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Indoor Positioning of Vehicles using an Active Optical Infrastructure

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***Abstract*—Indoor positioning is an enabling technology for advanced intra-logistic applications that employ tracking and tracing of goods and vehicles. For these applications, a positioning technology must offer a sufficient trade-off between accuracy, range, and costs. In this paper we present a novel positioning system based on optical technologies that is designed for tracing vehicles in a logistic environment. The major innovations of the system are an active optical infrastructure allowing absolute positioning without any other data source, and, on the receiver side, a hybrid data processing approach that combines signal and image processing. Using these optical technologies, a high accuracy can be achieved at lower costs compared to other approaches. The static positioning error is below 0.1 m.**

The active optical positioning approach joins signal and image processing technologies to a low-cost and high accuracy system. While designed for intra-logistic applications the technology can be adopted other fields such as building and shop-floor navigation.

***Index Terms*—Optical Positioning; Active Infrastructure; Data Transmission; Signal Processing; Image Processing**

I. Introduction

One of the first positioning system known in history is the ancient Lighthouse of Alexandria. Since then, engineers found various technical solutions for determining the position of a mobile device with affordable effort and sufficient accuracy. In modern intra-logistic applications these challenges are essentially similar. Accurately tracking logistic goods such as vehicles, pallets and equipment benefits logistic planning and control methods. However, investment is often limited for logistic facilities. As most intra-logistic facilities are indoor, using common (Global Navigation Satellite System (GNSS) technology is not feasible. Therefore, various approaches are made to the indoor positioning problem.

In this paper, we present a novel indoor positioning system based on an active optical infrastructure. Our key idea is to provide a sufficient position accuracy using low-cost optical components. The proposed positioning system consists of a network of beacons which transmit position signals via infrared (IR) channel to multiple mobile receivers. The position signals carry both the absolute beacon position and the transmit direction related to the beacons. The mobile receiver detects the contents, transmission direction and angle of arrival (AOA) of the position signals utilizing a receiver that consists of a photo detector and an image sensor device. Given two beacons within line of sight, the receiver can autonomously derive the absolute pose in a global coordinate system. Fig. 1 gives an overview of the positioning system.

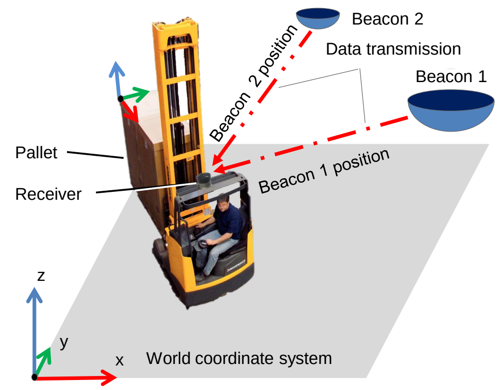

Fig. 1. System overview

A. Use Case

The intended use case of the positioning system is to track and trace pallets in a warehouse. For this purpose receiver devices are mounted at forklift trucks which actually actuate every pallet movement. Since the pose of the forklift relative to the receiver can be determined from simple coordinate transformations, the system is able to compute the pose of a pallet that is loaded on the forklift. The accurate pallet positions can then be exploited by a flexible warehouse management system (WMS) that organizes the storage locations based on the pallets pose instead of pre-determined locations. In this use case an accuracy of at least half the pallet dimensions is needed. The system is designed to achieve an even higher accuracy of 0.1 m. It is assumed that the forklift truck does not pitch or roll. Then, it is sufficient to determine the receiver pose in 4 dimensions, i.e. three-dimensional position and yaw/heading angle (rotation around world z-axis).

B. Related Work

We use an active optical infrastructure as a reference. According to the classification in [1], this can be regarded as a reference from coded targets. However, the code is actively

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sent instead of being printed as a marker or similar. Therefore, our approach does not rely on image processing alone, but combines data from a camera system with data gathered from an IR data transmission channel.

Our approach is comparable to the positioning system based on Visible Light communication (VLC) in [2]. The common idea is that light emitting diodes (LED) transmit their position via optical channels. The authors, however, do not provide a technical realization of the data transmission. There are various approaches on active optical senders for positioning such as LED array projections onto a dual image sensor as considered in [3]. A positioning system that detects the pose of a camera by means of sequentially flashing LED markers is described in [4]. The static photogrammetry system proposed in [5] employs active senders that transmit an ID which is detected by a fixed camera based on the flashing frequency. A frequency multiplex using coloured lights for a positioning system is proposed in [6]. Modulated signals of fluorescent lights are used for positioning in [7].

