Distance Measurement by means of Radio Waves
Comparison of Classical and High-Resolution Spectral Methods

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Abstract – Localization within buildings is a demanding task. The principles of a low cost radio technology are described, which allow to determine distance between a transponder and a receiver. Such information can be determined by performing phase measurements based on mathematical methods.

Two different methods for distance determination are described and their results are compared – the classical method of radio direction finding which is similar to the Wattson-Watt process [9] with implemented Fast Fourier Transformation (FFT), and high-resolution spectral methods, similar to the Capon method [3] or respectively MUSIC (Multiple Signal Classification) process [2] – for distance determination. The high-resolution spectral method (HiRes) can particularly be used for initial positioning and to support inertial navigation.

Keywords – indoor navigation; high resolution distance measurement; narrow bandwidth; inertial navigation; MUSIC

I INTRODUCTION

In the recent years, GPS technology is offering an excellent solution for most outdoor-localization tasks, however, for localization applications inside buildings, no comparable solution has yet been provided. Furthermore, for certain user groups, such as the members of a fire fighter team for example, the ability to track a distance run is a requirement of crucial importance.

Many different types of application require indoor localization as the basic principle. For indoor-navigation applications in larger buildings such as shopping centers and airports, as well for location based services, or monitoring tasks in certain security sensitive areas, indoor-operable localization technology can be used.

Unlike the solution presented here, in most cases, preliminary measures have to be taken, such as for example WiFi fingerprinting.

For localization tasks indoors, radio waves can be used, however, here the multipath propagation of radio waves constitutes a major challenge. The technology as presented here provides a viable solution for such cases.

One approach for indoor navigation is the use of high-quality and relatively expensive MEMS (Micro-Electro-Mechanical Systems) inertial sensors. These sensors are mounted as a unit, for example on the foot (IMU – Inertial Measurement Unit) and measure the accelerations, as well as rotational angle rates, the magnetic field, the air pressure and temperature. Due to a drifting of the sensors, only a short period of accurate navigation becomes possible. Such errors can be minimized in foot-mounted applications by Zero Velocity Updates and by using a kalman filter. However, the errors do accumulate over time.

In order to be able to use an inertial measurement unit as indoor localization and tracking technology for firefighters, the equipment has to work very reliably and relatively accurately. This is in contradiction to the possible error accumulating in an IMU, and in case of major disorders or errors in the IMU, it is hardly possible to resume tracking – an external support seems to be necessary.

Such external support should be able to virtually do without any extra efforts such as installation work, and by no means should require any preparatory measures such as installation or calibration. The high-resolution spectral method as presented here makes it possible to achieve this goal by adding a small extension and very cost-efficient antenna systems as infrastructure. Furthermore, the system allows for the use of much less costly sensors – which therefore come with greater errors.

II TECHNOLOGY

A. Distance Measurement (DM)

A.1. Basic Principle of DM by Narrow Bandwidth Phase Analysis

The distance measurement can be performed between two transponders or between one station S1 - also called receiver and one transponder T1.

A set of individual phase measurements is provided on different successive discrete frequencies. The individual phase measurements then constitute the basis for calculating the distance by means of mathematical methods.

Each individual measurement sets up a simulated (functional equivalent) ‘standing wave’ between station S1 and the low-cost transponder T1, see figure 2.

The patent protected method achieves the same result (see functional equivalent, figure 1) as if:

1. the unmodulated carrier of station S1 were transmitted to transponder T1,
2. there were an active (amplified) reflection in T1 and
3. the reflected signal were mixed with the emitted signal in station S1 and measured as a complex I/Q value.

The phase as measured (I/Q) is then constant (in a constant frequency and an unmoved system).

The phase as measured (I/Q), however, changes upon variation of the frequency (wave length) in direct proportion to the distance (ideal case without multipathing).

