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# Optical Indoor Positioning of Vehicles

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**Indoor positioning is the backbone of many advanced intra-logistic applications. As opposed to unified outdoor satellite positioning systems, there are many different technical approaches to indoor positioning. Depending on the application, there are different trade-offs between accuracy, range, and costs. In this paper we present a new concept for a 4-degree-of-freedom (4-DOF) positioning system to be used for vehicle tracing in a logistic facility. The system employs optical data transmission between active infrastructure and receiver devices. Compared to existing systems, these optical technologies promise to achieve better accuracy at lower costs. We will introduce the positioning algorithm and an experimental setup of the system.**

*[Keywords: Optical Indoor Positioning, Data Transmission, Signal Processing, Image Processing, Flexible Warehouse]*

## 1 INTRODUCTION

Positioning systems are required for any kind of navigation task. Main applications are motion control and route planning. These algorithms highly depend on precise and reliable positioning. Existing GNSS (global navigation satellite systems) already provide practical solutions for outdoor positioning problems, satellite positioning, however, cannot be used for indoor applications due to a high signal attenuation inside buildings. While GNSS have become the dominating system for open-sky, several systems share the indoor market; each having its own drawbacks, such as low accuracy, sophisticated infrastructures, limited coverage area or inadequate acquisition costs [Mau-08].

Indoor positioning opens numerous opportunities to logistics applications including tracking and tracing of goods, vehicle, and people movements. Generally speaking, such systems require as input data position information related to items or persons; in real-time and with sufficient accuracy. For any commercial application, system cost and implementation efforts are crucial. When accuracy demands are low enough (>1m) radio-based (RF) systems like RFID, W-LAN, Bluetooth and similar are well suited.

To our knowledge, there is no cost-effective and range-scalable solution for applications with higher accuracy demands. This is our main motivation for designing a novel positioning system based on optical technologies. Optical positioning covers a wide field of applications at all levels of accuracy, with its main application area in the sub-mm domain. The success of optical methods is fueled by improvements and miniaturization of actuators (e.g. lasers) and particular advancements in detector technologies (e.g. CCD sensors) [Mau-11]. Low-cost optical systems are inspired by the advent of consumer electronic devices that support a limited degree of positioning functionality for games and smart building applications. As an example, Nintendo Wii controllers can provide accurate positioning by detecting a ceiling-mounted IR LED array using a CMOS camera [Che-10]. However, the reported maximum sensing range of up to 530cm limits its use in warehouse facilities whose ceiling commonly exceeds 8m. Similar restrictions apply to other consumer devices which are primary designed for home use.

There are already emerging commercial indoor localization products for forklift trucks and other mobile vehicles based on low-cost optical technologies. The Zenotrack system employs a floor-headed camera system that determines the vehicle position based on stationary markers and relative displacement of the floor surface structure [Ess-10]. The system performance is promising, however still dependent on the floor surface readability and structural contrast which may vary and degrade in industrial environments. The Northstar indoor positioning system uses IR coded light spots which are projected onto the ceiling and detected by a mobile receiver using a camera. Most ceilings in industrial environments, however, are not suited well as projection planes due to obstacles and ceiling windows.

This paper is organized as follows: Section 2 describes in brief the positioning system we are developing. Then we explain the algorithm devised for 4-DOF positioning. A simple method for detecting active beacons within a video sequence is shown in section 4. A miniaturized demonstrator setup is shown in section 5 as a proof of concept. We conclude our paper by presenting

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experimental results of the system in an industrial environment and outline our future work.

## 2 SYSTEM DESCRIPTION

Our key idea is to provide a sufficient position accuracy using low-cost optical components. The proposed positioning system consists of an array of "beacons", i.e. light-emitting devices located at well-known positions in the facility layout. This infrastructure will be used by mobile receivers to autonomously determine their poses (position and orientation). Figure 1 gives an overview of the positioning system. Essentially, a beacon comprises an arrangement of LEDs (light emitting diodes) and a simple microcontroller. Beacons regularly broadcast their coordinates with respect to an arbitrary "world" coordinate system by modulating the LED intensities.

This, in fact, is a data transmission. It can be carried out by infrared or visible light. Visible light communication is easily integrated into standard illumination, thereby reusing existing infrastructure. However, infrared signals can be processed using standard off-the-shelf hardware. In the current implementation, we therefore selected infrared communication at 940nm. Our data transmission scheme uses a TDMA (time slot) approach in order to allow multiple beacons to share the same media.

