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PDOA Based Indoor Positioning Using Visible Light Communication

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ABSTRACT A novel indoor positioning algorithm with improved location accuracy is proposed for visible light communication system. The novelty of the positioning algorithm lies in a hybrid approach of making use of both frequency and variable phase of the transmitted signal. The algorithm has the capability of estimating the position of an object with localization error in millimeters when the signal passes through an optical channel. The LEDs are modulated at very high frequencies. The simulation results demonstrate that the positioning error is reasonably reduced compared with other existing approaches (algorithms). Unlike existing work, the current work also evaluates the performance of the positioning algorithm in the presence of different noise distributions and shows that $1-2$ cm positioning accuracy can be achieved in the presence of the noise. Finally, multiple potential applications are discussed in which the proposed positioning scheme can be deployed.

INDEX TERMS Visible light communication, variable phase, time difference of arrival, indoor positioning, optical channel.

I. INTRODUCTION

Visible light communication (VLC) is recently being used rigorously for data transmission due to its unique advantages over radio frequency (RF) technology such as low energy consumption, interference free spectrum, under water communication, safety, inherent security and robustness for positioning services [1]–[3]. Line of Sight (LoS) component is a stringent requirement in VLC resulting in its suitability to localization and positioning applications [4]. Influence of multi-path fading and interference due to non line of sight is not significant in VLC. Thus, high precision is achieved in positioning using VLC.

Several localization technologies have been developed in literature to obtain the distance information (which is crucial information for the positioning algorithms) such as scene analysis, proximity and triangulation. Each technique can be implemented for different applications with different constraints. In the scene analysis method, fingerprint characteristics are collected which are associated with each and every position in a scene and object's position is then determined by matching current measurements to these stored fingerprints. However, if there is a new scenario then this method cannot be deployed instantly [4]. In the proximity,there is dense grid with reference points having a known position. The target position is measured when it receives signal from a single reference point and target is considered to be co-located with that reference point. The drawback of this method is, to achieve more accuracy the number of reference points (transmitters) must increase [5].

Triangulation or trilateration is another localization technique used for indoor positioning [1]. Triangulation mainly has two branches, lateration and angulation. Lateration method is used when the location is estimated measuring the distance of target from multiple transmitters. In localization techniques, transmitters are also called as anchor points. The position or coordinates of anchor points are known to the receiver. The distance is measured indirectly by using different algorithms such as the received signal strength (RSS) [6]–[8], time difference of arrival (TDOA), and Time of Arrival (TOA) algorithm with multiple or single photodiodes (PDs) [9], [5].

TOA-based techniques demand the complete synchronization between the installed transmitters and receiver, and generally these techniques are not used for indoor positioning in visible light communication systems but are used for outdoor positioning systems i.e., GPS systems. TDOA-based localization is used in VLC based positioning systems. In the TDOA based methods synchronization among the transmitters is required only and these methods don't need synchronization between transmitter and receiver which makes it feasible to use in location estimation [10]. In this paper, location of the object is estimated using TDOA technique. The second category of triangulation is the angulation, in which location estimation is done by measuring the angles relative to the different reference transmitters (anchor points) and angle of arrival, (AOA) is calculated. Location is determined then by finding intersecting point of direction lines, which are the radii range from anchor points to the target. But this method is used quite often with the image sensor based receivers [1]. For such receivers the front-facing cameras are deployed widely, which are the image sensors. Moreover, smart-phones camera can also be used as the image sensor receiver and can be used for positioning in mobile consumer electronics [2], [11]. However, the field-of-view (FOV) angle of such cameras is limited and it is not useful for accurate positioning, therefore, in a real system to achieve the good performance, a very dense lighting grid must be provided for triangulation technique; otherwise, positioning accuracy will decay.

Currently, numerous position-aware services are implemented such as global positioning system (GPS) [10], infrared (IR) system [12], ultra-sonic or radio frequency (RF) system [13] etc. In GPS the triangulation and tri-lateration positioning algorithm is implemented. The GPS service relies on satellite signals, hence it is mainly used for out door positioning. Due to absence of satellite signals in the indoor environment, it cannot be used for indoor localization. [14].

Localization with IR Systems is deployed in [12] by using time of flight (TOF) based algorithm. The positioning accuracy of this IR system is $2cm$ within the area of $2 \times 2m^2$. But due to extra cost and additional time to implement this complex infrastructure, such IR systems are not feasible for indoor positioning [10].

