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Localization Algorithm Based on Zigbee Wireless Sensor Network with Application to an Active Shopping Cart

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Abstract—**This paper describes a localization algorithm based on hybrid sensor system with application to an active shopping cart. For a given experimental environment, the probability localization method is applied to confirm the global coordinate of the target customer. And a hybrid sensor system combining the Zigbee and odometry is used to improve the localization performance of the active shopping cart. The shopping cart is equipped with motors for mobility and sensors for tracking person. Through experimental work, we corroborate the feasibility of the proposed localization algorithm.**

I. Introduction

Super market is a self-service shop offering a wide variety of food and household products and it is organized by aisles. Customers use shopping cart to load the product they want to buy. However, a common shopping cart would not be suitable for everyone, especially for the disabled. Wheelchair users cannot pull a shopping cart easily. The aged do not have enough energy to carry a loaded shopping cart. The mother holding a baby is inconvenient to control the shopping cart. Besides, many people may forget the location of their shopping cart when talking to friends or paying much attention to goods of interest. So, the existing shopping cart and the environment of super market are not adequate to help those special groups.

In this paper, we develop an active shopping cart (ASC) system to solve the above mentioned problems. The ASC system includes several active shopping carts and a set of sensory system. The hybrid sensor based active shopping cart system will offer the following services.

1. Customer tracking service by the ASC
2. Localization of the target customer and the ASC.

There are a variety of human tracking approaches. Most of them are based on visual tracking [1] and laser-based human tracking [2]. Considering customer tracking problem by a shopping cart, the target customer can be occluded or lost temporarily by several reasons. In this case, a robust tracking method should be taken into account. A laser range finder (LRF) is adopted in this paper to track torso of the human-body, which was reported as the most robustly recognizable part of the body [3]. In order to be used in the shopping mall environment, the ASC should not only follow a customer, but also avoid other objects and other people for safety. Also in order to reduce error caused by incremental encoder and Zigebee, an extended Kalman Filter is used to compensate those errors.

However, customer tracking would fail due to the complexity of the shopping mall environment. In order for the shopping cart to retrack the customer upon failure of tracking, the ASC should know the position of the lost customer and its own position relative to the global coordinate system. To fulfill this point, wireless sensor network technique (WSN) will be used. In the field of WSN based indoor localization, there has been a considerable amount of research. Bahl, et al [5] proposed a RF-based system and Ni, et al [6] utilized a RFID-based positioning scheme for the location of people in an office environment. Helen, et al [7] used calibration method of RSSI-based location tracking system. Yu, et al [8] used ultra wideband (UWB) to execute indoor localization.

Comparing with other wireless sensor network techniques as mentioned above, received signal strength indicator (RSSI) based method is the most commonly used method in recent years. Zigbee is one of RSSI based technique. Ahn, et al[9] proposed en environmental-adaptive RSSI based indoor localization method using Zigbee. Blumentha, et al [10] proposed a weighted centroid localization algotithm of Zigbee-based sensor network system for outdoor environment. Alhmiedat, et al [11] proposed an improved fingerprinting localization approach for Zigbee WSN.

In this paper, Zigbee, which is capable of low cost, low power consumption, and self-forming, is chosen to establish wireless sensor network system in the shopping mall environment. We organized a Zigbee wireless sensor network by using CC2431/CC2430 sensor developed by Texas Instruments (TI).

In this paper, we discuss the development of an active shopping cart based on the proposed network system. After explanation of the automatic tracking algorithm of the ASC system in section II, Zigbee wireless sensor network and two different localization algorithms are described in section III. Design a motorized shopping cart and experimental results are described in section IV, and finally we draw conclusion in section V.

II. Automatic Tracking

A. Human Tracking

In order to make sure that the shopping cart moves and follows customer automatically, a human tracking technique is

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implemented. A laser range finder has been known to be a good means to detect objects. An IURG-04LX type laser range finder produced by HOKUYO [12] is installed on the ACS. From the viewpoint of robustness in real application, it would be better to scan non-oscillatory part of the human body. The torso part is preferable to track the human body as described in the previous work [4].

B. Customer Following Task

The ASC controls its linear velocity and angular velocity to follow a target customer during the shopping tour. Actually, he velocity of the ASC is decided according to the velocity of the target customer. For security, we control the linear velocity by reflecting the distance between the target customer and the ASC.

