuki et al. Topological structural analysis of digitized binary images by border following. *Computer Vision, Graphics, and Image Processing*, 30(1), 1985.