University of Pannonia
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Thesis Book

Methods for visible light-based indoor positioning using angle difference measurements and LED lighting infrastructure

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1 Introduction

Be it the positioning of a mobile phone, a passenger vehicle, or any autonomous transportation vehicle in a warehouse, the demand after new and more reliable positioning methods and technologies is high. While the outdoor case of object positioning is dominated by the Global Navigation Satellite Systems, indoor positioning is still under heavy research with various techniques competing with each other trying to provide the best solution for the different use cases and their requirements.

Indoor positioning can be achieved with numerous technologies, e.g., using radio signals, ultrasound, RFID tags, graphical markers, fingerprinting, and optical solutions. The thesis provides contributions to visible light-based indoor positioning systems utilizing cameras as to be positioned objects, and LED light fixtures as reference points that are pre-installed in known positions and can also be part of the environment's lighting infrastructure. The reference points (LED beacons) are identified by utilizing a Visible Light Communication protocol. The thesis introduces a possible implementation of such an indoor positioning system on which the results are based.

Section 2 describes the problem statements and research goals. Section 3 presents my research results. Section 4 provides a brief overview how these results may be utilized.

2 Problem statements and research goals

Off-the-shelf cameras present a promising opportunity for the development of indoor positioning systems due to the advancements of camera technology in recent years: their quality is increasing, yet they become more and more affordable and widely available. With the advancements of computer vision and image processing algorithms off-the-shelf cameras can be used to identify and track visible light patterns more accurately. This enables the development of robust positioning solutions that work effectively in complex indoor environments, where other positioning technologies may not be applicable.

My main research goal was to create a robust visible light-based indoor positioning system, that is able to provide real-time position and orientation estimates in the centimeter range, while still can be considered inexpensive.

Optical positioning techniques utilize "anchor" features in images to determine the position and orientation of the camera sensor. The position of these reference points is either estimated on the go, or measured at the installation phase of the system. Image feature extraction methods are used to detect possible anchor points based on their descriptive properties, which is a difficult task: there exists several algorithms tailored to specific needs, but there is no universal solution; it can be computationally expensive; its success rate may depend on the properties of the environment, and may provide several non-reliable, and false detections. Using modulated LED light fixtures as anchor points is beneficial in multiple ways: the detection of such features is not computationally demanding; they can be easily detected in the image as bright spots, and can be identified based on their unique modulation patterns; when operated in the visible light spectra, they may also be part of the environment's lighting infrastructure. It is also important to note that the modulation signal of the protocol needs to be high enough to achieve flicker-free operation that does not disturb the human eye (>> 200 Hz). However, the sampling rate (or frame rate) of off-the-shelf cameras is usually limited to 30-

60 Hz, inevitably causing undersampling. Thus, special communication protocols need to be used that can operate even when the transmitted data signal is undersampled.

Undersampled Frequency-Shift On-Off Keying (UFSOOK) [1] and Undersampled Phase-Shift On-Off Keying (UPSOOK) [2] are two visible light camera communication protocols found in the literature that can be used to transmit data between a light source and a camera sensor. They can also be adjusted to minimize the flickering for the human eye.

The features of UFSOOK and UPSOOK made them promising to be used for beacon identification for the visible light-based positioning system. My first goal was to analyze them and provide detailed explanation how various error sources may affect their operation.

While examining UFSOOK and UPSOOK it turned out that they need time synchronization and precise clock signal generators to operate reliably, which is not feasible in most practical cases, and reduces the beacons' cost-effectiveness. Also, their proposed decoding method depends on the sampled light intensity, which makes them impractical for positioning applications where the position of the transmitters and receivers may change over time (e.g., the receiver is fixated on a moving object).

My second goal during my research was to address the trackability and reliable identifiability of the beacons without synchronization by: designing an LED light fixture that is easy to track in the camera image and can be used to transmit beacon IDs for the positioning system; developing a robust communication protocol tailored for the periodical transmission of constant beacon data (e.g., identification number).