A receiver mounted on an "object of interest", e.g. a forklift truck, detects signals from a set of beacons in its vicinity. The receiver comprises a CCD (charged coupled device) camera and an array of photo diodes. These sensors allow the angle of arrival with respect to a beacon to be estimated from the received optical signals. 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.

Provided location and orientation of the receiver with respect to the object of interest are well defined, this allows the pose of the forklift to be determined from simple coordinate transforms. Moreover, the receiver is able to compute the pose of a pallet that is loaded on the fork. This is the intended use case of the system: tracking and tracing goods in a warehouse. Assuming all pallet movements in a warehouse are carried out by forklift trucks, tracing forklift poses in real-time will allow all pallet movements to be modeled on-line. This is a paradigm shift for organizing flexible warehouses. As opposed to traditional approaches, pallets can be recorded based on their pose instead of pre-determined locations leading to flexible storage locations that can be allocated and released on-the-fly. For this application, a flexible WMS (warehouse management system) software is being developed [Mee-11]. In this use case, for distinguishing pallets, an accuracy of at least half the pallet dimensions is needed. However, the goal of the system is to achieve an even higher accuracy of 10 cm while the vehicle stops, and 1 m while the vehicle moves.

The forklift truck is assumed not to pitch or roll. Then, it is sufficient to determine the pose in 4 dimensions, i.e. position in xyz and yaw angle (rotation around world z-axis).

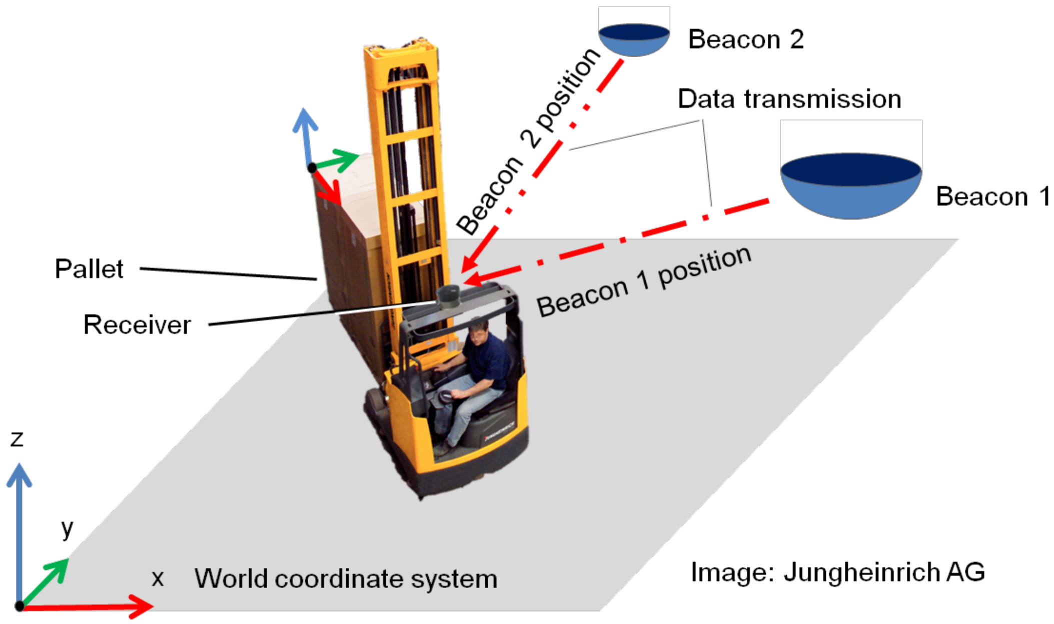


***Figure 1.*** ***System overview***

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## 3 Positioning algorithm

In this section, we describe how to compute the pose of the receiver by resolving camera projections of known beacon positions. By introducing constraints to the pitch and roll angle of the receiver orientation, we provide a computationally simple solution for the remaining 4 DOF. Furthermore, our solution can be calculated analytically and does not require numerical approximations or iterations. This offers a considerable simplification over general 6-DOF pose estimation methods such as given in [Hor-87]. The pitch and roll angles can be easily acquired using an accelerometer, i.e. a gravitational sensor. Thus, our positioning algorithm can be extended to 6-DOF using external sensors.

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, the following section assumes that this transformation has already been applied. Mathematically this is equivalent to assuming a receiver pointing upwards, strictly aligned with the z axis.

