Investigation of localization accuracy in UWB relative ranging system

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Abstract. The hybrid combination of a traditional positioning system with fixed reference points and a relative positioning system based on the relative position of network subscribers on the basis of measuring the distances between them increases the availability of the positioning system for moving objects in harsh environment and the accuracy of their positioning. Depending on the operating conditions, the cascade measurement of the distances between the nodes expands the working area with an acceptable positioning accuracy with the same number of fixed anchors.

1. Introduction
Due to their high resolution, ultra-wide band (UWB) systems are used for navigating indoor moving objects. With a very wide bandwidth of more than 500 MHz, carrier frequencies from 3 GHz to 7 GHz and signal processing algorithms, positioning accuracy can be up to 5 cm. Typically, UWB positioning systems rely on fixed reference points called anchors. To achieve high accuracy, the UWB tag on a moving object must be present in the line of sight of at least 4 anchors when determining the range using the time difference of arrival (TDoA) method [1]. The main interfering factors for such systems are multipath interference, fading and shadowing, i.e., line of sight obstruction between the mobile device tag and the base station.

Multipath effects are predominant to a large extent in industrial buildings, industrial areas such as factories, warehouses, mines with high conductivity of rocks. These conditions are also called harsh environments. A wide variety of interfering factors in such environments is due to the presence of "guide lines" in the form of metal structures, highly conductive layers of rock mass, as well as passive sources of shading and re-reflection of the microwave radio wave range, such as stationary units and technological structures, moving objects in the form of transport, special technological machines, directly people. Under these conditions, ensuring full coverage of working areas is associated with high economic costs for equipping with anchors, which eliminates the economic efficiency of measures to automate production and increase productivity. Also, when expanding the working area in traditional systems, it is first necessary to create infrastructure in new sections of the zone in the form of new fixed reference stations, which does not allow them to be characterized as quickly deployable systems.

Systems in which the calculation of the location of moving objects is based on the location of other moving objects and there is no need for fixed anchors are called relative navigation systems. Such systems originated on the basis of those in which fixed UWB reference stations are located in an open area next to a building in which GPS navigation is not available, and have precise coordinates with
GPS [2]. Moving objects, in turn, equipped with UWB tags, move near reference stations in an open area and in a building, and at the same time can receive information about their coordinates calculated in an ultra-wideband positioning system. However, under such conditions, there can be no question of any regular line-of-sight between the moving mark and the reference station.

Other supplements to increase the positioning accuracy is the use of inertial sensors, but they have a high error and, with prolonged autonomous operation and a lot of rotational operations, cannot provide reliable data [3].

2. Materials and methods

2.1. Hybrid relative navigation system

The solution for increasing the availability of positioning for moving objects in harsh environment and increasing the accuracy of their positioning is a hybrid combination of a traditional positioning system with fixed reference points and a relative positioning system based on the relative positioning of network subscribers on the basis of distance measurement between them. Coordinates in such a system are either only relative, or can be calculated in absolute terms, if there is information about the coordinates of the control point. The reference point in such a system is either a fixed reference station or another mobile UWB tag of this system. The UWB reference mark can be stationary at a given time, or it can have a known speed. Thus, a UWB tag that does not have a line of sight with reference stations can improve its positioning due to adjacent moving tags [4].

Difficulties that must be taken into account when building relative navigation systems - saving energy for working on the air, optimizing information transmission routes, optimizing the procedure for measuring distances between subscribers, regulating subscriber broadcasting on the air, synchronizing time scales, the ability to transmit reliable binding of individual system subscribers, self-organization of the system when turning on / off subscribers to / from the network. Much of the solution to these difficulties lies with the network protocol. The protocol should also take into account modern methods for determining distances, for example, SDS-TWR (symmetrical double-sided two-way ranging), which allows both interacting objects to obtain a range as a result of one radio interaction.