1) Distance control

In order to keep the desired tracking distance between the ASC and the target customer, a typical proportional controller is suitable. It is well-known that applying only proportional controller does not guarantee settling at the desired value, so it will retain steady state errors. However, we use these steady state errors as the safe distance between the target customer and the ASC. The following equation describes the proportional controller applied to the mobile robot.

$$v = K_{Pv}(\mathrm{D}_a - \mathrm{D}_d), \tag{1}$$

where v is the linear velocity of the ASC, K_{Pv} is the proportional gain, D_a denotes the distance between the ASC and the target customer, and D_d denotes the desired tracking distance, respectively. Eq. (1) explains that the linear velocity of the mobile robot increases as the tracking distance increases. However, reversely it can be said that the tracking distance increases as the linear velocity increases. By using this fact, the mobile robot automatically produces a longer safe tracking distance as the target moves faster.

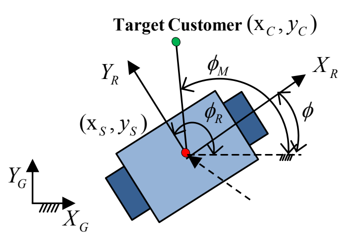

Fig. 1 Definition of angles in the global frame

2) Orientation control

The main function of the ASC is following a target customer in the human tracking period. Therefore, the angle between the heading direction of the ASC and the direction the ASC should be minimized. In order to compensate the angle error, a typical PID control is applied to the system as follows.

$$\omega = K_{p\omega} e_\omega + K_{I\omega} \int e_\omega + K_{D\omega} \dot{e}_\omega, \tag{2}$$

where ω is the angular velocity of the ASC, $e_\omega = \phi_M - \phi_R$, $K_{p\omega}$, $K_{I\omega}$, and $K_{D\omega}$ denote P-gain, I-gain, and D-gain of the PID controller, respectively. As described in Fig. 1, ϕ_R is the heading angle of the ASC with respect to the global reference coordinate system and is described by $\phi_R = \phi + \pi/2$, where ϕ is the angle between the x-axis of the global reference coordinate system and the x-axis of the ASC coordinate system and it is obtained by the odometry of the ASC. ϕ_M is the direction of the customer.

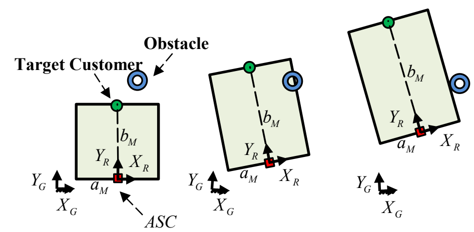

Fig. 2 Collision Avoidance

3) Collision Avoidance

In the shopping mall environment, shelves, walls, and other people, except the target customer, could be considered as obstacles. From the view point of the ASC, the position of the target customer can be the goal position for the ASC. We set up the obstacle detection range as a rectangle shown in Fig.2. The b_M is a time varying parameter and its length is the distance between the ASC and its target customer as shown in Fig.2. The minor radius a_M is a fixed parameter and is set 500mm.

If any obstacle is detected in the obstacle detection range, the distance control stops and then slows down the current linear velocity of the ASC. However, the orientation control keeps working to compensate an orientation error. Fig. 2 shows how the ASC avoids a collision in general cases. However, when b_M is larger than the detection range of laser range finder, the target will be lost. In this case, Zigbee wireless sensor network will execute the locating and approaching procedure to find the lost target customer.

III. Localization Algorithm

A. Zigbee Based Wireless Sensor Network

With the purpose of finding and approaching the lost target customer, the current position of ASC and the target customer need to know with respect to the global reference coordinate system of the shopping mall environment. For easy installation and maintenance, a wireless sensor network will be employed in the shopping mall environment. ZigBee technology provides a practical application with the characteristics of low rate, low cost, low power consumption as an open and global standard for WSN. Zigbee-based wireless sensor network is composed of a coordinator, reference nodes, and blind nodes. In this paper, reference nodes are used as the landmark known in the global coordinate system, and blind nodes provide their positions in the global coordinate system. The Zigbee coordinator is the root of the network system responsible for creating, initializing and maintaining the whole Zigbee Wireless Sensor Network, and communicating with a PC. In our Zigbee WSN, the coordinator is connected via RS232 serial interface to the PC. The main chip of coordinator and reference nodes are implemented using CC2430 developed by Texas Instruments .

