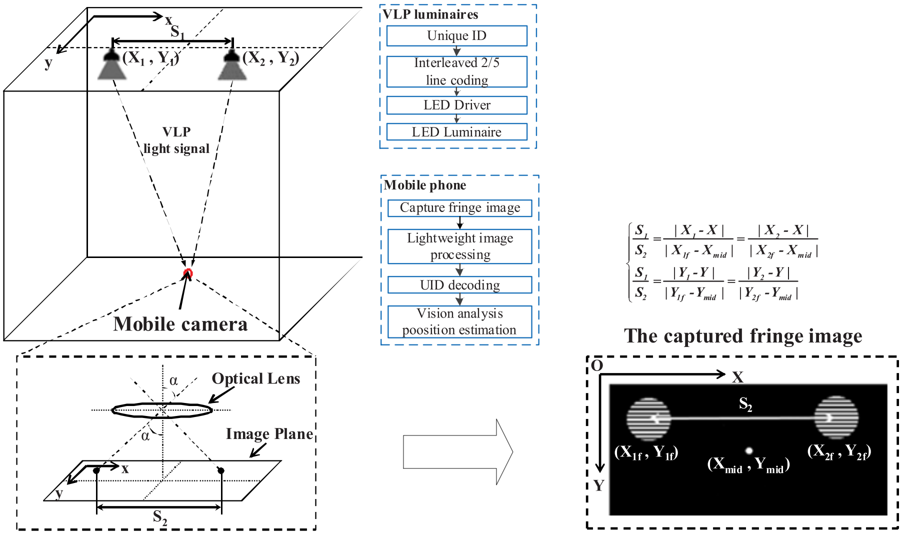
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

High-Speed Indoor Navigation System based on Visible Light and Mobile Phone

Volume 9, Number 2, April 2017

Junbin Fang
Zhen Yang
Shun Long
Zhuoqi Wu
Xiaomeng Zhao
Funian Liang
Zoe Lin Jiang
Zhe Chen



DOI: 10.1109/JPHOT.2017.2687947

High-Speed Indoor Navigation System based on Visible Light and Mobile Phone

Junbin Fang,[1,2,3] **Zhen Yang,**[2] **Shun Long,**[4] **Zhuoqi Wu,**[2]
Xiaomeng Zhao,[5] **Funian Liang,**[1] **Zoe Lin Jiang,**[6] **and Zhe Chen**[1]

[1]Guangdong Provincial Engineering Technology Research Center on Visible Light Communication and Guangzhou Municipal Key Laboratory of Engineering Technology on Visible Light Communication, Jinan University, Guangzhou 510632, China
[2]Department of Optoelectronic Engineering, Jinan University, Guangzhou 510632, China
[3]The Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON M5S 1A1, Canada
[4]Department of Computer Science, Jinan University, Guangzhou 510632, China
[5]Guangdong Provincial Key Laboratory of High Performance Computing, Shenzhen University, Guangzhou 518060, China
[6]Harbin Institute of Technology Shenzhen Graduate School, Shenzhen 518055, China

DOI:10.1109/JPHOT.2017.2687947

Manuscript received February 7, 2017; revised March 17, 2017; accepted March 22, 2017. Date of publication March 28, 2017; date of current version April 14, 2017. This work was supported in part by the National Natural Science Foundation of China under Grant 61401176, Grant 61402136, and Grant 61361166006; in part by China State Scholarship Fund (201506785014); in part by the Natural Science Foundation of Guangdong Province under Grant 2014A030310205; in part by the Science and Technology Projects of Guangdong Province (2014B010120002; 2016A010101017, 2016A010119093); in part by the Project of Guangdong High Education (YQ2015018); in part by the Science and Technology Project of Guangzhou (201605030002, 201707010253); and in part by the Special Fund Program for Guangdong College Student Research and Innovation Cultivation (pdjh2016b0057). Corresponding author: Zoe Lin Jiang (e-mail: zoeljiang@gmail.com).

Abstract: Visible light positioning (VLP) is widely believed to be a cost-effective answer to the growing demand for real-time indoor positioning. However, due to the high computational cost of image processing, most existing VLC-based systems fail to deliver satisfactory performance in terms of positioning speed and accuracy, both of which are crucial for the performance of indoor navigation. This paper proposes a novel VLP solution that provides accurate and high-speed indoor navigation via the designs of an elaborate flicker-free line coding scheme and a lightweight image processing algorithm. In addition, this solution has the advantage of supporting flicker mitigation and dimming, which are important for illumination. An Android-based system prototype has been developed for field tests on an off-the-shelf smartphone. Experimental results show that it supports indoor positioning for users moving at a speed of up to 18 km/h. In addition, it can achieve a high accuracy of 7.5 cm, and the computational time is reduced to 22.7 ms for single-luminaire and to 35.7 ms for dual-luminaries, respectively.

Index Terms: Indoor navigation, visible light positioning (VLP), mobile phone camera, line coding, image processing.

1. Introduction

There is a growing demand for real-time indoor navigation in many mobile applications, such as indoor service robots, indoor parking, indoor location-based services (LBS), etc. Various indoor positioning techniques have been proposed. They vary in accuracy and speed, which in turn decide the performance of indoor navigation. For instance, radio frequency (RF) based positioning technologies such as GPS and WiFi provide modest support for indoor scenarios [1]. Alternatively, visible light positioning (VLP) has been proposed as a promising solution for indoor positioning, and therefore, indoor navigation [2]–[6].