2.2. Cascade ranging

The accuracy of the relative location of UWB tags is determined by a non-zero error in determining the ranges between adjacent tags. Measurements using the TWR method (including SDS-TWR) are more reliable compared to TDoA (Time difference of arrival). The idea of developing a hybrid system with relative positioning is to determine the absolute coordinates of mobile UWB tags based on a chain of ranging measurements between other moving tags. To provide such a possibility, the network protocol must include the transmission of information about the ranges of other UWB tags, if the location is calculated on the server, or the coordinates of UWB tags, if the tag itself calculates its position. In terms of the function of transferring information between subscribers, such a system is similar to the Mobile ad-hoc network (MANET). Continuing the analogy, let's call UWB tags (mobile and fixed), endowed with the function of transmitting information, network nodes.

The principle by which the positioning of UWB tags that do not have a line of sight with fixed reference stations is as follows. There are fixed nodes in the network, in the form of reference stations, the location of which is known in advance, or the position is reliable as a result of long-term binding via GNSS systems. There are mobile nodes in the network that can calculate the position from the fixed stations, and their position is calculated with high precision.

There are nodes in the network that measure distances to other mobile nodes. They also get information about the coordinates of these nodes. These nodes determine their location with a certain error, knowing the ranges to their reference nodes and their coordinates. The error is the sum of the positioning error of the reference nodes and the error in measuring the ranges to these nodes.
And also, in the network there are nodes that in the same way calculate their location with a greater error. Thus, when considering the route from the initial fixed node to the final one, which indirectly determines its location, it is possible to enumerate the order of reliability of measurements, or, in other words, the order of relativity of measurements in relation to the initial fixed reference stations.

Undoubtedly, the positioning error increases with an increase in the order of relativity [4]. The variance of the position of a node in a Cartesian coordinate system will be the power of a random process generated by such factors as multipath and radio interference.

2.3. Determining LOS Channels
In terms of multipath error, channel noise in a received UWB multipath signal can result in a line-of-sight detection error earlier and later in relation to the true delay. This is the multipath error that affects the accuracy of the estimate of the signal arrival time. Statistical analysis shows that the multipath error can be modelled using a Gaussian distribution [5].

$$f_{\text{MP}}(x|u_{\text{MP}}, \sigma_{\text{MP}}) = \frac{1}{\sqrt{2\pi\sigma_{\text{MP}}}} \exp\left(-\frac{(x-u_{\text{MP}})^2}{2\sigma_{\text{MP}}^2}\right),$$

where $u_{\text{MP}}, \sigma_{\text{MP}}$ represent the mean and variance $n_{\text{MP}}$.

It is reasonable to assume that $u_{\text{MP}} \rightarrow 0$, since the offset $n_{\text{MP}}$ can be either positive or negative.

Previous studies of UWB pulse propagation in non-line of sight (NLOS) conditions indicated that, under certain conditions, the attenuation of the unreflected signal component can be large enough to cause a dominance of the reflected component or almost complete attenuation signal of direct propagation, and, in addition, cause an additional time delay [6]. In other words, the error in the absence of a straight line of propagation of the signal manifests itself in a bias in the estimate of the propagation delay, and therefore in the measurement of the distance between nodes.

In previous studies, the line-of-sight scenario introduces a noticeable bias error [7]. The feedforward signal is dominant in energy in the line of sight (LOS) channel, and the amplitude distribution is effective for identifying the non-line of sight scenario. To identify such a situation, the kurtosis coefficient, a measure of the severity of the peak of the distribution of a random variable, can also be used. The kurtosis describes the amplitude statistics of the UWB multipath channel, but it does not provide any information about the multipath delay. But the mean delay offset and the standard deviation of the delay characterize the delay information of the multipath channel. Typically, these two statistics are greater under NLOS than under LOS. This is suitable for distinguishing the case of NLOS from LOS and the subsequent selection of reference nodes for use in solving the navigation problem.