The blind node uses TI's CC2431 sensor as the main chip. CC2431 is a commercially-available System on Chip solution with a received signal strength indication (RSSI)-based hardware location engine. The CC2431 location engine implements IEEE 802.15.4 standard based radio location solution exploiting a maximum likelihood estimation algorithm. RSSI is given by [15]

$$\mathrm{RSSI} = -(10\,n\log_{10}d + A), \tag{3}$$

where d is the distance from the blind node to the reference node, n is the signal propagation constant or exponent, and A is the received signal strength at a distance of one meter. Basically, Eq. (3) provides a RSSI-based ranging strategy. The trilateration method (a real-time tracking method) [13] is employed to calculate the position of the blind node using at least 3 reference nodes.

It has been known that the positioning error of Zigbee is about 2 m in general. However, such error is acceptable in the shopping mall environment, because the customer is able to recognize the shopping cart visually within the distance of 5 meter from him or her.

B. Target Customer Localization Algorithm

As mentioned in section II, when b_M is larger than the detection range of laser range finder, the ASC will lose its target customer. In order to provide automatic and intelligent services to customers in a shopping mall environment, the ASC needs to find its target customer automatically using Zigbee WSN. For this, confirming the global coordinates of the ASC and the target customer is a prerequisite to handle this event. A localization algorithm based on Zigbee WSN is proposed to locate the target customer in the following.

In this paper, we adopt a $24m \times 20m$ cross-shape corridor as the experimental platform shown in Fig. 3. 4 reference nodes, CC2430, are placed in the ceiling. With respect to the global coordinate system of the corridor, the positions of the 4 reference points are $R_1(8,4.75), R_2(13.5,0.5), R_3(21.5,4.75)$ and $R_4(14.25,12)$. Among two blind nodes CC2431, one is installed on the active shopping cart and the other is taken by the tester.

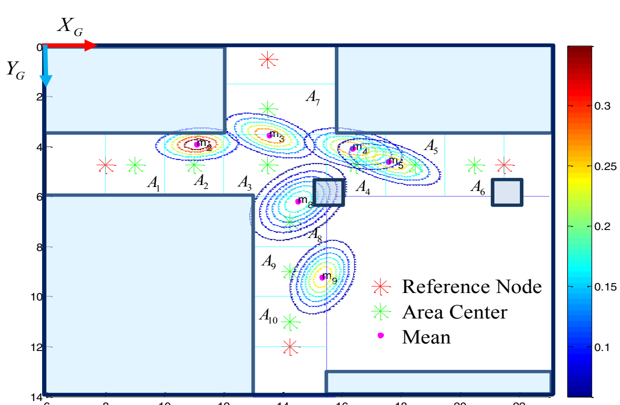

Fig. 3 Gaussian distribution of tester's position

TABLE I. COMPARISIONS OF ZIGBEE SENSOR DATA

No	Global Position		Condition 1 No disturbance		Condition 2 Cart with disturbance		Condition 3 Tester with disturbance	
			Mean	STD	Mean	STD	Mean	STD
1	x	9	10.25	0	10.1	0.67	10.46	1.01
	y	4.75	4.3	0.13	4.75	0.24	3.84	0.38
2	x	11	11.89	0.28	12.28	0.8	11.11	0.73
	y	4.75	4.95	0.24	4.71	0.34	3.9	0.34
3	x	13.5	13.75	0	13.5	0.72	13.56	0.84
	y	4.75	4.1	0.57	4.48	0.36	3.56	0.47
4	x	16.5	16.74	0.57	15.21	1.11	16.4	0.87
	y	4.75	4.19	0.11	4.16	0.51	4.08	0.43
5	x	18.5	19.5	0	18.37	0.84	17.61	0.82
	y	4.75	5.05	0.16	4.31	0.38	4.61	0.49
6	x	20.5	17.72	0.38	16.96	0.88	16.56	1.3
	y	4.75	5.17	0.15	5.93	0.55	8.12	0.86
7	x	13.5	14	0	14	0.09	13.72	0.59
	y	2.5	2.75	0	2.56	0.12	3.62	1.1
8	x	14.25	13.75	0	13.75	0.03	14.53	0.82
	y	7	6.8	0.22	7.25	0.62	6.2	0.77
9	x	14.25	15.5	0.05	15.6	0.5	15.38	0.55
	y	9	9.74	0.05	9.72	0.48	9.21	0.74
10	x	14.25	15.27	0.41	17.45	6.67	17.1	0.96
	y	11	9.75	0	8.78	7.92	7.84	1.01

