Evaluation of Indoor Positioning Technologies under industrial application conditions in the *SmartFactory*^{KL} based on EN ISO 9283

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Abstract: In order to evaluate indoor positioning technologies according to industrial standards, this paper presents a new mathematical approach based upon EN ISO 9283 giving a precise definition of positioning *accuracy* and *precision*. Following this approach, two indoor positioning systems (IPS) applying ultra wide band (UWB) and ultrasound technology have been tested in the the *SmartFactory*^{KL} to get a better understanding of their suitability for industrial location-based services (LBS). Testing has been conducted under optimal operating conditions and under realistic shop-floor conditions as well. Since both technologies show highly variable performance, measurement results are discussed and recommendations for further evaluation and research in the field of location technologies are given.

Keywords: positioning systems, tracking systems, location technology, ultra wide band, performance evaluation, positioning accuracy, positioning precision, error analysis, industrial location-based services

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1. INTRODUCTION

After gaining a first foothold in customer applications, location-based services (LBS) also become more and more important in the industrial sector. With the spreading of indoor positioning systems (IPS) to track positions of persons, products and means of production inside buildings, the door is opened for a whole class of new applications close to the production line. Especially in the fields of mobile maintenance or remote machinery control via mobile handheld devices (Görlich et al. (2007)), visionary scenarios for a possible use of location information come of age.

Due to the fact that any kind of LBS relies upon location information, IPS constitute the core part for all services of this class. Although IPS can be evaluated against many criteria like scalability, energy consumption, robustness or life cycle cost, *accuracy* and *precision* become the most relevant performance criteria being a measure for the quality of service an IPS can provide. As location data may act as input parameter for controlling and optimizing industrial processes, the systems must show predictable behaviour, high reliability and precise operation.

These high quality requirements are contrasted by the difficult shop-floor conditions which are expected to cause problems for sensible systems like IPS. The mix of concrete, steel and glass structures, dirt and dust, the presence of infrared radiation dissipated by tooling processes, ultrasound waves emitted by vibrating machines and increasing radio signal propagation due to a growing number of wireless communication systems provide various sources of error making position determination quite a tough job in today's industrial indoor environments.

IPS in a vast variety of technical realisations are currently the focus of extensive research. Most of this research concentrates on either setting up (inventing) yet another new system (e.g. Schroeder et al. (2005), Feldmann et al. (2003)) or on developing new applications using IPS (e.g. Fernandez-Madrigal et al. (2007), Corrales et al. (2008)).

In both cases, an evaluation of the quality of location information reflected in values for *accuracy* and *precision* is a crucial factor. Nevertheless, current approaches define *accuracy* and *precision* differently and often lack mathematical formulas on how to compute these values from a series of measurements and the true reference value (e.g. Hightower and Boriello (2001)). In addition to that, most evaluations and application studies of IPS have been undertaken in surroundings like offices (Coyle et al. (2007)) or warehouses (Fernandez-Madrigal et al. (2007)). Only quite few evaluations like Benson and Sreenan (2004) address the applicability of IPS in harsh (i.e. industrial) environments.

In order to evaluate whether state of-the-art IPS can provide a basis for the setup of industrial LBS, two prerequisites are deemed to be necessary. Firstly, a standard evaluation method must be postulated making it possible to yield comparable results and to benchmark systems towards each other. Secondly, testing must be conducted in an industrial environment to get insight in how systems perform outside the lab under real-life conditions.

To provide an IPS evaluation compliant to the above stated conditions, the paper examines ultrasound and ultra wide band (UWB) technology by means of a novel approach. Based on a case-study in the *SmartFactory*^{KL} measurements are discussed and suggestions for further research are given.

2. EVALUATED TECHNOLOGIES

2.1 Ultrasound

Ultrasound technology is found in location systems as it is able to provide fine granularity. Due to its low signal speed (approximately 343 m/sec at 20° C and $1 \cdot 10^5$ pa air pressure), very small minimum units of distances can be measured in comparison to other technologies. As precise distance estimation asks for sensitive ultrasound sensors, ambient ultrasonic noise emitted by machinery or simply by slamming doors or malfunctioning fluorescent light may result in bad position estimation (Kolodziej and Hjelm (2006)).