Section II of this paper describes the main components of the positioning system. Section III covers the positioning method which consists of four elements on the receiver side. An error estimation of the proposed system is presented in section IV. We conclude our paper by pointing out the main advantages of the system and topics for further research.

II. System Description

Like most positioning systems that use artificial references, our positioning system can be split into the infrastructure and receiver components. We will first discuss the novel beacon infrastructure and then focus the receiver components which allow an autonomous positioning.

A. Beacon Infrastructure

The stationary infrastructure of the positioning system is a network of optical beacons. Those beacons are light-emitting devices located at well-known positions in the facility layout. The beacons regularly broadcast their global position by means of optical data transmission. These beacon signals allow mobile receivers to determine their poses (position and orientation) autonomously. A beacon comprises an arrangement of LEDs and a simple micro controller. We chose IR-LED at 940 nm since IR signals can be easily processed using standard off-the-shelf hardware. However, the optical data transmission could also be carried out by visible light.

A beacon transmits data signals on 16 discrete channels. Each channel drives two LEDs at different polar angles. The azimuth angle between the channels is $22.5°$. The emitted light of the LEDs covers a hemisphere. We chose LED with an aperture angle of $22 - 30°$ so that the sectors overlap. Fig. 2 shows a working prototype of the beacon.

Our data transmission scheme uses a Time Division Multiple Access (TDMA) approach in order to allow multiple beacons to share the same media. Each time frame of 200 ms is divided into 25 time slots (8 ms). The beacons synchronize each others time base (crystal-controlled clock) in order to

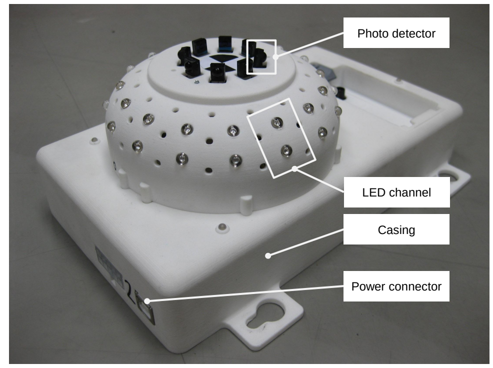

Fig. 2. Beacon Prototype

preserve the time sharing scheme. Each beacon uses a distinct timeslot for sending a message. For the half of the remaining idle timeslots, the beacon emits an unmodulated duty signal. Thus, for a camera receiver, the beacon appears to flash at frequency of 5 Hz.

The beacon signal has an intensity and phase modulated component. The intensity modulated component carries beacon-specific data such as the beacon position. The data signal is identical for all 16 beacon channels. It will be used as absolute reference data by the receiver. Intensity modulation parameters are chosen to suppress distortion sources such as fluorescent lights.

The phase modulated component depends on the emitting angle. Thus, the data signal of each channel is modulated by a phase delay pattern. Our approach uses a signal delay between two adjacent LED channels, that is a phase delay of $\frac{\pi}{2}$ with respect to the modulation period of 18 μs. Therefore, the channel signals are orthogonal. Based on this modulation scheme, the receiver can determine the transmission direction related to the beacon.

B. Receiver

The receiver detects signals from beacons in its vicinity. It comprises two sensory components: an image sensor camera and a photo detector. Since all beacons broadcast their position information in their optical signals, the beacon infrastructure enables all receivers to estimate their own pose in the world coordinate system without any a-priori knowledge.

1) Camera: We integrated two different camera models. The main characteristics of the camera models are shown in table I. The ZELOS camera is an industrial camera model that comes with a Full High Definition (Full-HD) resolution. We will show in section IV that the positioning system achieves the desired accuracy demands using this camera model. We also integrated a no-name PAL camera in order to compare the effect of different image resolutions on the positioning accuracy. Both cameras are equipped with an optical low-pass IR filter.