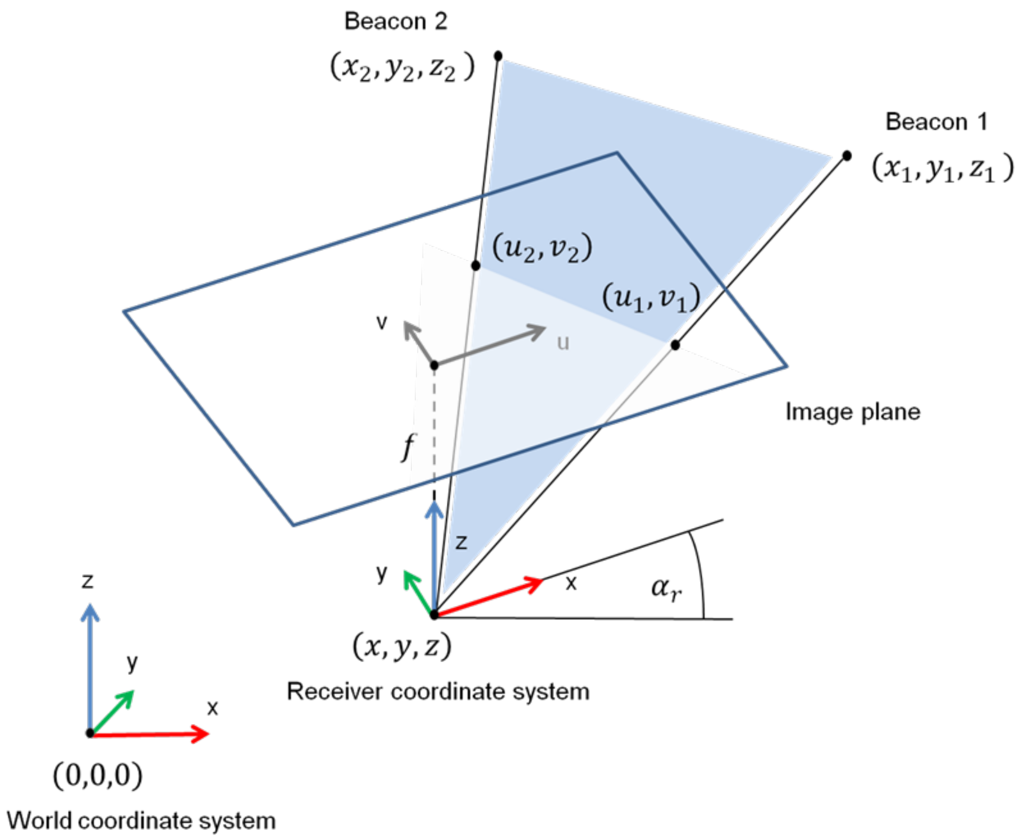


***Figure 2. Working principle of positioning algorithm***

Figure 2 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 $(x, y, z)$ in world coordinates and orientation $\alpha_r$. The receiver orientation $\alpha_r$ is also called yaw angle or heading. It is the angle between the world and receiver x axis.

The camera is modeled 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 $\alpha_r$ of the receiver is determined. Then, the position $(x, y, z)$ of the receiver is calculated. The two phases are described in the following sections.

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### 3.1 Orientation calculation

In the first phase, the receiver orientation $\alpha_r$ is determined. The receiver coordinates are not considered during this phase. Figure 3 shows the working principle of the orientation calculation. During this phase, 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 $\vec{r_1} = (u_1, v_1, f)^T$ and $\vec{r_2} = (u_2, v_2, f)^T$ define a plane $E$. The key task is to find a receiver orientation $\alpha_r$ such that the both beacons are afterwards shifted into the plane $E$ using the same translation.