Ultrasound based systems for determining location indoors are already around for several years. One of the most prominent systems is the MIT Cricket Indoor Location System (Priyantha (2005)) distributed by Crossbow Technology. The system is easy to deploy, includes an open programming library and lightweight MCS410CA motes that can be configured either as active beacons or as passive listener. Location determination is computed by the time difference of arrival of simultaneously emitted radio signals at 433 MHz and ultrasound impulses at 40 kHz. Kalman-filtering is used to merge sequentially available signals of at least 3 beacons into a resulting listener position. Communication between beacons is organized in a decentralized way similarly to the carrier sense multiple access / collision avoidance method (Dobson et al. (2007)). From measurements undertaken in Priyantha (2005) one can infer that the accuracy provided by this technology is below 0.15 m at most of the time.

2.2 Ultra Wide Band

UWB describes a radio frequency technology working over a wide bandwidth from 3.1 to 10.6 GHz (unlicensed frequency band). By emitting short pulses over a high band of frequencies, the technology is designed for robustness towards multipath effects which are common especially in indoor environments. Furthermore sending short discrete pulses of around 1 ns length provides inherent precision for time of arrival (TOA) and time difference of arrival (TDOA) measurements as the length of such a pulse is only about 0.3 m. This makes UWB superior to most other location technologies concerning *accuracy*. Although there are some ongoing problems in deploying UWB systems due to interference with frequencies in the licensed band, UWB is considered to have a dramatic impact on technologies used in data transfer, local area networks and location determination in the coming years (Kolodziej and Hjelm (2006)). Therefore, UWB-based systems are a fast-growing segment of the IPS market (Brunell (2007)).

Being the market leader in this field, offering high accuracy and an extensive software platform, Ubisense provides a state-of-the-art system ready for “out of the box” deployment. The system hardware consists of Ubisensors and active Ubitags. Pulses of short duration and high energy over a bandwidth between 6-8 GHz are emitted by the Ubitags and received by the Ubisensors. In addition to the unidirectional UWB signals for location computation, control information is exchanged bi-directionally in the 2.4 GHz band between tags and sensors. Location computation is conducted either by the angle of arrival principle (AOA), TDOA principle, or a combination of both. As a result of the utilization of these two distinct location principles and the characteristics of the UWB technology, Ubisense claims in Steggles and Gschwind (2005) to locate objects with an *accuracy* of about 0.15 m at a 95% confidence interval.

3. EVALUATION APPROACH

3.1 Currently common Approach

In order to evaluate the performance of an IPS, varying definitions for the crucial parameters *accuracy* and *precision* can be found. One of the most often cited definitions of *accuracy* and *precision* in literature is the one of Hightower and Boriello (2001). In their paper they define *accuracy* as grain size (e.g. “within 10 meters”) a system is able to locate positions within. In association with that, *precision* is defined by the percentage (e.g. 95% of sensor readings falling in this grain size) one can expect to get that *accuracy*.

This implicates that *accuracy* is a combined measure describing the diameter of a point cloud based on mean and variance of distances between single measured points to a reference point. In addition to that, *precision* is a measure describing the variance of the distances between measured points and the reference point. Hence, the value of *accuracy* is directly influenced by the value of *precision* as the percentage of sensor readings within a certain diameter directly influences its radius (increasing the value of *precision* results in lowering *accuracy*). A mathematical interpretation of these verbal definitions could start with the Gaussian mean of distances $\bar{d}$ and variance S following to

$$\bar{d} = \frac{1}{n}\sum_{i=1}^{n} d_i \qquad \textbf{(1)}$$

and

$$S = \sqrt{\frac{\sum_{i=1}^{n}\left(d_i - \bar{d}\right)^2}{n-1}} \qquad \textbf{(2)}$$

with d_i denoting the Euclidean distance between measured points $P_i\,(x_i, y_i, z_i)$; $i=1 \ldots n$ and a reference point $O_{ref}(x_{ref}, y_{ref}, z_{ref})$ to

$$d_i = \left\|P_i O_{ref}\right\| = \sqrt{\left(x_i - x_{ref}\right)^2 + \left(y_i - y_{ref}\right)^2 + \left(z_i - z_{ref}\right)^2} \qquad \textbf{(3)}$$