2) Photo detector: The photo detector comprises a single, omnidirectional IR detector and a tiny ATMEL micro controller. The IR detector model Vishay TSOP34156 is a device

TABLE I
RECEIVER CAMERA MODELS

Camera Model	Zelos	PAL
Vendor	Kappa Optronics	No-Name
Sensor type	CCD	CMOS
Resolution	1920 × 1080 (HD)	640 × 480 (extrapolated)
Field of view	65°	160° (fish-eye)
Focal length	4.8 mm	1.8mm
Pixel per mm	181.81	120 (estimated)

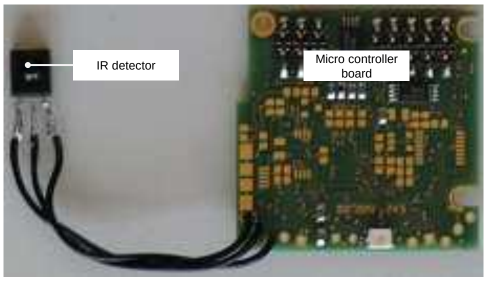

Fig. 3. Photo Detector Prototype

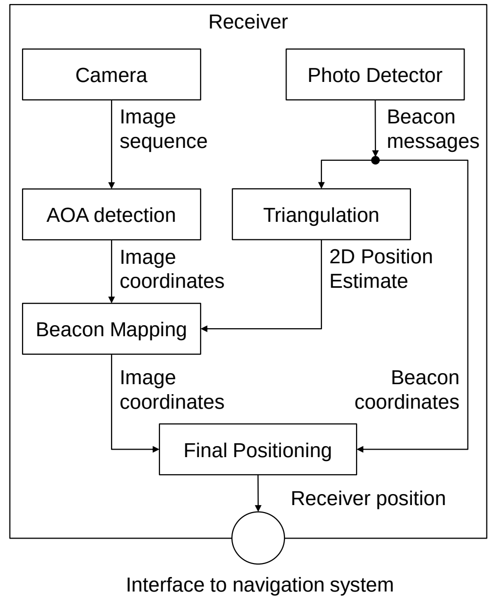

Fig. 4. Receiver data processing

used for remote control applications. The working prototype of the photo detector is shown in Fig. 3.

3) Data processing: The optical signals are processed by several image and signal processing blocks within the receiver. The structure of the receiver is shown in Fig. 4. The image sequence captured by the camera is fed into the AOA detection that localizes the beacons within an image (see section III-A). The photo detector signals are used in two ways: First, the global beacon coordinates contained in the beacon messages are used as input data for final positioning (see section III-D). Secondly, a triangulation (see section III-B) based on the transmit directions provides a first estimate for the (x, y) position of the receiver. This estimate allows to map beacon image coordinates to global beacon coordinates (see section III-C).

III. POSITIONING METHOD

A. AOA Detection

This section outlines a simple method for detecting the AOA of incident beacon messages. We will retrieve the AOA from an image sequence captured by a camera. Therefore, we will in fact determine the image coordinates (u_i, v_i) of beacons within a camera image.

We replaced conventional approaches such as image recognition or color/histogram tracking by signal processing methods. Since the beacons are active senders, we can use the signal features for beacon detection. Here, the flashing frequency of the beacons is detected in a video stream. Our new approach is to apply methods from one-dimensional digital signal processing to sequences of image frames. In this case, we designed a discrete multi-tone detector.

Digital signal processing methods usually deal with scalar time series. By considering each pixel in the frame sequence separately, we can apply standard tools for spectral analysis.

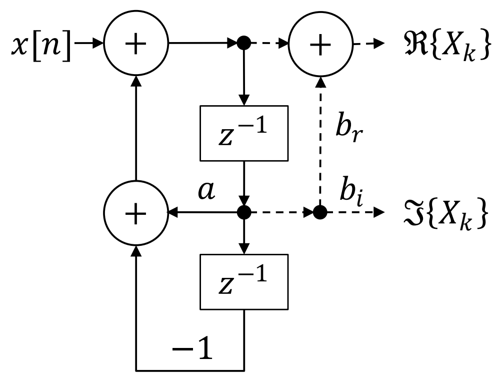

Fig. 5. Goertzel filter block diagram

A Discrete Fourier Transform (DFT) can compute the signal power P_k at a given frequency f_k which is the k-th harmonic to the sample rate f_s divided by the number N of samples taken. Thus, for the frequency $f_k = kf_s/N$ the signal power P_k can be derived from the Fourier coefficients $X[k]$:

$$P_k = \frac{2}{N^2}(\Re\{X[k]\}^2 + \Im\{X[k]\}^2) \tag{1}$$

We use the Goertzel algorithm [8], a computationally efficient method for detecting discrete frequency components in a signal. The Goertzel algorithm can be implemented as a second-order infinite impulse response (IIR) filter. Fig. 5 shows the block diagram of a Goertzel filter that estimates the Fourier coefficient X_k for a given frequency f_k. The filter coefficients a, b_r, and b_i derive from the normalized given frequency f_k and the sample rate f_s:

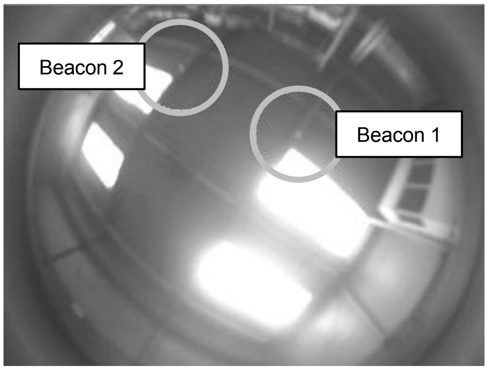

Fig. 6. Beacon image in time domain (video frame)

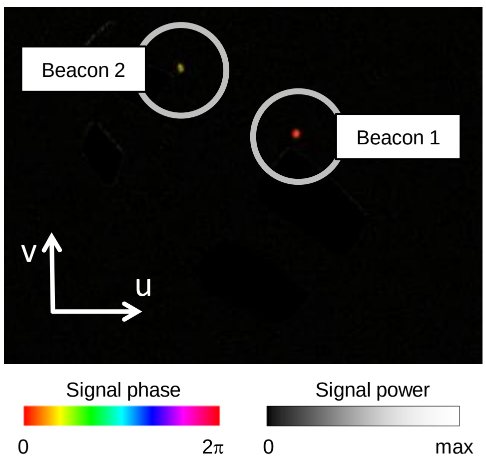

Fig. 7. Beacon signal phase and power at f_k = 5Hz, same scene as Fig. 6

$$b_r = \cos 2\pi f_k / f_s \tag{2}$$
$$b_i = -\sin 2\pi f_k / f_s \tag{3}$$
$$a = 2 b_r \tag{4}$$

We implemented the Goertzel filter for a video stream, so we considered each frame of the video sequence as a sample of the filter input sequence $x[n]$. For computing the fourier coefficient X_k we used pixel-wise image manipulating operators such as scalar multiplication and addition. Signal power is then derived using equation 1. Besides, we can compute the phase of the signal in order to separate distinct beacons within the image.

Fig. 6 shows two beacons mounted at the ceiling of a warehouse facility. The video was captured using the PAL camera. The beacons are flashing at a 5 Hz frequency. Fig. 7 shows the result of the power and phase estimation. The signal phase is encoded in the color range while signal power is encoded in the value. As can bee seen in the figure, the beacons can be easily detected.

The method described above is based on the assumption that each pixel in the video sequence can be treated independently. Therefore, the method only yields accurate results in case the camera does not move. In reality, beacon image positions will change over the frame sequence. For reliable detection at higher speeds, our beacon detection method is being expanded to compensate the camera motion. A promising approach is determining the optical flow within the image [9]. Given the optical flow of the image, we can transform the previous frames (i. e. the delay elements of the Goertzel filter implementation) and stabilize the analyzed signal in the image.

B. Triangulation

Triangulation is based on finding the intersection of two baselines that are defined by the beacon position and the transmission angle. It is sufficient to determine the horizontal transmission angle in the range $[0, \pi]$ since the baselines of other angles would overlap. Therefore, the opposite LED channels on the beacon are joined so that in effect there are 8 distinct channels.

We do not detect the angle sector (the LED channel), since the angular resolution would be only $22.5°$. A receiver that is in the overlap region of two LED channels will receive a superposition of the channel signals. Based on the ratio of superposition, the receiver can detect its two-dimensional position much more accurate. In case of ideal LED directivity the resulting signal delay is proportional to the transmission angle.

In case of more than two beacons in vicinity the estimated receiver position can be approximated by a least squares estimator. An alternative position estimate can be derived from the center of the convex hull of the intersecting lines.

C. Beacon Mapping

In section III-A we described how to measure the AOA of incoming beacon signals. In parallel, the photo detector branch of the receiver delivers the world coordinates of the beacons. The final positioning algorithm that will be described in section III-D needs the correct mapping between world coordinates (x_i, y_i, z_i) and image coordinates (u_j, v_j). After initializing the receiver this mapping is unknown. In other words, the world coordinates of the beacons will be ordered differently that the found beacon image coordinates.