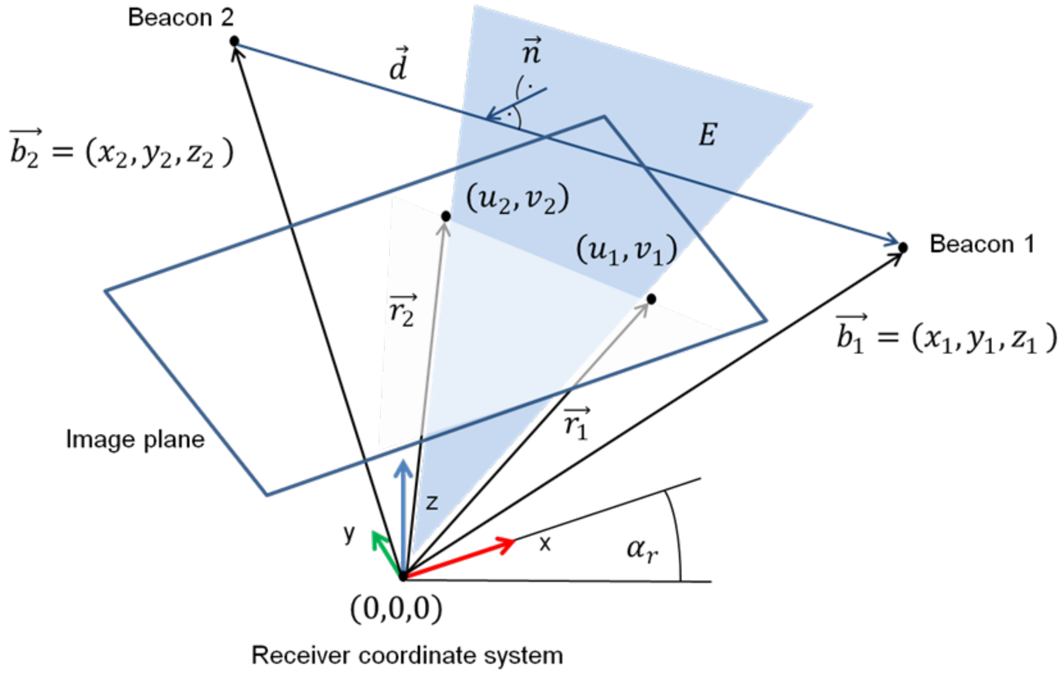


***Figure 3. Orientation calculation***

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

$$\vec{n_r} = \begin{pmatrix} (v_1 - v_2)f \\ -(u_1 - u_2)f \\ u_1 v_2 - v_1 u_2 \end{pmatrix} \tag{1}$$

In world coordinates, the orientation $\alpha_r$ must be considered. It is modeled as a linear rotation matrix $R_z(\alpha_r)$ transforming the plane normal from receiver coordinates into world coordinates:

$$\vec{n} = R_z(\alpha_r)\vec{n_r} = \begin{pmatrix} \cos\alpha_r & -\sin\alpha_r & 0 \\ \sin\alpha_r & \cos\alpha_r & 0 \\ 0 & 0 & 1 \end{pmatrix} \vec{n_r} = \begin{pmatrix} ((v_1 - v_2)\cos\alpha_r + (u_1 - u_2)\sin\alpha_r)f \\ ((v_1 - v_2)\sin\alpha_r - (u_1 - u_2)\cos\alpha_r)f \\ u_1 v_2 - v_1 u_2 \end{pmatrix} \tag{2}$$

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

$$a\cos\alpha_r + b\sin\alpha_r + c = 0 \tag{3}$$

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

$$a = \big((x_1 - x_2)(v_1 - v_2) - (y_1 - y_2)(u_1 - u_2)\big)f \tag{4.1}$$

$$b = \big((x_1 - x_2)(u_1 - u_2) + (y_1 - y_2)(v_1 - v_2)\big)f \tag{4.2}$$

$$c = (u_1 v_2 - v_1 u_2)(z_1 - z_2) \tag{4.3}$$

We simplify the trigonometric equation (3) by substituting $t = \sin\alpha_r$. Thus, we get a quadratic equation

$$(a^2 + b^2)t^2 + 2bct + (c^2 - a^2) = 0 \tag{5}$$

Equation (5) is solvable due to the model assumptions. By solving equation (5), we get two candidate solutions $\alpha_r = \sin^{-1} t$. In regular conditions, only one of the candidate solutions $\alpha_r$ fulfils the original equation (3). 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.

### 3.2 Position calculation

In the second phase, the receiver position $(x, y, z)$ is determined for a given receiver orientation $\alpha_r$ .

We rotate the image coordinates $(u_i, v_i)$ to $(u_i, v_i)'$ using the following transform

$$u_i{}' = u_i \cos\alpha_r - v_i \sin\alpha_r \tag{6.1}$$

$$v_i{}' = u_i \sin\alpha_r + v_i \cos\alpha_r \tag{6.2}$$

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 $(x, y, z)$ variables

$$(z_1 - z)u_1' = (x_1 - x)f \tag{7.1}$$

$$(z_2 - z)u_2' = (x_2 - x)f \tag{7.2}$$

$$(z_1 - z)v_1' = (y_1 - y)f \tag{7.3}$$

$$(z_2 - z)v_2' = (y_2 - y)f \tag{7.4}$$

The system of equations has rank 3. Thus, the system has a unique solution for the unknown $(x, y, z)$. Solving the equation set directly yields the receiver position.

## 4 Beacon detection

This section outlines a simple method for retrieving the input data needed for the positioning algorithm. At least it requires the image coordinates $(u_i, v_i)$ and the corresponding world coordinates $(x_i, y_i, z_i)$ of two beacons.

