Future Parking Applications: Wireless Sensor Network Positioning for Highly Automated in-House Parking

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Abstract: One of the bottlenecks for motorized individual transportation for end-to-end trips is the search for parking space. Common solutions to minimize spatial needs are in-house parking garages, but even in those, finding available parking lots can be quite time consuming. In this contribution we therefore present a cheap and retrofittable parking system, enabling automated entrance to parking lot reservation, navigation and clearing for already existing parking garages. One of its key component is a robust indoor positioning based on Wireless Sensor Networks (WSN) enabling vehicle independent and automated routing. We will provide a general overview of WSN measurement principles and propose two possible technology candidates, a 2.4 GHz narrow-band technology and Ultra-Wide Band (UWB). Furthermore, a robust range-only positioning approach utilizing Markov Localization, called Probability Grid Positioning (PGP), is presented. With the help of UWB and IEEE 802.15.4 ranging modules the algorithm is qualitatively evaluated with measurements in a car park in Leipzig, Germany. Our proposed PGP approach leads to overall smoother trajectories compared to a state-of-the-art Least Squares Estimation (LSE) and thus achieves accurate and robust positioning in demanding heavy-multipath environments. This can build the foundation for future work in the field of highly-automated in-house parking.

1 INTRODUCTION

Mobility is one of humanity's fundamental needs. With a worldwide constant increase of urbanization energy-, time- and space-efficiency for transportation processes are indispensable. For motorized individual traffic, the search for parking space is the bottleneck of efficient source to sink tours in urbanized areas. Many kilometers are covered by a car driver in search of free parking lots every year. For this reason, the focus of Future Parking solutions is becoming increasingly important in research and development.

Since parking space on streets or open areas are extremely limited in cities, parking garages or underground car parks are often provided alternatively. For indoor parking applications, there are approaches that use Wireless Sensor Networks (WSN) to support the driver in finding a parking space up to fully automated parking approaches where the driver simply leaves the vehicle in front of the parking garage (Friedl et al., 2015).

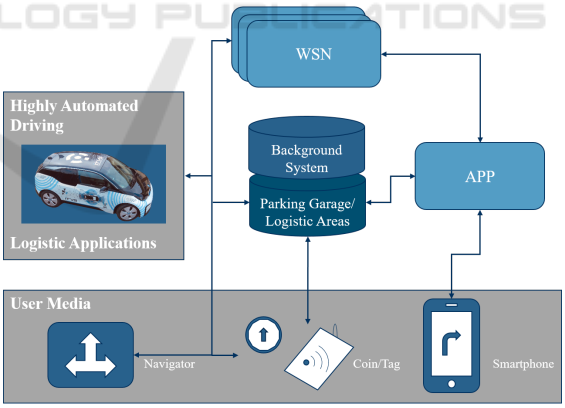

Figure 1: System overview.

(Ibisch et al., 2013) present a system for localization and tracking of vehicles in a parking garage using a network of Light Detection and Ranging (LIDAR) sensors. These LIDAR sensors, which are embedded in the environment, are adjusted near the ground and parallel to the ground level to enable measuring points on the wheels as a basis for detection. An advantage of the system is the accuracy on wide lanes, while other sensors fail due to their limited range.

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(Crisostomo et al., 2019) proposed an image-processing based smart parking system for multi-storey parking garages. The system was validated with several video-feeds from different in-house parking garages. It determines whether the parking lots are occupied by indicating a red outline if a car is occupying a parking space and then turns green when it is unoccupied.

An approach using light sensors to determine the presence of a vehicle is presented in (Srikanth et al., 2009). The WSN subsystem forwards the information to a management server which transmits the occupancy information of the parking spaces to the guiding nodes and entrance system. A full-featured prototype model was implemented in order to validate the parking management system which includes also the availability of reservation.

Fully automated car parking relies often on mechanical handling. (Eswaran et al., 2013) proposed a lift mechanism which transports the car to an allocated parking lot. Various sensors, motors and software are necessary to detect and transport the car. The disadvantage of these systems is the initial cost of building such parking garages. Another approach uses the conventional concrete garages that can be transformed into an automated parking system without the deployment of sensors in each of the parking lots (Nayak et al., 2013). The presented technology uses robotic valets, which are the vehicle carriers that park them compactly in a given space of the parking area.

