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HVLP: Hybrid Visible Light Positioning of a Mobile Robot

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***Abstract*— In recent years energy efficient LEDs have become a commonplace lighting solution. It is possible to create an indoor positioning system (IPS) from existing lighting infrastructure by making minor modifications to the luminaire drivers. In this paper we develop and implement an IPS by augmenting the luminaires with collocated Zigbee radios. The Hybrid Visible Light Positioning (HVLP) system utilizes a two-stage process where it first localizes which room a mobile robot resides in, followed by estimating the robot's position within the room itself. Experimental results conducted in two adjacent rooms with dimensions 4.8 x 5.7 x 2.5, 4.8 x 3.3 x 2.5 show that the HVLP system attains a median error of 5.8 cm, which is a significant improvement on existing approaches.**

Keywords*— *Visible Light Positioning; RSSI; mobile robot; 802.15.4; Zigbee; indoor localization

I. INTRODUCTION

Localization techniques that utilize existing lighting infrastructure have become a hot topic of current research as they offer reduced cost and implementation complexity. Visible Light Communication (VLC) [1] is an emerging technology that intends to utilize LED luminaires for simultaneous illumination and communication. This can be extended further by developing Visible Light Positioning (VLP) that offer localization services. Existing VLP techniques typically make use of ceiling mounted consumer-grade LED luminaires, and an active device that uses photo-diodes to infer its position relative to the luminaires.

The smart automation industry manufactures network enabled lighting for both commercial and residential applications. This means that smart lights provide the opportunity to localize an entity by estimating the power of the incoming wireless and optical signals. In common wireless technologies like Zigbee and Wi-Fi, this estimate is readily available as the Received Signal Strength Indicator (RSSI). Wireless localization, while not as accurate as VLP, has the advantage of working in non line of sight (NLOS) scenario.

Indoor Positioning Systems (IPS) for mobile robots commonly rely on odometry or map-based techniques, due to unavailability of the absolute localization methods like GPS. There have been numerous research efforts to develop an absolute IPS by utilizing projected patterns on ceiling or walls, landmarks [2], radios [3], or lasers [4]. However, these methods suffer from various shortcomings. For example projected patterns only work on flat surfaces. Landmarks are not effective in crowded or dynamic environments. VLP looks to address this by having a low implementation cost, while also having high sensor density due to the utilization of luminaires within an existing built environment. This allows for the system to work within various indoor environments, including stairwells and crowded dwellings, which previously posed as issue for IPS implementations.

II. BACKGROUND

A number of approaches have been taken for VLP. Tanaka et al proposed a method for localizing an image sensor by detecting ceiling mounted coloured LEDs, followed by utilizing an accelerometer to determine system orientation [5]. The proposed method achieved an accuracy of 5cm which was sufficient to control a robot. However the coloured LEDs require intrusive environment modification and the requirement of a camera increases costs and limits the system’s suitability for many applications.

Bai et al used TDOA with VLP to determine the position of vehicles approaching a traffic light intersection by using separate VLP sensors mounted in each of the vehicles headlights. Numerically they proved the feasibility of such an approach, however no physical testing was carried out and the simulation lacked a model for environmental noise [6]. Another popular approach is to use intensity modulated direct detection (IM/DD) with a single photo-diode. Lights are ceiling mounted in known locations and their intensity is modulated in

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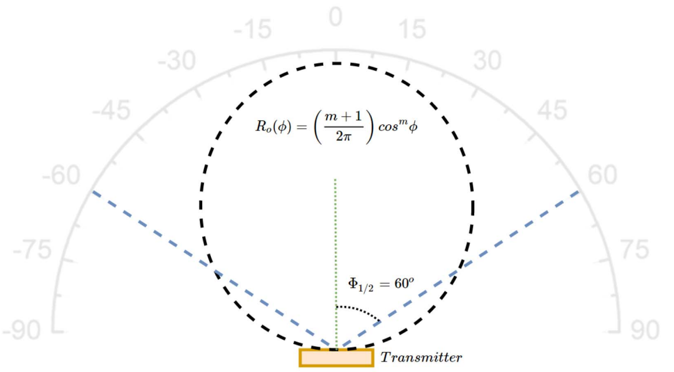

Fig. 1. Lambertian Radiance

a way that individual LEDs can be directly detected by the receiver's photo-diode [7].