Therefore, a method is devised to map beacon signals and world coordinates to beacon image coordinates. Using the triangulation described above, the two-dimensional position (x_r, y_r) of the receiver has already been estimated. Given the beacon image coordinates we are estimating the unknown pose parameters z_r and α_r. The receiver orientation α_r is also called yaw angle or heading. It is the angle between the world and receiver x axis. This procedure is only necessary in the initialization phase. Given an initial estimation, we project the beacon world coordinates onto the image plane and map the detected image positions using a nearest neighbour method.

We are considering the initial situation in the case of two visible beacons in a projection onto the (x, y) plane (top view) as shown in Fig. 8. The mapping of beacon numbers 1 and 2 to the image coordinates (u_k, v_k) and (u_l, v_l) is unknown. The azimuth angle between the u-axis of the camera coordinate system and the image points shall be denoted φ_k and φ_l.

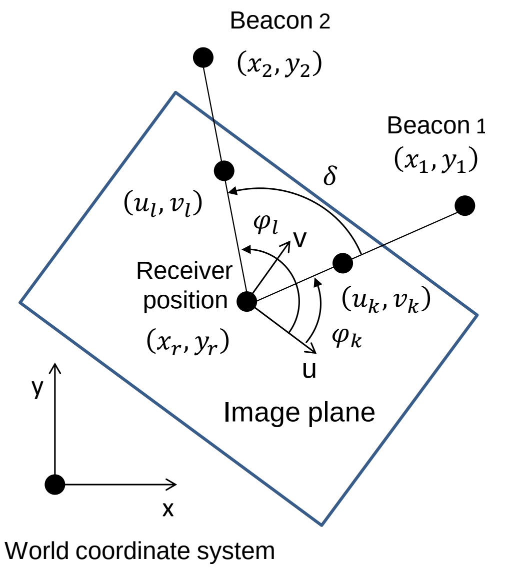

Fig. 8. Beacon mapping: Local azimuth angles

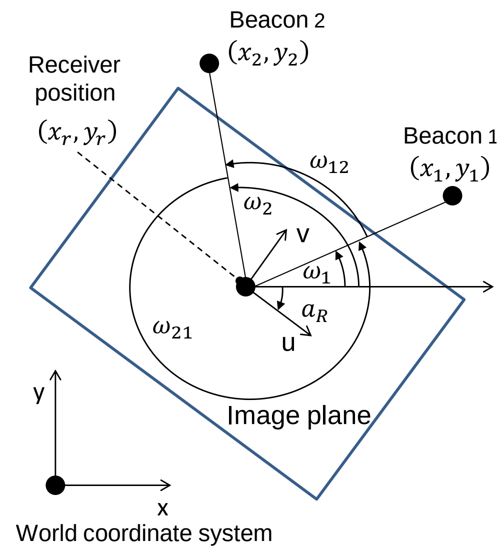

Fig. 9. Beacon mapping: Global azimuth angles

The azimuth angles are given in common convention (rotation counter-clockwise). The difference $\delta = \varphi_l - \varphi_k$ of the local azimuth angles is mapped to the interval $[0, 2\pi]$.

$$\phi_k = atan2(v_k, u_k) \tag{5}$$
$$\phi_l = atan2(v_l, u_l) \tag{6}$$

Given the two-dimensional position (x_r, y_r) a similar computation can be carried out using global azimuth angles as shown in Fig. 9. Then, the unknown pose parameter α_r can be determined using the global azimuth angles ω_1 and ω_2 that are the azimuth angle on the known beacon positions. We will consider the differences $\omega_{12} = \omega_2 - \omega_1$ and $\omega_{21} = \omega_1 - \omega_2$ of the global azimuth angles. Again, all angle differences are mapped to the the interval $[0, 2\pi]$.

$$\omega_k = atan2(y_1 - y, x_1 - x) \tag{7}$$
$$\omega_l = atan2(y_2 - y, x_2 - x) \tag{8}$$
$$\tag{9}$$

Given the angle differences d, ω_{12}, and ω_{21}, the correct mapping can be resolved by a simple comparison:

- $(k \to 1, l \to 2)$ if $\delta \sim \omega_{12}$
- $(k \to 2, l \to 1)$ if $\delta \sim \omega_{21}$

Now the unknown pose parameter α_r relates the following equations.

$$\omega_1 - \phi_1 = \alpha_r \tag{10}$$
$$\omega_2 - \phi_2 = \alpha_r \tag{11}$$