While these approaches and parking garages using robotic valet parking systems in general are very promising in regards to time and space efficiency, they are usually newly built at high costs. Hence, we present an approach in which existing parking garages can be retrofitted cost-effectively with an entrance to parking lot booking and navigation system, enabling a completely new car park management concept. Figure 1 gives an overview of the in-house parking technology with an automated booking system. In addition to the goal of intelligent control of parking garages, the inner-city traffic flow is also to be controlled. On the basis of this technology, for example, parking spaces can be sublet or micro-hubs can be implemented for inner-city logistics. Specifically, a radio-based indoor localization technology is being developed, whereby vehicles are navigated from the barrier at the entrance to the booked parking space using a Sensor-Tag (Coin) (cf. figure 2) and a Parking App. Only the infrastructure and no vehicle information is used with this technology. The great advantage of this approach is therefore the independence from different vehicle features and the possibility to also deploy the system with so-called legacy vehicles. Via the background system the car park operator can monitor the current parking space occupancy and the current events in the car park in real time using the monitoring portal.

Figure 2: Test vehicle with sensor tag on the dashboard.

Next to presenting the previously described system, this contribution discusses different technologies for WSN indoor positioning, as a robust positioning is a key feature for navigation within the parking garage. For applications with high demands in terms of accuracy, range-based approaches (cf. section 3) are often utilized, directly measuring distances between fixed anchors and mobile tags. In our conducted work, we discuss both the usage of Ultra-Wide Band (UWB) and a narrow-band technology at 2.4 GHz for the described application. Furthermore, a robust position estimation scheme is presented, utilizing Markov Localization, also referred to as Probability Grid Positioning (PGP), which is compared to a state-of-the-art positioning method, revealing its superiority in terms of accuracy.

The rest of the paper is organized as follows: section 2 provides an overview of the proposed automated in-house parking system, followed by section 3 giving an overview on available measurement principles to obtain spatial information within a WSN as well as the discussion on possible technology candidates as a basis for robust indoor positioning. Finally, section 4 introduces a robust state estimation based on a presented Markov Localization approach. The paper concludes with a summary and proposals for future research work in section 5.

2 SYSTEM OVERVIEW

In this section we provide an overview of the proposed automated in-house parking system in detail especially about the necessary infrastructure and information technology. A general overview of our approach gives figure 1 as already described in section 1.

The WSN as basis for the robust indoor positioning consists of fixed anchors distributed in the parking garage and mobile tags which are issued to the driver at the barrier. Figure 3 shows the physical architecture of our proposed automated in-house parking system. The anchors are linked to multiband antennas via a serial interface. This opens up the possibility of covering several frequency bands with a single radiating element. Details about the WSN including its special aspects are described in the following sections.

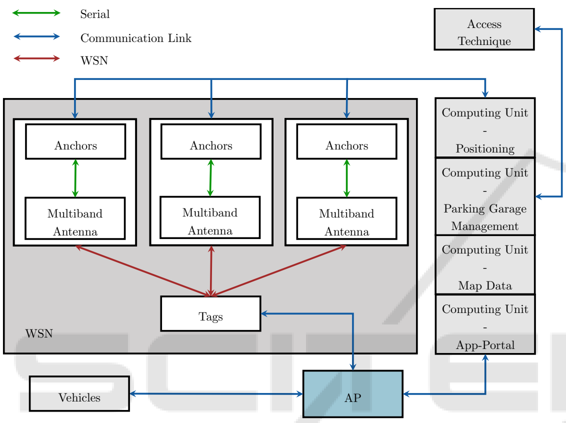


Figure 3: Physical architecture.

Besides the WSN and its components there are different computing units for the automated processes. Each mobile tag transmits his radio-frequency data over a central Access Point (AP) to the positioning computing unit where the sensor information is used to estimate the position of the vehicle. A possible approach to robust positioning is proposed in section 3. The computing unit for the map data is responsible for the upper-level navigation process from the barrier to the booked parking lot. In addition to the static and dynamic map data of the entire parking garage, the trajectories to each parking space for the route guidance are also stored in this unit. Robust and precise positioning is an essential requirement for autonomous driving. With a digital map, the errors of a positioning system can be compensated by suitable map matching algorithms. For the whole booking and reservation process as well as the monitoring of the parking space occupancy the management computing unit is used which controls the access technique based on all processed events.