The RF systems in [7] and [15], RSS based algorithms have been used for positioning, but these RF systems have expensive infrastructure [16]–[18]. Moreover, their positioning accuracy is worse than that of VLC systems. Therefore, because of the above mentioned limitations in existing positioning services, VLC based positioning is implemented in the indoor environment and thus, apart from the main functionality of LEDs which is the illumination, visible light system also handles the function of indoor positioning and can be deployed in any building with little cost [9], [19], [20].

In literature, different VLC based systems have been modeled for indoor localization. In [21], [22], and [2], array of LEDs is used as optical transmitters and the two image sensors as optical receivers to estimate the position of the receiver using geometric relationships of trilateration . However, it is worth-noting that the accuracy of this algorithm is poor as the localization error is $22cm$. In [23] the positioning algorithms using AOA-RSS provide positioning error of $20cm$ which was reduced to a few centimeters by using suitable and appropriate optical filter.

Similarly, in [24] the simultaneous three channel transmission method was used to determine the target position. In order to achieve reasonable accuracy, an additional adjustment process was carried out using normalization, making the receiver complexity very high. Intensity modulation/direct detection is implemented in this paper and the maximum achievable accuracy is of $2.4cm$ using this method which is worse than the proposed algorithm providing error in millimeters.

In [25], the algorithm is based on frequency division multiplexing (FDM), and however, variable phase was not considered in their approach (it was assumed to be constant). Moreover , the modeled system in this paper was considered noiseless and distortion less and positioning algorithm was implemented by taking the ideal system without considering the channel conditions.

Furthermore, various attempts have been made using VLC based positioning with different algorithms in [15] and [26]–[29].

In the current work, we have used a novel approach which is of hybrid nature in the sense that it conveys positioning information using both frequency and phase and the transmitted signal. Frequency division multiplexing (FDM) has been employed with adjustable predetermined phase delay in our work, therefore this scheme is called as Phase Difference of Arrival (PDOA). The proposed algorithm is based on trilateration method and more precisely time difference of arrival (TDOA) because in this technique we only require synchronization between the transmitters and not between the transmitter and receivers (as discussed above). The algorithm provides accurate results for positioning as the mean localization error is in millimeters supporting improved communication range up to $4m$. Simulation results also compare the performance of the proposed positioning algorithm (with FDM and variable phase) with existing one. Finally, the positioning accuracy has also been tested in the noisy environment (which is absent in the existing works, e.g., [10], [25]).The Figure 1 depicts the indoor localization system with source(LED), receiver(photodiode) and optical channel.

II. SYSTEM MODEL

In Figure 1, the complete system model with specific parameters is given which is implemented in the current work. The system model comprises five LED ceiling lamps and a single photodiode. The $\hat{v}_{T_n}$ is the transmitter orientation vector and $\hat{v}_{R_n}$ is the receiver coordination vector. The transmitted signal passes through optical wireless channel (OWC). In the current work, *Lambertian* radiation pattern is considered. The impulse response of Lambertian OWC with LOS conditions

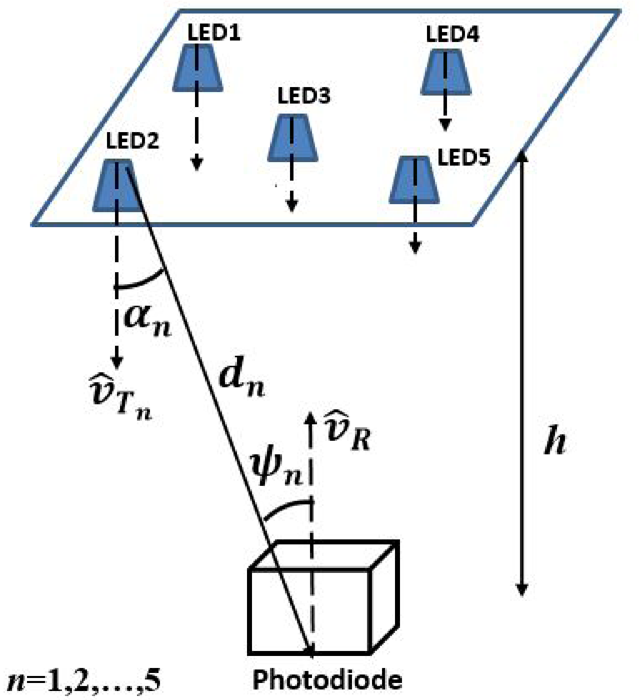

FIGURE 1. System model with parameters.

