Long Distance VLC-based Beaconing for Indoor Localization Applications

Gergely Zachár, Gergely Vakulya, Gyula Simon
University of Pannonia
Department of Computer Science and Systems Technology
Veszprém, Hungary
Email: {zachar,vakulya,simon}@dcs.uni-pannon.hu

Abstract—**In this paper an LED-based beacon and a camera-based detector is proposed, which can serve as a building block for optical localization systems. High-power LEDs are proposed as beacons, possibly using or replacing the original lighting infrastructure. Regular smartphone or PC cameras can be used as sensors.**

The modulation and the detection technologies are similar to that of visible light communication (VLC). While VLC systems are optimized for the highest achievable bandwidth, localization systems require transferring short IDs only, possibly using existing infrastructure and handheld devices. An important goal here is the accurate beacon position detection.

A proof of concept system was built with several LED beacons and a regular PC camera. It can provide fast and accurate detections with small number of false positives and can detect multiple beacons at the same time, from large distances.

I. INTRODUCTION

As cameras in handheld devices (e.g. smartphones) are getting widespread and less expensive, a demand arose for camera-based localization systems. One possible approach is to use only the images of the environment and estimate the viewing position using a priori information [1]. Another approach uses infrastructure nodes (LED beacons) with known positions, which can dramatically improve the accuracy of the position estimation.

Existing VLC-based localization systems utilize blinking lamps (LEDs) as beacons, and cameras as detectors, exploiting the rolling shutter phenomenon [2]. The high freqency modulation of the lamp, not visible for human eyes, is observable on the rolling shutter image as fringes, which can be used to detect the blinking frequency/pattern [3]. The advantage of the rolling shutter-based solutions is that the beacon identification can be done using only one image. The disadvantage of such solutions is that the projection of the beacon on the image must be sufficiently large (several thousand pixels) for successful detection, thus the beacon must be close to the camera.

Other methods utilize only one photodiode for the detection [4]. In these applications the oscillating light intensity is measured for several beacons and based on a propagation model, ranging is performed. These models should characterize not only the light intensity changes over distance, but also the angle-dependent emission and sensitivity variation characteristics of the LEDs and the photodiode. Infrared LED arrays were also proposed, which can be detected by cameras even under adverse ambient lighting conditions [5].

Our proposed solution uses modulated LEDs as beacons and the detector can be a camera with either rolling or global shutter. The detection of the beacon is based on undersampling of the modulated light in time with a sequence of images; with right choice of modulation conventional cameras can be used to detect the modulated signal. The advantage of the proposed method is that beacons can reliably be detected from high distances (since only a few pixels are necessary), while the disadvantage is the somewhat longer detection time.

The proposed system is illustrated in Figure 1. The emitted light of the LEDs is modulated by the driver, to transmit unique beacon IDs. The detector utilizes a camera, which provides an image with the detected pixels, for each beacon. The localization system then estimates the unknown location from the detection image and the a priori information on the beacon positions or the camera position/orientation. Notice that the last step (localization) is not the topic of this paper, although we will introduce two proof of concept systems, as case studies.

In Section II the proposed beaconing scheme and the detector will be introduced. Section III contains the evaluation of the beacon detection, using measurements. In Section IV two possible applications will be shown and their performance will also be illustrated. Section V concludes the paper.

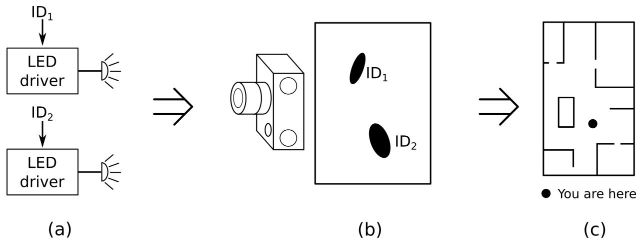


Fig. 1. The proposed system architecture. (a) Modulated LED beacons. (b) Detector using a camera. (c) Position estimation.

II. PROPOSED SYSTEM

The proposed system contains the beacons and the camera based detector for an infrastructure-based localization system.