Existing VLP room-scale approaches either do not meet the required accuracy [8-10], have a roof height that is unrealistic for existing built environments [11], or suffer a significant decrease in accuracy when moving outside the small (<1m^2) target area [12]. For robotics applications it is important to maintain a low localization error to allow for various tasks like docking maneuvers.

Localization services can also be provided for indoor positioning systems by the RSSI. RSSI is commonly utilized in localization systems due to its off-the-shelf availability in 802.15.4 [13] and Wi-Fi [14] equipment. This paper focusses on Zigbee as it offers mesh networking, does not introduce interference to existing Wi-Fi infrastructure and is commonplace within standard home automation lighting such as the Philips Hue bulbs [15].

III. LOCALIZATION APPROACH

The proposed localization follows a two stage process. Stage 1 utilizes the Zigbee radios to locate which room the robot currently resides within. Stage 2 receives the room estimate from Stage 1 and utilizes the VLP system to provide an estimate of the robots position within the room.

A. *Stage 1*

During stage 1, the robot receives the Zigbee RSSI streams and estimates the median over a 3 second period for each stream. The median values are then added together for each room to attain a 'room score'. The room with the highest 'room score' is the room within which the robot is currently located. This is an extremely simplistic localization approach but benefits from requiring no calibration. Four streams per room may seem excessive to identify a room. However as discussed previously, Zigbee enabled smart lights are becoming readily available in a smart home. The benefit of utilizing 4 streams per room was that multipath induced RSSI variations (within a single stream) would not significantly affect the overall 'room score'. Our experience suggests that this approach requires at least 3 ceiling mounted Zigbee radios to function correctly, if no multipath mitigation is performed.

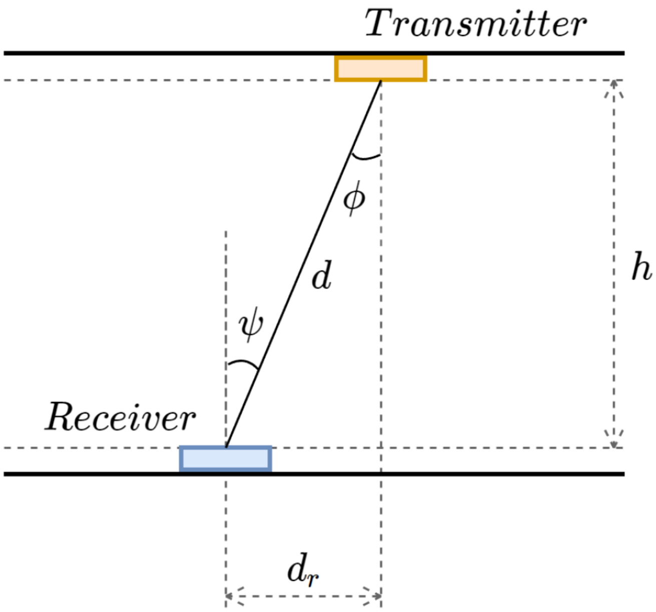

Fig. 2. Side view of VLP system

B. *Stage 2*

Once the room has been identified, the VLP takes over and estimates the position within that room. The distance between the line-of-sight (LOS) optical path is calculated using the RSS. Fig. 1 shows that LED transmitters in a VLP system can be described as a first order Lambertian emitter [16].

Equation 1 represents the power at the VLP receiver, which is equivalent to [10, eq. (5)].

$$P_r = \frac{P_t}{d^2}\left(\frac{m+1}{2\pi}\right) cos^m(\emptyset) A cos(\varphi) \tag{1}$$

Where:

- P_t is the transmitted power
- d is distance between the transmitter / receiver
- m is the Lambertian order
- $\emptyset$ is the irradiation angle
- A is the area of the VLP detector
- φ is the incidence angle

By assuming the LEDs are a lambertian light source, the angle of divergence, i.e $\emptyset_{1/2} = 60^{\circ}$. This means that (1) can be simplified to:

$$P_r = \frac{P_t}{d^2}\left(\frac{m+1}{2\pi}\right) cos(\emptyset) A cos(\varphi) \tag{2}$$