is given as [30]:

$$H_n(t)=\frac{A_r(m+1)}{2\pi d_n^2}\cos^m(\alpha_n)T_s(\psi_n)g(\psi_n)\cos(\psi_n)\delta\left(t-\frac{d_n}{c}\right) \tag{1}$$

where,
m is the mode number for Lambertian emmission.
A_r is the surface area of the photodetector.
T_s is the gain of the optical filter which is unity for the current model.
d_n is the distance between the n^{th}LED and photodiode.
g is the gain of optical concentrator and c is the speed of light.

H_n is the channel connection between n^{th} LED and photodiode. The transmitted signal through LEDs is given as:

$$x_n(t) = P_T + P_T \cos(2\pi f_n t + \theta_n) \quad 1 \le n \le 5 \tag{2}$$

where, f_n is the frequency of n^{th} LED. It is worth-noting that f_1 is the frequency for the reference LED (LED_1) and the frequency for the other LEDs will be the odd multiples of f_1, i.e.,

$$f_n = (2n-1)f_1 \tag{3}$$

where, $1 \le n \le 5$. The phase of the transmitted signal, θ, is chosen such that the phase difference $(\theta_1 - \theta_n)$ is the odd multiples of π [19]. θ_1 is uniformly distributed and $\theta_n = \theta_1 + (2n-3)\pi$ where $2 \le n \le 5$.

The photodiode receives the signals transmitted by all the LEDs. The signal received from all five LEDs by the photodiode is obtained as follows:

$$r(t) = \sum_{n=1}^{5} x_n(t) \otimes H_n(t) \quad 1 \le n \le 5 \tag{4}$$

where, $x_n(t)$ is the input signal, $\otimes$ is the convolution operator and $H_n(t)$ is the channel response. In current work, the received signal after passing through bandpass filter (BPF) is expressed as follows:

$$r_n(t)=\zeta H_n(0)\, RP_T^2 \cos\left[2\pi f_n t+\theta_n-\left(2\pi f_n-\frac{d_n}{c}\right)\right] \tag{5}$$

where, ζ is the proportionality constant.
$H_n(0)$ is the DC gain of the optical channel (distortionless).
R is the photodiode responsivity.

The proposed algorithm is based on the FDM and the phase difference information. The detection of phase difference requires the signals having unified frequency. Therefore, frequency down conversion (FDC) is used with a BPF. After FDC, the signal can be represented as:

$$R_n(t) = \gamma \cos[\pi f_1 t + \theta_n - (2n\pi f_1 d_n/c)] \tag{6}$$

where $\gamma = H_n(0)RP_T^2$.
Figure 2 represents the block diagram of the proposed solution in the current work. The information signal is multiplexed over frequency and variable phase (VP) and the signal from each LED will have unique frequency with its associated phase. LED driver circuits enable the LEDs to transmit the signal with different switching frequency. The signal passes through the *lambertian* channel and PD receives the intensity modulated signal transmitted by LED. After passing through amplifiers and bandpass filter, the received signal frequency is down converted by the frequency down converter and PDOA based positioning algorithm is implemented to determine the target location.
The phase of the received signal depends on the distance d and additional predetermined phase θ. This phase information and FDM approach leads towards the computation of receiver position which is explained in the subsequent section.

III. PROPOSED SOLUTION

The proposed solution is based on PDOA technique. Each signal, arrived at the photodetector, experiences a different time delay depending on the distance value. Therefore, the phase difference is determined based on different time delays. The information, related to distance d (between LED and PD), is in the phase of the received signals. Hilbert Transform technique is employed to find the phase difference [10]. The procedure is explained below:
According to the defination of Hilbert transform,
if,