Our system uses IR data transmission to broadcast the world coordinates, all that remains is deriving image coordinates of the beacons from a frame sequence in a dynamic environment. Those can be detected by conventional approaches such as image recognition or color/histogram tracking methods like the CAMSHIFT algorithm [Bra-98]. Since we have an active sender, we can use artificial features for beacon detection. Here we chose to modulate the beacon intensities at a low frequency. The flashing frequency of the beacons is then detected in a video stream. Our approach is new in the sense, that we 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. A DFT (discrete fourier transform) 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

$$f_k = k\frac{f_s}{N} \quad (8)$$

the signal power $P_k$ can be derived from the Fourier coefficients $X[k]$:

$$P_k = \frac{2}{N^2}(Re\{X[k]\}^2 + Im\{X[k]\}^2) \quad (9)$$

Different beacons may be easily distinguished when they emit optical signals of different spectral content. For the minimal setup with two beacons it is sufficient to analyze two distinct frequency components in the input sequence. We use the Goertzel algorithm [Goe-58], a computationally efficient method for detecting discrete frequency components in a signal. Figure 4 shows the block diagram of a Goertzel filter that estimates the signal power at a given frequency $f_k$.

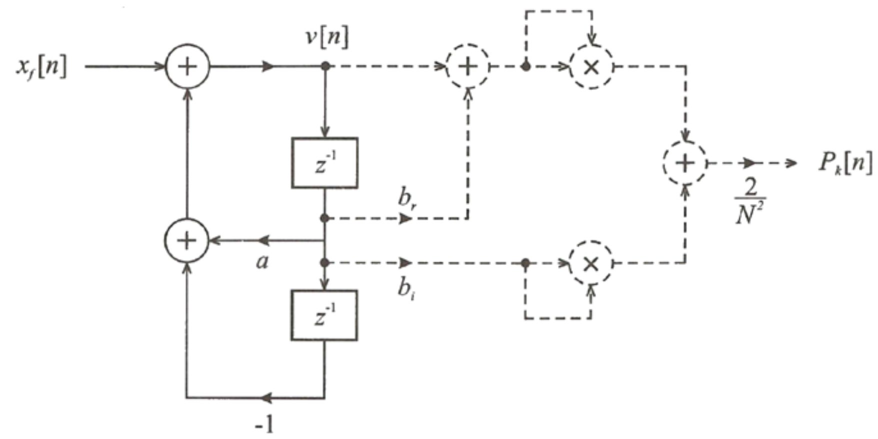


***Figure 4. Goertzel filter for estimating power at given frequency [Grü-04]***

The Goertzel algorithm is commonly implemented as a second-order IIR (infinte impulse response) filter shown above. Since we implement the Goertzel filter for a video stream, we treat each pixel as a distinct input sequence $x[n]$. The pixel-wise processing enables a parallel approach, since all pixel values can be treated independently by image manipulating operators.

The method described above only yields exact results in case the camera does not move. In reality, beacon image positions will change over the frame sequence. Nevertheless practical application shows good results even in case of a moving camera provided the speed is slow compared to the frame rate. A beacon signal will span several pixels in the camera image. Hence the spectral component can be detected even under influence of slow camera motion. For reliable detection at higher speeds, our beacon detection method will need to be expanded to compensate the camera motion. Such methods are known as image registration and Global Motion Estimation [Zit-03]. A suitable approach is determining the optical flow within the image [Hor-81]. Once the e. g. affine transformation from image to image is known, we can transform the previous frames (i. e. the delay elements of the Goertzel filter implementation) such that the analyzed signal is stabilized in the image. A similar process is given in [Ver-07]. We will show our results in a subsequent contribution.

## 5 DEMONSTRATOR SETUP

We implemented the proposed positioning method in a miniaturized demonstrator setup as shown in figure 5. The main goal of the demonstrator setup is a rapid feasibility test of the proposed system. For this purpose, we equipped a forklift truck model with a wireless CCD camera. The truck model can be manually moved around a horizontal whiteboard that simulates a facility layout. For our demonstrator setup we made two simplified beacons that are mounted above the simulated facility layout. Each beacon consists of a single LED light source that is controlled by a programmable logic controller.

A 160° FOV (field of view) fish-eye lens is mounted on the camera. Thus, the camera image covers nearly the entire visible half-space. This fish-eye lens introduces a radial distortion that must be compensated by calibrating the intrinsic camera parameters. We applied a standard calibration method using multiple views of a rectangular chessboard calibration pattern. From multiple views of the

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same pattern the intrinsic and extrincic camera parameters can be derived. Also, the radial distortion coefficients are determined to compensate for the fisheye effect. The resulting camera parameters are used to undistort the beacon image positions after the beacon detection. All computations are carried out in the distorted camera image which is adaequate since no geometric features are considered. As an alternative, the entire image can be undistorted before beacon detection, at the cost of much higher computation efforts.