Smartphone with built-in camera provides an ideal platform to integrate VLP-guided indoor navigation with various mobile applications. Nowadays, even low-end smartphones are equipped with high-resolution complementary metal-oxide-semiconductor (CMOS) sensor cameras. Several smartphone-based VLP system prototypes have been developed, for instance Epsilon [7], Landmark [8], Luxapose [9], and PIXEL [10]. However, in terms of either positioning accuracy [7], [8] or positioning speed [9], [10], these systems yield relatively modest performance, usually not enough for practice. This is mainly because the information carried by light signal has to be extracted via image processing, whose computational complexity is too high for embedded processors used in smartphones, despite the fact that their processing power has been greatly improved in recent years. Inevitably, trade-offs have to be made between accuracy and latency in these systems. In some cases, auxiliary hardwares [7], [10] are needed, which not only increase complexity and cost but sacrifice user-friendliness as well. In addition, most of these systems do not support dimming which is necessary for illumination. In brief, these above solutions are not ready yet for high-speed indoor navigation in practice.

In this paper, we propose a practical VLP-based high-speed indoor navigation solution with flicker mitigation and dimming support. Via an elaborate flicker-free line coding scheme and a lightweight image processing algorithm, we significantly reduce the computational complexity for accurate LED signal based positioning. In comparison to the prior works [7]–[10], our solution provides reliable positioning support for indoor navigation at high moving speed, with high accuracy and in real-time manner. In addition, it can be easily adopted on commercially available smartphones without custom auxiliaries. A prototype system has been implemented on an off-the-shelf Android-based smartphone. The experimental results show that the proposed solution supports real-time indoor navigation to users moving at a speed of up to 5 m/s (≈18 km/h). It provides an average positioning accuracy of 7.5 centimeters (cm) and an average computational time of only 22.7 ms for single-luminaire and 35.7 ms for dual-luminaire, respectively. Therefore, it is believed that this proposed solution can provide real-time indoor navigation support to mobile robots, low-speed vehicles in indoor parking areas, as well as pedestrians in large venues.

The rest of this paper is organized as follows. Section II reviews previous experimental VLP systems. The details of the proposed techniques and the proposed indoor navigation system are provided in Section III. The experimental results are shown and discussed in Section IV, before some concluding remarks in Section V.

2. Related Work

The last decade has seen various indoor positioning approaches based on different technologies be proposed, for instance, Radio Frequency Identification (RFID), wireless local area network (WLAN), Ultra-Wide Band (UWB), Cellular, Bluetooth, etc. [11] Received signal strength (RSS) is used by many of these RF based systems to estimate the distance between the receiver and the transmitter. However, it is inevitably affected by electro-magnetic interference and multi-path reflection in indoor situations. To the best of our knowledge, there is no simple and robust approach to accurately determine either the distance or direction of the transmitter from the received signal.

In contrast, VLP typically has line of sight (LOS) between a transmitter and receiver. It can achieve accurate positioning information by measuring time of arrival (TOA), angle-of-arrival (AoA) or via vision analysis [12]. Several smartphone based VLP systems have been proposed and implemented in recent years [7]–[10], [13]. Table 1 provides a brief comparison of these VLP systems.

Rajagopal *et al.* [8] suggest that mobile devices with rolling shutter camera can use visual light landmarks to provide semantic (e.g. room-level) localization. But neither accurate position nor orientation can be obtained, and the data rate is only 1.25 bytes per second, giving a maximum location ID refresh rate of close to 2 Hz. Epsilon [7] uses LED beacons and a custom light sensor

TABLE 1
Comparison of Various Smartphone-Based VLP Systems

Schemes	Auxiliaries	Time	Accuracy	Mobile phone	CPU	Camera
Landmark [8]	No	528 ms	room-level	iPad 3	Apple A5X	3 Megapixel
Epsilon [7]	A light sensor	700 ms	0.4 ∼ 0.8 m	Samsung Galaxy S III	Samsung Exynos 4412	Custom receiver
Luxapose [9]	No	9,040 ms	7 cm	Nokia Lumia 1020	Qualcomm Snapdragon S4	33 Megapixel
PIXEL [10]	A polarizer	1,200 ms	30 cm	Samsung Galaxy SII	Samsung Exynos 4210	8 Megapixel
Kim *et al.* [13]	No	Not given	6.5 cm	Not given	Not given	354 × 472 pixels
U-beacom [14]	No	Not given	sub-meter	Not given	Not given	Not given
ByteLight [15]	No	Not given	5 ∼ 10 cm	Not given	Not given	Not given
Lumicast [16]	No	100 ms	∼10 cm	Not given	Not given	Not given

board connected to a smartphone through the audio jack. It can achieve sub-meter accuracy despite that users are expected to hold the smartphone in various positions/orientations. The main shortage of these above systems is that their relatively low accuracy may not be enough for certain scenarios.

