Method for the verification of indoor localization systems with regard to road traffic applications by means of electromagnetic fields

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***Abstract*—Fully autonomous automotive vehicles using localization services are desired by manufacturers and end customers to reduce the number of accidents, the environmental pollution, and the costs of mobility. Much effort has been spent on the development of satellite based localization services with low-cost devices for the mass market. However, all of the developed solutions fail when satellite based localization is not available under indoor conditions like tunnels or dense treetops of avenues. In this case indoor localization systems can be used to fill the gap. The accuracy performance of such systems is hard to compare, due to the heterogeneous information given in the data sheets by the manufacturers. Additionally, the way how the accuracy performance was determined is very often unclear. In view of safety-relevant applications, the quality of such indoor localization systems has to be verified by a reference measurement system using a physically independent measurement principle. As measurement principle for this work electromagnetic sensing has been chosen as this measurement principle is independent of the most principles used by indoor localization systems on the market. The developed measurement set-up is described in this paper. Results of a test run show that the reference measurement system is able to provide a position information with a sufficiently high accuracy for verifications of indoor localization systems.**

***Index Terms*—Reference Position, Verification, Safety, Road Traffic Applications**

I. Introduction

The rapid progress in the automation of all kinds of vehicles will prospectively lead to a partially or fully autonomous behavior of the automated vehicles. Nowadays, fully autonomous vehicles constitute individual and spatially bounded solutions for individual applications. By contrast, in the field of road traffic's mass market fully autonomous vehicles have already been desired for years [1], but not realized until now. This is because of the challenging task to localize each vehicle at every time at every place of the road network with a high accuracy in a reliable way. The knowledge of the vehicle's position is commonly considered as one of the most important components of new so called *advanced driver assistance systems* which represent a first step to fully autonomous automotive vehicles.

Currently, much effort is spent on the development of satellite based localization services with low-cost devices for the mass market. However, all of the developed solutions fail, when the environment is comparable to indoor conditions like in tunnels or under dense treetops of avenues.

One approach to provide a position information even at difficult operating conditions is the use of satellite independent localization solutions. In [2] a method for generating a relative position information by combining several vehicle sensors and sophisticated filter techniques is recommended. However, the drift increases by and by so that the measurement system is time-variant. This approach is too complex for a proof of the reference's measurement uncertainty, as, in particular, the propagation of measurement uncertainties through complex filter algorithms is still unsolved.

Many localization systems have been developed especially for indoor applications where GPS is typically unavailable. There are several systems available on the market that claim to provide a highly accurate position information. One example is the Local Positioning Radar (LPR) of the Symeo company [3] which is based on the measurement principle described in [4]. The *accuracy* of the LPR system under realistic conditions is specified as 5 cm [3]. Normally, the accuracy performance is hard to compare, due to the heterogeneous information given in the data sheets by the manufacturers. Terms describing the quality of a sensor system like *accuracy*, *correctness*, *precision* or *measurement uncertainty* are well-defined in the field of metrology, nevertheless they are often mixed up in practice. Usually no coverage interval is attributed to the measurement uncertainty information. Additionally, the way how the accuracy performance was determined is very often unclear.

With respect to safety-relevant road traffic applications, the quality of such indoor localization systems has to be verified by a reference measurement system using a physically independent measurement principle. For the verification a determination of the measurement deviation is needed. Therefore, the reference measurement system has to generate a reference position that can be compared with the position of the indoor localization system to be verified. The goal of the work described in this contribution is the development of such a reference measurement system.

The proposed measurement set-up is described in section II. Section III shows the results of a test run and the evaluation of the reference measurement system's quality. Finally, the results of the paper are summarized in section IV.