The equations are over-determined, so we calculate an estimate α_r that minimizes the sum or angle errors $\epsilon = (a_r - (\omega_1 - \varphi_1))^2 + (a_r - (\omega_2 - \varphi_2))^2$. Minimizing ϵ with respect to α_r finally yields estimate for α_r:

$$\alpha_r = ((\omega_1 - \varphi_1) + (\omega_2 - \varphi_2))/2 \tag{12}$$

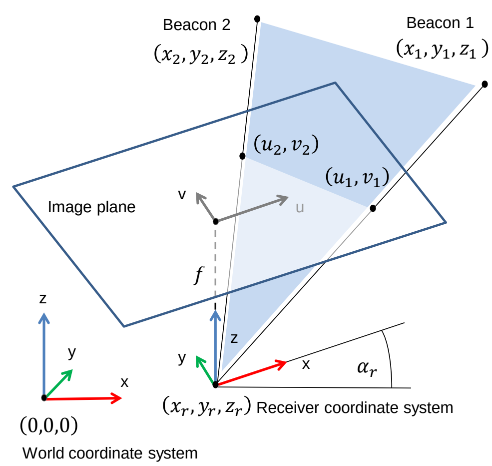

Fig. 10. Working Principle of Final Positioning

D. Final positioning

In this section, we describe how to compute the pose of the receiver by resolving camera projections of known beacon positions. The algorithm has already been described in a previous contribution [10]. By introducing constraints to the pitch and roll angle of the receiver orientation, we provide a computationally simple solution for the remaining 4 DOF (degrees of freedom). Furthermore, our solution can be calculated analytically and does not require numerical approximations or iterations. This offers a considerable simplification over general 4-DOF pose estimation methods such as given in [11].

We assume that the pitch and roll components of the receiver are known so that the optical axis of the receiver can be transformed on the z axis of the world coordinate system. For simplicity, it is assumed that this transformation has already been applied. Mathematically this is equivalent to assuming a receiver pointing upwards, strictly aligned with the z axis.

Fig. 10 shows the working principle of the positioning algorithm. Each beacon is located at distinct world coordinates (x_i, y_i, z_i). We define a local receiver coordinate system with z axis parallel to the world z axis. We want to determine the receiver´s 4 DOF, i.e. its position (x_r, y_r, z_r) in world coordinates and orientation α_r. The camera is modelled as an ideal pinhole camera with focal length f. The focal point defines the origin of the receiver coordinate system. The optical axis is aligned in z direction, i.e. the camera points upwards. The camera projects the beacons onto a two-dimensional, horizontally aligned image plane that has an orthogonal uv-coordinate system with u axis aligned with the receiver x axis. The origin of the image coordinate system is defined by the intersection of optical axis with the image plane. The camera performs a perspective transform of three-dimensional points into the image plane. As an example, beacon 1 at position (x_1, y_1, z_1) is projected onto image point (u_1, v_1).

The algorithm consists of two phases. First, the orientation α_r of the receiver is determined. Then, the position (x_r, y_r, z_r) of the receiver is calculated. The two phases are described in the following sections.

1) Orientation Calculation: In the first phase, the receiver orientation α_r is determined. The receiver coordinates are not considered during this phase. Instead, the receiver coordinate system is pinned at the origin $(0, 0, 0)$ of the world coordinate system. We consider two beacons with projected image points (u_1, v_1) and (u_2, v_2). The local position vectors $\vec{r} = (u_1, v_1, f)^T$ and $\vec{r} = (u_2, v_2, f)^T$ define a plane E. The key task is to find a receiver orientation α_r such that the both beacons are afterwards shifted into the plane E using the same translation.

The cross product of the incidence vectors yields the plane normal $\vec{n_r} = r_1 \times r_2$, given in receiver coordinates:

$$\vec{n_r} = \begin{pmatrix} (v_1 - v_2)f \\ (u_1 - u_2)f \\ u_1 v_2 - v_1 u_2 \end{pmatrix} \quad (13)$$

In world coordinates, the orientation α_r must be considered. It is modeled as a linear rotation matrix $R_z(\alpha_r)$ which transforms the plane normal from receiver coordinates into world coordinates $\vec{n}$:

$$\vec{n} = \begin{pmatrix} ((v_1 - v_2)\cos\alpha_r - (u_1 - u_2)\sin\alpha_a)f \\ ((v_1 - v_2)\sin\alpha_r + (u_1 - u_2)\cos\alpha_a)f \\ (u_1 v_2 - v_1 u_2) \end{pmatrix} \quad (14)$$