Two VLP systems with enhanced performance have been proposed in the past two years. Luxapose [9], proposed in 2014, integrates visible light beacons, unmodified smartphone, and cloud/cloudlet server to determine the location and orientation of a smartphone. Decimeter accuracy is achieved by uploading the captured image to the cloud server for processing and location estimation. However, it takes a MacBook Pro (with a 2.7 GHz Core i7 CPU) about 9 s to identify a location from a full 33 MegaPixels image. In other words, it cannot support real-time navigation for object moving faster than 0.243 km/h. In 2015, a lightweight indoor positioning system named PIXEL [10] was proposed to solve the flicker problem and to reduce the computational complexity. The flicker problem is avoided by modulating the lights polarization instead of its intensity for communication. Low-frequency modulation rate is adopted to alleviate the computational burden on a smartphone. However, a polarizer must be set in front of the receivers camera in order to detect any change of light polarization. In addition, due to the low modulation rate, the system takes 1200 ms air time to transmit 17 bits with a localization error of less than 300 mm in 90% of all test cases. In brief, the obvious shortages in additional hardware requirement, low accuracy and/or high latency prevent these two approaches from supporting high-speed indoor navigation in practice.

Kim *et al.* proposed a vision analysis method for VLP based on the real coordinates of two LED lightings and a captured image [13]. A positioning accuracy of 6.5cm can be achieved. However, it focuses mainly on the positioning algorithm/method, and provides no detail about its positioning speed.

Several commercial VLP or indoor navigation systems have also been proposed in recent years. The U-beacon system [14] from Great Aim Optical Communication Technology Company (GAOC) offers sub-meter accuracy, and a trial system has been launched in Changzhou, China in 2014. Acuity Brands [15] claims that an indoor positioning accuracy of 5–10 cm can be achieved via the ByteLight indoor positioning technology solution they proposed. In 2016, Qualcomm launched its Lumicast [16] system which promises positioning accuracy on the order of ten centimeters and acquisition time of a tenth of a second. However, no technical detail has been unveiled.

3. The Proposed System

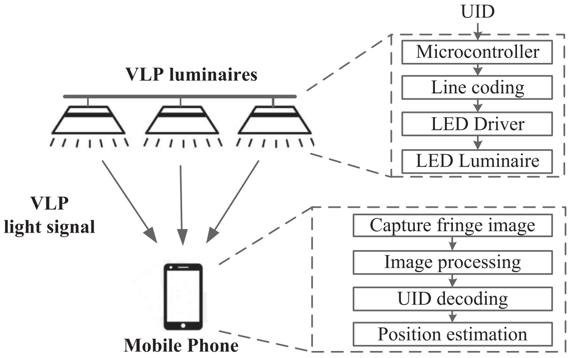


Fig. 1. System architecture.

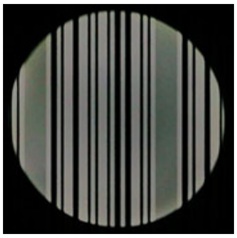


Fig. 2. Fringe image captured by mobile phone's rolling shutter camera.

3.1. System Architecture and Workflow

As shown in Fig. 1, the proposed VLP system is mainly comprised of two hardwares: VLP luminaires and an off-the-shelf smartphone.

The VLP luminaires provide illumination and broadcast their positioning signal simultaneously. Each VLP luminaire is assigned a unique identifier (UID) when it is manufactured. When it is installed, this UID will be associated with a unique set of coordinates, and the VLP system maintains a UID coordinates mapping table once all luminaires are in position. Each VLP luminaire is embedded with an 8-bit microcontroller unit (MCU) which encodes the UID to a codeword suitable for not only optical transmission but also flicker mitigation and dimming support. The LED driver is responsible for converting this codeword into modulated digital signals and driving the LED luminaire to transmit the signals using on-off keying intensity modulation (OOK IM).

As shown in Fig. 2, at the receiver (smartphone) end, the modulated light signals is received and captured as a fringe image by the built-in camera which usually has a rolling shutter CMOS image sensor. It is worth noting that a rolling shutter camera does not capture the whole image at an instant of time. Instead, it scans or activates a horizontal row of pixels. When the LED luminaire is on, the bright pixels are stored at the activated row of pixels. When it is off, the dark fringe is stored at the activated row of pixels. If the LED luminaire is modulated at a frequency higher than the frame rate of the CMOS camera, the modulated light signal can be captured as interleaving bright and dark fringes in a single image. The captured image is then processed in order to extract from the fringe areas a pattern that can be scanned as 0-1 bit stream. This above approach provides a data transmission rate much higher than the camera's frame rate [17].

When only one LED luminaire is captured, the position of the receiver can simply be determined by using the coordinates associated with the UID, as there is no additional transmitter information for the vision analysis algorithm to make a more accurate estimation [13]. In other words, the accuracy depends on the distance between the VLP luminaires in this case. Otherwise, in the case that there are multiple VLP luminaires available in the field of view (FOV) of the camera, the captured image contains multiple fringe patterns, i.e. multiple bit streams. Once the bit streams are decoded to recover the corresponding UID(s), a more accurate position can be calculated by applying vision analysis to the associated coordinates from the decoded UIDs and the (relative) pixel coordinates of the fringes in the image plane.

