Resolving Height Uncertainty in Indoor Visible Light Positioning Using a Steerable Laser

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Abstract—We propose an indoor Visible Light Positioning (VLP) system that augments Lambertian emissions from conventional luminaires with a single steerable laser. By knowing the exact angles between the laser and the receiver being positioned as well as received-signal-strength (RSS) from the Lambertian sources to the receiver, we can predict the position of a receiver in three dimensions (3D).

Most RSS-based VLP algorithms assume a constant operating plane (height) of the receiver to stabilize trilateration to produce 2D estimates. By using the angles provided by laser steering, we show that 2D and 3D error can be reduced to near zero for a known height and 3D mean square error is less than 12.89 cm for 95% of the reference volume when the height is unknown a priori. Finally, we show that unlike trilateration-based methods, the technique can operate using as few as a single luminaire, making it more versatile than other RSS-based approaches for establishing receiver position.

Index Terms—visible light communications, visible light positioning, LiFi, multi-cell lighting

I. INTRODUCTION

GPS is the de facto positioning system used outdoors, whether that be for navigation, tracking, or automation. For indoors, a robust approach to positioning has not yet emerged. However, the need for positioning is just as necessary indoors as it is outdoors. In fact, there is a greater need for precise tracking indoors than outdoors given that the operating space is smaller and therefore the same margin of error is more significant indoors than outdoors. Virtual headsets are a new realm of devices that could benefit greatly from knowing the precise positions of the headsets. Imagine being able to steer a line-of-sight (LOS) high data rate LiFi beam onto a headset to service a high resolution, high frame rate wireless connection.

Replicating the GPS paradigm indoors is not as feasible as one may think. Radio frequency (RF) waves attenuate and fluctuate greatly due to walls and obstacles. As such, fingerprinting techniques and machine learning algorithms are popular RF indoor positioning solutions [1]. However, these solutions only provide meter-level accuracy [2]. Low accuracy positioning using a beaconing technique is also popular where precise positioning is sacrificed for the benefit of cheapness and readiness, e.g., Bluetooth-low-energy (BLE) and RFID technology. Ultra-wide band (UWB) positioning is promising but requires additional infrastructure costs. Microsoft conducted a competition for indoor positioning, where the primary

positioning solutions were RF based, and across four years, the real-world accuracy of these solutions is at best in the decimeter range [1]. In addition, the RF spectrum is already highly congested.

Light-based positioning is also an option. This has the advantage of using an existing lighting infrastructure or piggybacking the cost of installation to the lighting infrastructure. Given that connected LED lighting has become standard in modern infrastructures, this is not much of an additional cost problem. In fact, one such application gathering steam in light of the RF bandwidth crunch in multi-purpose lighting is Visible Light Communication (VLC), which is free space optical communication in the visible spectrum [3]. VLC relies on taking advantage of regularly placed luminaires that provide LOS exposure and data connectivity to most locations in a space [3]. Using the same paradigm as VLC, many researchers have enabled indoor positioning systems combining coded light, received signal strength (RSS), and trilateration with fixed-positioned luminaires and simple mobile receivers. These systems achieve accuracies in the centimeter range [4]–[7]. While these techniques would appear to be readily deployable on commodity lighting units with conventional design rules (regular spacing, common z-plane, same intensity), the same rules limit the diversity necessary to resolve in three dimensions. In fact, a fixed height, or plane of reception, is assumed in each of these works. Alternatively, some research targets the receiver design to introduce angular measurement. This work includes the use of: multiple apertures and photodiodes [9], multiple tilted photodiodes [10], and multiple fixed location receivers [11]. There is also work where angular diversity is introduced at the transmitting end by using multiple LEDs at each transmitting luminaire [12]. However, these techniques are all still at their cores trilateration and triangulation but with more densely packaged detectors and emitters.