Based on that, the *accuracy A* follows to

$$A = \bar{d} + 2S \qquad \textbf{(4)}$$

with the factor of 2 denoting a confidence interval of 95% (e.g. a factor of 3 would indicate a confidence interval of

99%). Following the definition above, *precision P* denotes the percentage of values falling in this confidence interval.

The weakness of this approach is that the used definition of *accuracy* and *precision* only supports a simple error model not distinguishing between systematic and random errors. It is not possible to draw any conclusions about the distribution of measured points within a point cloud and by that getting a hint if maybe a wrong calibration of the system or background noise is the reason for a weak performance.

3.2 Proposed approach following EN ISO 9283

In order to benchmark IPS according to industrial quality standards and in a highly reproducible way, an evaluation procedure following EN ISO 9283 (1999) is proposed.

This standard comprises performance criteria and related test methods for manipulating industrial robots. It defines *accuracy* A_s as the difference between the position of a reference point O_{ref} (x_{ref}, y_{ref}, z_{ref}) and the center of gravity $\overline{P}(\overline{x}, \overline{y}, \overline{z})$ of a point cloud consisting of all measured points P_i (x_i, y_i, z_i); $i=1...n$ (Fig. 1.).

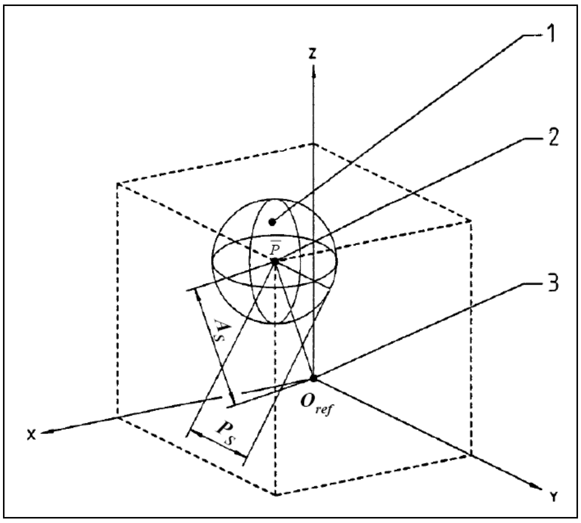

Fig. 1. *Accuracy* and *precision* according to EN ISO 9283. 1) Example for an actual position; 2) Position of the center of gravity; 3) Reference position O_{ref}.

The mathematical definition of the *accuracy* A_S (referred to as *positioning accuracy* in EN ISO 9283) follows as the Euclidean distance according to

$$A_s = \left\| \overline{P} O_{ref} \right\| = \sqrt{\left(\overline{x} - x_{ref}\right)^2 + \left(\overline{y} - y_{ref}\right)^2 + \left(\overline{z} - z_{ref}\right)^2} \qquad \textbf{(5)}$$

with

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i;\ \overline{y} = \frac{1}{n}\sum_{i=1}^{n} y_i;\ \overline{z} = \frac{1}{n}\sum_{i=1}^{n} z_i\ . \qquad \textbf{(6)}$$

Regarding (5) and (6), it becomes obvious, that *accuracy* is a measure based exclusively on the distance between the mean of the measured points (center of gravity) and the reference point; the variance is not considered.