A. Beaconing

The beacon ID is encoded into a continuously repeated bit pattern. The codes begin with a header (1110), which is not allowed in any other position of the ID's bit pattern. In the proposed system the length of the code (including header) was 11 bits.

The channel encoding (Figure 2) generates the appropriate blinking pattern and the power level settings for the LEDs. During the *one* bits the LED is driven at full power and blinked with 50% duty cycle. The *zero* bits are encoded as constant light with half brightness.

The proposed encoding has an advantage that human eyes cannot see the modulation and flicker-free operation can be provided, with sufficiently high modulation frequency. The finite sampling (shutter) time of the camera somewhat limits the maximum usable frequency, but most cameras allow modulation frequencies much higher than 100Hz. In the proposed system the modulation frequency was 165 Hz. The length of a single bit is 150 ms, thus the transmission of the ID takes 1.65 seconds.

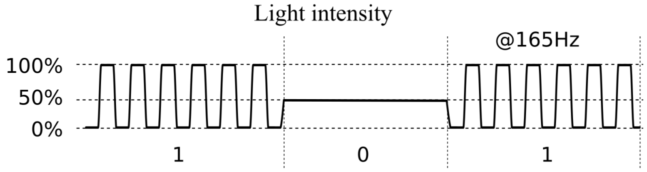


Fig. 2. Encoding the 1 and 0 bits. Ones are encoded with 165 Hz blinking full power light, zeroes are encoded with constant half power constant light.

B. Detector

On the receiver side the LED beacons are observed with a camera. Regular (e.g. 30 FPS) cameras with standard settings cannot follow high speed light intensity changes. However, with high speed shutter mode the camera takes short samples from each frame. With this method the undersampled alias frequency can successfully be detected, as shown in Figure 3. Notice that the 165 Hz blinking frequency provides a 15 Hz alias frequency, using the 30 FPS sampling frequency.

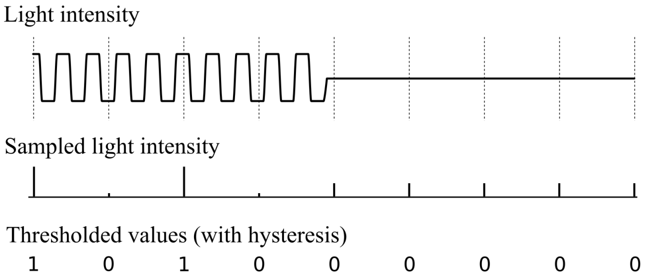


Fig. 3. Undersampling the fast blinking with a regular camera leads to an alias frequency. Signal is cleaned with adaptive thresholding.

After adaptive thresholding of the camera images a bit stream with oscillating and constant segments is computed for each pixel, as shown in Figure 4. The segments are then identified with the bit detection algorithm.

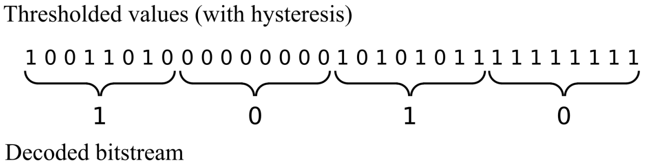


Fig. 4. Oscillating and constant segments are identified with the bit detection algorithm.

The code detection algorithm continuously tries to match the currently detected bit sequence to all possible IDs, thus it can detect all identifiers in parallel. The output of the algorithm is a set of matching pixels for every corresponding ID. Note that the code detector can detect the correct ID in any bit position due to the cyclic property of the codes, thus the 1.65 s transmission time is enough to detect a valid ID. For increased robustness, longer detection times may be used.

C. Implementation

A proof of concept system was built to validate the proposed design. The beacons utilized 10 Watt power LEDs. To drive the LEDs and to generate the blinking pattern a driver circuit was made for each lamp. The pattern was generated by an Atmega128RFA1-based sensor network node running TinyOS. Although this task could be easily solved with a much simpler device, this solution provides many convenient features (e.g. switching on and off the beacons or changing the IDs remotely).

The LEDs were driven by LM3414 switch mode drivers providing constant current with good efficiency. In the circuit, the half brightness drive can be precisely trimmed. Each device can drive up to 4 LEDs with up to 2 channels with optionally different IDs. In Figure 5 the photo of the driver is shown.