Our work seeks to extend the current RSS-based paradigms of light-based positioning with angular information without adding complicated receivers or transmitters. We propose to add a single, low cost narrow beam laser to augment the RSS provided by diffusive, Lambertian luminaires to provide precise angular information that will help to resolve height and overcome noise. This scenario is illustrated in Fig. 1. This approach works using one or more luminaires and does not rely on trilateration or triangulation; a notable deviation from the current state of the art. With a steerable laser, and positioning being low latency, we can also use our technique to track
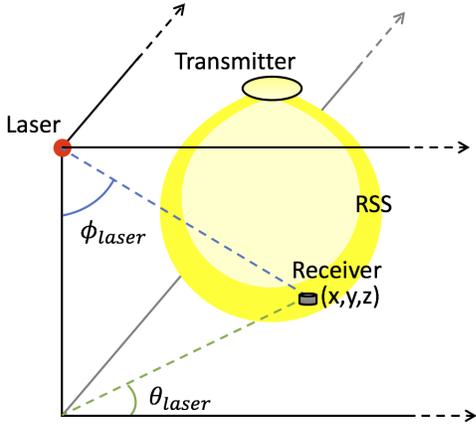
Fig. 1: Model of laser-Lambertian positioning. Given known locations and RSS of Lambertian source(s), θ_{laser}, ϕ_{laser}, we solve for x, y, z position of the receiver.

multiple targets. There is also no need for additional hardware at the receiving end, as the laser light can be received by the same broad-spectrum VLC receiver. In addition, our approach does not require ranging or timing synchronizations needed for time-of-flight (TOF) solutions, as might be achieved with a more expensive LIDAR.

The remainder of the paper is organized as follows. Section II describes models for laser and Lambertian sources. Section III proposes our novel positioning scheme using RSS in conjunction with a laser source. Section IV shows simulation results benchmarking our scheme. And Section V concludes the paper.

II. LASER AND LAMBERTIAN SOURCES

A. Laser Beam Profile

A laser source is modeled as a Gaussian beam with a narrow waist as defined as:

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \qquad (1)$$

$$z_R = \frac{\pi w_0^2}{\lambda}, \qquad (2)$$

where $w(z)$ is the beam waist as a function of distance, z, z_R is the Rayleigh Scattering distance, λ is wavelength, and w_0 is the initial beam waist size. For an inexpensive red laser with $\lambda = 632nm$, $w_0 = 1.6mm$, and a maximum change in height, $z = 3m$, the maximum change in beam diameter is $45\mu m$. As such, in an indoor scenario, we will model the laser beam waist as a point as the errors propagating from noise and positioning is much larger than the maximum change in waist size of the laser beam.

Next, we look at steerable angle resolution and its effect on the maximum deviation in position. Steerable microelectromechanical systems (MEMs) such as the Mirrorcle MEMs offers 16-bit resolution for $6.2262°$ in the x-axis and $6.2083°$ in the y-axis. With a maximum change in height of $3m$, those

specifications correspond to a maximum change in position of $5\mu m$. Again, noise and positioning error is much larger than the maximum change in position. Together with the previous assumption, we can model the laser source as a line with a point size waist.

Signal strength of the laser is negligible as long as a receiver can detect its presence. This is a design decision to simplify the hardware addition of the laser as a precise measurement of the laser signal strength is not required for the VLP algorithm to operate.

B. Lambertian Luminaire Profile

Here we model lighting luminaires capable of a wide field-of-view (FOV) as Lambertians. The Lambertian model is dependent on transmitter and receiver characteristics and is defined as follow [13]:

$$H_{LOS}^{DC} = \begin{cases} \frac{m+1}{2\pi} cos^m(\phi) \frac{A}{d^2} T_s(\psi)g(\psi)cos(\psi), & 0 \le \psi \le \Psi_c \\ 0, & \psi > \Psi_c \end{cases}, \qquad (3)$$

where Ψ_c is the concentrator FOV, A is the detector area, ψ is the angle of incidence w.r.t. to receiver axis, ϕ is angle of radiance, d is distance, m is Lambertian order, and $T_s(\psi)$ is the signal transmission of the filter (losses over wavelengths). $g(\psi)$ is the concentrator gain and relies on the refractive index, n, of the concentrator and is defined:

$$g(\psi) = \begin{cases} \frac{n^2}{sin^2\Psi_c} & 0 \le \psi \le \Psi_c \\ 0 & \psi > \Psi_c \end{cases}. \qquad (4)$$