It is worth noting that, although our solution adopts an existing localization algorithm first proposed in [13], its main contributions lie in its flicker-free line coding scheme and a lightweight image processing algorithm which takes full advantage of the features of the captured images. These two features ensure both high speed and high accuracy for indoor navigation when compared to the prior counterparts discussed above. In addition, it has the advantage of flicker mitigation and dimming support, as explained later.

3.2. Flicker-Free Line Coding with Dimming Support

VLP systems use OOK modulation to convert a codeword into LED light signal. The brightness and stabilization of lighting are affected by the distribution of 1's and 0's in the codeword, because the LEDs are turned on or off based on the value of the codeword bits. Therefore, to converge illumination and data transmission, VLP technology must take into consideration two lighting related requirements in flicker mitigation and dimming support [18].

To avoid flicker, the changes in brightness must fall within the maximum flickering time period (MFTP), defined as the maximum time period over which the light intensity can change without being perceived by human eyes. In general, a frequency greater than 200 Hz (MFTP $<$ 5 ms) is considered safe [19]. In the proposed system, the modulation frequency is set 25 kHz, which is sufficient to prevent flickers raised from regular data transmission. However, if the run length of 0 s or 1 s in a codeword is too long, the actual frequency of switching between “ON” and “OFF” symbols/signals may be lowered. This leads to lighting intensity fluctuation over a short period, which may exceed the persistence of the human eye and causes noticeable brightness change, i.e. flicker. Therefore, the coding scheme needs to be carefully designed to keep the run length of “ON” or “OFF” symbols limited in order to mitigate any potential flicker.

Dimming support is another important VLP concern in practice because users may adjust the LED light intensity according to both the current environment and their own needs. It is desirable to maintain the system functionalities even if a user arbitrarily dims the light source. Since the LEDs are turned on or off according to the data bits in OOK modulation, the average light intensity over the duration of the codeword transmission is determined by the number and the duty cycle (pulse width) of the “ON” or “OFF” symbols in transmitting the data frame.

IEEE 802.15.7 [18] suggests that Manchester code, a run-length limited (RLL) line code, be used to break long runs of 1 s and 0 s for OOK modulation with frequency lower than 200 KHz. It is DC balanced and therefore expected to work with compensation symbol (CS) insertion in order to achieve arbitrary dimming ratio. However, it is a rate-1/2 code which encodes one bit into two symbols. The transmission efficiency is therefore significantly reduced. Alternatively, interleaved two of five (ITF) code [20], originally a continuous two-width barcode symbology, is adopted in our solution to effectively avoid flickers and support dimming simultaneously, with a higher transmission efficiency than Manchester code (i.e. 0.5 bit per symbol).

This proposed line coding scheme shares the same character sets, coding truth table as well as checksum formula as ITF. It encodes pairs of decimal digits. As demonstrated in Fig. 3, the first digit (“5”) is encoded in the five bars (or dark fringes), while the second digit (“7”) is encoded in the five spaces (or bright fringes) interleaved with them. Two out of every five bars (or spaces) are wide (hence exactly 2 of 5), while the other three are narrow. Bit “0” or “1” is represented as a narrow bar (or space) or a wide one respectively in the barcode as shown in Fig. 3. Each fringe image is considered as one data frame in our proposed system, and it is designed to contain four digits in accordance with the image acquisition speed of the smartphone camera and the modulation frequency. Therefore, there are four digits (e.g., “5,” “7,” “4,” and “6”) represented by 20 interleaving bright and dark fringes (10 bright and 10 dark) in one captured image (received data frame). Because the bright and dark fringes are interleaved, the LED is turned “ON” or “OFF” alternatively and quickly without long runs of “ON” or “OFF” symbols. In addition, the average brightness of each data frame remains stable as the proportion of the duration of “ON” and “OFF” symbols is constant

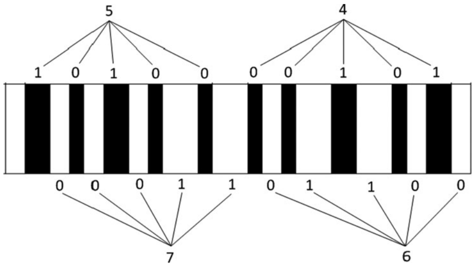


Fig. 3. Flicker-free line coding scheme based on ITF barcode symbology.

for every data frame. This proposed line coding scheme guarantees that no noticeable flicker will be introduced during data transmission. Furthermore, because two decimal digits may represent 100 different combinations in total, which can carry $\log_2(100)$ bits of information, the transmission efficiency of the proposed scheme is $\log_2(100)/10 = 0.66439$ bits per symbol, which is higher than that of Manchester code.

It is worth noting that the proposed line coding scheme supports arbitrary dimming ratio. As described above, each data frame contains 4 digit characters, which are encoded as 20 bright or dark fringes, including four wide bright fringes, six narrow bright fringes, four wide dark fringes, and six narrow dark fringes. Since the dimming ratio is actually the average proportion of the duration of the "ON" symbols (or the width of bright fringes), the dimming ratio R_{dim} can be expressed as follows:

$$R_{\text{dim}} = \frac{4W_{b1} + 6W_{b0}}{4W_{b1} + 6W_{b0} + 4W_{d1} + 6W_{d0}} \tag{1}$$

where W_{b1} is the duration (width) of wide bright fringe, W_{b0} is the duration (width) of narrow bright fringe, W_{d1} is the duration (width) of wide dark fringe, and W_{d0} is the duration (width) of narrow dark fringe. Therefore, an arbitrary dimming ratio can be achieved by adjusting the duration (width) of the dark and bright fringes.

