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Weighted Pseudo-Range Method of Positioning in Local Ultra-Wide Band Navigation Systems

Roman Kulikov
Radio&Electronics Department
National Research University MPEI
Moscow, Russia
coolicof@gmail.com

Alexander Chugunov
Radio&Electronics Department
National Research University MPEI
Moscow, Russia
iamchugunov@gmail.com

Vladimir Pudlovskiy
FSUE "VNIIFTRI"
Moscow region, Mendeleevo, Russia
pudlovskiy@vniiftri.ru

Dmitry Tsaregorodtsev
Radio&Electronics Department
National Research University MPEI
Moscow, Russia
tsdv95@mail.ru

***Abstract* — Navigation systems play an important role in solving a large number of military and civilian tasks. The actual standard for use in open space are GNSS GLONASS, GPS, Galileo, Beidou and their various functional additions. At the same time, it is relevant to solve the problem of indoor navigation and navigation in areas of poor GNSS coverage. One of the most promising approaches to solving such problems is an ultra-wideband local navigation system. In this paper, we describe a variant of constructing such a system with one-way-ranging architecture that does not limit a number of consumers in its operation zone and implements a Time of Arrival (ToA) or Time Difference of Arrival (TDoA) method of determining coordinates with a sub-meter accuracy including strong multipath conditions. The pseudo-range positioning method is described. Weighted pseudo-range method and weighted delta-range method are investigated.**

Key words — radio navigation, local navigation systems, ultra-wide band, UWB, pseudo-range

I. INTRODUCTION

The urgency of solving the problem of navigation in conditions of poor or absent GNSS provision is confirmed by the large number of approaches on this topic in the world and a wide range of technologies used [1-7].

The potential application areas of local positioning systems are navigation of service and industrial robots, including flying ones, navigation of vehicles in tunnels and on covered parking lots, positioning of pedestrians in buildings, tracking of human body movements for medical, sports and entertainment purposes, personnel monitoring at industrial enterprises and in offices and many other uses.

A short overview of known indoor navigation solutions and the technologies used are described in detail in [8].

Each technology and approach has its own advantages and disadvantages. Currently, there is no any unified standard for indoor navigation yet and research and development of new approaches are going on.

For example, the main reason of a low accuracy of narrow-band systems if multipath. Multipath is characteristic of radio wave propagation near walls and other obstacles. The most effective way to reduce the influence of multipath is increasing of signal bandwidth: the shorter the navigation signal pulses, the more reliably the receiver emits a direct signal pulse from a mixture of pulses from reflected signals.

For this reason, the new ultra-wideband local positioning systems (LPS) are one of the promising approaches to solving the problems of precise indoor navigation. The main advantages compared to lidars are independence from weather and light conditions, as well as the lower cost of component base.

Examples of usages and features of the ultra-wide band component base are described in detail in [8].

In this paper we present the pseudo-range method of positioning in local ultra-wide band positioning system. The following section details the object of study. The following briefly describes the features of the construction of local positioning system. Then the features of the pseudo-range positioning method are described. The measurements of considered system are the differences of ranges. An analytical comparison of the pseudo-range method and the difference-distance method is presented.

II. PROBLEM STATEMENT

The purpose of the work is to analyze the possibilities of implementing the pseudo-range method to determine the coordinates using the ultra-wideband signals of the LPS with sub-meter error (by the maximum absolute value), a high rate of updating the navigation data and an unlimited number of consumers.

Tasks needed to be solved are following:

- Choice of the ultra-wide band component base
- Synthesis of the pseudo-range positioning method
- Holding of the experiment
- Comparison of the pseudo-range method and difference-distance measuring method

Tasks solutions are described in following sections.

III. SYSTEM OVERVIEW

Ultra-wide band transceivers LPS2 Mini by Loligo Electronics are used as anchors and tags [9]. It's a tiny module that includes radio frequency frontend and omni-

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antenna. The module based on Decawave's integrated circuit DW1000, receiving and transmitting and digitally processing ultra-wideband signals in accordance with the IEEE802.15.4-2011 standard.