Collecting some terms, Lambertian radiant intensity is defined as:

$$R_0(\phi) = \frac{m+1}{2\pi} cos^m(\phi). \qquad (5)$$

Further simplifying, $g(\psi)$ and $T_s(\psi)$ can be rolled into one function, the effective responsivity of the photodiode, $R_{eff}(\psi)$. In addition, assuming the transmitter is parallel to the transmitting plane and the receiver is parallel to the receiving plane, $\psi = \phi$, Fig. 2. So:

$$H_{LOS}^{DC} = \begin{cases} R_0(\psi) \frac{A}{d^2} R_{eff}(\psi) * cos(\psi), & 0 \le \psi \le \Psi_c \\ 0, & \psi > \Psi_c \end{cases}. \qquad (6)$$

Furthermore, noise is modeled as white Gaussian noise (AWGN) and such we get a final received signal strength at each position of the room:

$$P_r = P_t H_{LOS}^{DC} + w, \qquad (7)$$

where P_r is power received, P_t is transmitter power, H_{LOS}^{DC} is the Lambertian channel model from above, and w is AWGN and is defined relative to SNR:
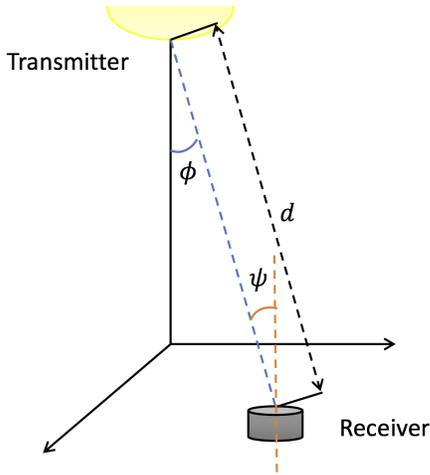
$$SNR = \frac{P_t H_{DC,LOS}}{w}. \qquad (8)$$

Fig. 2: Transmitter and receiver geometry. If the receiving plane and transmitting planes are parallel, $\psi = \phi$.

Fig. 3: Setup of the room with the laser source at the origin.

III. Proposed VLP Concept

We propose to use a single laser source in combination with diffusive Lambertian sources to actively position a receiver. The narrow-beam laser source can be steered and aligned to a receiver to provide precise angular information, whereas a Lambertian (lighting) source has a wide dispersion and provides information about how far away radially the active receiver is from itself provided each Lambertian source can be separated from the others. This can be done using a coded light VLC scheme. As such, the laser source is used to pinpoint where in this radius the active receiver is: i.e. there is only a limited number of points in the isointense curve that the active receiver can be in for a given received signal and angle. Therefore, given RSS and angle, we can solve for positioning, Fig. 1.

Aligning the laser and multiplexing the Lambertian sources efficiently are not a focus of this paper. However, both are realizable and will be described in subsequent work: beam alignment can be done through coarse beaconing followed by scanning, and multiplexing the Lambertian sources can be achieved by orthogonal frequency division multiplexing (OFDM) or time division multiplexing (TDM).

A. Reference Room Model

For the reference room setup, Fig. 3, origin is taken at the ceiling plane, i.e. the receiver will be a negative distance away from the origin. The room is 6 m $\times$ 6 m $\times$ 3 m. Lambertian sources are placed at $(2, 2, 0)_{TX_1}$, $(2, 4, 0)_{TX_2}$, $(4, 2, 0)_{TX_3}$, $(4, 4, 0)_{TX_4}$. This replicates the conditions described in [4] for comparative benchmarking of our results. A laser source is placed at the origin.