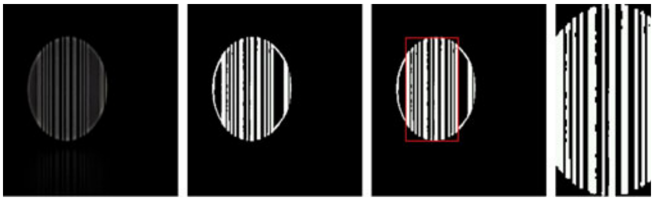
In short, the proposed line coding scheme can inherently provide dimming support and flicker mitigation for illumination, compared with the other VLP systems.

3.3. Lightweight Image Processing

As a visible light signal receiver, smartphone camera captures the encoded and modulated LED light signals as LED signal fringe images. Image processing techniques are then applied to extract sharp fringe patterns from these high-quality images, before the results being decoded based on the coding rules. However, most smartphones have limited memory capacity and processing power, which hinders the applicability of computation-intensive image processing techniques in real-time VLP systems. This is because the positioning latency would inevitably increases if these techniques were applied.

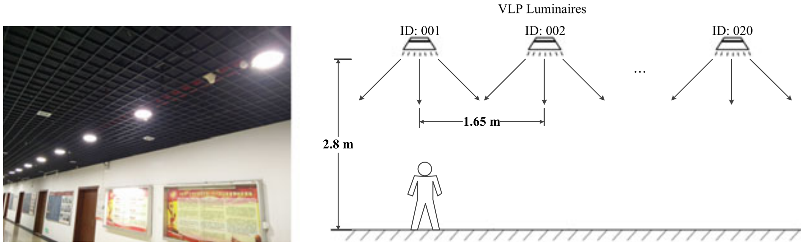
Our proposed system adopts a lightweight image processing algorithm to cooperate with the edge-lit lighting LED luminaires for fast VLP and indoor navigation. The procedure is illustrated in Fig. 4. First, a raw image is captured by the smartphone camera which is assumed to work at underexposure mode, as shown in Fig. 4(a). Most regions in the captured image are dark except in that LED light-emitting area where the fringes are captured by the rolling shutter of the camera. The original gray image is binarized to eliminate the speckles in it and to make the area of LED light signal stand out. Because edge-lit lighting LED luminaire has a uniform light-emitting surface, the contour and the fringes of the light signal area are sharply clear in the resulting binarized image, as shown in Fig. 4(b).

Considering the fact that all the fringes are vertical in the image due to the rolling shutter effect, we can use a simplified contour detection and image segmentation algorithm to extract the fringes, instead of using a conventional computation-intensive one. Fig. 4(b) shows that the pixel values of



(a) (b) (c) (d)

Fig. 4. Processing pipeline of fringes extraction. (a) Original image. (b) Binarized image. (c) Fringe area detection. (d) Fringe pattern extraction.



(a) (b)

Fig. 5. Field environment and experimental setup. (a) Field environment. (b) VLP luminaire installation.

most regions in the binarized image are zero (dark) except for the areas of fringe patterns. It is worth noting that the sum of the pixel values in each row (column) is near zero except for those with fringe patterns. By accumulating the pixel values vertically, we can easily locate the starting and ending positions of a fringe pattern on horizontal axis. Similarly, the range of a fringe pattern on the vertical axis can also be obtained by accumulating the pixel values horizontally. The pixel coordinates of the top left and bottom right corners are therefore obtained, which identify the rectangle area that contains a fringe pattern, as marked with a red rectangle in Fig. 4(c). Because of the leading and trailing symbols placed at the start and end of the data frame, the corresponding fringes generated do not occupy the entire light-emitting area. Therefore there is no need to extract the circle contour of the whole area. Once the fringe pattern is extracted (as illustrated in Fig. 4(d)), the average intensity vertically over the pixels is calculated, and the pattern becomes a linear intensity sample stream, which can be easily decoded according to ITF coding rules.

This simplified method specified above reduces the time for image processing to the order of tens of milliseconds (ms) even on an off-the-shelf smartphone. This means that a smartphone can finish the processing of an image before the next one arrives. In comparison, Luxapose system [9] adopts an image processing algorithm which is composed of six steps in blurring, binary OTSU filtering, contour finding, vertical blurring, ToZero OTSU filtering and Canny edge detection. On average, it takes 0.3 s to process a 33 megapixel image on a laptop (MacBook Pro with a 2.7 GHz Core i7 CPU). In addition, because such a heavy workload cannot be accomplished by a smartphone locally, it takes Luxapose an additional 3.41 s to upload the captured image to the laptop for processing.