$$x(t) = \cos(2\pi f t) \tag{7}$$

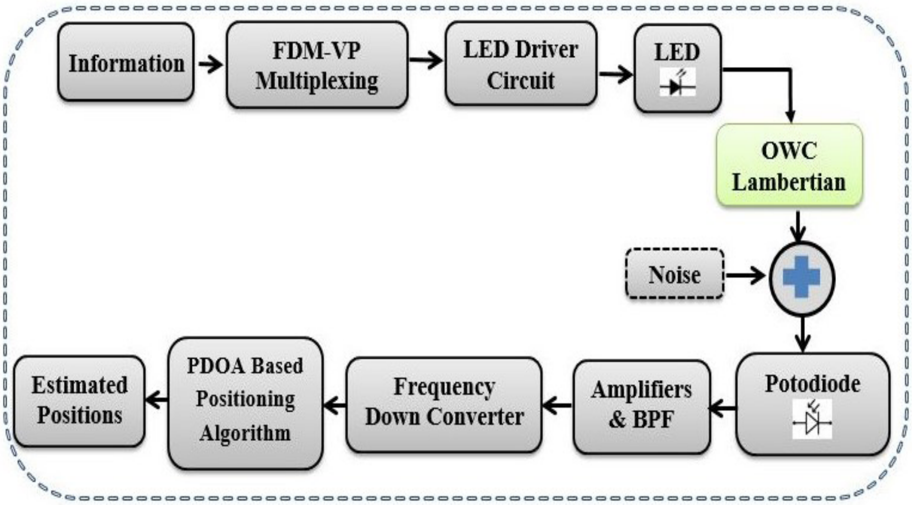

FIGURE 2. Block diagram of VLC transceiver design.

then,

$$Hilb\,(x(t)) = \cos\,(2\pi ft - \pi/2) \tag{8}$$

$$\Delta\Phi_{1n} = tan^{-1}\left(\frac{P_{1n}}{Q_{1n}}\right) \tag{9}$$

where,

$$P_{1n} = R_1(t).Hilb(R_n(t)) - Hilb(R_1(t)).R_n(t) \tag{10}$$

$$Q_{1n} = R_1(t).R_n(t) + Hilb(R_1(t)).Hilb(R_n(t)) \tag{11}$$

where $2 \leq n \leq 5$. The signal received by the photodiode is passed through the bandpass filters tuned at the available frequencies. The signal received from LED_1, after passing through the bandpass filter tuned at f_1, gives $R_1(t)$ signal. Similarly, the signals received from other LEDs, after passing through the bandpass filter tuned at f_2, f_3, f_4 , and f_5, provide $R_n(t)$. After applying Hilbert transform method, we obtain the phase difference of the signals as follows:

$$\Delta\Phi_{12} = 2\pi f_1\left(\frac{d_1 - 3d_2}{c}\right) + \theta_2 - \theta_1 = tan^{-1}\left(\frac{P_{12}}{Q_{12}}\right) \tag{12}$$

$$\Delta\Phi_{13} = 2\pi f_1\left(\frac{d_1 - 5d_3}{c}\right) + \theta_3 - \theta_1 \tag{13}$$

$$\Delta\Phi_{14} = 2\pi f_1\left(\frac{d_1 - 7d_4}{c}\right) + \theta_4 - \theta_1 \tag{14}$$

$$\Delta\Phi_{15} = 2\pi f_1\left(\frac{d_1 - 9d_5}{c}\right) + \theta_5 - \theta_1 \tag{15}$$

Similarly,

$$\Delta\Phi_{21} = 2\pi f_1\left(\frac{d_2 - 3d_1}{c}\right) + \theta_1 - \theta_2 \tag{16}$$

$$\Delta\Phi_{21} = tan^{-1}\left(\frac{P_{21}}{Q_{21}}\right) \tag{17}$$

Here, θ_n $(1 \leq n \leq 5)$, f_1, and c (speed of light) are known parameters whereas $\Delta\Phi$ can be determined using Hilbert transform. Only unknown parameter is the distance, d. As the received signal is the sum of sinusoid signals, it is obvious that the minimum value of received signal always occurs when $\Delta\Phi = \pi$ (or an odd multiple of π) and the maximum always occurs when $\Delta\Phi = 0$, or (or an even multiple of π). The difference between the maximum peak-to-peak value and the minimum peak-to-peak value depends on the relative amplitude of two received components [19].