Example

Supposing, (at c=300,000km/s), the following 10 frequencies are used:

\[ f_0 = 2401 \text{MHz}, \quad f_1 = 2402 \text{MHz}, \ldots, \quad f_9 = 2410 \text{MHz}. \]
Wave lengths:
\[ \lambda_0 = 0.124948m, \lambda_1 = 0.124896m \ldots \]

Distance to be determined:
10m for one way, 20m for both ways

For \( f_0 \) (20m / 0.124948m) = 160.067 waves (measured I/Q phase = 0.067 = 24°) are obtained
For \( f_1 \) (20m / 0.124896m) = 160.133 waves (measured I/Q phase = 0.133 = 48°) are obtained
Etc.

Thus (in an ideal case), per 1MHz of frequency change, a phase shift between the measurements of ca. 24° can be observed respectively. Twice the distance leads to a double phase shift. So much concerning the ideal case without multipathing - with multipathing included, everything becomes much more complex.

However, methods such as Fourier analysis and high resolution methods are applicable (except small restrictions), because this is a linear system.

A.1.1  Multipathing

The measured result represents the sum of all individual signal portions. Nevertheless, a resolution of the different signal portions is possible. The phases and amplitudes are summarized as complex number to provide signal portions. Nevertheless, a resolution of the different paths by way of reflection, diffraction, etc. by a low cost chip.

A.2.  In practice: simulating the standing wave with low cost parts

In practice, the “simulating standing wave” is realized by a sequence of single frames of clean carriers which are exchanged between the two partners S1 and T1. Only one partner is transmitting at a time [4].

The sequence is initiated by regular packet data communication. One first longer frame \( f_1 \) is used for time synchronisation and to approximate frequency in the second partner. In the following, for each frequency, each partner sends one frame of e.g. 2ms, consisting of a clean carrier \( f_{n,S1}, f_{n,T1} \). The partner receives such frame and measures its frequency and phase difference in comparison to his own local oscillator.

The transmission frequencies of both partners can be different, but should be similar (e.g. difference < 800Hz).

The system used in the prototypes is a little more complex because gain-control mechanisms are necessary and multiple antennas are used in the station.

A.3.  Complex technology, low-cost realisation possible

The complete system of a transponder can be realized by a low cost radio chip, in this case a TI CC2500 (costs 1.4$ / 1k) and a very small FPGA A3PN030 with 30k system gates by Microsemi (formerly Actel) (costs 3.4$ / 1k) for data acquisition together with a small microcontroller TI MSP430F2272 (costs 2.05$ / 1k). The future will offer low-cost single chip solutions.

Station S1 needs to be an antenna array providing 8-10 antennas to de-correlate the signal parts from each other and is largely equal to the transponder.

III IMPLEMENTATION

The present prototype system of localization technology is composed of a localization device and a transponder. Several transponders can be localized, a combination of several localization devices is possible. The current software status is optimized for the use of one localization device plus four transponders. The frequency band 2.4 – 2.5 GHz is used, others, such as 868/915 MHz or
5.8 GHz are also possible and have partially been tested. The optimum frequency range depends on the exact type of application.

In order to be localized by means of a localization device, a transponder needs to be carried. The transponder prototypes differ in their output performance, power supply, built-in sensors and size. The smallest transponders provide the following dimensions and respectively weight, including power supply:
- Yankee 7 conductor board: 77 * 45 * 2.5mm, ~9g
- Zulu conductor board: 70 * 43 * 8.5mm, ~40g

The transponders do not provide any operating elements, they are permanently working, are equipped with an IMU and only have a relevant power consumption, when the localization device requires them to transmit or the IMU tracking is activated.

An antenna array providing 14 antennas (approximately 8-10 will be enough for a product) is built into the localization devices (figure 5). This very cost-efficient and simple station can be mounted on vehicles, on mobile tripods or can be firmly installed in public buildings. By means of this station, the distance between station and transponder can be measured.

For localization tasks in rescue applications (buried or missing persons or team members), a prototype of a handheld localization device (ca. 1.2 kg) with a color display has been developed. The handheld localization device allows to search for transponders, without providing any infrastructure whatsoever. By using a combination with few cost-efficient stations, a highly reliable rescue system is obtained.