4. Experimental Results

Experiments with field tests have been conducted to evaluate the performance of the proposed indoor navigation system in terms of positioning accuracy, positioning speed, and decoding success rate. The field environment is illustrated in Fig. 5(a). 20 VLP luminaires using 17.5 cm diameter 18 W commercial LED luminaires are installed along a straight line on the ceiling. The vertical height from the LED luminaires to the ground is 2.8 meters, and the horizontal space between two LED luminaires was set as 1.65 meter. A OnePlus 2 smartphone [21] equipped with a Qualcomm

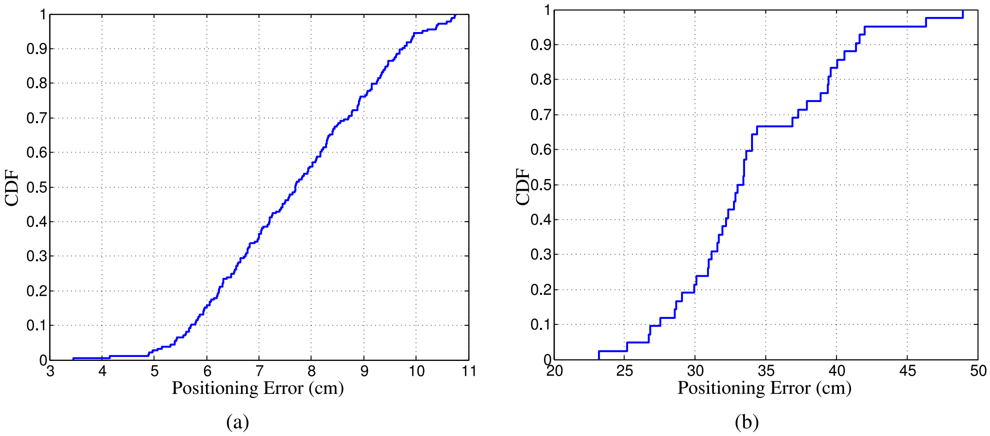


Fig. 6. Positioning accuracy. (a) With mobile phone laying flat. (b) With mobile phone laying tilted 10-degree.

Snapdragon 810 ARM CPU, 3 GB LP-DDR4 RAM and a 5 megapixel front-facing camera was used in our experiment. The image resolution for the experiments was set as 1280 × 960.

4.1. Positioning Accuracy

As discussed in Section III, if only one VLP luminaire is perceived, the user is considered located at the corresponding VLP luminaires position because there is no other positioning information available. In this case, the positioning accuracy is about half of the horizontal distance between two adjacent LED luminaires. To evaluate the accuracy in cases that more than one VLP luminaires are captured by the smartphone camera, 100 locations were randomly chosen in the experimental field, and at each location, there are at least two VLP luminaires perceived by the camera. Then, the positioning error for each location was calculated by comparing the actual spatial position and the estimated position. The statistical result is shown in Fig. 6(a) where the cumulative distribution function (CDF) of positioning error (e) is plotted against positioning accuracy (Ac) under the condition that the mobile phone is laid flat. CDF is defined as the probability that random positioning error e takes on a value less than or equal to the positioning accuracy Ac, i.e. $CDF_e(Ac) = P(e \leq Ac)$. The positioning error is upper-bounded by 10.7 cm, while the mean positioning accuracy is 7.5 cm, which is close to that in [9]. However, the positioning accuracy deteriorates when the smartphone is tilted. The positioning error is upper-bounded by 60 cm and the mean positioning error rises to 33 cm if given a tilt angle of 10 degrees, as shown in Fig. 6(b). Since the tilted angle could be detected using the built-in gyro sensor of the smartphone, the error increased by tilting could also be compensated, as suggested in [13].

4.2. Positioning Speed

Positioning speed is another important factor that affects the practicability and user experience of a positioning system. Low positioning speed hinders the efforts of adopting indoor positioning in practice. For example, the median positioning time of Luxapose is 9 s, including 4.46 s for taking a picture, 3.41 s for uploading the captured image to the server, 0.3 s for image processing at the server, and 0.87 s for location calculation. This means that a user cannot move at a speed faster than 6.75 cm/s (0.0243 km/h) [9], which is far slower than the normal walking speed of a pedestrian, not to mention vehicle navigation, etc.

A trial Android-based real-time indoor navigation APP has been developed for testing purpose, as demonstrated in Fig. 7. This APP provides various functionalities such as positioning, navigation, as well as information pushing. For instance, once the user specifies the destination, the APP can plan the route (as the green line between the Starting Point and Destination suggests in Fig. 7). As

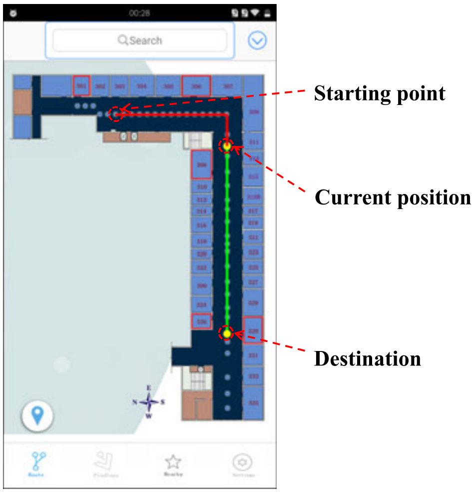


Fig. 7. Trial Android APP based on the proposed indoor navigation system.

he moves, the APP can track his position, push relevant information to him whenever appropriate, and guide him to the destination. In Fig. 7, the trajectory in red refers to what the user has already travelled and the one in green refers to the remaining route.