A rechargeable battery inside the model powers the camera which continuously transmits an analog video signal via radio (2,4 GHz). The receiver, connected to a PC, delivers a composite video signal which is then captured by a USB frame grabber and processed by dedicated software. The software determines the beacon image positions in the video stream and calculates the forklift truck model position.

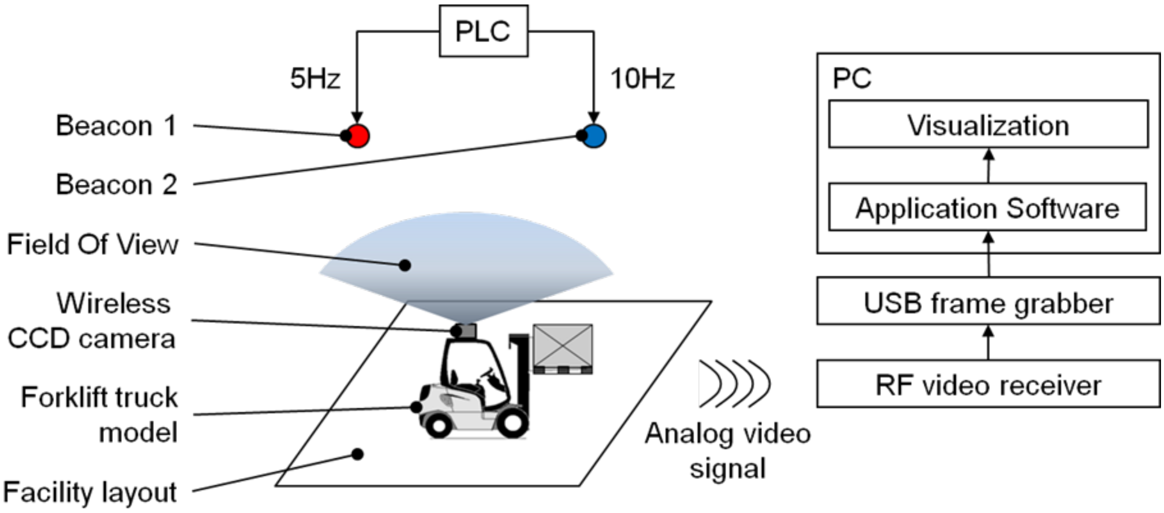


***Figure 5.*** ***Experimental setup***

For this demonstrator, beacons are modulated at frequencies of $f_1$= 5Hz and $f_2$= 10Hz. The sample rate $f_s$ is 25Hz (frames per second, FPS). In the Goertzel algorithm, we can chose 5, 10 and 15 as the number $N$ of samples. Figure 6 shows results of signal processing. On the left, the original camera image is shown in time domain. The video signal sequence is transformed into frequency domain using the Goertzel filtering approach shown in section 4. On the right, the spectral power is shown for 5Hz (red) and 10Hz (blue) frequencies. The image pixel with the maximum signal power $P_k$ is chosen as the center of the beacon signal flashing at frequency $f_k$. As can be seen from the figures, each beacon corresponds to an image spot that has a diameter of several pixels. Therefore, the beacon detection works at slow movements even without an image stabilization component.

The application software was built in C++ using Microsoft © Visual Studio 2008 Professional. Our image processing is based on the OpenCV library revision 2.4.5. We used a Panasonic © CF-19 Toughbook with Intel ® Core™ i5 CPU @1,2 GHz running Microsoft © Windows 7 Professional. The video stream can be processed in real time (40ms/25FPS) at image size 320x240 pixel. We did not measure the video stream latency nor the accuracy of the demonstrator setup. We carried out such experiments in an industrial setup as described in the following section.