The Lambertian coverage is calculated for sample points in the room. Here, samples are evenly spaced $0.05m$ from each other in each dimension. To get a noisy signal, noise, w, is added per Eq. 8 to the Lambertian coverage to obtain an RSS for each point. For each point, the angle is assumed perfect
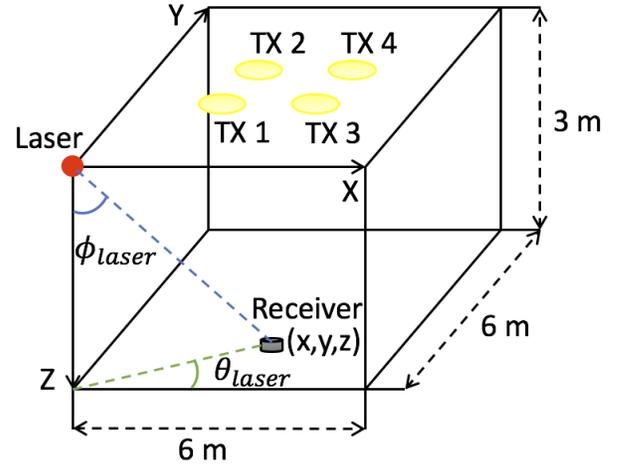
as the errors in angles would result in negligible position errors as discussed in Section II-A. Receiver characteristics, such as FOV and photodiode area are adopted from reference [4] for the purposes of comparative benchmarking. Table I summarizes the parameters used in the simulation.

TABLE I: Parameters used in modeling and simulation.

Parameter	Value
Room [LxWxH]	[6 m x 6 m x 3 m]
4 Transmitters	$(2, 2, 0), (2, 4, 0), (4, 2, 0), (4, 4, 0)$
1 Laser	$(0, 0, 0)$
PD Area	$1\ cm^2$
TX Power, P_t	2 W
FOV, Ψ_c	$70°$
Optical Filter Gain, $T_s(\psi)$	1
Refractive Index, n_c	1.5
SNR	30 dB

B. Laser-Lambertian Positioning

Based on Section II-A, we assume the laser is a narrow line, akin to ray tracing, and we only look at the geometric characteristic of the beam from the source. This greatly simplifies the calculation and becomes a calculation of minimum error.

For each available transmitter, using the known angles, θ_{laser} and ϕ_{laser}, we calculate the expected RSS values using Eq. 7 with no noise for this line. Since each point on the line can be described by a unique height and the known angles, we simplify the equation to relying only on height:

$$RSS_{x,y,z} = \begin{bmatrix} RSS(z_1) & RSS(z_2) & ... & Rss(z_K) \end{bmatrix}. \quad (9)$$

The noisy received signal, P_r, is compared to every point on this line. The N smallest error deviations are taken.

$$D_{N,i} = \operatorname*{argmin}_{i} |RSS_{x,y,z} - Pr|, \quad (10)$$

where argmin refers to the argument correlating to the z-position of the i-th smallest error deviation for $i = 1, 2, ...N$.

There is the possibility that the laser beam line will intersect twice with the isointense curve, Fig. 4. But usually, the first intersection point happens much closer to the ceiling and can just be thrown out with the assumption that the active receiver is not that close to the ceiling. We do this by using a median absolute deviation (MAD) outlier algorithm,