The positioning time of the proposed VLP system was measured carefully. The positioning time is composed by three parts: the time for taking an image, the time for processing the image and the time for estimating the position. Since the camera in this system is set to work at an underexposure mode with a fast exposure time and a small aperture, the time for taking an image is usually fixed according to frame rate. Furthermore, as the operation of capturing an image by the camera sensor is usually done via direct media access (DMA) mode, the time for taking an image can be overlapped with the computational time. Therefore, we mainly investigate the computational time, which includes the time used for image processing and position estimation. In the case that only one VLP luminaire is perceived, the average computational time is 22.7 ms and the upper bound is 35 ms. In the case that two VLP luminaries are captured by the camera, the average computational time rises to 35.7 ms due to the increment of the fringe pattern. Although the upper bound in this case is 64 ms, a computational time of lower than 48 ms was needed in 90% of our test cases.

As the typical frame rate of smartphone camera is 15 $\sim$ 30 fps, i.e. there is a 33 $\sim$ 66 ms interval between two consecutive image frames, this ensures that the proposed VLP system can process the images in time. In other words, the real-time processing of the captured images is guaranteed, and so is the real-time positioning service. Experimental results show that our proposed approach can support real-time positioning for a mobile phone mounted on a vehicle moving at a speed of up to 5 m/s (i.e., 18 km/h). We observed that, once the speed goes beyond 5 m/s, the success rate for decoding starts to decrease dramatically. In-depth analysis suggests that this is because the fringes in the captured image turn blur due to the high speed. Therefore, in practice, the supported moving speed is lower than the upper bound deduced from theoretical analysis [22].

4.3. Decoding Success Rate

Decoding success rate is an indicator of the robustness of a VLP system, since error in decoding leads to wrong position information and, as a consequence, needs re-positioning, which causes high latency and unstable positioning service.

The decoding success rate varies with the vertical distance between the luminaire and smartphone, as shown in Fig. 8. In our test scenarios, it reaches its highest (100%) when the vertical distance is less than 1.3 meter. It remains 90% or higher if this distance is no more than 1.8 meter. Such a success rate ensures the robustness of the proposed VLP system in practice because,

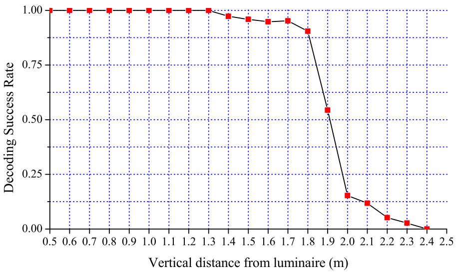


Fig. 8. Decoding success rate versus vertical distance.

TABLE 2
Decoding Success Rate Versus Dimming Ratio

Dimming ratio	W_{b1}	W_{b0}	W_{d1}	W_{d0}	Success rate
0.2	2	1	8	4	0.29
0.3	3	1	6	3	0.68
0.4	4	2	6	3	0.87
0.5	5	2	5	2	0.94
0.6	6	3	4	2	0.95
0.7	8	4	3	2	0.83
0.8	8	4	2	1	0.60

as a handheld device, smartphone is usually held vertically higher than 1.0 m above the ground. However, if the vertical distance increases to 1.8 m or higher, the area of LED light signal on a captured image shrinks and the resulting fringe pattern becomes too small to recognize. As a result, the decoding success rate drops rapidly. It is worth noting that this decoding success rate problem caused by long distance could be eased by increasing the image resolution to obtain a bigger area of fringe pattern.

The decoding success rate varying with dimming ratios has been measured, and the results are shown in Table 2. The numbers in column 2–5 are the relative width of wide bright fringe (W_{b1}), narrow bright fringe (W_{b0}), wide dark fringe (W_{d1}), and narrow dark fringe (W_{d0}), respectively. Note that the vertical distance between the luminaires and the smartphone is fixed at 1.7 m, and the relative width of 1 unit is 40 us in the experiments.

The experimental results show that the decoding success rate reaches the maximum at $d = 50\%$ and it starts to decrease significantly when the dimming ratio is increased over 0.7 or decreased under 0.4. If the dimming ratio is too low (< 0.2), the fringe patterns in the captured image may be blurred due to the extreme underexposure and they may be decoded incorrectly. Therefore, the decoding success rate drops at dimming ratio under 0.2. For dimming ratios higher than 0.8, the decoding success rate is also low but due to a different reason in a very narrow width of the narrow dark fringes.

5. Conclusion and Future Work

This paper presents a novel VLP indoor navigation solution which promises not only cost efficiency and robustness but also high speed and high accuracy. Detailed explanations are given to its flicker-free line coding scheme and lightweight image processing techniques. In addition to its functionalities of flicker mitigation and dimming support for illumination, this proposed solution not only achieves a high positioning accuracy of 7.5 cm but also reduces the positioning latency to 35.7 ms on an off-the-shelf smartphone, as shown by the experimental results. A trial Android APP has been developed to provide real-time indoor navigation for indoor robots, pedestrians or low-speed vehicles with moving speeds of up to 5 m/s (18 km/h). The above performance improvement observed suggests that indoor navigation may become more practical with this proposed solution than with its prior counterparts. Considering the growing demand in 3-D navigation, future work will involve applying this proposed solution to 3-D scenarios, especially for unmanned aerial vehicles (UAVs).