2.4. Accounting the order of relativity of measurements
Another innovation is that in the transmitted information packet the nodes must report their coordinates their order of relativity. Then the end node, which uses the information about the location of the reference node, must take into account the reliability of the reported measurements of the reference node. It is the order of relative that is meant to symbolize relativity.

In the protocol of information exchange, a register must be entered, which reflects the order number. The number of the order of relativity is transmitted in information exchange with other nodes. When using their coordinates in calculations, the order number is added or decreased. Since the positioning error rapidly increases with an increase in the order of relativity, we accept the condition that the order of the moving node will be 1 greater than the maximum order of relativity present in the solution of the navigation problem.

The use of the order number is relatively done by setting the priority and deciding on the choice of certain movable nodes as reference points. In the future, the order of relativity can be taken into account using weighting factors when solving the navigation problem. Also, in the future, it is possible
to introduce self-checking by the value of the error determined from the residual of the ranges when solving the navigation problem.

3. Results and discussion
Let us estimate the rate of increase in the positioning error with an increase in the order of relativity of measurements. The location of the fixed support nodes is known reliably. Further, for example, we can take the root mean square error (RMS) of the location of nodes of the 1st order of relativity equal to 7 cm due to the line-of-sight presence with 3 fixed reference stations. The error in their positioning is the sum of the error in determining the ranges involved in solving the navigation problem.

Then the RMS of the positioning error of the 2nd order mobile node can be methodologically estimated as the root of the sum of the position variances of each of the 3 nodes participating in the solution of the navigation problem by the 2nd order node. For a 3rd order RMS mobile node, positioning errors can be estimated similarly. And then in order. The increase in the error is shown graphically in figure 1.

![Figure 1: n-th order node positioning accuracy.](image)

As you can see, the error can be large. The 3rd order of relativity as a maximum may be acceptable. However, the position error can be reduced by the visibility of other nodes of low order of relativity, for example, first or zero order.

The model of the network of moving nodes with different form factors of premises, the density of obstacles, the number of moving nodes, the number of fixed support nodes is very difficult for an isolated study of factors affecting the statistically average positioning error of nodes with a large order of relativity.

On the one hand, there are more nodes, more nodes of the 1st order, which means less error in positioning nodes in general. On the other hand, the room is larger with the same density of obstacles, then the presence of communication lines between nodes of the 1st and 2nd order is less common, there are more lines between nodes of the 2nd and 3rd order. This means that the determining factor is the density of nodes in the area of the room.

Thus, the primary iteration of the model should represent a worst-case scenario where 1st order nodes use 3 1st order nodes, 2nd order nodes use 3 1st order nodes, 3rd order nodes use 3 2nd order nodes. We consider the use of 3 control points due to the use of the TWR method for determining the distance. And such a geometric pattern, repeating itself, will be the implementation of the largest positioning errors in accordance with figure 1. Let the side of the square of the depicted area in figure 2 is 50 m.

The presented model in figure 2 sets the previously described initial conditions. Certain geometric combinations give rise to movable nodes of various orders of relativity, indicated by a number on the circle. The dark circle represents a stationary reference station. Isolation and propagation of such patterns allows to set initial conditions and simulate their statistical manifestation. When removing a node of the 0th order from the upper right corner, we get a symbol of the lack of infrastructure in this direction of the development of the working area of the industrial site.
To ensure coverage of the working area, at least 3 times more reference stations are required for the classic system architecture. Due to the introduction of a new positioning scheme, the number of reference stations has been reduced.

Statistical modelling was carried out using the Octave software according to the principle of random movement of objects in perpendicular directions. For various room geometric models, the overall performance metric of the new network architecture will be the percentage of positioning time with an acceptable positioning error.

Let the movable nodes move at the same constant speed of 0.5 m/s, and the simulation step is 0.1 s, allowing a movement of 5 cm. Instead of setting the conditions for the signal-to-noise ratio (SNR), the error in determining the range between two nodes was set, based on the known accuracy indicators for fixed reference stations in figure 1. The model involves 11 movable nodes.