Precision P_s (referred to as *positioning repeatability* in EN ISO 9283) is defined as the distance of all measured points P_i from the center of gravity describing a sphere with a certain radius around $\overline{P}$ (Fig. 1.). The mathematic equation defining the *precision* follows as

$$P_s = \overline{l} + 3S_s \qquad \textbf{(7)}$$

with

$$\overline{l} = \frac{1}{n}\sum_{i=1}^{n} l_i \qquad \textbf{(8)}$$

denoting the Gaussian mean distance of the measured points P_i from $\overline{P}$ and

$$l_i = \left\| P_i \overline{P} \right\| = \sqrt{\left(x_i - \overline{x}\right)^2 + \left(y_i - \overline{y}\right)^2 + \left(z_i - \overline{z}\right)^2} \qquad \textbf{(9)}$$

describing the distance of each measured point P_i from $\overline{P}$. The variance S_s is calculated according to

$$S_s = \sqrt{\frac{\sum_{i=1}^{n}\left(l_i - \overline{l}\right)^2}{n-1}}\ . \qquad \textbf{(10)}$$

By that, P_s is a combined measure describing the mean and variance of the distances between the measured points and the center of gravity. If the measured points are considered as a cloud, A_s describes how far the center of this cloud is from the reference point O_{ref}. As a confidence interval of 95% is by far not precise enough for industrial application contexts, in (7) a factor of 3 is chosen by EN ISO 9283 in order to guarantee a confidence interval of 99%.

$\overline{l}$ is a measure for the extended size or "diameter" of the cloud and S_s is a measure describing the "deformation" of it. For example, A_s can be zero, if $\overline{P}$ is located at O_{ref}; still $\overline{l}$ can be of a certain value. Furthermore if S_s is zero, all the points within a cloud are arranged in concentrical spheres around $\overline{P}$ (Fig. 2.).

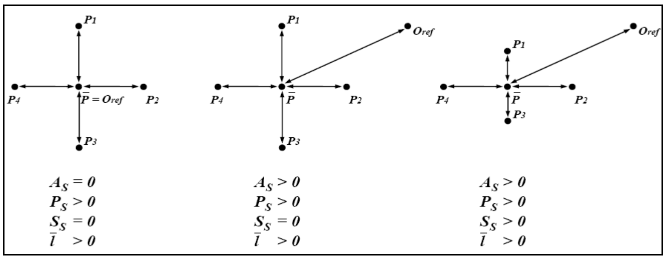

Fig. 2. Geometric illustration of the interrelation between accuracy A_s, precision P_s, the "diameter" of a point cloud indicated by $\overline{l}$ and the "deformation" of a point cloud indicated by S_s.

Hence, the proposed evaluation method does not only deliver values for *accuracy* and *precision*, it also allows for an interpretation of the results and to distinguish occurring errors in systematic errors (resulting in high values for A_s) and random errors (resulting in high values for P_s).

4. CASE-STUDY

4.1 The SmartFactory^{KL}

Founded in 2005 the *SmartFactory*$^{\textbf{KL}}$ in Kaiserslautern, Germany is the first European multi-vendor research, development and demonstration center for industrial information and communication technology (Zuehlke (2008)). Being organized as a public-private-partnership, the technology initiative opens a creative space for both providers and users of factory technologies to jointly work together with academic researchers.

In order to make the vision of a future intelligent production site come true, the *SmartFactory*$^{\textbf{KL}}$ conducts various activities in the field of factory automation with location based services being a part of current research. It provides excellent conditions for the evaluation of IPS under shop-floor conditions. Besides the modular production facility consisting of a process and a production technology part including lots of metal structure, piping, glass vessels and machinery, several structural obstacles like concrete pillars, sharp building edges and heavy workshop equipment can be expected to affect the proper function of IPS.

4.2 Scenario for Optimal Operating Conditions

In order to verify if the chosen systems are performing as advertised, initial trial measurements under optimal operating conditions are conducted. Optimal operating conditions are defined as following: 1. no obstacles inhibit signal propagation between tags and sensors; 2. no other radio or ultrasound signals interfere with positioning signals during measurements; 3. positioning signals can be received by enough tags/ sensors to perform best possible position estimation. Based on these preconditions, the chosen systems are deployed and a suitable area to identify reference points for measurements is defined.