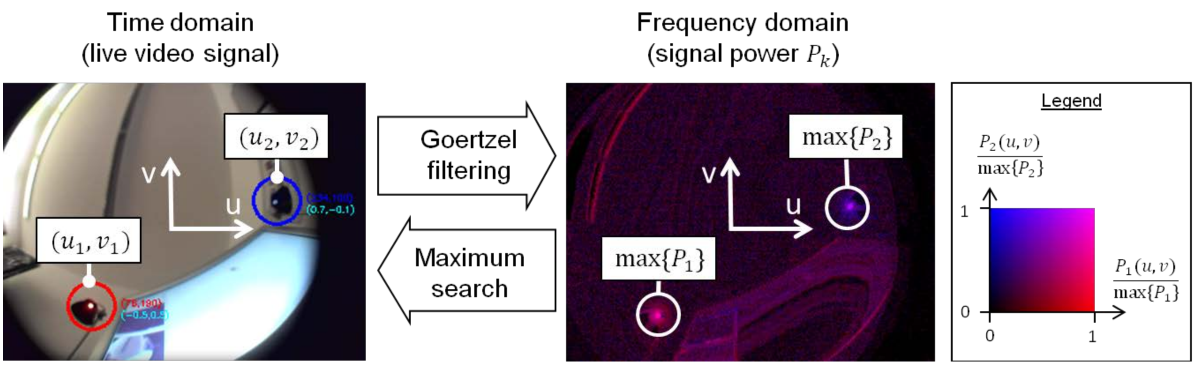


***Figure 6.*** ***Live video image (left) and signal power image (right) for detecting beacons***

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## 6 Industrial Setup

Based on the feasibility study using the demonstrator setup we conducted tests in a real-world industrial environment. The main goal of the industrial setup is to determine the effective accuracy and processing time of the proposed positioning system. For this purpose, two beacons have been mounted on the facility ceiling which is approximately 8m above ground level. Both beacons emit a periodic coded IR signal at a 5 Hz frequency. The beacons can be distinguished based on this signal.

Similar to the demonstrator setup, the camera signals are captured by a low-cost camera which is equipped with an IR filter. An IR filter is not mandatory, but obviously it enhances the image content with respect to the beacon signals. We ran the camera at a 640x480 pixel resolution. Beacon detection and positioning is carried out by a PC-based evaluation software. Figure 7 (left) shows a snapshot of the image sequence captured by the camera (comparable to fig. 6, left). In the image, both beacons can be seen as a light spot on the left side of the image. Another stationary light source can be seen at the right side of the image. Figure 7 (right) shows the result in the spectral domain (comparable to fig. 6, right). The true beacons can be easily detected based on their unique periodic signal. Other light sources can be filtered out due to the absence of this signal, which is a major advantage compared to static optical markers and features. Therefore, we expect the system to be suitable for environments with high light pollution.

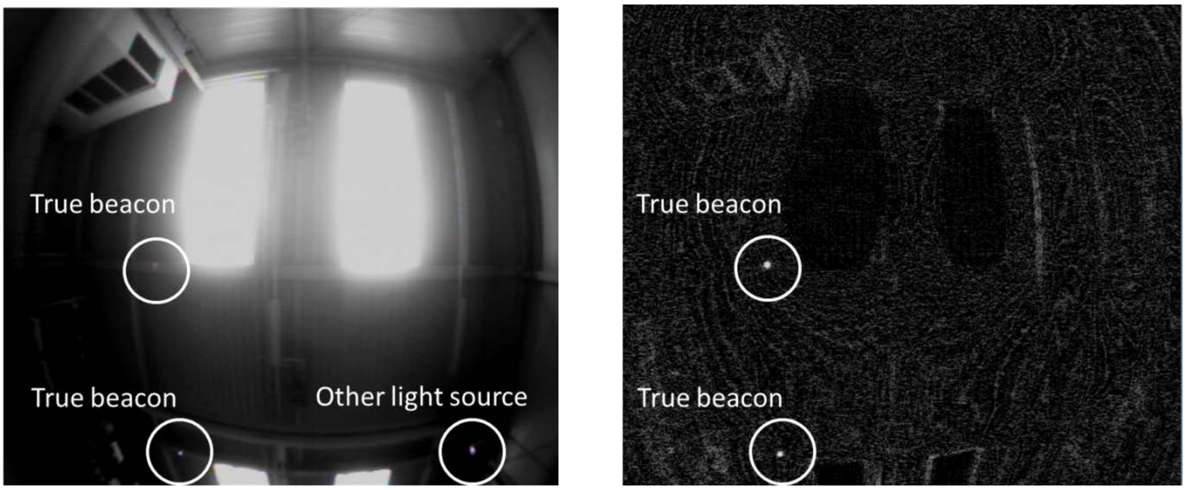


***Figure 7.*** ***Live video image (left) and signal power image (right) for detecting beacons***

For evaluating the positioning accuracy we positioned the receiver at well-defined poses on a rectangular grid at ground level. Multiple position measurements at each pose have been compared to the true receiver position using an euclidean distance measure in the ground plane. These positioning errors have been averaged for each position. Figure 8 shows the beacon position and the distribution of the average positioning error over the rectangular test grid. In total, 63521 single measurements at 288 poses have been considered. Using the low-cost 640x480 camera, an average error of less than 400mm can be achieved in the static case, i. e. while the vehicle does not move.