With a significantly long simulation time, 100000 iterations, at which a node can pass up to 6 times around each obstacle, a statistically average time spent by a mobile node in each of the values of the order of relativity, shown in figure 3 is obtained. It is the moving units that are taken into account, i.e., with the order of relativity 1 or more. To refine these statistics by the number of nodes with different orders of relativity seems to be a rather difficult and useless task, since the integral assessment of the system's efficiency is the positioning accuracy assessment shown in figure 4.

![Geometric model of 3rd order relativity node.](image)

**Figure 2.** Geometric model of 3rd order relativity node.
In figure 3 movable nodes of the 1st order of relativity, using only fixed reference nodes, are present in their line of sight only 32% of the observation time. In a classical system with TWR, more than 68% of the time there would be insufficient data to solve the navigation problem. With additional positioning on mobile nodes of the 1st and 2nd orders, the system's inaccessibility becomes at the level of the order of 1%.

The results in figure 4 allow to set the observation time of the nodes with an acceptable position error due to the additional relative positioning of the nodes. For a significant part of the time when nodes move 77%, the root mean square error of location is 0.14 m, which is 45% more than without the use of chains of relative measurements. The level of acceptable positioning error depends on the operating conditions. When used in underground mine workings, this value can be taken at the level of 0.2 m, which is represented by 88.6% of observations. The concentration of indicators in the region of low error may be due to the low frequency of scenarios, in which, within the framework of a given geometric model, the control points are nodes of the 2nd order of relativity, taken in the solution of the navigation problem due to the lack of nodes with a lower order of relativity in the line of sight. However, this increases the availability of the system by more than 10%.

4. Conclusions
Improving positioning accuracy due to the receipt of additional data through software, namely the measurement protocol and data transmission, is an improvement in the ad-hoc network of mobile nodes of the UWB positioning system. With much fewer fixed anchors, the positioning system remains available. Such a system can maintain a low level of system error that accumulates when combined with inertial sensors, but these methods can complement each other.

The presence of the mobile node information about its own position and the location of the target mobile node, the system allows you to optimize the routes of the mobile nodes in real time, the system expands the capabilities of monitoring labor productivity and production processes. If the technological transportation processes are ordered in descending order of subordination, then the hybrid relative navigation system provides feedback for maintaining, stabilizing and regulating work processes at the production facility, for example, on the movement of equipment, the sequence of technological operations, product movement, increasing the intensity of the use of assets, which brings economic effect.

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References

[1] Website of Decawave Retrieved from: https://www.decawave.com/

[2] Han H, Wang J, Liu F, Zhang J, Yang D and Li B 2019 An emergency seamless positioning technique based on ad hoc UWB networking using robust EKF Sensors (Switzerland), 19(14) doi:10.3390/s19143135

[3] Liu R, Yuen C, Do T-N, Zhang M, Guan Y L and Tan U-X 2020 Cooperative positioning for emergency responders using self IMU and peer-to-peer radios measurements Inf Fusion 56:93-102 10.1016/j.inffus.2019.10.009

[4] Krasnov T V 2020 An ultrawideband indoor positioning system with distributed ranging between tags Journal of Physics: Conference Series 1679(3) doi:10.1088/1742-6596/1679/3/032041

[5] HeiDari M and Pahlavan K 2007 A new statistical model for the behavior of ranging errors in TOA-based indoor localization Proc. Conf. on Wireless Communications and Networking Conference, WCNC’07, Hong Kong pp 2566–2571

[6] Khan A R and Gulhane S M 2018 A highly sustainable multi-band orthogonal wavelet code division multiplexing UWB communication system for underground mine channel Digital Communications and Networks 4 264-276

[7] Xu J, Ma M D and Law C L 2006 Position estimation using UWB TDOA measurements Proc. Int. Conf. on Ultra-Wideband ICUWB ’06 (USA) pp 605–610