$$MAD = median(|D_{N,i} - median(D_N)|) \qquad (11)$$

$$V = |D_N - median(D_N)| < 3MAD, \qquad (12)$$

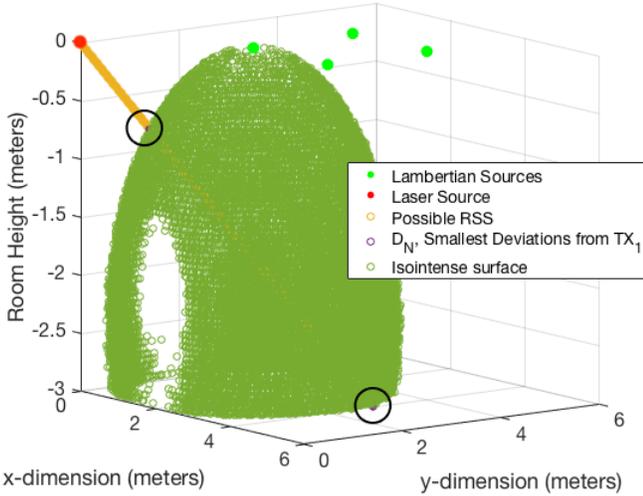to get rid of points that appear too close to the ceiling, Fig. 5.

Fig. 4: Isointense curve penetrated by a laser, yellow points, with a given set of angles, $\phi_{laser}, \theta_{laser}$.

Finally, the mean positions of the remaining positions are taken as the predicted value:

$$z_{predicted} = mean(V). \qquad (13)$$

X and Y are predicted based on z_{pred}, θ_{laser}, and ϕ_{laser}:

$$x_{pred} = z_{pred} \tan \phi_{laser} \sin \theta_{laser} \qquad (14)$$

$$y_{pred} = z_{pred} \tan \phi_{laser} \cos \theta_{laser}. \qquad (15)$$

These predicted x-y-z coordinates can be averaged for any number of available transmitters. In the next section, we explore position accuracy with different number of transmitters. It should be noted that the laser-Lambertian positioning algorithm is used to resolve height ambiguity. As such, if we know the height of the receiver prior to prediction, as is assumed in most RSS-based VLP approaches, the error in x-y predictions reduces to zero.
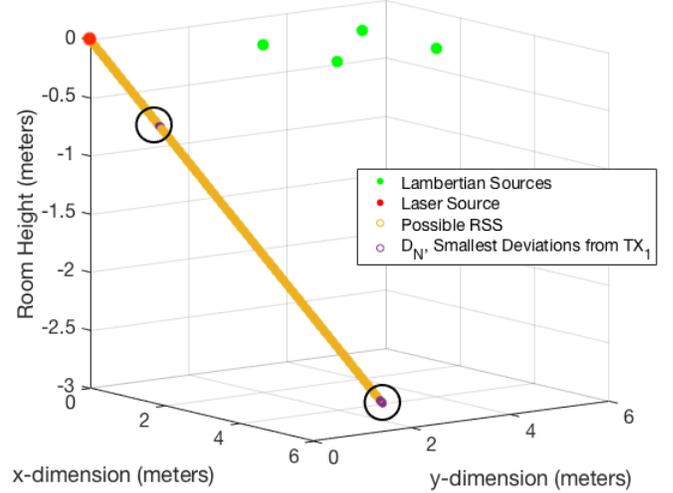

Fig. 5: The yellow points are every possible position for a given set of angles, $\phi_{laser}, \theta_{laser}$. Purple shows the $N = 50$ minimum error positions. Regions of interests are circled. The outlier region is filtered out.

IV. RESULTS

Using the derived models, we investigate performance by simulating noise in the distribution of light from the luminaires and in the measurement of RSS at the receiver. We use the room setup described in Section III-A and the parameters in Table I.

First, we benchmark against prior work using the trilateration technique described in reference [4]. This related work uses a linear least square estimator to predict position. The linear least square estimator relies on fitting the trilateration model to a set of linear equations, represented by a matrix, and finding its inverse matrix to solve the linear equations. Since the transmitters are placed at the same height, there is no height diversity and the linear least square estimator will not converge. Therefore, for their work, height is fixed or known a priori, and distance equations are derived using this fixed height. As mentioned before, if we fix height, our laser-Lambertian positioning algorithm will perform perfect 2D positioning (Fig. 6). Fixing height however is an unrealistic assumption as the mobile target will tend to move in x, y, and z directions. This is a shortcoming of many RSS-based positioning techniques that do not rely on angle measurement.