Since we are tracking an indoor autonomous robot with the VLP sensor mounted on the top plate, we have made the following assumptions:

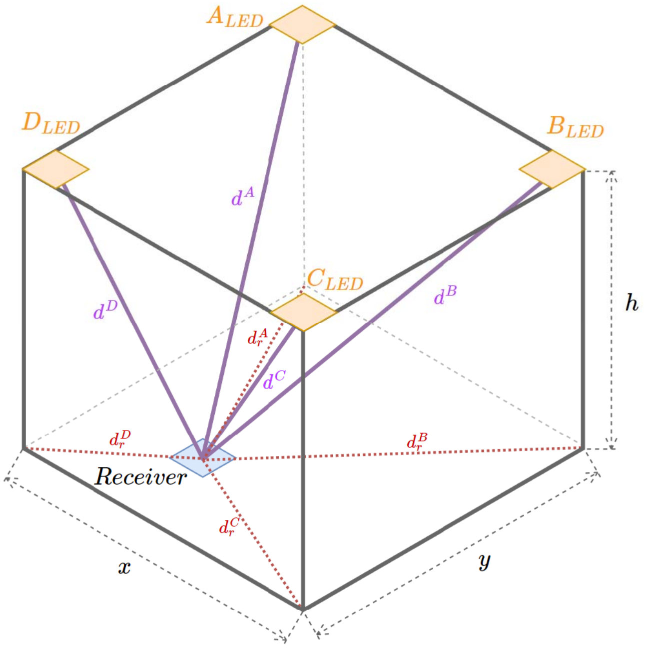

Fig. 3. VLP Triangulation

1) The distance between the robots VLP sensor and the roof (h) remains constant
2) The VLP receiver sensor remains parallel to the ceiling VLP transmitters , thus: $cos(\emptyset) = cos(\varphi) = \frac{h}{d}$

These assumptions allow (2) to be simplified to:

$$P_r = P_t G \frac{h^2}{d^4} \tag{3}$$

Where G is a constant gain of $A\left(\frac{m+1}{2\pi}\right)$.

We have followed the process of [17] and attain:

$$d = \sqrt[4]{\frac{P_t G h^2}{P_r}} \tag{4}$$

By using Pythagoras theorem, we can determine the radial distance is:

$$dr = \sqrt{d^2 - h^2} \tag{5}$$

$$dr = \sqrt{\sqrt{\frac{P_t G h^2}{P_r}} - h^2} \tag{6}$$

Utilizing triangulation with the radial distances from at least 3 VLP transmitters allows for the localization of the mobile robot as shown in Fig. 3.

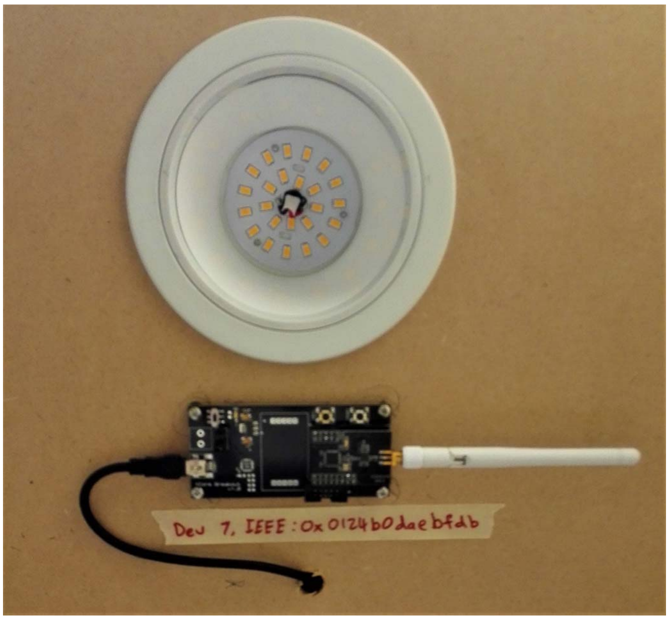

Fig. 4. Allume luminaire and Texas Instruments CC2530 board

IV. EXPERIMENTAL SETUP

We aimed to establish a lighting solution that is comparable to existing commercial offerings such as the Phillips Hue bulbs [15]. We coupled a standard ceiling mounted LED luminaire (Allume 3000K – PLU 73278) with a Zigbee radio, shown in Fig. 4, as an analog of a network enabled smart bulb.