IV Comparison of the Two Methods FFT and HiRes

For the measurement of the distance between receiver and transponder, two different methods were implemented by Lambda:4. These are the implementation of the classical spectral method of radio direction finding technology which measures the distance of the main energy between two points on the one hand, and a high-resolution spectral method, which determines the shortest distance contained in a distance spectrum on the other hand.

For both methods, measurement areas were implemented, one measurement area lying down the maximum distance which by such setting can be measured. Since one component of the measurement error depends on the measurement area, such measurement area should be selected as ideally as possible.

A Classical Methods of Radio Direction Finding

In the classical methods of radio direction finding, the angle of incidence of the signal portion with the highest energy is measured by means of spectral methods.

If two signal portions providing approximately the same energy almost coincide, the two can hardly or not at all be differentiated. An identification of a signal by using Fast Fourier Transformation becomes difficult already for a difference of 10 dB or less as compared to the signal sum. This problem is observed, if there is no line of sight (LOS) and if many different reflections within the buildings are possible.

If there is LOS, the measurement results are very close to the distance in reality. In measurements with no LOS, the measurement results always are higher than the real distance, and depending on the conditions of the environment or on the materials used, they may be even much higher.
In high-resolution spectral methods, as shown here in the example of MUSIC, a high-resolution distance spectrum is measured.

The MUSIC algorithm is a high resolution MUltiple SIgnal Classification technique based on exploiting the inherent structure of the input covariance matrix. It provides information about the number of incident signals, direction of arrival of each signal, strengths and cross correlations between incident signals, noise power, etc.

Even if the portion providing the shortest distance, does not contain the highest power level, this portion can still be identified. The resolution capacity of such method with the present hardware structure provided by Lambda:4 amounts to ca. 20 dB. All signal portions which are weaker by up to 20 dB than the signal sum, can be resolved.

By means of the MUSIC-algorithm, even two almost coinciding signals can be differentiated and individually evaluated.

If there is LOS, the measurement results are very close to the distance in reality as well. In measurements with no LOS, the measurement results always are somewhat higher than the real distance, however, usually only by a small amount.

V Evaluation / Performance / Limits

To compare the two methods, the data of distance measurements from several field tests were recorded. A test subject moved around on a floor in an office building at walking pace, and continuous distance measurements were taken at ca. 1.5Hz.

Route points located on the way were measured – with an accuracy of +/- 10cm. By means of these route points the distances measured were put in relation to the real distances. The real distances between transponder and station were interpolated by means of the route points over the elapsed period of time. In this method, an additional error of up to +/- 25cm is to be expected.

By means of a test we have considered the distribution of absolute errors in ca. 2000 distance measurements in a time period of 24 minutes. In such test, distances of 0 to 11 meters between transponder and station were reached. Figure 10, 11 and 12 show the frequency of errors occurring in three distance ranges.
By means of these charts, the quality of the HiRes method as compared to the FFT method becomes very clear. In all three distance ranges, the HiRes method shows superior results and a clear majority of measurements with small errors becomes apparent – even with larger distances.

The general performance of the technology was tested in different environments. With an unobstructed line of view, a range of ca. 1500m was achieved in the city park of Hamburg [5], in other, non-documented tests in the Alps, up to 5 km.

Indoor tests were run in airports, subway stations, in office buildings and underground parking garages. Here the ranges obtained very much depend on the structural conditions. In one office building a vertical range of ca. 7-8 floors was reached [6]. On the airport pier in Hamburg a reach of 550m horizontally, and three floors vertically was obtained [7]. In underground parking garages, a transponder was reliably located through 2-3 parking levels [8].

The accuracy of the distance measurement inside buildings typically amounts to 1-5m, depending on the wall materials and other conditions of the environment (for example, many people moving around). With an unobstructed view over distances of 100-500m, the maximum error typically lies around 10 to 20 meters. In the case of very long distances or strong signal attenuation respectively, a distance measurement is not always possible.

References