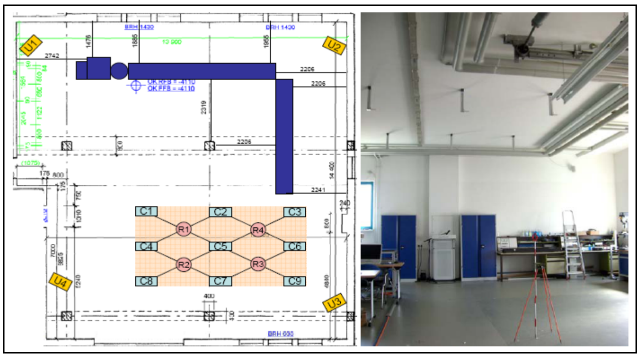

Fig. 3. Arrangement of Ubisensors (U1-U4), Cricket beacons (C1-C9) and reference points (R1-R4) for measurements under optimal operating conditions in the front area of the *SmartFactory*^{KL}.

In order to fulfil the above mentioned preconditions, both systems need to be installed differently. As the Ubisensors are capable of spanning comparably large cells with distances between sensors from 10 to 100 m, they can easily cover the whole testing site by installing them close to the edges of the hall. Still, in the chosen front area it can be guaranteed that at least two or more sensors can receive signals emitted by the Ubitags, resulting in the highest possible 3D accuracy (Ubisense AG (2007)). As the range and transmitting power of the Cricket beacons is quite limited it is not possible to cover the whole area of the *SmartFactory*^{KL}. Hence, with a number of nine beacons on hand, a symmetric 6-by-3-m grid is installed at the ceiling to cover a certain space in the dedicated front area. In order to ensure that at least signals of three beacons reach a listener, the reference points are located right in the geometric middle of neighbouring beacons of the grid. By that, optimal visibility of reference points for both, the Cricket and the Ubisense system is achieved.

4.3 Scenario for Shop-Floor Operating Conditions

After performing initial tests under optimal conditions for calibration, the system behavior in a factory-like surrounding with a heterogeneous environment is examined.

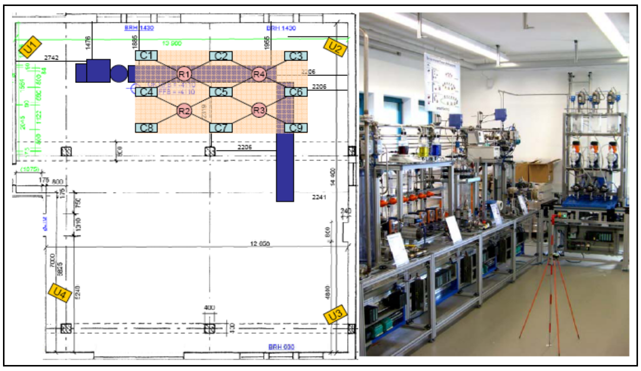

Fig. 4. Arrangement of Ubisensors (U1-U4), Cricket beacons (C1-C9) and reference points (R1-R4) for measurements under shop-floor operating conditions in the back area of the *SmartFactory*^{KL}.

To do so, the whole grid of Cricket beacons is rearranged right above the production facility of the *SmartFactory*^{KL} in a geometrically similar arrangement as before, including reference points for measuring (Fig. 4.). A relocation of the Ubisensors is not necessary, as the testing area is still covered by the existing cell.

4.4 Setup of a Coordinate System and Reference Points

In order to give a concise statement concerning *accuracy* and *precision* of an IPS, the true position of reference points must be determined. Furthermore the exact coordinates of sensors and beacons within a 3D space must be determined as they serve as input parameter for system calibration. Therefore the entire production site of the *SmartFactory*^{KL} is surveyed with a tachymeter to determine coordinates of reference points and system equipment with an accuracy in the range of +/-2mm. Based upon about 150 measurements a digital representation is created containing all coordinates of relevant points within the *SmartFactory*^{KL}. All surveyed positions are in reference to an established right-handed, global coordinate system, making it easy to compare data from both the Ubisense and the Cricket system without coordinate transformation.