The core of the Zigbee radio nodes is a TI CC2530 [18], with an RFX2401 PA/LNA front end as shown in Fig. 5. These chips are running a custom application built on TI's Z-Stack Home Automation 1.2.2a network stack. This firmware is therefore fully compliant with Zigbee Alliance standards [19], and ensures that this experiment is representative of commercial products running on similar network stacks. The RF network in this experimental setup consisted of 10 such Zigbee nodes, connected in a mesh network topology. The physical setup consists of a network coordinator connected to a PC via a COM port, an active router onboard the mobile robot, and 8 static routers collocated with the luminaires. Nodes transmit at +19 dBm, and operate at channel 0x26, which is free from in-band 802.11 interference.

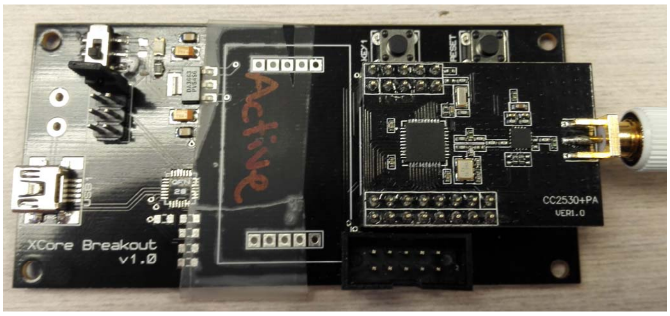

Fig. 5. Close-up of custom Texas Instruments CC2530 breakout board

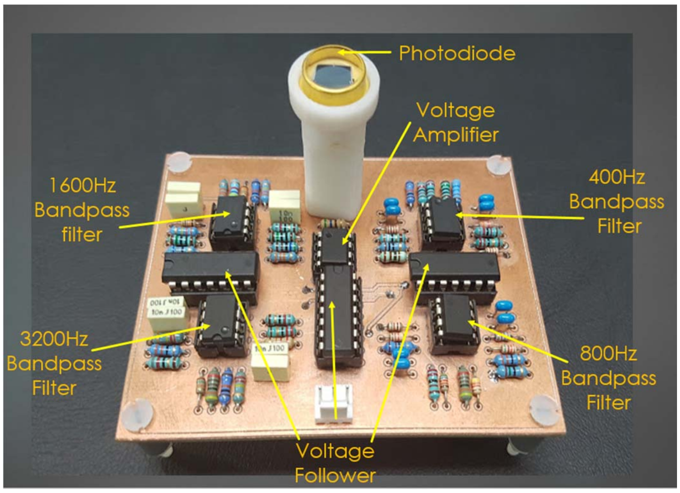

Fig. 6. Custom VLP receiver board

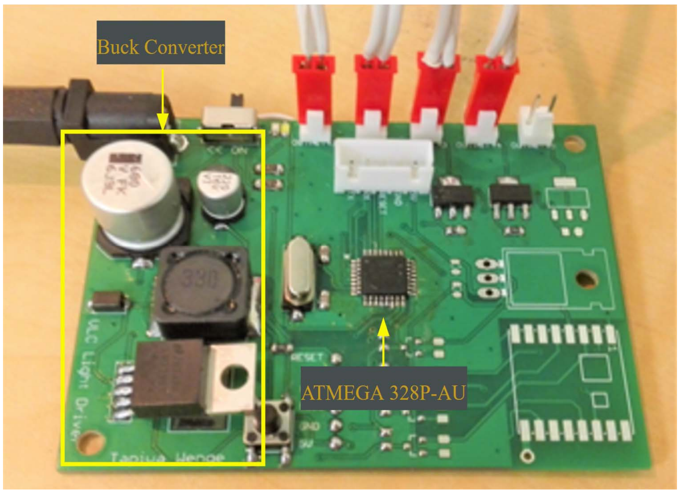

Fig. 7. VLP Driver Board

The network performs the following sequence to retrieve RSSI data from the network. First, the coordinator sends a multi-hop unicast to the active node. On receiving this packet, the active node sends a single-hop broadcast to all static routers within range. The packet's RSSI is recorded, and returned to the coordinator in the payload of a final multi-hop packet. The coordinator then sends this data, including the packet's source address, to the PC for processing, where the address is compared against a look up table. Algorithms to determine the coarse room-level location of the active node are then run in real time. All static routers transmit simultaneously, and rely on Clear Channel Assessment (CCA) and Carrier Sense Multiple Access\Collision Avoidance (CSMA/CA) to reliably transmit data.