The third topic of my research was directed towards the positioning methods used in the system. Most solutions require at least 6 beacons to operate, due to the degree of freedom in a general, 3-dimensional case (e.g., in case of MLPnP [3]). The type of lens used for the camera also has an impact on the expenses of the system: by using a fisheye lens, the field of view of the camera sensor is gradually increased, lowering the beacon count needed for the operation of the positioning system. For most practical applications, the estimation of a 2-dimensional position and orientation is sufficient, which decreases the degree of freedom, and further decreases the minimum number of beacons required by the system. A reliable positioning solution also has to handle outlier measurements in the system, whose occurrence is unavoidable in most cases due to reflections and other measurement error possibilities.

My third goal during my research was to develop robust, fast positioning solutions that can provide 2-dimensional position and orientation estimates in real-time while mitigating the impact of outlier measurement errors in the system.

3 Theses

Thesis 1

I provided the detailed analysis of various error sources affecting the communication performance of the Undersampled Frequency-Shift On-Off Keying (UFSOOK) and Undersampled Phase-Shift On-Off Keying (UPSOOK) visible light communication protocols. With the achieved results the protocol's parameters can be designed to achieve optimal data transmission between LED light fixtures and digital cameras with regard to the protocol's limitations. I validated the theoretical results with simulations and real measurements.

1.1 I proposed a new equivalent mathematical operation model for digital cameras operating with modulated light sources to allow the mathematical analysis of the protocols' behavior.

1.2 I determined the bit error rate (BER) in the presence of frequency slip that is inevitable when there is no synchronization between the transmitter and the receiver. I proved that the best achievable BER depends on the frequency slip for both data symbols of the protocols.

1.3 I determined the BER as a function of threshold parameter Q, which is used by the protocol to determine the state of a transmitter. I proved that the value of Q has no effect on the BER for symbols utilizing same transmitter states (SPACE for UFSOOK, MARK for UPSOOK). I also proved that there is an optimal range for parameter Q, where the BER is minimal, for symbols using opposite transmitter states (MARK for UFSOOK, SPACE for UPSOOK).

1.4 I determined the effect of the measurement noise on the BER, for both data symbols. I proved that the effect is highest for values Q near the extrema of the sensed signal. The effect of noise is minimal for Q values at the mean signal amplitude.

1.5 I determined the frequency of occurrence and size of unsafe intervals, where the operation of the protocols may possibly be faulty. I showed that in case of UPSOOK, the unsafe intervals are aligned, as opposed to UFSOOK. I determined the packet error rate (PER) for the UPSOOK protocol based on the aforementioned achieved results.

Related publications: [S1], [S2], [S3], [S4], [S5]

Other related publications: [SO1], [SO2], [SO3], [SO4]

Thesis 2

I proposed two novel visible light communication solutions that address the issue of trackability and robust identifiability of beaconing infrastructures in visible light-based positioning systems. The proposed Trackable UPSOOK (TUPSOOK) solution, achieved through a special beacon design, makes it possible to detect the beacons in every image frame of a camera, even from large distances, while maintaining its communication capabilities and usability as practical environmental lighting infrastructure. The proposed Robust UPSOOK (RUPSOOK) protocol is able to operate in an error-free manner on a wide range of system parameters and can be used with the beacon design of TUPSOOK to also fulfill the trackability requirement. I verified the usability of the solutions with simulations and real measurements.

2.1 I proposed a novel beacon design containing an internal circular LED and an outer ring-shaped LED around it. The proposed architecture allows continuous detection and thus, continuous tracking of the transmitter. I modified the coding scheme of UPSOOK, to only utilize two transmitter states and one data frequency. The modified coding scheme (TUPSOOK) fits well the new beacon design. The price of the modifications is the somewhat decreased data rate.

2.2 I proposed a novel encoding-decoding scheme (RUPSOOK) for visible light communication based on Manchester coding and equivalent sampling, which is able to periodically transmit constant data (e.g., beacon ID). I proposed a design method to determine the nominal frequency slip to achieve optimal robustness in the protocol. I proved that the RUPSOOK protocol is robust over a finite range of system parameters, including: exposure time, frequency slip, threshold, jitter, saturation, and noise.

2.3 I proposed an adaptive thresholding method which provides robust transmitter state detection for changing signal amplitudes that may inevitably occur when the transmitter or the receiver is moving.