4.5 Measurements at Optimal Operating Conditions

In the first round of trial measurements the systems' ability to provide accurate and precise values for tag positions under optimal operating conditions is examined. In Table 1 exemplary results for reference point 1 and 2 are displayed.

Table 1. Measurement results for positioning at optimal operating conditions

Ref. Pt.	*A(m)*	*P (%)*	A_S *(m)*	P_S *(m)*
Ubisense System				
1	0.128	99	0.097	0.070
2	0.244	99	0.098	0.228
Cricket System				
1	0.038	99	0.017	0.028
2	0.051	99	0.035	0.041

Although a *precision P* of 99% is asked for, measurement results for *accuracy A* still lie within the range of expected values that can be found in literature (Priyantha (2005)) or product specifications (Steggles and Gschwind (2005)) indicating that the system setup is close to the optimum. Following the proposed evaluation approach, a second and even more precise evidence for the correct calibration of the two systems can be found. With A_S being comparably small in relation to P_S it is obvious that occurring errors are mainly due to system noisiness and not to systematic bias caused e.g. by wrong installation or equipment handling.

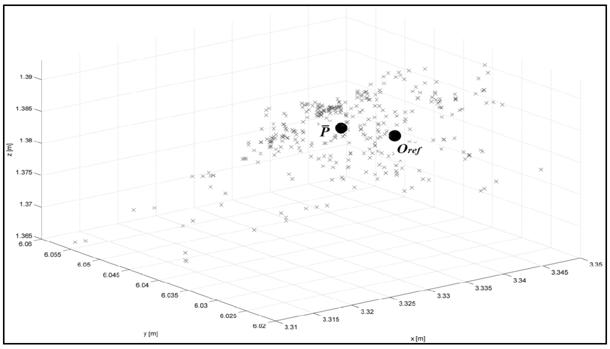

Fig. 5. Scatter Plot of measurement results at reference point 1 (Cricket system) showing that the true value of the reference point is located within the point cloud of measured values ($A_S > P_S$).

The true values for reference point 1 and 2 are surrounded by the point cloud of measured values (Fig. 5. for point 1). Therefore, values around 0.07 m to 0.25 m for the Ubisense System and 0.02 m to 0.05 m for the Cricket System can be regarded to be the optimum performance considering *accuracy* and *precision*.

4.6 Measurements at Shop-Floor Conditions

After initial benchmark tests in a surrounding with very few potential sources of error, system performance under industrial, factory-like conditions is in the focus of interest. The setup of both systems remains unchanged. Only the new beacon coordinates are hardcoded in the Cricket system, due to the rearrangement of the beacon grid.

Table 2. Measurement results for positioning at shop-floor conditions

Ref. Pt.	*A(m)*	*P (%)*	A_S *(m)*	P_S *(m)*
Ubisense System				
1	1.125	99	0.609	1.271
2	0.616	99	0.475	0.125
3	1.243	99	0.907	0.475
4	0.351	99	0.156	0.306
Cricket System				
1	--	99	--	--
2	0.078	99	0.059	0.029
3	0.064	99	0.051	0.019
4	0.072	99	0.015	0.079

Table 2 displays exemplary results for reference points located near and within the production facility of the *SmartFactory*^{KL}. As shown in Fig. 4 reference points 1 and 4 are located within the production facility. Under these conditions, a comparably low performance for the Ubisense system can be observed at reference point 1. UWB signals from a tag can not reliably reach Ubisensors, resulting in low values especially for P_S indicating a high fluctuation of incoming signals, probably due to severe reflections on metallic structures in the vicinity of the reference point. In contrast to that, point 4 shows surprisingly good values for A_S and P_S as well. Its characteristics differ only from point 1 in the fact that three Ubisensors can receive signals from this point resulting in significantly higher system performance. This indicates that *accuracy* and *precision* are related to the number of sensor measurements that can be obtained at a measurement position. The values for *accuracy* and *precision* at reference points 2 and 3 indicate quite interesting system behaviour. Those points are located in front of the production facility with a certain distance to infrastructure and obstacles leading to the fact that UWB signals can be received by at least three Ubisensors. This high degree of visibility results in quite good values for P_S. In contrast to that the high values for A_S indicate that system behaviour is influenced by constant changes in signal travel time or angular deflection resulting in biased positioning information (Fig. 6.).