The proposed VLP system requires multiple clusters of VLP transmitters with each cluster serving a particular region of a building. The implemented VLP system consists of two separate clusters of VLP transmitters. Each cluster serves a room and consists of 4 VLP transmitters operating on separate frequencies (400Hz, 800Hz, 1600Hz, and 3200Hz), and utilizing an on/off keying (OOK) modulation scheme [12]. The frequency assignment is based on the fact that square waves produce odd harmonics of the fundamental frequency. OOK was chosen for its simplicity which enables low cost modulator circuitry as well as a simplified VLP receiver, as shown in Fig. 6. Fig. 7 shows the custom driver board we fabricated for the VLP transmitters.

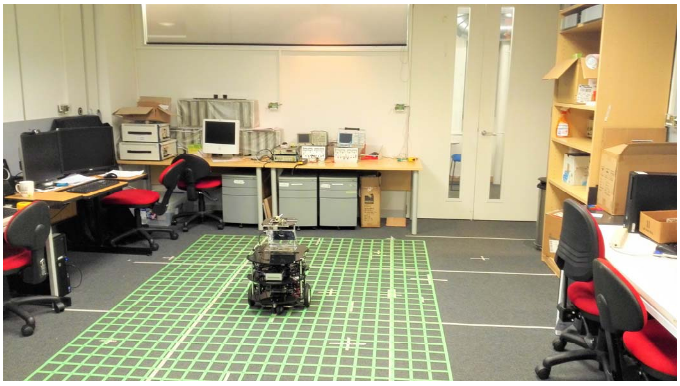

Fig. 8. Room 1 with HVLP autonomous robot

The test environment consists of two adjacent rooms as shown in Fig. 8 and Fig. 9, with both rooms having a ceiling height of 2.5m. Each room contains 4 ceiling mounted luminaires coupled with collocated CC2530 radios. The HVLP receiver mounted on top of the mobile robot contains a CC2530 Zigbee radio and a custom VLP receiver board consisting of a photo-diode and associated bandpass filters for demultiplexing. The ceiling mounted CC2530 antennas were kept in parallel with the mobile robots CC2530 antenna to minimize RSSI variations caused by orientation changes.

V. EXPERIMENTAL RESULTS

We randomly selected 30 test locations in Room 1, and 10 test locations in the smaller Room 2. It should be noted that we did not pick any test locations that were under desks as shown in Fig. 9. Fig. 10 shows the localization results for test locations within Room 1. Stage 1 of the localization process correctly estimated the robots current room with 100% accuracy.

The system performed accurately with lower than 6 cm median error in localization estimation, as reported in Table 1 below.

TABLE I.

Rooms	**HVLP Error (m)**			
	Mean	***Median***	***RMSE***	***Max***
Room 1	0.059	0.058	0.065	0.108
Room 2	0.069	0.058	0.083	0.151

It is interesting to note that the accuracy of the VLP system decreases as the tracked robot comes directly under one of the luminaires. This occurs because the received power at a