Related publications: [S3], [S4], [S6], [S7]

Other related publications: [SO1], [SO2], [SO3], [SO4]

Thesis 3

I proposed two novel positioning methods for angle difference of arrival (ADoA)-based positioning to determine the position and orientation of a sensor based on angle difference measurements of reference points (beacons). The proposed solutions require the sensor's normal vector (e.g., facing upwards) and the position of reference points to be known. A minimum number of 3 beacons is needed for their operation, which makes them useable for practical applications. The solutions are able to filter outlier measurements to provide robust operation. I verified the usability of the proposed solutions with simulations and real measurements.

3.1 I proposed a geometry-based heuristic method (HIAL) to determine the position and orientation of a sensor using angle difference measurements of reference points, provided that the normal vector of the sensor is known. The advantage of the proposed method with respect to the general (3D) geometric solutions is that the search is performed on a plane instead of space, thus the speed and performance is improved. The algorithm calculates potential solutions by constructing circular arcs based on beacon pairs and subsequently determining intersections based on arc pairs; each intersection point represents a potential solution. I proposed a heuristic ranking to quantify the relative confidence of these possible solutions, using two distance-based filtering parameters.

3.2 I proposed a novel, outlier-tolerant, RANSAC-based method (RBL) to determine the position and orientation of a sensor using angle difference measurements of reference points, given that the normal vector of the sensor is known. The proposed solution calculates an initial position and orientation estimate with RANSAC using a linearized equation system. Subsequently, it refines the pose estimate utilizing the best consistent beacon group of the initial estimate. The solution uses location-independent, angle-based outlier-filtering criteria, which are simple, and user-friendly to set, in contrast to HIAL's filtering parameters. The estimate-refinement step of the method provides a consistent output.

3.3 I provided a method to determine the number of necessary trials for the RANSAC-based selection of the initial beacon set based on an upper bound for outliers, and a hit rate probability design parameter. With the proposed solution the number of necessary trials can be reduced by orders of magnitude while still maintaining the desired hit rate probability of a good initial beacon set.

Related publications: [S8], [S9]

4 Utilization of results

Achieving synchronization for visible light communication protocols using LED light sources as transmitters and digital cameras as receivers may be difficult or too expensive to implement in practical cases. The analysis of UFSOOK and UPSOOK protocols, when operated in an unsynchronized manner, not only demonstrates how to fine-tune the protocols for optimal transmission performance in practical scenarios, but also provides insight into how and why various error sources affect their data transmission rates.

With the proposed beacon design and decoding method of Trackable UPSOOK it is possible to identify and also track LED beacons in a global shutter camera's image stream, even when one or both of them are moving. The proposed Robust UPSOOK protocol's encoding scheme and decoding method based on equivalent sampling can provide error-free periodical data transmission on a wide range of system parameters without the need of synchronization. This makes RUPSOOK a robust solution for practical use cases, given that the transmitted data is constant (identification number, installation coordinates, etc.). By utilizing the RUPSOOK protocol in conjunction with the proposed beacon design and size-based transmitter state detection of TUPSOOK, an ideal solution with error-free identification and tracking of beacons in visible light-based indoor positioning systems, where the displacement of transmitters and/or receivers is inevitable, can be achieved.

Outlier measurements (false reference point detections, extreme measurement errors, caused by reflections, etc.) in visible light-based indoor positioning systems are not uncommon. Thus, robust positioning methods should be employed that is able to handle these outlier measurements. The proposed HIAL ADoA principle-based solution provides an out-of-the-box outlier-tolerant solution for positioning that is easy to implement, and only requires a minimal number of 3 beacons to operate. A key benefit of the method is that it operates on a 2D plane, instead of the general 3D space, thus its computation speed is greatly improved. However, the distance-based filter parameters of the method require simulations or trial-and-error approach to be set correctly. HIAL can be used in practical scenarios utilizing e.g., ~12 beacons for an estimation, but the computation performance of the method scales poorly. The proposed RBL method using random sample consensus and post-refinement of the initial estimate has improved performance in computation speed and provides a smoother, more consistent output over HIAL, while keeping the required minimum number of 3 beacons to operate. The proposed positioning methods require the sensor's normal vector to be known, however, this requirement can be easily satisfied in numerous practical scenarios. E.g., if a vehicle moving in a warehouse is equipped with a fisheye lens camera facing upwards, the normal vector is approximately parallel to the real-world z axis (given that the surface beneath the vehicle is flat). The inclination of the sensor's normal vector may also be compensated using an inertial measurement unit in case the environment contains non-flat, or elevating regions (e.g., ramps), to satisfy this requirement.