The communication link (e.g. WiFi or in the future 5G) between the individual subsystems offers a reliable communication to provide centrally processed position data in the vehicles. This enables a coupling with the navigation system of the vehicle for future automated processes.

3 INDOOR POSITIONING: WIRELESS SENSOR NETWORKS

For indoor applications specifically, the go-to positioning technology Global Navigation Satellite System (GNSS) is typically not available or its performance is degraded up to the point, where reliable position estimation is not possible anymore. Therefore, different technologies have to be exploited. Since this contribution presents a system which is intended to be retrofitted in existing parking garages and independent of any sensor information provided by customers and their cars, only several approaches are applicable.

3.1 WSN Localization

As already stated, the proposed future parking system aims to provide a retrofittable and vehicle independent indoor positioning system, leading to restrictions for localization baseline technology selection as on-board sensors like Inertial Measurement Units (IMUs) cannot be used. Similar to GNSS, WSN can determine geometric relations utilizing transmitted and received signal properties. Figure 4 gives an overview of different principles to obtain geometric relations within a WSN.

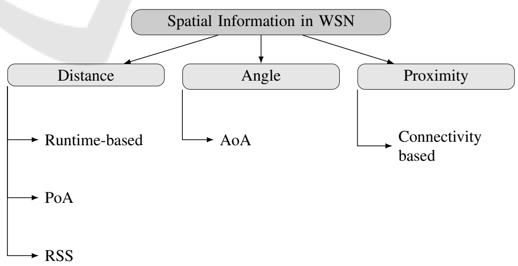


Figure 4: Overview of different measurement principles in WSN used to obtain spatial information.

In general, WSN localization approaches are classified between range-based and range-free methods (Mendoza-Silva et al., 2019). Range-free methods mainly include proximity based methods like Centroid or DV-HOP (Paul and Sato, 2017). The main advantage of these approaches are their cheapness, low complexity and energy efficiency. However, the resulting accuracies are highly dependent on various influences like network topology and density of nodes (Mesmoudi et al., 2013).

We therefore focus on range-based methods, which generally include both distance and angle measurements as input information. Since the incorporation of additional hardware like antenna arrays are necessary for Angle of Arrival (AoA) estimation, these are not considered for our described use case.

3.2 Range-only Localization

The most common localization applications for WSN include distance based methods. Up first, Received Signal Strength (RSS) measurements can easily be used as they are provided by almost all radio devices. The concept behind this approach is to use channel models for the occurring path loss considering known transmission power and hardware (e.g. antenna gain) and estimating distances in comparison with the measured RSS. However RSS distance measurements are not very robust as the environment has a large impact on possible fading occurrences (slow and fast fading). Additionally, channel modelling can be a difficult task. To overcome these downsides, RSS profiling or fingerprint approaches can be applied, creating a map with signal strengths for different locations beforehand. However, accuracies are still fluctuant especially in challenging environments (cf. figure 5).

The measurement of the phase shift, also known as Phase of Arrival (PoA), is another common method for determining the distance between two sensor nodes. One advantage of this method is that the transceivers do not need to be synchronized in time (Bensky, 2008). The PoA concept makes use of the phase difference of two different frequencies caused by a signal propagation delay and estimates the distance between the two sensors with their transceivers. The PoA method is extremely suitable for applying ranging for narrow-band radio-frequency transmission systems.

Runtime-based distance measurements include a variety of measurement principles, such as Time of Arrival (ToA), Time Difference of Arrival (TDoA), Two-Way ToA or Symmetrical Double-Sided Two-Way Ranging (SDS-TWR). The distance measurement in ToA procedures is made possible by determining the signal propagation time (Bensky, 2008). Such a Time of Flight (ToF) measurement is performed by recording different time stamps of transmitted and received messages. This requires precise synchronization between transmitter and receiver. To avoid this source of error, the Two-Way ToA method is based on measuring the signal propagation time twice based on an asynchronous and asymmetrical process. The SDS-TWR method can be seen as an extension of the Two-Way ToA. In contrast, it is based on a symmetrically initialized measurement of the distance twice, thus on a total of 3 messages (Jiang and Leung, 2007).