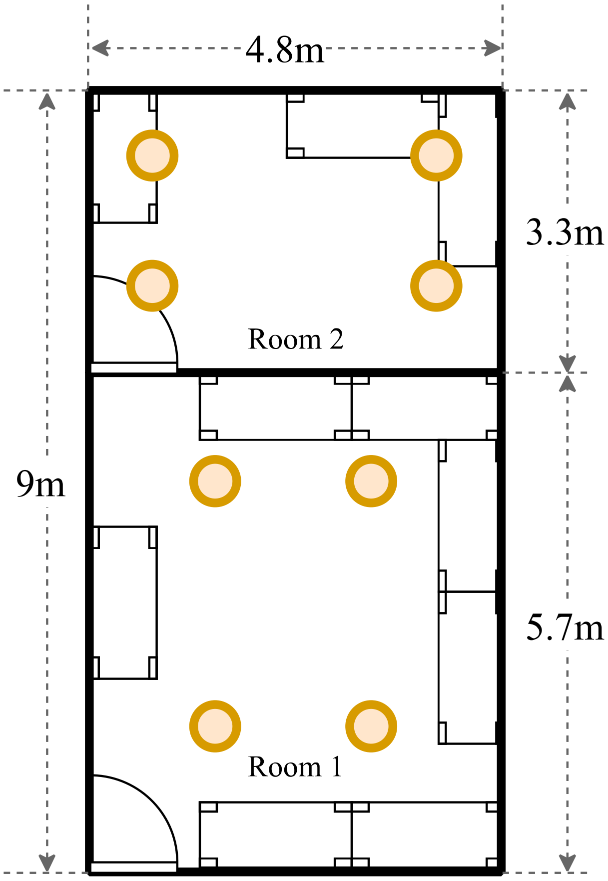

Fig. 9. Room 1 and Room 2 Layout

particular radial distance can be approximated by a cosine falloff. This means that when the radial distance is very small, the change in received power between distances is also very small. This results in a reduction in the Signal to Noise Ratio (SNR), leading to decreased accuracy.

VI. CONCLUSION

In this paper we presented the design and implementation of HVLP, an augmented wireless/visible light IPS system. Through testing we have shown that our HVLP system can accurately localize a robot within a typical office environment with a median error of 5.8cm. To the best of our knowledge this is the first reported work to attain sub 10cm accuracy in a room-scale IPS based on Visible Light without utilizing expensive sensors or actively reducing ambient light levels. Our work confirms the potential of visible light for high accuracy indoor localization, and demonstrates how some of its limitations can be overcome by augmenting it with Zigbee.

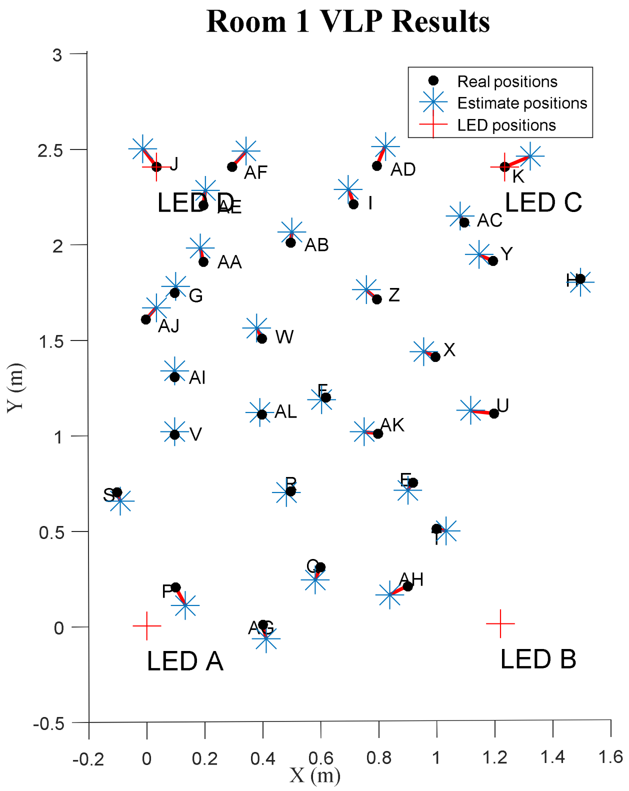

Fig. 10. Room 1 VLP Results

The developed method does not leverage wireless localization to eliminate potential blind spots of the VLP system. Future work should investigate how a fusion of wireless and visible light information using an extended Kalman filter can increase the accuracy and coverage. The OOK modulation based multiplexing scheme is not very efficient as it reduces the light from each luminaire by half. It also generates a lot of harmonics which puts a constraint on the number of lights that can be used in a cluster whilst still demultiplexing each signal. Future research should look into developing more efficient and scalable multiplexing schemes. Future work can also include whether applying a Fast Fourier Transform (FFT), rather than band-pass filters for demultiplexing can make the system more scalable and flexible. Further work needs to be done on increasing the accuracy of the system when the detector is directly under lights.

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