Considering the layout of the shopping mall and the system error of Zigbee blind node in general disturbance environment, we divide the whole place into several rectangles with about $2m$ in length. In our test platform, a cross-shaped corridor, are divided into 10 areas denoted by $A_{1,\ldots,}A_{10}$ as shown in Fig. 3. The center $C_i(\mathrm{x},\mathrm{y})$ of each area, marked by a green dot, stands for the coordinates of the area A_i. In the area A_i, the distance between any point to C_i is less than 1.5m, which is smaller than the error of Zigbee WSN, in x - or y -direction.

In order to employ Zigbee WSN, the signal distribution properties of Zigbee should be analyzed with consideration of several conditions of environmental disturbance. The disturbance includes several kinds of noise, WIFI signal, and human activity. For experiment, we display 4 Zigbee reference nodes by red points and then measure the center coordinate $C_i(\mathrm{x},\mathrm{y})$ of each area hundred times in 3 different conditions, where i is from 1 to 10. The first condition is that a blind node is installed on the ASC without any disturbance. The second and the third conditions are that the ASC and the tester carry a blind node, separately, with disturbance.

X_i and Y_i denote the vectors storing the position of each area A_i. Based on the measured data, we calculate the mean value $(\bar{\mathrm{x}}_i, \bar{\mathrm{y}}_i)$ and covariance matrix Σ_i of $C_i(\mathrm{x},\mathrm{y})$ as follows

$$\Sigma_i = \begin{bmatrix} \sigma_{xi}^2 & \rho_i\sigma_{xi}\sigma_{yi} \\ \rho_i\sigma_{xi}\sigma_{yi} & \sigma_{yi}^2 \end{bmatrix}, \tag{4}$$

where ρ_i is the correlation between X_i and Y_i, σ_{xi} and σ_{yi} denote the standard deviation (STD).

The mean value and STD of A_i are summarized in Table1. From Table 1, it is noted that Zigbee has relatively small system error under condition 1. However, experiments under condition 2 and condition 3 with consideration of environmental disturbance yield bigger errors. In light of this fact, this paper employs a probability localization method to better estimate the position of the target customer in the shopping mall environment.

The first step is to set up the probability density of Gaussian distribution of A_i and make data packets to store information of A_i based on measured data. The area near to the reference node has big errors as mentioned in [15]. So, when setting up Gaussian distribution and performing experiment, the areas except A_1, A_6, A_7 and A_{10} will be considered. Fig. 3 also shows Gaussian distribution of each $C_i(\mathrm{x},\mathrm{y})$ in conditions 3. Pink dots express mean value $(\bar{\mathrm{x}}_i, \bar{\mathrm{y}}_i)$ of measurement values at the center of A_i. Therefore, the data packet $DP_i = \{\bar{x}_i \quad \bar{y}_i \quad \Sigma_i\}$ contains mean value $(\bar{\mathrm{x}}_i, \bar{\mathrm{y}}_i)$ and covariance matrix Σ_i of $C_i(\mathrm{x},\mathrm{y})$. In the customer localization stage, the element in DP_i should be comprised by the results in condition 3.

In the second step, the system will estimate the position of the target customer. When receiving current global coordinate $P(\mathrm{x},\mathrm{y})$ of the target customer, the system will compare $P(\mathrm{x},\mathrm{y})$ with each data packet DP_i respectively, and calculate the corresponding probability $p_i(\mathrm{x},\mathrm{y})$ given by [14]

$$p_i(\mathrm{x},\mathrm{y}) = G\exp\left(-\frac{1}{2(1-\rho_i^2)}\left[\frac{(\mathrm{x}-\bar{x}_i)^2}{\sigma_{xi}^2}+\frac{(\mathrm{y}-\bar{y}_i)^2}{\sigma_{yi}^2}-\frac{2\rho_i(\mathrm{x}-\bar{x}_i)(\mathrm{y}-\bar{y}_i)}{\sigma_{xi}\sigma_{yi}}\right]\right) \quad \text{where} \quad i = 1\cdots N \tag{5}$$

$$G = \frac{1}{2\pi\sigma_{xi}\sigma_{yi}\sqrt{1-\rho_i^2}}. \tag{6}$$

Finally, the estimated coordinate of the target customer will be derived as follow.

$$(x_{est}, y_{est}) = \frac{\left(\sum_i x_i p_i(x,y), \sum_i y_i p_i(x,y)\right)}{\sum_i p_i(x,y)}, \tag{7}$$

where x_i and y_i are the center position of the area A_i.