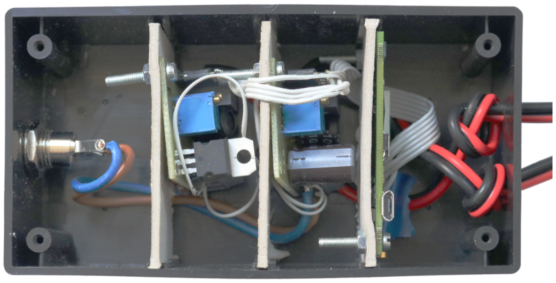


Fig. 5. The photo of the pattern generator and the LED drivers in the plastic enclosure.

To provide high-speed operation, the detection algorithm was implemented as a multithreaded C program. For the tests the images were split into slices, each to be processed in a separate thread. The image loading and processing subtasks were synchronized with a simple mutex-based barrier method. For the tests an Intel i5-3210M CPU was used with 4 cores. 3 cores were dedicated to the image processing and one to all other tasks. The implemented detector was able to process the 30 FPS 1080p video stream in real time.

The output of the detector is a bitmap image for each ID, where white pixels represent successful ID detections.

III. PERFORMANCE EVALUATION

A. Detection accuracy

Detection images may contain false positives, forming individual pixels or pixel groups (blobs). Real detections also form blobs in the images. One obvious solution to distinguish between real and false detections is to find the largest blob on each detection image and also ignore small blobs under a minimal size. Wrong detections passing this filter are called false positives, while ignored real detections are called false negatives.

In this test 500 measurements were recorded using 4 beacons, placed at various positions, and 16 IDs (including the 4 utilized ones) were used in the detector. Figure 6 shows the frequency of false positives (straight line) and false negatives (dotted line) vs. the blob size threshold. According the measurements a cluster size around 7 keeps the rate of false positive and false negative detections around 5%.

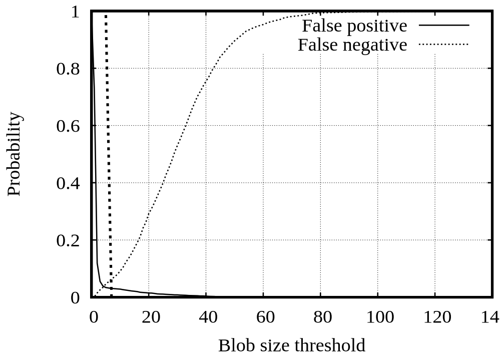


Fig. 6. Probability of false positives and false negatives.

B. Cluster size vs. distance

As clearly shown from the previous experiment, the quality of the detection highly depends on the blob size. There is a strong correlation between the blob size, and the distance between the LED beacons and the camera. In this experiment the distance was varied between 5 and 50 meters and in each position 50 measurements was made. To model real scenarios, the camera and the LED was not facing each other, but rather each device pointed 45 degrees into the camera–LED axis. The average and the minimum/maximum values are shown for each measured distance in Figure 7.

IV. APPLICATIONS

In this section two possible application scenarios are shown for the proposed beaconing method. In the first application the beacons are fixed at known positions and the camera is to be localized. The other application utilizes a fixed and calibrated camera to detect the unknown position of beacons.

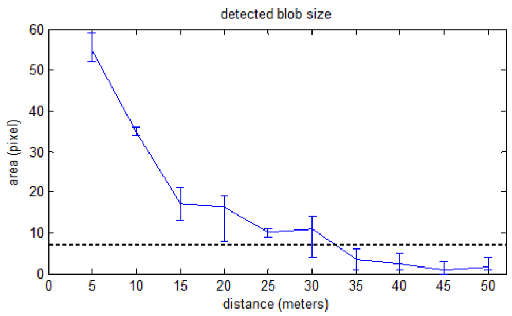


Fig. 7. Blob size vs. the distance between the camera and the LED beacon.

A. Fixed beacons, unknown camera location

In this localization scenario, shown in Figure 8, the beacons are mounted on fixed, known positions and the user wants to estimate the location of the camera. In this case the beacons can be a part of the lighting infrastructure, which is convenient and unnoticeable for the end user. Since the detection does not require special cameras, the system can be used with smartphones as well, to provide an accurate indoor positioning.