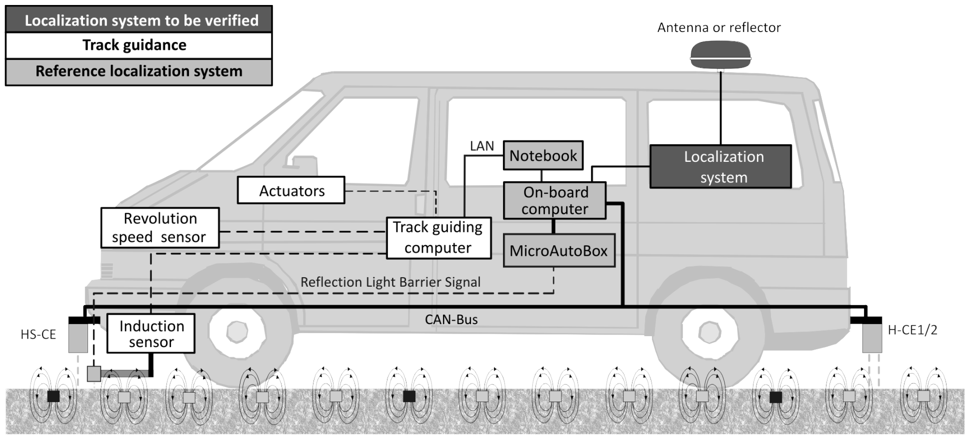

Fig. 1. Components of the reference measurement system

II. Proposed and realized measurement set-up

In this section the measurement set-up (fig. 1) and the concept of sensor data fusion (fig. 2) is described. The measurement set-up consists of a reference track with its infrastructural components and a test vehicle. In the following the most important elements of the reference measurement system are discussed briefly.

The reference track of the reference measurement system has a length of 860 m. Previous examinations have shown that the use of permanent magnets is a suitable technology for the purpose of vehicle guiding [5], [6]. This concept of tracking permanent magnets is also used at the proposed reference measurement system.

For every discrete tracking point four cylindric NdFeB magnets have been stacked to magnet packs offering a sufficient magnetic field intensity. Afterwards, the magnet packs have been embedded perpendicularly into the ground at a depth of 5 cm. By these discrete markings the track to be followed by the vehicle is defined. Because of the small distance of 50 cm between these points it is possible to realize a proper tracking. Furthermore, every 40^{th} magnet stack is defined as a reference measuring point (RMP). That means it has been georeferenced with geographic coordinates in the the fixed *World Geodetic System 1984* (WGS84) by geodesists.

Another essential part of the reference measurement system is the test vehicle which is a common Volkswagen T4 Caravelle. It is a series-production vehicle that has been augmented by additional measurement and computer equipment.

A. Lateral control

In contrast to rail-bound vehicles, in which the lateral deviation is neglectable due to the railtracks, an automotive vehicle has to be controlled with high accuracy. This task cannot be fulfilled by a human driver. Therefore, a lateral control using *Quantitative Feedback Theory* (QFT) has been developed according to [7] ensuring a repeatable track guidance. The lateral deviation is determined by an inductive sensor which is mounted at the front of the vehicle. This sensor is made up of two induction coils delivering different voltages and phase angles that are used for the calculation of the lateral deviation. The lateral control provides the steering angle as input variable to the steering actuator so that the lateral deviation decreases.

B. Longitudinal control

The tracking of a predefined velocity profile is realized using an H_∞-optimal longitudinal control, developed in [8]. The control uses the induction sensor as well, but for the determination of the longitudinal velocity which is the input variable of the controller. The accelerator position serves as an actuator for the longitudinal control. In addition, algorithms have been developed and implemented for automatic drive-away and automatic gear shifting.

C. Generating the reference position

The reference points of the reference track are marked by reflection foils and are detected by an optical sensor – a reflection light barrier – mounted at the front of the vehicle. In fig. 1 the reference measuring points are represented by dark filled magnets. The signal of the light barrier is logged by a MicroAutoBox with a sampling rate of 500 Hz. At the beginning of every test run the timestamps from board computer and MicroAutoBox are synchronized, non-recurring for the rest of the run. Therefore, all measurement data have a consistent timestamp. The vehicle orientation, i.e. the sideslip angle β, the pitch angle θ and the roll angle φ, have significant influence on the position of the antenna, due to the quite long lever arm. A so called CORREVIT sensor system with a sampling rate of 250 Hz is used for the – with respect to the velocity – slipless measurement of the sideslip, pitch and roll movement. The CORREVIT sensor system consists of one sensor mounted at the front of the vehicle (HS-CE sensor) and two sensors at the vehicle's rear (H-CE1 and H-CE2). Before each test run this sensor system is calibrated to compensate potential bumpiness or roughness of the road surface. An essential point is that this kind of measurement is absolute, i.e. driftless, in contrast to the principle of commonly used integrating inertial measurement units (IMUs).