The authors would like to thank Prof. K. Ren from the Department of Computer Science and Engineering, State University of New York at Buffalo (SUNY Buffalo), USA.

References

[1] Z. Zhou, M. Kavehrad, and P. Deng, "Indoor positioning algorithm using light-emitting diode visible light communications," *Opt. Eng.*, vol. 51, no. 8, 2012, Art. no. 085009.
[2] J. Armstrong, Y. A. Sekercioglu, and A. Neild, "Visible light positioning: a roadmap for international standardization," *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 68–73, Dec. 2013.
[3] S.-H. Yang, E.-M. Jeong, D.-R. Kim, H.-S. Kim, Y.-H. Son, and S.-K. Han, "Indoor three-dimensional location estimation based on led visible light communication," *Electron. Lett.*, vol. 49, no. 1, pp. 54–56, 2013.
[4] G. B. Prince and T. D. Little, "A two phase hybrid RSS/AoA algorithm for indoor device localization using visible light," in *Proc. IEEE Global Commun. Conf.*, 2012, pp. 3347–3352.
[5] M. S. Rahman, M. M. Haque, and K.-D. Kim, "Indoor positioning by led visible light communication and image sensors," *Int. J. Elect. Comput. Eng.*, vol. 1, no. 2, pp. 161–170, 2011.
[6] M. Yoshino, S. Haruyama, and M. Nakagawa, "High-accuracy positioning system using visible led lights and image sensor," in *Proc. IEEE Radio Wireless Symp.* 2008, pp. 439–442.
[7] L. Li, P. Hu, C. Peng, G. Shen, and F. Zhao, "Epsilon: A visible light based positioning system," in *Proc. 11th USENIX Conf. Netw. Syst. Design Implementation*, 2014, pp. 331–343.
[8] N. Rajagopal, P. Lazik, and A. Rowe, "Visual light landmarks for mobile devices," in *Proc. 13th Int. Symp. Inf. Process. Sensor Netw.*, 2014, pp. 249–260.
[9] Y.-S. Kuo, P. Pannuto, K.-J. Hsiao, and P. Dutta, "Luxapose: Indoor positioning with mobile phones and visible light," in *Proc. 20th Annu. Int. Conf. Mobile Comput. Netw.*, 2014, pp. 447–458.
[10] Z. Yang, Z. Wang, J. Zhang, C. Huang, and Q. Zhang, "Wearables can afford: Light-weight indoor positioning with visible light," in *Proc. 13th Annu. Int. Conf. Mobile Syst., Appl. Services*, 2015, pp. 317–330.
[11] Y. Gu, A. Lo, and I. Niemegeers, "A survey of indoor positioning systems for wireless personal networks," *IEEE Commun. Surveys Tut.*, vol. 11, no. 1, pp. 13–32, 2009.
[12] T.-H. Do and M. Yoo, "An in-depth survey of visible light communication based positioning systems," *Sensors*, vol. 16, no. 5, pp. 678-40, 2016.
[13] J.-Y. Kim, S.-H. Yang, Y.-H. Son, and S.-K. Han, "High-resolution indoor positioning using light emitting diode visible light and camera image sensor," *IET Optoelectron.*, vol. 10, no. 5, pp. 184–192, Oct. 2016.
[14] U-beacon. [Online]. Available: http:www.u-beacon.com. Accessed Sep. 14, 2016.
[15] Bytelight. [Online]. Available: http://www.acuitybrands.com/solutions/services/bytelight-services-indoo r-positioning. Accessed Sep. 14, 2016.
[16] Lumicast. [Online]. Available: https://www.qualcomm.com/lumicast, Accessed Sep. 14, 2016.
[17] C.-W. Chow, C.-Y. Chen, and S.-H. Chen, "Enhancement of signal performance in led visible light communications using mobile phone camera," *IEEE Photon. J.*, vol. 7, no. 5, pp. 1–7, Oct. 2015.
[18] S. Rajagopal, R. D. Roberts, and S.-K. Lim, "IEEE 802.15. 7 visible light communication: Modulation schemes and dimming support," *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 72–82, Mar. 2012.
[19] S. M. Berman, D. S. Greenhouse, I. L. Bailey, R. D. Clear, and T. W. Raasch, "Human electroretinogram responses to video displays, fluorescent lighting, and other high frequency sources." *Optometry Vis. Sci.*, vol. 68, no. 8, pp. 645–662, 1991.
[20] T. Sriram, K. V. Rao, S. Biswas, and B. Ahmed, "Applications of barcode technology in automated storage and retrieval systems," in *Proc. Int. Conf. Ind. Electron., Control, Instrum.*, 1996, pp. 641–646.
[21] Oneplus2. [Online]. Available: http://www.oneplus.cn/product/oneplus2. Accessed Sep. 14, 2016.
[22] H. S. Liu and G. Pang, "Positioning beacon system using digital camera and leds," *IEEE Trans. Veh. Technol.*, vol. 52, no. 2, pp. 406–419, Mar. 2003.