The transceiver supports carrier tuning ranging from 3.5 to 6.5 GHz, the signal bandwidth is 500 MHz. This value corresponds to a radio impulse duration of the emitted signals of 2 ns [9].

LPS requires the presence of the infrastructure in the form of reference points (anchors) of two types - Master and Slave. A necessary condition for the operation is the presence of at least one Master type anchor, which accounts for a certain number of Slave type anchors. Their number can vary from a few to a few dozen. The reference anchors, including the master beacon, are located around the perimeter of the room (Fig.1).

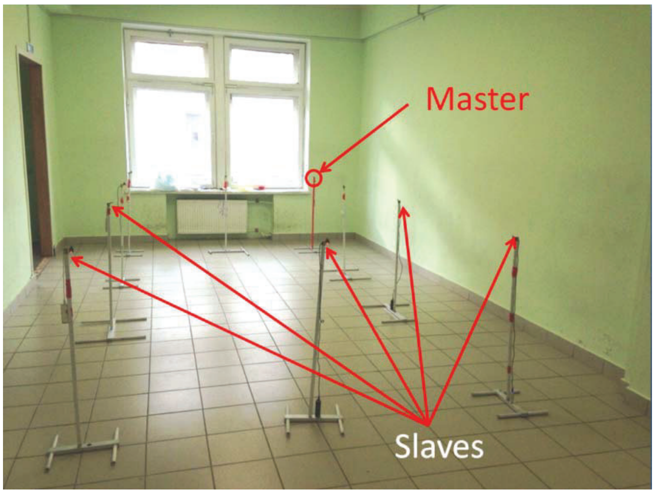

Fig. 1. Local positioning system

The maximum distance at which reliable radio reception is ensured is 40..45 meters [9]. Thus, the maximum area of a cell is 5..6 thousand square meters. Such an arrangement also requires a direct line of sight between the Master and the Slaves anchors.

Described LPS does not require time synchronization of the time scale of the Tag with the time scale of the system. Anchors are separated by time and the Tag works only in receive mode. In this regard, the system is query-free, which means the possibility of using an unlimited number of tags.

IV. MODELS AND ALGORITHMS

In the considered LPS, the one-step method of positioning is used. Since measurements of distance differences arrive successively in time, a solution can only be obtained after receiving signals from all anchors (some signals may "fall out", for example, due to obstacles in the path of radio signals). The rate of issuance of navigation solutions is 40-60 ms.

The ranging method for positioning using the signals of such LPS was considered earlier in [8] by the least squares method (LSM). Next, we present the main relations for the pseudo-range method algorithm for determining the coordinates of the tag.

Set the state vector in the form of the coordinates of the consumer in the local Cartesian coordinate system:

$$\mathbf{x} = (x, y)^T \tag{1}$$

The input of the algorithm for calculating the coordinates of the signals LPS received measurements of the form

$$\mathbf{Y} = (y_1\, y_2\, \dots\, y_N)^T \tag{2}$$

where $y_i = \Delta R_i + n_i$, N – amount of Slaves, n_i – measurement noise of i-th Slave, $\Delta R_i -$ i-th difference of ranges calculated as:

$$\Delta R_i = \|\mathbf{x} - \mathbf{x}_i\| - \|\mathbf{x} - \mathbf{x}_M\| \tag{3}$$

Formula (3) relate the coordinates of the tag $\mathbf{x} = (x, y)^T$ with measured differences of ranges: $\mathbf{x}_i = (x_i, y_i)^T -$ coordinates of i-th Slave, $\mathbf{x}_M = (x_M, y_M)^T -$ coordinates of Master.