To verify the accuracy of the proposed localization algorithm, an experiment is conducted as follows. The tester holds a blind node and enters each area. In each area, 40 random data for the tester's position are obtained. They are denoted in Fig. 4 by 6 different shape marks. Blue marks stand for the measured position. Using Eq. (5), Eq. (6), and Eq. (7), Fig. 5 demonstrates estimated positions of the tester in each area. Red marks stand for relevant estimated positions. It is noted that the proposed method improves the accuracy of Zigbee WSN to a great extent. Comparing with original measurement data, the estimated data tends to converge to the center of each area.

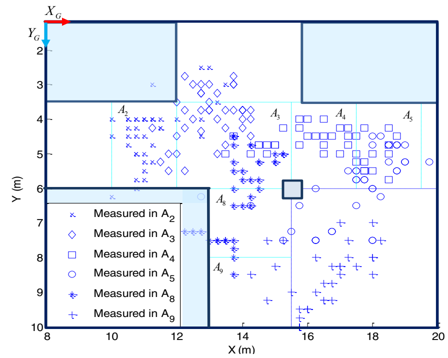

Fig. 4 Raw position of the target tester

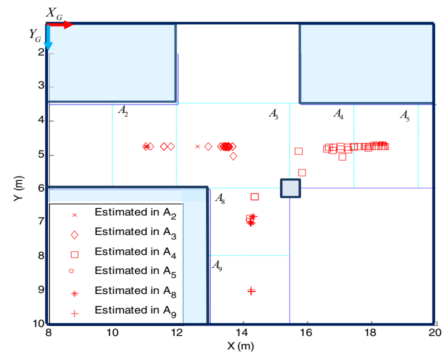

Fig. 5 Estimated position of the target tester

C. ASC Localization Algorithm

In order to improve the accuracy and reduce errors, we need to investigate ACS localization algorithm using hybrid sensor system. In our experiment, we combine sensor information of Zigbee and incremental encoder mounted on the wheels of the shopping cart. It is noted that Zigbee has some system errors but that it has no accumulative error. On the other hand, the incremental encoder gives more precise information but it has accumulative errors. Combining merits of the two sensors would enhance the performance of the localization process.

Now, we describe the kinematics. The ASC is a mobile robot with the kinematics of a unicycle, described as

$$\begin{pmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{pmatrix} = \begin{pmatrix}\cos\theta\\ \sin\theta\\ 0\end{pmatrix} + \begin{pmatrix}0\\ 0\\ 1\end{pmatrix}\omega. \tag{8}$$

The location of the cart is provided by $u = (\mathrm{x},\mathrm{y},\theta)$, where x and y is the Cartesian coordinates of the cart center and θ is the angle between the axle and the horizontal axis of the global coordinate system. The sensor system used in this section includes two incremental encoders and a set of Zigbee sensors.

In order to enhance the position accuracy of the sensor system, an extended Kalman Filter (EKF) based localization system is organized. The structure of the localization system for the ASC is designed as Fig. 6. At the step k, the incremental sensor (i.e., encoder) provides δs_k^L , δs_k^R , and the travelling distances of left and right wheels during the sampling time k . Based on Zigbee WSN, the estimated data z_k is derived by employing probability localization method to modify the original measurement value z_k^{Ori} . Passing the incremental sensor data onto the odometric prediction model of the ASC, it is possible to compute an odometric prediction $\hat{x}_{k/k-1}$ and an odometric prediction covariance matrix $P_{k/k-1}$. An observation prediction $\hat{z}_k$ is matched with the estimated measurement data z_k offered by Zigbee WSN. Results of matching are the innovation term v_k and the associative covariance matrix S_k . These values are utilized by EKF to generate the state estimate $\hat{x}_k$ and its covariance matrix P_k .