Next, we look at our laser-Lambertian performance on each axis as well as the total positioning error. Here we fix the plane of actual receiver positions to $3m$ away from the ceiling. Using the parameters defined in Table I, specifically for an SNR of $30dB$, which is a realistic low assumption for indoors, Fig. 7 shows the cumulative distribution function of the positioning mean square errors (mse) with average positioning mse of $3.14cm$, $3.15cm$, $3.91cm$, $4.96cm$, and $6.45cm$ respectively for x, y, z, xy, and total error. For 95% coverage, we can get accuracies of up to $8.37cm$, $8.42cm$, $8.31cm$, $10.15cm$,
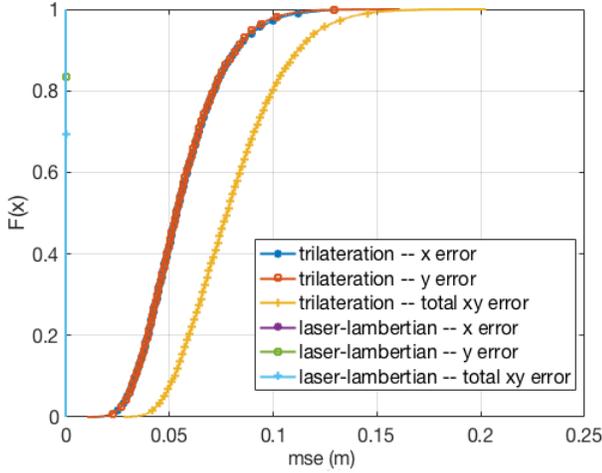
Fig. 6: CDF for trilateration positioning and laser-Lambertian positioning for a fixed height, $h = 3m$. Laser-Lambertian performs perfectly.
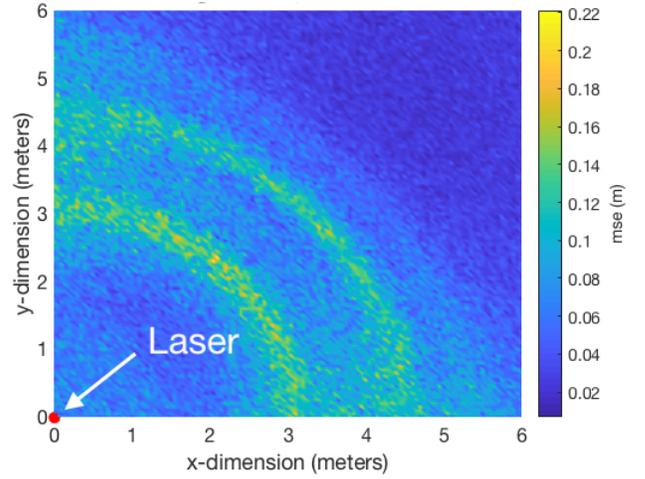

Fig. 8: Total 3D MSE for each location on a 2D plane, $h = 3m$, for easy visualization. The laser source is placed at the origin.
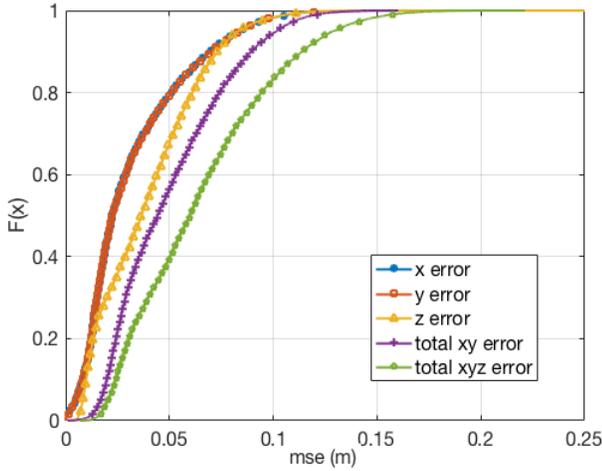