Since the image points are assumed to be known, the plane normal $\vec{n}$ is known except the orientation α_r. We now choose α_r in such a way that there exists a successive translation of the beacon positions b_i into the plane E. Both beacons can be translated with the same transformation, if and only if $\vec{n}$ is orthogonal to the vector $\vec{d} = b_1 - b_2$. In other words, after applying the orientation α_r to the receiver coordinate system, the straight line that connects b_1 and b_2 must be parallel to the plane E. Thus, we can express α_r by expanding the condition $\vec{n}^T \vec{d} = 0$ to the trigonometric equation

$$a\cos\alpha_r + b\sin\alpha_r + c = 0 \quad (15)$$

The coefficients a, b, c are derived from known values.

$$a = ((x_1 - x_2)(v_1 - v_2) - (y_1 - y_2)(u_1 - u_2))f \quad (16)$$

$$b = ((x_1 - x_2)(u_1 - u_2) + (y_1 - y_2)(v_1 - v_2))f \quad (17)$$

$$c = (u_1 v_2 - v_1 u_2)(z_1 - z_2) \quad (18)$$

We simplify the trigonometric equation 15 by substituting $t = \sin\alpha_r$. Thus, we get a quadratic equation

$$(a^2 + b^2)t^2 + 2bct + (c^2 - a^2) = 0 \quad (19)$$

Equation 19 is solvable due to the model assumptions. By solving equation 19, we get two candidate solutions $\alpha_r = \sin^{-1} t$. In regular conditions, only one of the candidate solutions α_r fulfils the original equation 15. In certain singular conditions, the position must be calculated for both candidates as shown in the following section.

The true solution must satisfy the condition $z_i > z + f$ for all beacons. This condition definitively holds for all points located in front of the camera lens.

2) Position calculation: In the second phase, the receiver position (x_r, y_r, z_r) is determined for a given receiver orientation α_r. We rotate the image coordinates (u_i, v_i) to $(u_i, v_i)'$ using the following transform

$$u_i' = u_i \cos\alpha_r - v_i \sin\alpha_r \quad (20)$$

$$v_i' = u_i \sin\alpha_r + v_i \cos\alpha_r \quad (21)$$

In the rotated coordinate system the camera projection can be easily expressed. For two beacons, a system of 4 linear equations is derived for 3 unknown (x_r, y_r, z_r) variables. The system of equations has rank 3. Thus, the system has a unique solution for the unknown (x_r, y_r, z_r). Solving the equation set directly yields the receiver position.

IV. Error Estimation

The essential characteristic of a positioning system is the guaranteed accuracy. A typical measure for the accuracy is the expected error range. Since the positioning algorithm shown in section III-D yields an analytical solution, we do not consider numerical stability which usually affects approximation-based methods. In other words, the positioning algorithm is exact if there are no measuring errors. Therefore, we will discuss common measuring error sources that affect the positioning accuracy. For the AOA measurement as the most crucial measurement error we will show the effect of the camera characteristics on the positioning error. We do not focus dynamic errors and only consider the accuracy in the static case.

A. Error Sources

After the installation of the beacons, the beacon positions must be calibrated by external measuring equipment. Obviously, there will be a measuring error during the calibration measurement. However, this error refers to an absolute reference and is not inherent in the positioning system. In other words, if the position of the beacons in an absolute reference system can only be given at a certain accuracy, it is conclusive

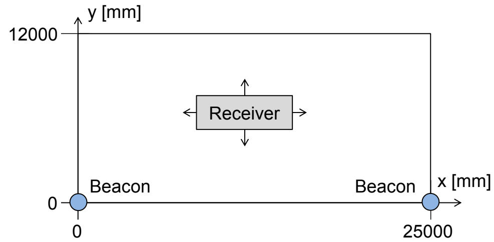

Fig. 11. Simulation environment

that the accuracy of the positioning system cannot exceed this accuracy.

Typical error source of optical positioning (and communication) systems are volatile light conditions, masking of objects and reflections. This will lead to biased AOA measurement results. The positioning accuracy depends on the relative position of the receiver to the beacons within line of sight. The eventual effect on the positioning accuracy is non-linear due to the trigonometric relations exploited by the algorithm.