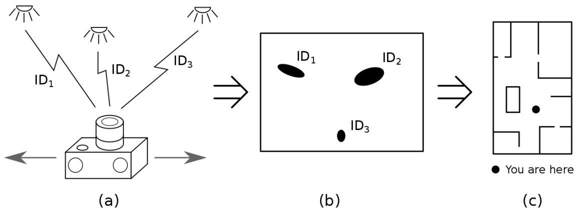
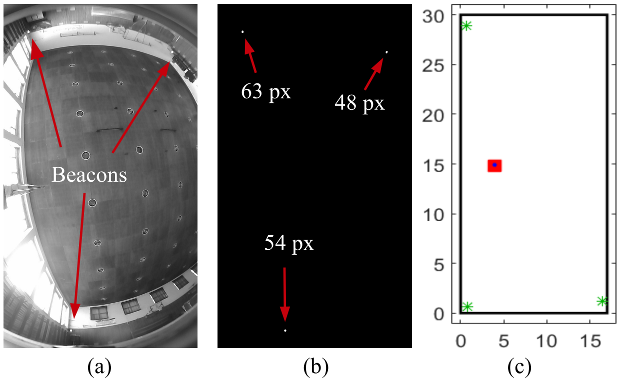


Fig. 8. Localization of a camera, using fixed beacons. (a) Beacons at unknown locations observed by the camera. (b) Detected beacons. (c) Estimated location.

Such systems possibly utilize multiple beacons (Figure 8(a), which can be detected with the proposed solution (Figure 8(b). From the detections and the associated known beacon positions the actual camera position can be calculated using triangulation (Figure 8(c). Note that, in this scenario, several beacons provide the necessary anchor positions; therefore with increased density of visible beacons the localization error can be reduced. On the other hand, with this solution, location information can be provided only for one object per camera.

A real world example can be seen in Figure 9. This measurement utilizes 3 beacons, placed at the corners of a gymnasium of size 17 m x 30 m, at different heights between 3 and 4 meters. Since the anchors are placed far from each other, a wide angle (e.g. fisheye) lens has to be used. Using the known locations of the beacons and the detected beacon positions, the placement of the camera can be triangulated. Note that the camera image is highly distorted, therefore it should be transformed either to a plain model or to a hemisphere model. The actual choice greatly depends on the angle of view of the used lens, and the localization method. In the sample application, shown in Figure 9 the hemisphere model is used and the triangulation is based on the calculated angles from the model. The actual location of the camera was



(a) (b) (c)

Fig. 9. Localization of the camera in a gymnasium. (a) Camera image. (b) Detected beacons with blob sizes. (c) Localization. Green stars: fixed beacons, blue dot: true position, red square: estimated camera position.

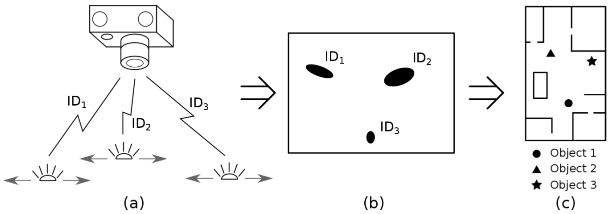


Fig. 10. Localization of beacons with one fixed camera. (a) Beacons observed by the fixed camera. (b) Beacon detection. (c) Estimated locations.

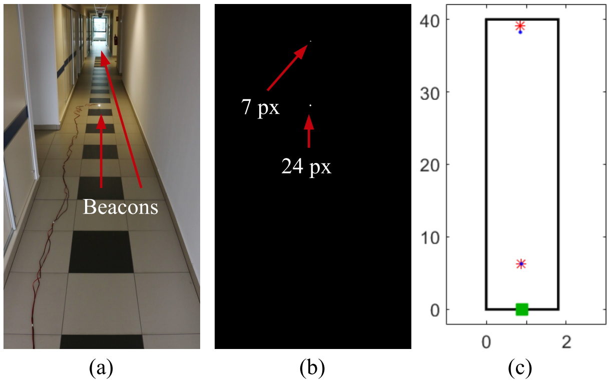
(3.95 m, 14.88 m) and the estimated position was (3.99 m, 14.79 m), resulting localization error of 0.1 m. Notice that the images are saturated at several locations (e.g. windows), but due to the temporal oscillation of the beacons they can successfully be identified.

