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Indoor Localization System in the Multi-block Workspace

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Abstract: As service robots and the ubiquitous technology have evolved, an increasing need for the autonomous navigation of mobile objects has arisen. In a large number of localization schemes, the absolute position estimation method relying on navigation beacons or landmarks has been used widely with its economical and accurate advantages. However, few of them have expanded the applications to complicated workspace which involves many rooms or blocks. As the navigation of mobile objects in complicated workspace is vital for the ubiquitous technology, the multi-block application is necessary. This paper presents methodologies and techniques for the multi-block applications of the indoor localization system with active beacon sensors. This new design of indoor localization system includes the optimal auto-calibration, selection of the reliable beacons and the fault detection and isolation algorithm using redundant measurement.

Keywords: Indoor Localization, Multi-block, Active Beacon

I. INTRODUCTION

The problem of determining the location of a mobile robot in a room has been investigated in a number of ways during recent years. The relative positioning such as dead reckoning is simple, inexpensive, and easy to implement in real time. But it has the problem of accumulating wheel slippage error. The absolute positioning scheme is exemplified by the well-known satellite GPS system. Due to its expensive cost and the shielding effect, it is difficult to use GPS for indoor applications. Some GPS like indoor localization systems, such as the ultrasonic positioning system [1], has been developed to provide absolute position information to the mobile objects.

In practice, the trade-off between accuracy and cost in positioning system must be considered. At Pusan National University, we have previously focused on maximizing accuracy at relatively low cost, and have developed an Active Beacon System (ABS) which is designed based on the beacon sensors [2].

An auto-calibration algorithm has been developed in order to deploy the ABS system in an easy and reliable manner [3]. The algorithm only requires the user to measure several reference locations on the floor. The system will collect a variety of distance data from the seeds to the beacons, then analyses the data, calculates the beacon positions, and get ready for trilateration.

As the service robot and the ubiquitous technology required, the localization system should be deployed in complicated workspace with multi-rooms and multi-blocks. This paper proposes a multi-block application of the indoor ABS localization system.

II. MULTI-BLOCK APPLICATION

In multi-block application, the deployment and the initialization of the beacons become extremely complex. Some of the beacons will not be initialized well using a small number of reference locations and the traditional auto-calibration algorithm. In order to provide precise beacon information for the localization, an optimal auto-calibration has been suggested in this paper. In order to evaluate the beacon reliability, the definition of DOP (Dilution of Precision) is introduced. The failure ultrasonic signals, usually caused by echoes, interferences or obstacles, often result in remarkable errors in the navigation process. A fault detection and isolation (FDI) algorithm named Signal Integrity Monitoring is proposed to eliminate this effect.

The structure of the multi-block application is shown in Fig.1. With the space ID getting from the spatial identification, the relevant beacons' information is downloaded to the user equipment, the RFID transmitter send trigger signals to activate the relevant beacon. The beacon sensor sends an ultrasonic signal back. The distance from the beacon to the mobile robot can be calculated by the TOF measurement. The received data is evaluated by the Signal Integrity Monitoring algorithm to detect and isolate the failure. Only the healthy signals and high reliable beacons can be selected to compute the user position. If there are still redundant measurements after the Signal Integrity Monitoring and the beacon reliability selection, the DOP analysis is implemented to determine which group of signals and beacons can get the best precise user position. The scheme of the beacon selection is shown in Fig. 2.