B. Effect of Angle of Arrival Bias

We evaluated the influence of biased AOA measurements on the positioning error. In a simulation environment we compared the exact position of a receiver to the positioning result with biased AOA input data and determined an expected error in the (x, y)-Plane for each position. In fact, we applied biased pixel coordinates to the exact beacon projections on the image plane. This simulates a distorted AOA measurement.

The simulation environment is shown in Fig. 11. We placed two beacons in 25 m distance and 8 m height above ground. The dimensions are random, however, they relate to practical use cases for the system. We moved a virtual receiver in the (x, y)-plane between the beacons and with a lateral offset of 12 m. If the offset was wider, the next beacon (in 25 m distance) would move in sight of the receiver. The receiver is at ground level ($z_r = 0$) and zero degree heading ($\alpha_r = 0$).

We applied a pixel bias of 5 px which we considered a realistic accuracy of the AOA detection method in III-A. We ran the simulation for the ZELOS and PAL camera models. The determined error distributions are shown in Fig. 12 and Fig. 13. It can be clearly seen that the error distribution is non-linear in the simulated grid. The error is lowest and notably almost constant on the direct connection between the beacons. The error increases with increasing lateral offset. The unscaled behaviour of both cameras is comparable within the simulation.

We also examined the influence of varying pixel bias on the simulation results. The error ranges are shown in table II. It can be seen that the pixel bias has a linear effect on the error range.

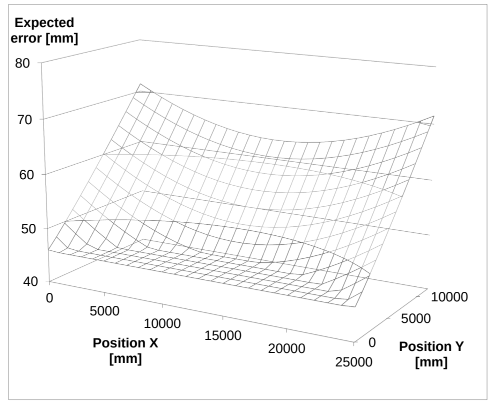

Fig. 12. Error distribution for ZELOS Camera

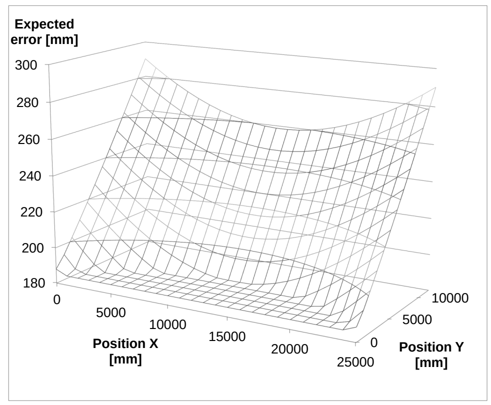

Fig. 13. Error distribution for PAL Camera

TABLE II
ERROR RANGES FOR VARYING PIXEL BIAS

Pixel Bias	ZELOS	PAL
1px	10-15mm	38-58mm
2px	19-29mm	75-116mm
3px	28-43mm	112-174mm
4px	37-58mm	149-232mm
5px	46-72mm	186-291mm

V. CONCLUSION

We proposed a versatile optical positioning method using off-the-shelf optical components. The positioning system we created for our specific use case and equipment delivers an accuracy below $0.1m$. In our error estimation we found that the accuracy depends on the camera characteristics and the beacon configuration. Therefore, the system is scalable: a denser beacon grid and higher camera resolution will lead to a higher accuracy. On the other hand, for lower accuracy demands cheaper cameras can be used.

Our future work will consider the dynamics of the system. We will extend the AOA detection using an optical flow correction as indicated above. Furthermore, we are considering sensor fusion concepts using INS (inertial measurement systems) and extending the positioning system to 6 DOF, thus including pitch and roll angles. At the time of writing this article we are preparing real world tests with the system. The main objective of these tests is to evaluate the estimated accuracy and reliability of the system.

A possible extension of the system is a stand-alone triangulation system without camera components. For a small camera-only installation with just two beacons the phase computation during the AOA detection can be used for distinguishing the beacons. So the beacon mapping would be obsolete, hence the photo detector and the successive triangulation. Replacing IR with VLC is another attractive approach, since VLC is easily integrated into standard illumination, thereby reusing existing infrastructure.

Our positioning method can be understood as a blend of common aviation navigation systems NDB (Non-Directional Beacon) and VOR (Very High Frequency Omnidirectional Ranging) by optical means. Thus, as a brief summary, we created lighthouses for indoor positioning.

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