Using Eq.(12) and Eq.(16), we can compute the distance,

$$d_1 = -\frac{c}{16\pi f_1}\left[\Delta\Phi_{12} + 3\Delta\Phi_{21} + 2\theta_2 - 2\theta_1\right] \tag{18}$$

Having determined d_1, the other distance values can be obtained in a similar way as follows:

$$d_n = \frac{f_1 d_1}{f_n} - \frac{c}{2\pi f_n}\left[\Delta\Phi_{1n} + \theta_1 - \theta_n\right] \tag{19}$$

where $2 \leq n \leq 5$. The distance values are determined by using the phase information and also we know that the distance between any two points can be given as

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \tag{20}$$

Eq.(20) takes the following form for computing receiver's location using first LED,

$${d_1}^2 = (x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2 \tag{21}$$

where x_1, y_1 and z_1 are the known coordinates of LED_1 and x, y, z are the receiver coordinates.

The distance values are determined by using the phase information and also we know that the distance between any two points can be given as

$${d_n}^2 = (x_n - x)^2 + (y_n - y)^2 + (z_n - z)^2 \tag{22}$$

TABLE 1. Simulation parameters.

Parameter	Value
Room Size	$5m \times 5m \times 3m$
Receiver Height	$3m$
PD Responsivity	0.45 A/W
Area of PD	$1cm^2$
Receiver FOV	70 deg
LED Power	12 W
Semi-angle	60 deg

x_n, y_n and z_n are the known coordinates of LED and x, y, and z are the receiver coordinates. Hence, the unknown position of receiver can easily be computed given the values d_n^2, x_n, y_n and z_n. This system of homogeneous linear equations can be solved using simultaneous equations or matrix method. The presented results have been obtained by matrix computations. The positioning algorithm for proposed system model is given as:

Algorithm 1 PDOA Based Positioning Algorithm

1: **Procedure** read(N)
2: **Input:** $X_{T,n}(t)$
3: **Output:** x_n, y_n **and** z_n
4: **for** $N = 1$ **to** $N = 289$
5: Convolution: $X_{T,n}(t) \otimes H_n(t)$
6: $r_n(t)$ is obtained by the receiver
7: FDC is applied on $r_n(t)$ to get $R_n(t)$
8: Hilbert Transform method to calculate the $\Delta\Phi_n$
9: d_n is obtained from $\Delta\Phi_n$
10: Least Square method to find x_n, y_n, z_n
11: localization error is measured
12: $N = N + 1$
13: **end**
14: Mean localization error is calculated
15: **end Procedure** read(N)

where, N is the point of grid where the receiver is present, $X_{T,n}$ is the signal transmitted by the n^{th} LED and x_n, y_n and z_n are the receiver coordinates.

IV. SIMULATION RESULTS

The accuracy of the proposed algorithm is analyzed through simulations. Figure 3 shows a simulation model. The room dimensions $5m \times 5m \times 5m$ with transmitted power 12W and frequency 1MHz. The general operating frequency for LEDs is considered as 1MHz [10]. Other parameters used in the simulations are provided in Table 1 [1], [25].

We assume that the receiver is always located at the ground. A grid is made on the floor with equal spacing of 0.25m. The receiver is placed at all the grid points and then the position is determined using the system of equations developed in this work.

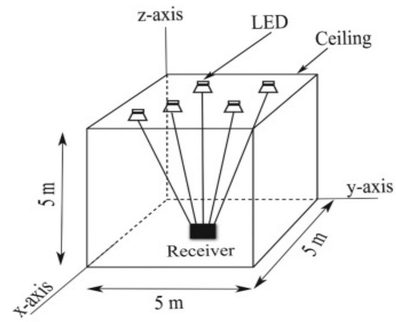

FIGURE 3. Implemented system model.

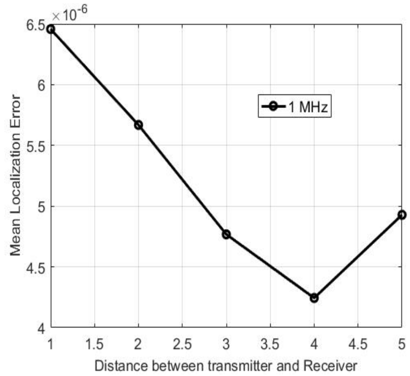

FIGURE 4. Localization error at different heights of receiver, (m).

At $4m$ height, the mean localization error is found to be $0.0041mm$ which can be observed in the Figure 4. This algorithm is suitable in applications where less than $1mm$ error is required, e.g., indoor robotics, warehouses, parking lots etc. Furthermore, $4m$ height is found optimal because the error is minimum at this height. The error increases other than this optimal height value.