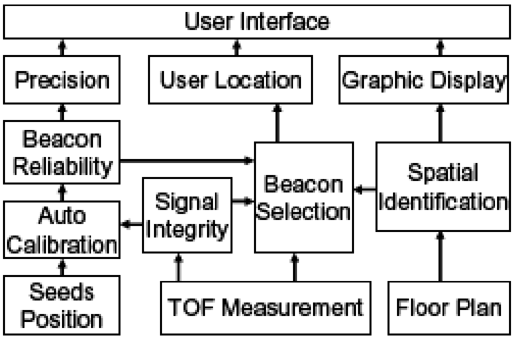


Fig.1. The structure of multi-block navigation

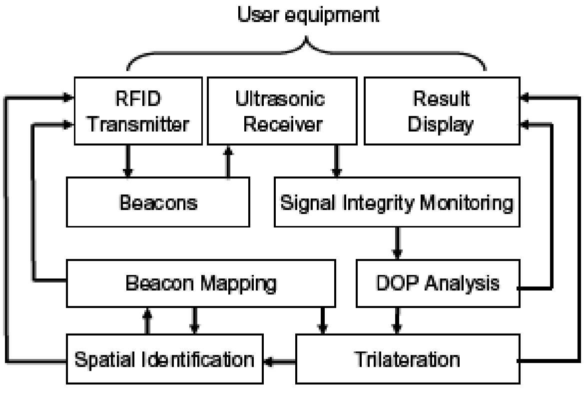


Fig.2. The scheme of the beacon selection

III. DILUTION OF PRECISION

The performance of the trilateration algorithm is affected by the ranging errors and by the geometrical arrangement of the beacons and the user's position. The geometry causes the DOP effect, i.e. the ranging error amplification when the position vector is computed. Assume that the range measurement errors are un-correlated with the same variance σ^2. The definition of geometric DOP [4] is given as:

$$\mathrm{GDOP} = \frac{\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}}{\sigma} \tag{1}$$

The observation equations in three dimensions for each beacon with known coordinates (x_i, y_i, z_i) and unknown user coordinates (X, Y, Z) are given by

$$Z = \rho^i = \sqrt{(x_i - X)^2 + (y_i - Y)^2 + (z_i - Z)^2}\ . \tag{2}$$

These are nonlinear equations that can be linearized using Taylor series [5]. Then we can get the basic measurement relationships of trilateration:

$$y = \mathbf{H}x + \upsilon_\rho \tag{3}$$

where the additive white noise $\upsilon_\rho \in N(0, \sigma^2)$; y is the difference between the actual measured range and the predicted range based on the nominal user position; x is the three components of true position deviation from the nominal position; $\mathbf{H}$ is the usual linear connection matrix arrived at by linearzing about the nominal user position.

The least squares solution can be obtained as [10]

$$\hat{x} = \left(\mathbf{H}^T\mathbf{H}\right)^{-1}\mathbf{H}\,y\ . \tag{4}$$

The error covariance is represented as

$$E\left\{(\hat{\mathrm{x}})(\hat{\mathrm{x}})^T\right\} = \sigma^2\left(H^T H\right)^{-1}. \tag{5}$$

For $\hat{\mathrm{x}} = [\Delta X \quad \Delta Y \quad \Delta Z]^{-1}$,

$$E\left\{\hat{\mathrm{x}}(\hat{\mathrm{x}})^T\right\} = \begin{bmatrix} E\{\Delta X^2\} & E\{\Delta X\Delta Y\} & E\{\Delta X\Delta Z\} \\ E\{\Delta Y\Delta X\} & E\{\Delta Y^2\} & E\{\Delta Y\Delta Z\} \\ E\{\Delta Z\Delta X\} & E\{\Delta Z\Delta Y\} & E\{\Delta Z^2\} \end{bmatrix} \tag{6}$$

We are principally interested in the diagonal elements of

$$\left(H^T H\right)^{-1} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix}. \tag{7}$$

From the GDOP definition, we can get

$$GDOP = \sqrt{A_{11} + A_{22} + A_{33}} \tag{8}$$

GDOP is used to evaluate the beacon reliability. The best reliable beacons have the least DOP data.

IV. SIGNAL INTEGRITY MONITORING

In multi-block application, a signal integrity monitoring is proposed based on the ABS system. Its basic principle is using the redundant TOF measurements to detect and exclude the fault. To obtain a 3D position solution, at least three measurements are required. To detect a fault, at least four measurements are required, and to isolate and exclude a fault, there must be at least five measurements available.

The QR factorization decomposition of the $n \times 3$ matrix $\mathbf{H}$ is [6]:

$$\mathbf{H}_{n\times 3} = \mathbf{Q}_{n\times n}\begin{bmatrix} \mathbf{R}_{3\times 3} \\ \mathbf{0}_{(n-3)\times 3} \end{bmatrix} \tag{9}$$

where $\mathbf{Q}_{n\times n}$ is an orthogonal matrix (meaning that $\mathbf{Q}^T\mathbf{Q} = \mathbf{I}$), $\mathbf{R}_{3\times3}$ is an upper triangular matrix, $\mathbf{0}_{(n-3)\times3}$ is a zero matrix. If we premultiply both sides of Equation (9) by $\mathbf{Q}^T$, the result will be

$$\mathbf{Q}^T\mathbf{H}_{n\times3} = \mathbf{Q}^T\mathbf{Q}_{n\times n}\begin{bmatrix}\mathbf{R}_{3\times3}\\ \mathbf{0}_{(n-3)\times3}\end{bmatrix} = \begin{bmatrix}\mathbf{R}_{3\times3}\\ \mathbf{0}_{(n-3)\times3}\end{bmatrix}. \quad (10)$$