Fig. 7: CDF for laser-Lambertian positioning for x-error, y-error, z-error, xy-error, and xyz-error.
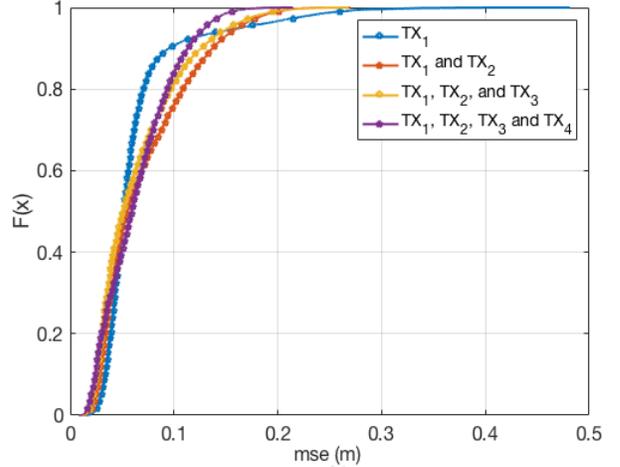

Fig. 9: CDF for laser-Lambertian positioning for using different number of transmitters.

and $12.89cm$ respectively for x, y, z, xy, and total error. Fig. 8 shows that the larger errors are most likely to occur closer to the laser. This could be remedy by moving the laser further away from the Lambertian sources and by placing it in different locations.

Using more transmitters for positioning does not necessary result in better performance at any given point as seen in Fig. 9 where the blue curve is further left for a certain coverage percentage. This is a consequence of weighing each transmitter equally when predicting position. A cleverer estimator would weigh the more reliable transmitters and combine the received RSS values into a single estimator. However, in this simple case, using greater than a single transmitter does result in a better overall coverage. Using all four transmitter results in the lowest error for the most coverage percentage.

Moving closer to the ceiling creates increased error (Fig. 10). This is due to the fact that moving closer to the ceiling results in more errors propagating from the RSS information. However, we expect the near-ceiling use case to be unusual, and will be considered in future volume exclusion heuristics that will isolate this issue.

V. CONCLUSION

We propose a new VLP technique to combine angular information provided by a steered laser with RSS-based signals originating from overhead luminaires. As compared to known RSS VLP trilateration schemes, our use of angular information from the laser source can effectively reduce error estimates to zero when the operating plane (height) of the receivers is known.
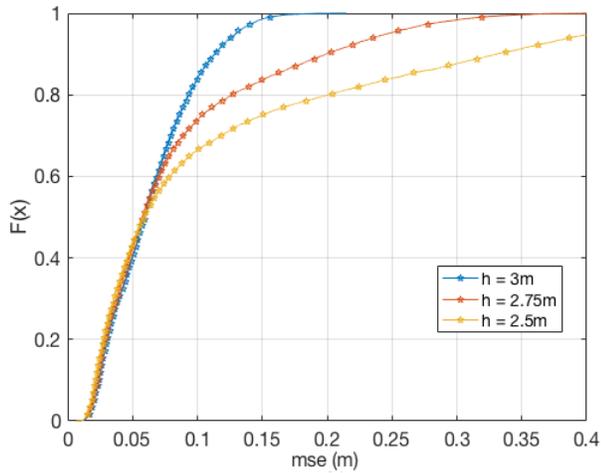
Fig. 10: CDF for laser-Lambertian positioning for different height planes.

In the presence of height uncertainty, the proposed technique performs VLP using as few as a single luminaire and can produce error estimates comparable to existing RSS methods, but also in three dimensions throughout the volume of interest. For larger spaces, the technique can exploit the Lambertian emissions of multiple luminaires.

Extensions of this work will show additional avenues of improvement including the use of a maximum likelihood estimator to exploit multiple RSS values and angular information into a single estimator. We also expect to show how heuristics applied to the occupied volume and expected occupancy zones can be used to reduce uncertainty in selected parts of the volume (e.g., near the ceiling).

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