The proposed methods were tested in a warehouse. In a 23 x 23 m area 12 beacons (with a diameter of ~8 cm) were installed approximately at the height of the 190° field of view fisheye lens-equipped global shutter grayscale camera's horizon, which was attached to an automated guided vehicle. The indoor positioning system was able to operate with an average error of 1.4 centimeters, providing 30 position and orientation estimates per second, while the beacons were also used to provide extra illumination for the environment.

Related publications

[S1] M. Rátosi and G. Simon, "Performance Analysis of the UFSOOK Protocol," *2019 IEEE International Symposium on Measurements & Networking (M&N)*, Catania, Italy, pp. 1-6, 2019
DOI: 10.1109/IWMN.2019.8805018

[S2] G. Simon and M. Rátosi, "Characterization and Measurement of Performance Properties of the UFSOOK Camera Communication Protocol," in *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 10, pp. 7982-7989, 2020
DOI: 10.1109/TIM.2020.2981219
IF: 3.658

[S3] M. Rátosi and G. Simon, "Towards Robust VLC Beacon Identification in Camera Based Localization Systems," *2019 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Pisa, Italy, pp. 1-8, 2019
DOI: 10.1109/IPIN.2019.8911767

[S4] M. Rátosi and G. Simon, "Robust VLC Beacon Identification for Indoor Camera-Based Localization Systems," *Sensors*, vol. 20, no. 9, p. 2522, 2020
DOI: 10.3390/s20092522
IF: 3.576

[S5] M. Rátosi, G. Simon, "Undersampled On-Off Keying Camera Communication Methods for Beacon ID Transmission," Pannonian Conference on Advances in Information Technology (PCIT2019), Veszprém, Hungary, pp. 36-41, 2019
ISBN: 978-963-396-127-8

[S6] M. Rátosi and G. Simon, "Trackable Visible Light Beaconing and Detection for Indoor Localization Applications Using Undersampling Cameras," *2018 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Nantes, p. 4, 2018
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[S7] G. Simon, G. Vakulya and M. Rátosi, "On the Utilization of Equivalent Sampling in Undersampled Asynchronous Camera Communication Protocols," 2022 IEEE International Symposium on Measurements & Networking (M&N), Padua, Italy, pp. 1-6, 2022
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[S8] M. Rátosi and G. Simon, "Real-Time Localization and Tracking using Visible Light Communication," *2018 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Nantes, France, pp. 1-8, 2018
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[S9] M. Rátosi and G. Simon, "Fault Tolerant Indoor Positioning Based on Azimuth Measurements," *2021 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Lloret de Mar, Spain, pp. 1-12, 2021
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(accessed on 15 Jan 2024)

Other related publications

[SO1] G. Simon, M. Rátosi and G. Vakulya, "Automatic Measurement of Digital Cameras' Exposure Time Using Equivalent Sampling," in *IEEE Transactions on Instrumentation and Measurement*, vol. 71, pp. 1-10, Art no. 5015110, 2022
DOI: 10.1109/TIM.2022.3186372
IF: 5.332

[SO2] G. Simon, G. Vakulya, and M. Rátosi, "The Way to Modern Shutter Speed Measurement Methods: A Historical Overview," *Sensors*, vol. 22, no. 5, p. 1871, 2022
DOI: 10.3390/s22051871
IF: 3.9

[SO3] M. Rátosi, G. Vakulya and G. Simon, "Measuring Camera Exposure Time Using Equivalent Sampling," 2021 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Glasgow, United Kingdom, pp. 1-6, 2021
DOI: 10.1109/I2MTC50364.2021.9459789

[SO4] M. Rátosi, G. Vakulya, G. Simon, "Methods for High Precision Shutter Speed Measurements," AIS 2021 – 16th International Symposium on Applied Informatics and Related Areas, Székesfehérvár, Hungary, pp. 30-34, 2021
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