If we define the parity matrix $\mathbf{P}$ to satisfy $\mathbf{P}\,\mathbf{H} = 0$

$$\mathbf{P} = \textbf{bottom } (n-3) \textbf{ rows of } \mathbf{Q}^T. \quad (11)$$

The parity vector p is given by $p = \mathbf{P}y$ [7], so

$$p = \mathbf{P}y = \mathbf{P}(\mathbf{H}x + \upsilon_\rho) = \mathbf{P}\,\upsilon_\rho. \quad (12)$$

A signal risk factor F_S is defined as below, and is used as the test statistics:

$$F_S = p^T p. \quad (13)$$

The probability of missed detection is expressed by the following equation [8]:

$$P_{MD} = P\left(F_S < \mathrm{T}_S \,\middle|\, \text{fault occurred}\right) \quad (14)$$

The value of a threshold could be determined by the probabilities of missed detection (the users' requirement). When the test statistic (signal risk factor) exceeds the threshold, a fault detection warning will be displayed on the user interface.

In the presence of a bias fault $\mathbf{b}$, the measurement Equation (3) becomes:

$$y = \mathbf{H}x + \mathbf{b} + \upsilon_\rho. \quad (15)$$

Assume that the i-th measurement is fault,

$$\mathbf{b} = \begin{bmatrix}0 & \cdots & b_i & \cdots & 0\end{bmatrix}^T. \quad (16)$$

Substituting Equation (15) and (16) into Equation (12) gives

$$p = \mathbf{P}y = \mathbf{P}\,\upsilon_\rho + p_i b_i \quad (17)$$

p_i is the i-th column vector of the parity matrix $\mathbf{P}$. p_i is also called the i-th channel vector since it is related to the i-th beacon. The direction of p_i which is associated with the failed beacon is most closely aligned with parity vector p.

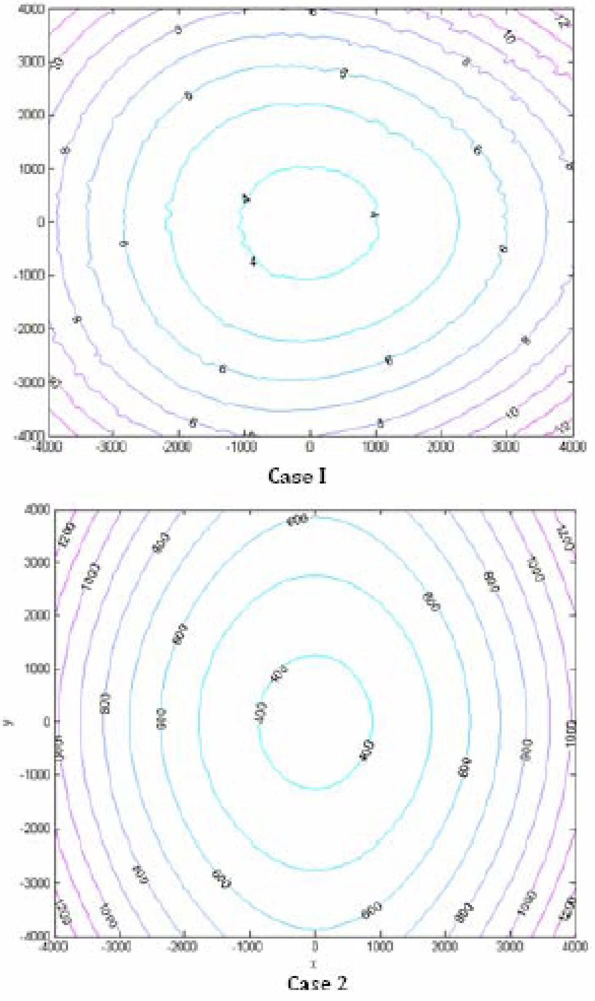
The failed signal can be identify as:

$$n_f = \arg\max_{i=1,\ldots,n} \frac{\left|\mathbf{p}^T\mathbf{p}_i\right|}{\left|\mathbf{p}_i\right|} = \arg\max_{i=1,\ldots,n}\left(\cos\theta_i\right) \quad (18)$$