In [25], the optimum height of receiver was $2.5m$ by using the algorithm based on FDM and the transmitting power 12W. Thus, the optimum height range is increased in the proposed algorithm without increasing the transmiting power and the complexity of receiver. At $4m$ height, the lowest mean localization error is achieved in millimeters.

The simulation results are extended to evaluate the performance of proposed algorithm in realistic system where the addition of noise is also considered in the received signal. The wireless channel adds the noise in the transmitted signal and then the obtained received signal can be expressed as:

$$r(t) = \sum_{n=1}^{5} x_n(t) \otimes H_n(t) + n(t) \tag{23}$$

In the current work, two different noise distributions (Gaussian and Poisson) have been considered to analyze the effect of noise on the received signal. The reason for using these two noise distributions is that they are widely used in optical wireless channel. *Gaussian Noise* is implemented with zero mean and variance σ^2. We have used additive white Gaussian

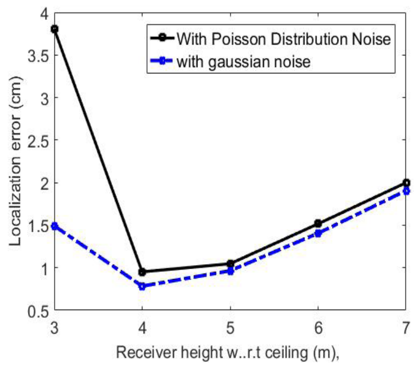

FIGURE 5. Comparison of results; with gaussian and poisson noise.

noise (AWGN) in our simulation program. The noise is non zero and additive nature, which reduces the received signal strength and localization error increases as shown in Figure 5. It can be observed that the positioning error increases with the Gaussian channel conditions as compared to ideal (noiseless) system as depicted in Figure 5. However, the error does not increase dramatically and it is in the range of a few centimeters (0.784cm in the simulations at the height of 4m) which validates that the proposed algorithm is robust enough that it produces error of less than 1cm even through noisy channel.

In second type of noise, i.e., Poisson noise, the channel is considered having Poisson noise which is also called as shot noise. The effect of Poisson noise on the localization error can be observed in Figure 5. The localization error curve shows that that the error is less than 1cm at the optimum height 4m which again agrees to the above argument regarding robustness of the algorithm as the increase in error is very small and it is 0.95cm (even less than 1cm) in simulated results.

The simulated results with Gaussian noise are better than the Poisson noise and this would be helpful for some real world applications in which Gaussian distribution is used such as in biomedical engineering and management, counting problems and to model financial variables for the optimization problems of economics etc.

Reason of Optimum Height: Photodiode is always placed at some distance from the transmitter (LED). It is important that the photodiode must not to be placed too close to the LED. Because in that situation, it will be saturated as it draws large DC component due to multiple scattering of the incident photons and hence, the photodiode will not respond to the light level appropriately. Similarly, it should also not be at a point which is far away from the LED. This is because the photodiode receives very small power which is insufficient for it to work properly.Therefore, the photodiode must be placed at some optimum distance [30]. Moreover, minimum error is observed at any point if the height is made exactly equal to the distance between the transmitter and the receiver. This is because $cos(\alpha)$, the ratio of the height and the distance, becomes unity which means that the target is placed exactly under the installed transmitter (α is zero) resulting in both maximum received power and minimum localization error.

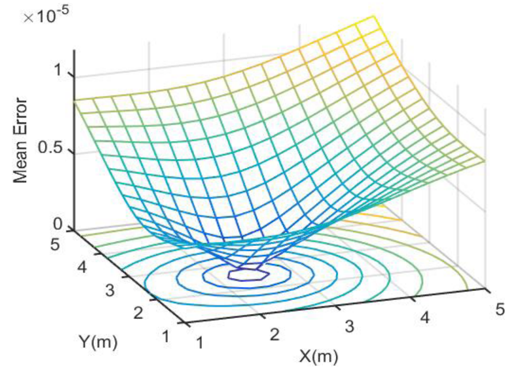

FIGURE 6. 3D plot of localization error with the frequency and phase algorithm.