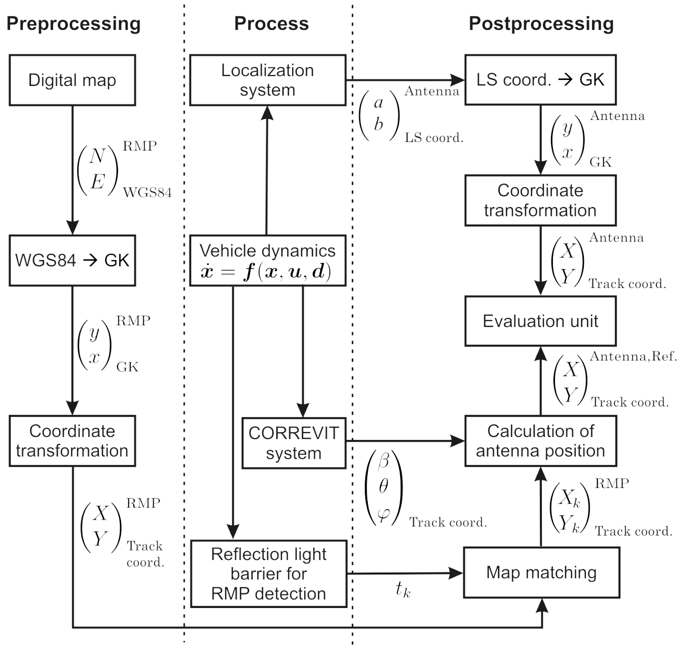

Fig. 2. Concept of the sensor data fusion

D. Sensor data fusion

Fig. 2 depicts the developed concept for the sensor data fusion of the data provided by the reference measurement system and an arbitrary localization system. The separation from left to right in *preprocessing*, *process* and *postprocessing* represents the time course of the data evaluation. The preprocessing, depicted in the first column, is done only once. The measurements during the process and the postprocessing have to be done for each test run. For the preprocessing the reference measurement points are georeferenced using the WGS84. The reference coordinates, consisting of a north and an east value, are stored in a digital map. Afterwards, they have to be converted into the Cartesian coordinate system *Gauß-Krüger* with a y-coordinate (northing) and an x-coordinate (easting) in order to reduce the complexity of the calculations during the later data evaluation. The Gauß-Krüger reference coordinates are rotated and shifted. This transformation defines an own coordinate system that is called *track coordinate system* in the following. The track coordinate system is defined by the direction of travel (X-axis), the lateral motion (Y-axis) and the first reference measuring point (origin). This transformation is done to further simplify the evaluation. Thus, the reference coordinates are available in an appropriate form, so that they can be used to carry out the data evaluations after the test runs very easily.

During a test run, the localization system to be verified measures the position of a roof-mounted antenna or reflector. It provides its measured quantities (a, b), e.g. coordinates of a two-dimensional position or distance and angle to the measured object, in its own coordinate system. Furthermore, the sideslip angle β, the pitch angle θ and the roll angle φ, are measured by the CORREVIT sensor system. In addition, the reference measurement system determines the timestamp t_k, when the reflection light barrier detects the k-th reference measurement point.

During the postprocessing the measurement data consisting of several quantities, which are described in different coordinate systems, have to be combined. Depending on the quantities provided by the localization system it may be necessary to convert e.g. the distance and angle information into a position information within the Cartesian Gauß-Krüger coordinate system. Subsequently, the same coordinate transformation used during the preprocessing can be used again to convert the position of the localization system into the common track coordinate system. By means of the processed reference coordinates of the digital map, the coordinates of each reference measuring point are mapped to the corresponding timestamp. Considering the vehicle orientation it is possible to generate the reference position which is attached to the measured timestamps by the reflection light barrier.

The timestamps at which the localization system provides position data sets are not identical to the timestamps at which reference positions are generated. Hence, the discrete reference position signal is interpolated in order to allow a comparison of both measurements. The next section shows the result of this sensor fusion with the help of an exemplary test run.

III. Testing the reference measurement system

With the help of the test run results shown in fig. 3 and fig. 4 the quality of the reference measurement system, consisting of the data integrity and the accuracy, are evaluated in the following.

Fig. 3 depicts the lateral deviation of the controlled vehicle's position to the set trajectory measured by the induction sensor. As the mean value of the lateral deviation is not meaningful, the 95% boundaries have been added. The figure shows that the control algorithm is capable of keeping the lateral deviation within a ± 2 cm interval about the mean value. This assures a reliable detection of all reference measuring points placed on the reference track.

For the generation of the reference position it is assumed that the lateral deviation caused by the control is negligible in order to reduce the complexity of the coordinate transformation. The reference position of the roof antenna and the roof reflector respectively shown in fig. 4 is generated by considering the vehicle orientation. The positions of the georeferenced magnets at a distance of 20 m are marked by crosses. As the reference point of the vehicle is located about 4 m behind the front of the vehicle, the plotted reference points are always shifted by this distance compared to the corresponding dashed lines. The shown lateral deviation is a result of the slip, pitch, and roll movement of the vehicle, which is performed, as no control can avoid the control error completely. One insight of this figure is, that already small angles ($< 3°$) can lead to a significant influence on the reference coordinates. Finally, the depicted reference position can be interpolated to generate a quasi-continuous reference position, as described in section II.