V. RESULTS

1. Simulation of DOP

We examine the GDOP for two representative cases. In the first case, the three beacons form an equilateral triangle on the XY plane inscribed in a circle centered in the origin of radius 1000 distance units. The locations of the beacons are $\left(-500\sqrt{3},-500,3000\right)$, $(0,1000,3000)$, $\left(-500\sqrt{3},-500,3000\right)$, The data-acquisition area of the system is a square area at the base plane, spanning in each direction from -4000 to 4000 units. In the second case, the stations are located at $(-500,-5,3000)$, $(0,5,3000)$, $(-500,-5,3000)$, i.e., they are almost aligned along the X axis. The acquisition area in this case is also the base plane.



Case I

Case 2

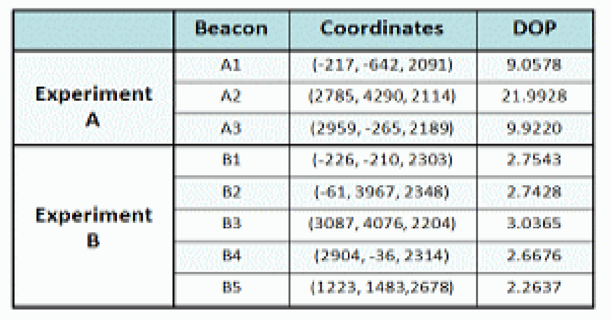
Fig.3. The simulation of DOP

Fig.3 shows the contour plots of each case. We observe that while in Case 1, the GDOP value increases as we move away from the equilateral triangle's barycenter; in Case 2, the GDOP is much bigger for the robot and three beacons are almost coplanar.

2. Experiments

We made two experiments to demonstrate the performance of the Multi-block application. The experiment A is the traditional navigation method with three beacons which are initialized by traditional auto-calibration using three reference locations. The experiment B use the multi-block application method proposed in this paper. In this experiment, we use five beacons which are initialized by optimal auto-calibration method with twenty reference locations. And for each localization process, the five range measurements are evaluated by the Signal Integrity Monitoring algorithm to detect and isolate the fault. Then the beacon selection module chooses the best three beacons to calculate the robot position with trilateration. The auto-calibration results and the DOP value in the auto-calibration is shown in Table 1.

Table 1. The beacon deployment of experiments



	Beacon	Coordinates	DOP
Experiment A	A1	(-217, -642, 2091)	9.0578
	A2	(2785, 4290, 2114)	21.9928
	A3	(2959, -265, 2189)	9.9220
Experiment B	B1	(-226, -210, 2303)	2.7543
	B2	(-61, 3967, 2348)	2.7428
	B3	(3087, 4076, 2204)	3.0365
	B4	(2904, -36, 2314)	2.6676
	B5	(1223, 1483,2678)	2.2637

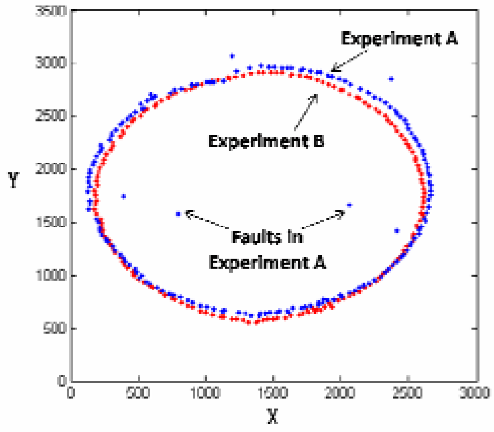


Fig.4. The illustration of navigation

The XY coordinate routes of the mobile robot getting from two experiments are compared in one figure (Fig. 4). As we expect, the navigation result of experiment A has several faults. They are the points out of the path in the figure. In the experiment B, these faults are avoided and the route is smoother than the experiment A.

VI. CONCLUSION

In this paper, the multi-block application of ABS indoor localization system is presented for the navigation of the mobile robot in the complicated environment. A beacon selection algorithm is used to activate the most appropriate beacons and derive the best user position. With given user requirements of navigation performance, the signal integrity algorithm can detect and isolate the failure during the ultrasonic TOF measurement. An optimal auto-calibration algorithm is suggested to deploy and initialize the beacons precisely. Using the multi-block application of the ABS system, the mobile robot can move freely among the different blocks of the workspace with the ubiquitous navigation service which includes coordinate, spatial identity and navigation precision information.

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