To go to pseudo-range method, we present the unknown distance to the Master as an unknown difference in the time scales of the Master and Tag in the form

$$c\Delta = \mathrm{R_M} = \|\mathbf{x} - \mathbf{x}_\mathrm{M}\| \tag{4}$$

Then (3) may be written as:

$$\Delta \mathrm{R_i} = \|\mathbf{x} - \mathbf{x}_\mathrm{i}\| - \mathrm{R_M} \tag{5}$$

Note that the right side in the formula (5) is unchanged for any i and corresponds to the distance between the Tag and the Master R_M. However, in contrast to the relatively slowly varying real difference of time scales, this R_M value depends on the position of the Tag. This value can also be estimated with the coordinates of the Tag. We introduce a new state vector:

$$\boldsymbol{\lambda} = (x\; y\; z\; R_M)^T = \begin{pmatrix} \mathbf{x} \\ R_M \end{pmatrix} \tag{6}$$

In this form of the state vector, using the R_M component directly for determining coordinates is not convenient. Therefore, we can introduce an additional "virtual" observation associated with this quantity, which can be represented as follows:

$$y_0 = \|\mathbf{x} - \mathbf{x}_\mathrm{M}\| - R_\mathrm{M} \equiv 0 \tag{7}$$

We write the functional relationship between the measurements and new state vector:

$$\Delta\mathbf{R} = \mathbf{F}(\boldsymbol{\lambda}) = \begin{pmatrix} \|\mathbf{x} - \mathbf{x}_\mathrm{M}\| - R_M \\ \|\mathbf{x} - \mathbf{x}_1\| - R_M \\ \dots \\ \|\mathbf{x} - \mathbf{x}_N\| - R_M \end{pmatrix} \tag{8}$$

Then the design matrix may be written as

$$\mathbf{H}(\boldsymbol{\lambda}) = \begin{pmatrix} \dfrac{(\mathbf{x} - \mathbf{x}_\mathrm{M})^\mathrm{T}}{\|\mathbf{x} - \mathbf{x}_\mathrm{M}\|} & -1 \\ \dfrac{(\mathbf{x} - \mathbf{x}_1)^\mathrm{T}}{\|\mathbf{x} - \mathbf{x}_1\|} & -1 \\ \dots & \\ \dfrac{(\mathbf{x} - \mathbf{x}_N)^\mathrm{T}}{\|\mathbf{x} - \mathbf{x}_N\|} & -1 \end{pmatrix} \tag{9}$$

Further, the state vector is calculated by an iterative method using the well-known weighted least square method [10]:

$$\mathbf{x} = \mathbf{x} + (\mathbf{H}^{\mathbf{T}}\mathbf{W}^{-\mathbf{1}}\mathbf{H})^{-1}\mathbf{H}^{\mathbf{T}}\mathbf{W}^{-\mathbf{1}}\boldsymbol{\rho}, \qquad (10)$$

where $\mathbf{W}$ – covariance matrix of navigation measurement errors, which is calculated as:

$$\mathbf{W} = \sigma_0^2 \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & W_1 & 1 & 1 \\ 1 & 1 & \ddots & 1 \\ 1 & 1 & 1 & W_N \end{bmatrix}, \qquad (11)$$

where σ_0^2 – dispersion of the “virtual” measurement, and the elements of the matrix W_i are calculated by the formula

$$W_i = 1 + \frac{\sigma_i^2}{\sigma_0^2}, \qquad (12)$$

where σ_i^2 – dispersion of i-th measurement.

The next section compares the errors in determining the coordinates using pseudo-range method and difference-distance method with taking into account the covariance matrix **W** (weighted LSM) and without this account.

V. EXPERIMENT

For experimental measurements, the architecture is chosen, corresponding to Fig. 1. For the purpose of simplification, a planar navigation is considered: the estimation of two planar coordinates at a known user height.

The Tag was stationary at the center of the LPS working area at a point with known coordinates. This made it possible to estimate the values of the standard deviation (STD) and the mathematical expectation of the coordinates determination errors for all algorithms based on the results of experiments.

The results of the experiments are presented in Figures 2 - 5 in the form of histograms of errors in the coordinates of the consumer relative to a known position. Figures 2 and 3 show the distribution of errors in estimating the difference-distances method using and without using an a covariance matrix, respectively. Figures 4 and 5 show similar data when pseudo-range method is used.

Statistical characteristics of coordinate errors: STD σ_x, σ_y and mathematical expectation m_x, m_y for the considered algorithms are given in table 1.