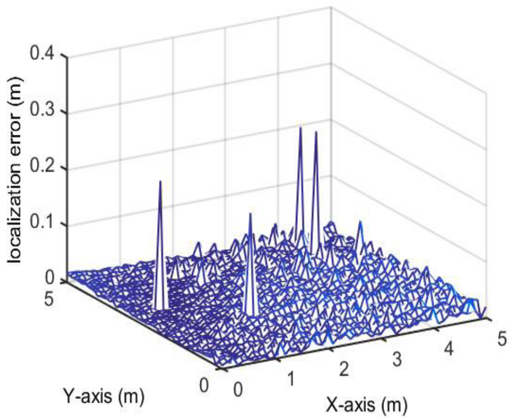

FIGURE 7. 3D plot of localization error under gaussian noise.

Simulation results have been presented in Figure 6.

Figure 6 shows the 3D plot of the localization error (without any noise consideration) under the proposed algorithm. It can be observed that the localization error is significant at the corner points of the room. The is because the LEDs are installed at the center of the room, and therefore, the error becomes more pronounced at the corners owing to receiving low signal strength. However, it should be noted that it is still less than 1mm. Moreover, the object receives the maximum signal strength at most of the locations (the points) in the room, therefore, the mean localization error remains in millimeters and it is 0.0041mm in our simulated results.

Figure 7 shows the 3D plot of the localization error (considering Gaussian noise) under the proposed algorithm. The plot shows that the error is far less than (1cm) except at a few points (spikes of 1 or 2cm) which are insignificant compared to overall points. The exact mean error is 0.784cm. Finally, the 3D plot of the localization error (considering Poisson noise) has been shown in Figure 8. The mean error is 0.95cm which is approximately two times the error under ideal case (noiseless as demonstrated in Figure 6.

V. APPLICATIONS

There are many applications for the proposed algorithm and some of its suitable applications are given as follows:

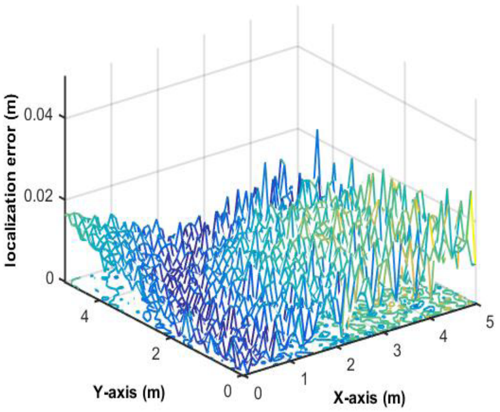

FIGURE 8. 3D plot of localization error under poisson noise.

(a) (b)

FIGURE 9. Pick and place robot.

A. ROBOTICS

In industries and warehouses, many applications based on automatic storage and retrieval system require the robots which performs the functions of picking and placing objects automatically. For that purpose, firstly robot must localize itself on the arena of warehouse, then it follows the predefined trajectories on the grid arena to pick the object and place it on specific locations as shown in Figure 9. In such applications, high positioning accuracy is the key requirement. The proposed algorithm is suitable for such applications as it allows the positioning accuracy up to $0.0041mm$ and robot will estimate the position of objects more precisely and accurately.

B. COMPUTERIZED EMBROIDERY

Computerized embroidery machine shown in Figure 10, is used to produce the most complicated designs and patterns in textile industry. These machines are able to reproduce designs in perfect quality. Such devices can follow every detail without any flaws or errors. Once the process is stabilized and the design file is loaded, the equipment can be started. In order to ensure that all the changes are carried out properly, localization accuracy must be high.

VI. CONCLUSION

We have proposed a hybrid approach using frequency and phase information to locate the target with greater precision. The proposed approach provides low positioning error with increased communication range (distance between the transmitter and the receiver). In a communication system, it is desirable to maximize the communication range while

FIGURE 10. Computerized embroidery machine.

maintaining the error location to minimal value which is achieved by using this algorithm. The effect of Gaussian and Poisson noise has also been observed with the proposed algorithm which verifies the robustness of the proposed algorithm because in the case of noisy environment the positioning accuracy can be achieved with the localization error of a few centimeters which is less than $2cm$ in simulated results.

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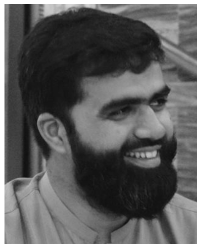

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