3.3 Used Hardware for Validation

To validate the robust range-only approach proposed in detail in section 4 we use two different WSN technologies. Table 1 shows a comparison of the 2.4 GHz narrow-band technology from Metirionic (MetirionicGmbH, 2020) and the 6.5 GHz UWB MDEK1001 evaluation kit from Decawave (Decawave, 2017).

Table 1: Comparison of used WSN technologies.

	2.4 GHz	UWB
Standard	IEEE 802.15.4	IEEE 802.15.4a
Frequency Range	2400-2483.5 MHz	6240-6739.2 MHz
Point-to-point range	up to 1 km	up to 60 m (RTLS: 25 to 30 m)
Ranging method	PoA, Advanced ToA	Two-Way ToA
Hardware	Demo-Kit Metirionic GmbH	Decawave MDEK1001

Both technologies are based on the IEEE 802.15.4 wireless standard. In contrast to UWB, the 2.4 GHz Metirionic technology can be regarded as a narrow-band wireless technology with 83 MHz bandwidth (MetirionicGmbH, 2020). Its limited bandwidth poses great challenges in determining the distance between two sensor nodes compared to UWB with about 500 MHz. However, the big advantage of the technology is the long range and functionality in Non-Line-of-Sight (NLOS) environments as well as in complex environments (e.g. through several walls). Due to the lower transmission power, the devices from Decawave have a smaller point-to-point range from up to 60 m (Decawave, 2017). By using the Real-Time Location System (RTLS) in combination with Bluetooth to access the raw data, this is limited to 30 m.

4 ROBUST POSITIONING FOR IN-HOUSE PARKING

4.1 Problem Formulation: Multipath Environments

The quality of the distance measured using radio-frequency techniques is highly dependent on the environment and subject to certain propagation phenomena, including Line-of-Sight (LOS), NLOS or multipath reception, leading to different effects in the measurement domain. The effects of these occurrences highly differ between possible technologies used for obtaining distance information between anchors and mobiles. An example for the variety of possible multipath reception paths in an parking garage obtained by a radio wave simulation tool is depicted in figure 5. The mobile tag is located between two parking rows and is in a NLOS relation to one anchor mounted on the ceiling.

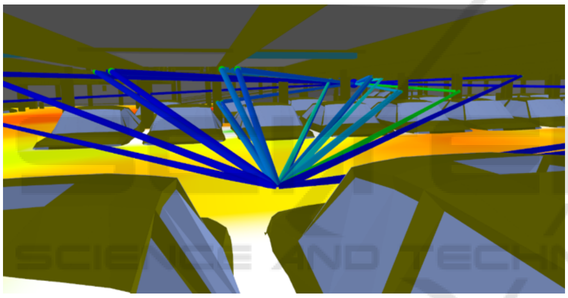


Figure 5: Selective multipath reception between two parking rows.

Without loss of generality, a ranging measurement R is given as the sum of the true distance d_t^a between a tag t and an anchor a defined as $d_t^a = \|\mathbf{x}^a - \mathbf{x}_t\|_2$ and occurring measurement errors ε:

$$R = d_t^a + \varepsilon \qquad (1)$$

with $\mathbf{x}_t = [X,Y,Z]^\intercal$ and $\mathbf{x}^a = [X,Y,Z]^\intercal$ representing the three-dimensional tag and anchor positions in a local cartesian coordinate system.

For ToF based distance measurements and with respect to the previously mentioned types of signal reception, ε includes the following possible distance measurement errors:

- Gaussian (white) noise for LOS,
- (positive) ranging errors caused by NLOS,
- positive and negative ranging errors caused by multipath interference and
- gross outliers.

These effects are tied to specific occurrence probabilities, which differ depending on employed technologies as well as surroundings (e.g. UWB vs. narrowband technology or open space vs. indoor), but generally lead to non-gaussian measurement residuals. These arbitrary or sometimes even multi modal measurement distributions strongly degrade the performance of state estimation approaches which rely on normally distributed errors, such as Least Squares Estimation (LSE) or Extended Kalman Filtering (EKF).