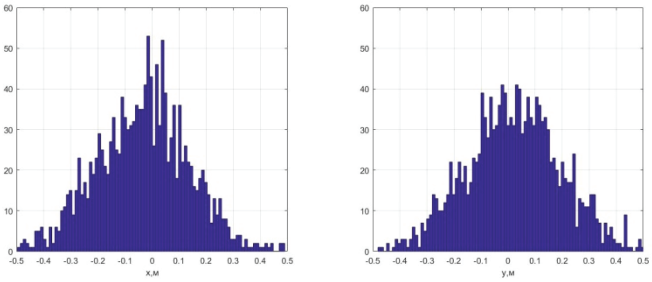

Fig. 2. Delta-range method

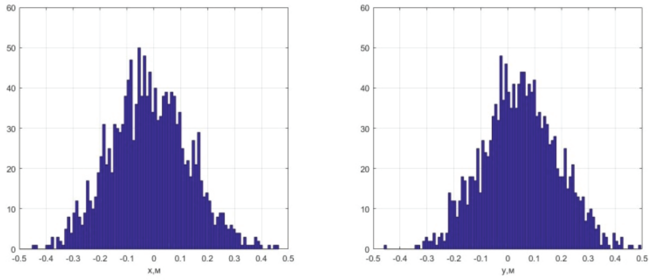

Fig. 3. Weighted delta-range method

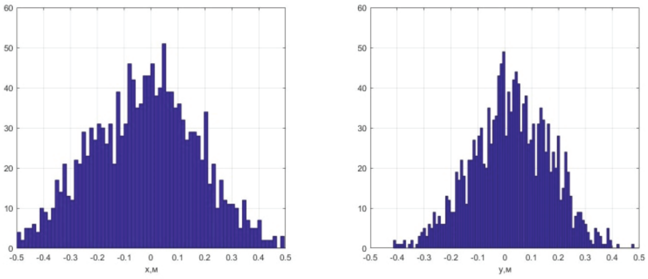

Fig. 4. Pseudo-range method

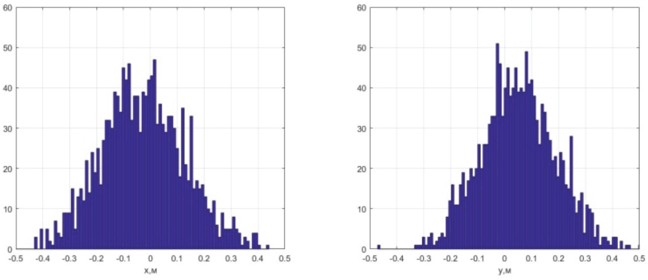

Fig. 5. Weighted pseudo-range method

VI. ANALYSYS OF RESULTS

Analysis of the data presented in Table 1 shows that the errors of coordinates using pseudo-range method and difference-distance method differ little. This can be explained by the fact that in both algorithms only the differences of the distances between the anchors and tag were used as measurements, and not the values of the pseudo-ranges to each of the anchors, as is necessary for the pseudo-ranges method.

In both methods the dispersion of the determined coordinates is noticeably reduced when using information about the a priori dispersion of measurement noise in algorithms.

The further work envisages the development of filtration algorithms for processing measurements with the current estimate of their errors, which will make it possible to achieve centimeter accuracy of navigation definitions in LPS.

VII. CONCLUSION

Ultra-wide band local positioning system with a selected component base provides sub-meter accuracy of coordinates estimating.

TABLE 1. CHARACTERISTICS OF MEASUREMENT ERRORS

	σ_x, m	σ_y, m	m_x, m	m_y, m
Delta-range method	0.171	0.176	-0.036	0.023
Weighted delta-range method	0.146	0.139	-0.016	0.047
Pseudo-range method	0.211	0.145	-0.029	0.024
Weighted pseudo-range method	0.154	0.138	-0.027	0.051

The coordinates obtained by pseudo-range or difference-distance methods are not significantly different in accuracy.

The use of even a priori dispersion of measurement noise in LPS algorithms allows one to significantly improve the accuracy of determining the coordinates.

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