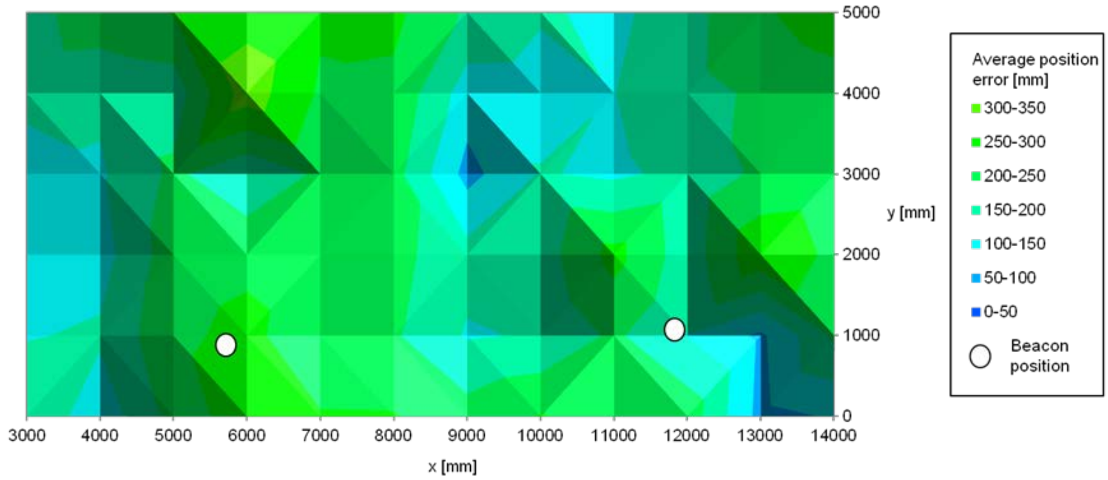


***Figure 8.*** ***Average position error using low-cost 640x480 camera***

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The runtime of the signal processing algorithm determines the update rate of the positioning system, i. e. the number of position measurements per time interval. On our current PC platform (see section 4) a single position calculation takes less than 400 ms for a 640x480 pixel sequence of 5 images, resulting in an update rate of 2,5 Hz. The calculation can be parallelized for multiple blocks, so that on a dual-core processor the calculation time effectively reduces to 200 ms, leading to an update rate of 5 Hz. The update rate affects the positioning accuracy during the vehicle movement. A forklift truck driving at a maximum speed of 5 m/s will move approximately 1 m at the update interval of 200 ms. This latency of the positioning system will, in the worst case, increment the static position error by the distance moved during that period.

The range of the beacon signals, i. e. the detectability of the beacons in the camera image depends on the camera resolution on the receiver side. Whenever too few, i. e. less than two beacons can be detected the system is unavailable. In the industrial setup so far, we found that beacon-to-receiver distances of more than 15m heavily degrade the system availability. Since the positioning algorithm requires at least 2 beacons within line of sight, beacons would have to be mounted with no more than 15m distance from each other. The number of beacons actually needed for a particular setup depends on the facility layout, e. g. storage racks can block the line of sight to the beacons and require more beacons that an open hall area.

## 7 FUTURE WORK

We showed that a 4-DOF positioning method is feasible using off-the-shelf optical components. For our demonstrator setup, hardware requirements are minimal: A camera and a set of simple, active beacons are sufficient. The full-scale positioning system of the industrial setup requires more sophisticated beacons, however, the hardware cost is still attractive. A positioning accuracy of 400 mm has been achieved. This section gives an overview of the work in progress and our future research.

We are working on a fully developed receiver that will include an HD image sensor. The increased resolution will increase the positioning accuracy and extend the beacon to receiver range. We then expect the receiver to achieve an accuracy of less than 100 mm and a beacon to receiver range of 25m. At the time of writing this article the appropriate mechanical and electrical design of the camera is being implemented.

The beacon detection shown above currently does not cope too well with rapid movements, so we are finalizing the motion-compensated beacon detection using an optical flow correction as indicated above. A complementary research direction is the integration of a position estimation concept to smoothen the receiver output. We will be considering extended Kalman filtering (EKF) and sensor fusion concepts as well.

Finally, we will continue to examine the accuracy and reliability of the system in both the static and dynamic cases. Thereby we intend to verify our system constitutes a cost-effective solution with sufficient range and accuracy for warehouse applications.

## ACKNOWLEDGEMENTS

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