To represent any non-gaussian and heavy-tailed ranging residuals resulting from the occurences of the described error types, we use Gaussian Mixture Models (GMM), which can approximate any type of arbitrary distribution using a variable amount of C Gaussian components associated with different weights w, means μ and variances Σ (2).

$$P \sim \sum_{c}^{C} w_c \cdot \mathcal{N}(\mu_c, \Sigma_c) \qquad (2)$$

Figure 6 shows an exemplary heavy-tailed ranging residual histogram as well as an approximation of the underlying probability distribution using a GMM.

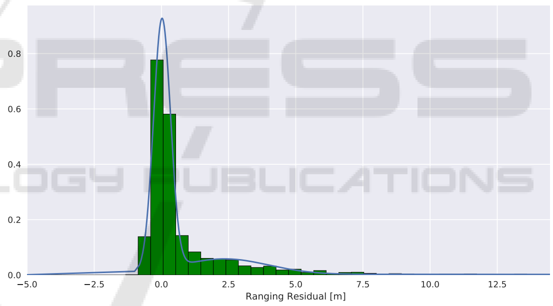


Figure 6: Histogram of heavy-tailed ranging residuals (green) in an indoor environment, including a GMM approximation of the underlying probability distribution (blue).

4.2 Probability Grid Positioning

Based on the presented distance measurements, we want to present a possible approach to robust positioning using a classical Markov Localization approach. This method is a special kind of Recursive Bayes Filter (RBF), more specifically a Discrete Bayes Filter (DBF), as it uses a discrete, ordered sample probabilistic state space representation for state estimation. Essentially, the presented Markov Localization realization is a two-dimensional Histogram Filter (HF), which is also referred to as PGP. The utilization of a discrete state space representation over a Gaussian (Kalman Filter) or a random sample (Particle Filter, PF) representation was explicitly chosen for the following reasons:

- NLOS or multipath reception is inherent in the described parking garage scenario, leading to non-gaussian observation errors. These drastically degrade the accuracy of conventionally used state estimation approaches like LSE or EKF.
- The state space only has to cover the inside parking spaces, leading to a bounded state space, facilitating DBF applications.
- As described in section 2, positioning for all vehicles is performed at a central instance. Unlike PF, PGP samples are immovable, which means the defined state space can be used for all participants. The corresponding likelihoods or probabilities for all grid cells are then stored individually.

Like any RBF respectively DBF implementation, the presented approach follows a prediction-correction structure as shown in figure 7. This structure estimates the current state x_k at timestep k with respect to the last given state information x_{k-1} based on Markov assumption and Bayes' Rule (Thrun et al., 2005).

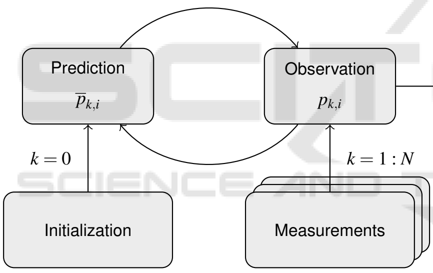


Figure 7: Structure of PGP framework.

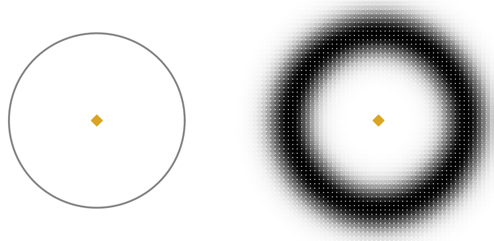
The simplest form of a sorted sample state space is an equidistant grid (cf. figure 8b) (Burgard et al., 2011). The predefined grid cells represent possible realizations of the state and their size constitutes the trade-off between computational complexity and achievable accuracies of the filter.

The DBF prediction step $\overline{p}_{k,i}$ for the i-th grid cell at k can then be formulated as:

$$\overline{p}_{k,i} = \sum_i P(x_{k,i}|x_{k-1})p_{k-1,i} \quad \forall i = 1,2,\ldots,n \qquad (3)$$

The probability density from (3) is then combined with the observation z_k Likelihood function $P(z_k|x_{k,i})$ and multiplied with a normalization factor η following the Bayes' theorem, resulting in the overall probability density representation at time-step k:

$$p_{k,i} = \eta P(z_k|x_{k,i})\overline{p}_{k,i} \qquad (4)$$



(a) (b)

Figure 8: Visualization of a 2D distance measurement from a known fix point (yellow): (**a**) Explicit circular position line. (**b**) Sample based representation given noise.