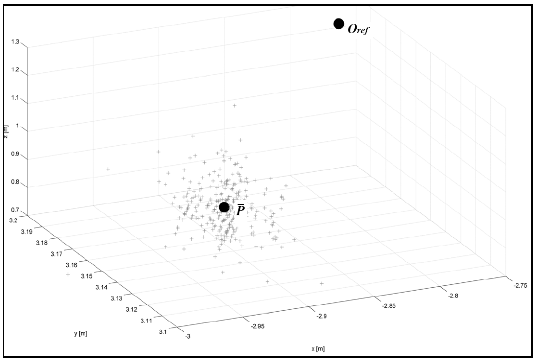

Fig. 6. Scatter Plot of measurement results at reference point 2 (Ubisense system) showing that the true value of the reference point is located far outside the point cloud of measured values ($P_S > A_S$).

Although the Cricket system can deliver a higher *accuracy* and *precision* than the Ubisense system, still it shows a comparable behaviour in correlation to the location of reference points. In case that reference points lie within the infrastructure of a facility (point 1 and 4), the lack of line of sight from listener to beacons and various refractions caused by close obstacles (e.g. huge glass vessel at point 4) result in either no incoming sensor data or in a high value for P_S. In case measurements were taken at reference points in the proximity of the facility (point 2 and 3), indirect effects of irritation caused by infrastructure seem to be predominant leading to biased measurement results showing high values for A_S and relatively low values for P_S. In general, both systems show significantly lower positioning performance under shop-floor conditions than under optimal operating conditions caused by the above mentioned effects.

5. CONCLUSIONS & OUTLOOK

In this paper a new mathematic approach following EN ISO 9283 has been presented in order to evaluate IPS according to industrial standards and to give insight in their suitability to create industrial LBS. In contrast to current approaches, the method delivers a clear mathematical interpretation for the values of *accuracy* and *precision*. Additionally it allows for a better interpretation of results by distinguishing systematic from random errors. By means of this method ultrasound and UWB technology have been tested in the *SmartFactory*$^{\text{KL}}$.

Under optimal operating conditions, both systems performed as advertised and provided values around 0.07 m to 0.25 m (UWB technology) and 0.02 m to 0.05 m (ultrasound technology) for *accuracy* and *precision*. However, under industrial operating conditions, both IPS performed significantly lower. With the proposed method, it could be discovered that, nevertheless, both technologies showed similar behavior during measurements. At positions inside the production facility high fluctuations of received signals result in high values for P_S (low precision), at positions within a certain range around infrastructure the results are influenced by biased signals resulting in high values for A_S (low accuracy). System performance for the UWB technology ranges from 1.30 m down to 0.12 m. For the ultrasound technology system performance ranges from 0.08 m down to 0.015 m for *accuracy* and *precision* values. Since fluctuations between measured values are reaching up to a magnitude, excessive testing throughout the whole deployment area in a factory is necessary to adapt sensor or beacon positions to infrastructural restrictions and to optimize system behavior under challenging conditions. Since IPS show variable performance at different areas in a factory, the creation of location profiles could provide a basis for the development of heuristics to compensate errors or to combine different systems by sensor fusion.

As the proposed method fosters the generation of transparent and reproducible measurements, more technologies like infrared, laser or Bluetooth could be evaluated to learn about their behavior in a factory environment. Besides the precise determination of *accuracy* and *precision* a technology can provide, future evaluations should also take other dimensions of performance like latency, energy consumption or dynamic behavior into account to get a more holistic view on current location technologies.

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