B. Fixed camera, unknown beacon positions

In this application scenario (Figure 10) the camera is mounted on a fixed and known position, while the positions of beacons are to be estimated. In this case a single camera is utilized, which can provide localization information for several objects. Here the positioning accuracy highly depends on the quality of the camera, therefore in such scenario a professional, high quality camera is recommended.

In this system the transformation T between the image plane and the ground can be determined by a priori camera calibration. Then, applying T to each of the detected beacons, the object locations can be estimated.

A real world example can be seen on Figure 11. The beacons are placed on the floor of a corridor, 6.28 m and 38.2 m from the camera. The beacons are detected as blobs containing 24 pixels and 7 pixels, respectively. For the localization the projection transformation T between the image plane and the ground plane were determined. For this, a set of of matching anchor point pairs were selected in both plains (i.e. the real object locations and the corresponding pixel positions were provided), from which the homography matrix was computed. In this example some of the tile corners were used as reference points. With the homography matrix and the center coordinates of the detected beacons, the object locations can be estimated. In the example, shown in Figure 11 the real object locations were (6.28 m, 0.90 m) and (38.23 m, 0.87 m), while the estimated positions were (6.31 m, 0.88 m) and (39.12 m, 0.87 m), resulting localization error of 0.04 m and 0.89 m, respectively. Note that the accuracy of the method can further be increased with the correction of the camera distortions, which was not part of this sample application.



(a) (b) (c)

Fig. 11. Localization of two beacons in a corridor with one fixed camera. The beacons were placed at 6.28 m and 38.2 m from the camera. (a) Camera image. (b) Result of the beacon detection with blob sizes. (c) Localization. Green square: fixed camera, blue dots: true beacon positions, red stars: estimated beacon positions.

V. CONCLUSION

A beacon-detection scheme was proposed using LED lights, which provides flicker-free user experience and also can be used with ordinary cameras present in modern handheld devices. The proposed solution subsamples the high-frequency beacon signal in time. The detector requires only a small number of image pixels to provide robust beacon detection and identification. In the presented proof of concept system, using 10 W LEDs, the beacons were reliably detected form distances larger than 30 m. The proposed beaconing scheme was illustrated in two localization case studies, where the unknown camera location was determined using fixed beacons, and unknown beacon locations were determined using a fixed camera, both systems providing accuracy in the decimeter range.

REFERENCES

[1] N. Ravi, P. Shankar, A. Frankel, A. Elgammal, and L. Iftode, “Indoor localization using camera phones,” in *Seventh IEEE Workshop on Mobile Computing Systems & Applications*, 2006, p. 49.

[2] Y.-S. Kuo, P. Pannuto, K.-J. Hsiao, and P. Dutta, “Luxapose: Indoor positioning with mobile phones and visible light,” in *Proceedings of the 20th Annual International Conference on Mobile Computing and Networking*, ser. MobiCom ’14. New York, NY, USA: ACM, 2014, pp. 447–458.

[3] C. Danakis, M. Afgani, G. Povey, I. Underwood, and H. Haas, “Using a CMOS camera sensor for visible light communication,” in *IEEE Globecom Workshops*, 2012, pp. 1244–1248.

[4] L. Li, P. Hu, C. Peng, G. Shen, and F. Zhao, “Epsilon: A visible light based positioning system,” in *Proceedings of the 11th USENIX Conference on Networked Systems Design and Implementation*, ser. NSDI’14. Berkeley, CA, USA: USENIX Association, 2014, pp. 331–343.

[5] I. Fernández, M. Mazo, J. L. Lázaro, D. Pizarro, E. Santiso, P. Martín, and C. Losada, “Guidance of a mobile robot using an array of static cameras located in the environment,” *Autonomous Robots*, vol. 23, pp. 305 – 324, 2007.