This is also reffered to as the current belief *Bel* about the current state. The final estimation of the current vehicle position is obtained by maximizing $p_{k,i}$, following the Maximum A-Posteriori estimation:

$$\hat{x}_k = \underset{x_k}{\operatorname{argmax}}\ Bel(x_k) \qquad (5)$$

Implementational details for PGP can be found in (Thrun et al., 2005).

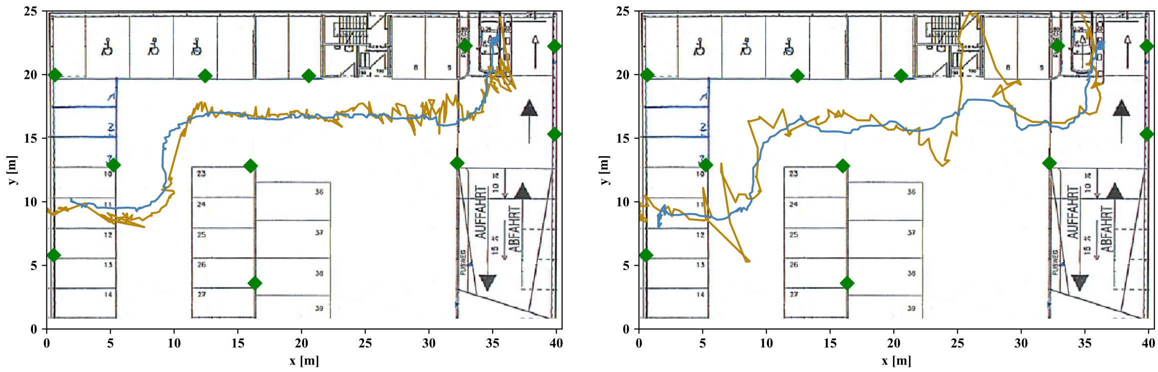
4.3 Performance Results

In this subsection we want to provide qualitative performance results for both the introduced WSN technologies as well the performance of the proposed PGP approach compared to a Gauss-Newton LSE. For this purpose, several test drives in a parking garage in Leipzig, Germany were performed (cf. figure 2). The test run we are presenting went from the entrance of the car park at the barrier at the top right side of figure 9 to parking space number 11, located at the middle of the left side.

For the presented data set, two significant results are observable:

- UWB generally provides higher ranging accuracies and less environmentally induced outliers, leading to overall higher positioning accuracies.
- The proposed PGP approach manages to mitigate outliers for both technologies, leading to overall smoother trajectories compared with LSE.

The achieved accuracy of UWB depends on the high bandwidth and thus the higher temporal resolution to distinguish the direct path from the others. Despite this fact, the narrow-band technology from Metirionic GmbH is the focus of our future research work. Due to the higher coverage (cf. subsection 3.3) the infrastructure devices and thus costs can be reduced. One way to compensate the distance-dependent loss of accuracy of the ranging measurements is the use



(a) UWB. (b) Narrow-Band 2.4 GHz.

Figure 9: Comparison of UWB (**a**) and narrow-band 2.4 GHz (**b**) ranging technologies, including fixed anchors points (green), PGP estimation results (blue) and Gauss-Newton estimation (golden).

of beamforming antennas. In general, NLOS measurements as well as multipath reception in a parking garage (cf. Figure 5) can be compensated during position estimation with the PGP.

5 CONCLUSION

In this paper, we introduced a novel approach for a highly automated parking for already existing in-house parking areas, enabling efficient parking garage management for operators and time saving park space search for customer. A core component of this system is robust indoor localization. We have discussed the demands for accessible and vehicle independent sensor information, leading to the application of WSNs. For these, we have discussed and introduced several localization and measurement principles. Lastly, a robust probabilistic state estimation approach for range-only localization is introduced and qualitatively evaluated for in-house parking usage.

For further work, we want to put more emphasis on necessary performances as well as system architectural to build a foundation for fully automated parking. Additionally, we will conduct a comprehensive quantitative validation for different setups, technologies and test drives. This will also include more details on method implementation and a comparison with other state-of-the-art positioning methods. The overall goal is to qualify WSN based localization as a key enabler for automated in-house parking.

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