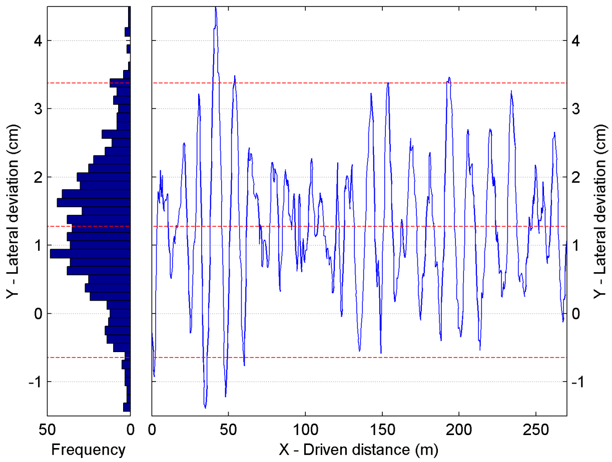

Fig. 3. Lateral deviation of the controlled vehicle to set trajectory and its 95% interval

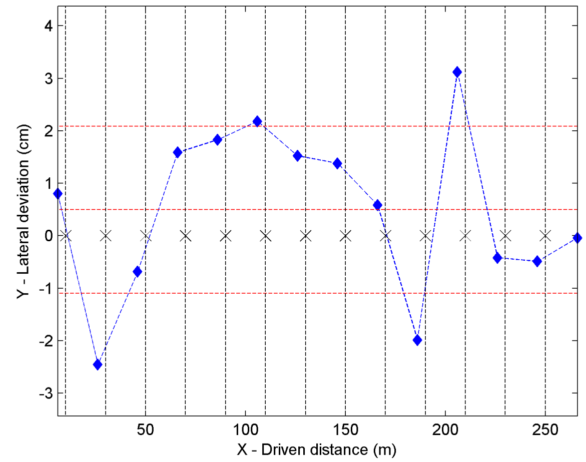

Fig. 4. Generated reference position and its standard deviation

By definition accuracy consists of two components: correctness and precision. In general the mean value can be used for quantifying the correctness and the empiric standard deviation can be taken as a measure for the precision. Concerning the accuracy corresponding to fig. 3, where the loss of accuracy due to the control error is shown, a mean value of 1.3 cm (correctness) and a empiric standard deviation of 1.0 cm (precision) is calculated.

In addition the movement of the reference position due to the vehicle orientation depicted in fig. 4 has to be considered. Fig. 4 shows that all 14 reference measuring points within the depicted sector of the reference track are reliably detected by the reflection light barrier. The distance between the generated reference coordinates in the direction of travel is, as expected, about 20 m and can be considered as equidistant neglecting the vehicle orientation.

The mean value of the reference position (fig. 4) is only 0.5 cm. This means that the reference trajectory is led very close along the predefined set trajectory, as the antenna or the reflector is mounted in the middle of the roof with respect of the lateral direction. The precision of the reference position is determined by the empiric standard deviation of 1.6 cm. Since there are only a few reference measuring points, it does not make sense to give a statement about the probability density function or an interval that covers 95% of all values.

It is assumed that the total measurement deviation is a stochastic quantity which is the sum of the measurement deviations according to fig. 3 and fig. 4. This leads to a total correctness of 1.9 cm. The application of the law of variance propagation yields a total precision of 3.8 cm (95% coverage intervall), as both signals are not correlated and the central limit theorem holds. The total correctness is assumed to be sufficient for the verification of indoor localization systems. The achieved total precision is also sufficient to verify indoor localization systems like the LPR system mentioned in section I.

IV. Conclusion

This paper highlighted the necessity of the verification of indoor localization systems for safety-relevant applications like autonomuos road traffic in tunnels. A measurement set-up is proposed in this contribution that allows the generation of a reference position. Keeping in mind the well-defined metrology terms related to the accuracy, the verification is done by calculating the measurement deviation between the indoor localization system and the reference measurement system. The test run showed that the reference position is generated with a sufficiently high correctness and precision. The side condition, which is that the complexity of the measurement set-up has to be so low that a proof of the reference's measurement uncertainty is possible, is fulfilled as well. Thus, the reference measurement system can be used in order to verify e.g. radar based indoor localization systems which are very suitable for the considered use case.

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