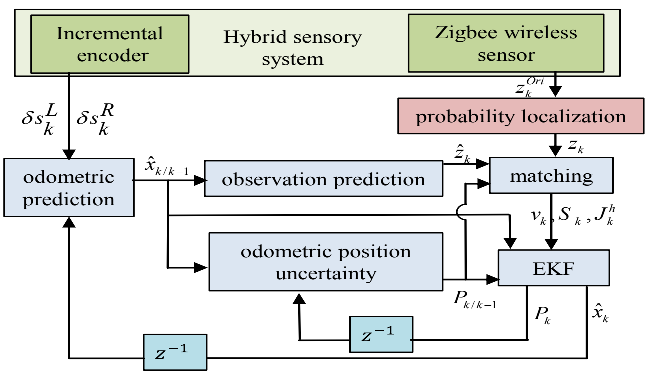

Fig. 6 Structure of localization method for ASC

IV. Experiment

A. Introduction of Active Shopping Cart

To better help customer during the shopping trip, a new design of the shopping cart is developed as shown in Fig. 7. An extended structure for mobility is installed on the bottom of a conventional shopping cart. The structure is composed of a double-decker telescoping structure (DDTS) and two motors. An active shopping cart system should have the ability to compute all the values that the system need. To implement the active shopping cart, we developed an embedded system that mainly consists of a laser sensor , a DSP controller, three motor drivers, a set of wireless communication system (Zigbee), three actuators with encoder, two DC lead-acid batteries, and a voltage converter. The main part on CPU board is a dsPIC chip. The control circuit board is connected to the computer through RS232 serial communication.

Fig 7. Active Shopping Cart

Based on the proposed localization algorithms, two experimental trials have been carried. In experiment 1, localization performance of ASC is tested based on section III. Besides, experiment 2 aims at locating and approaching the lost tester based on the two localization algorithms presented in section IV. The attached video clip shows experiment 2. Current global coordinate of the ASC is obtained by ACS localization algorithm based on hybrid sensor system. And current global coordinate of the tester is the blind node's estimated coordinate which is derived by using target customer tracking algorithm based on Zigbee WSN in section IV. Before the experiments, Zigbee WSN should be set in advance. A and n in (3) are tested and set to 39 and 16, respectively.

Experiment 1 (Localization of ASC)

This experiment aims at showing the performance of the proposed ASC localization method. In order to design a reference path, the operator pulls the ASC so that ASC follows the desired path denoted by T-shape in Fig. 8. During the journey, the path of ASC calculated by the odometry-based localization method is compared to that of ASC generated by proposed localization method.

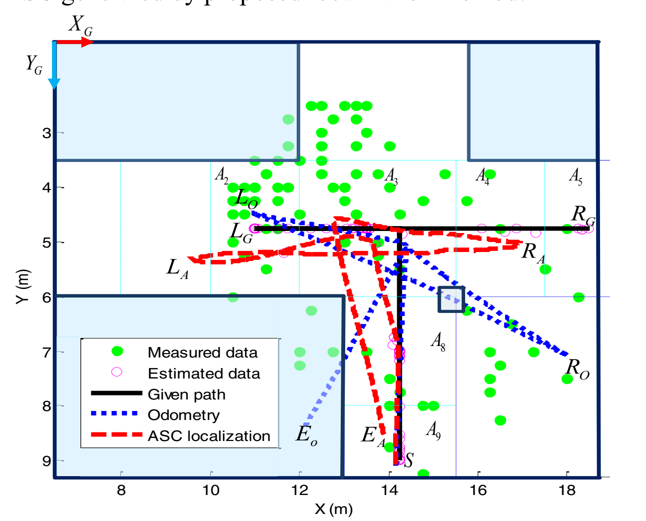

Fig. 8 Comparison of the proposed ASC localization method and odometry method. (Given path $[S-L_G-R_G-S]$, odometry path $[S-L_O-R_O-E_O]$, and ASC path $[S-L_A-R_A-E_A]$)

From the starting point (marked 'S'), the ASC moved to L_G point, then it moved to R_G point. Finally, it moved back to the starting point. During the journey, we obtained Zigbee data (filled circles), then we applied Eq. (7) to the Zigbee data for estimation of the ASC's positions. The results are shown as circles in Fig. 8. When the odometry information is only used, there exist accumulated errors (blue dotted line). However, when the odometry and Zigbee data are combined by EKF, the result has bounded errors denoted as the red dashed line through many experimentations. As shown in this experiment, the proposed ASC localization algorithm is appropriate to be used for the shopping cart application.

Experiment 2 (Localization of ASC and tester)

This experiment is to locate and approach the lost tester (refer to the attached video clip). During the approaching procedure, every 10 second, ASC gives announcement to draw attention of the tester. If the distance between the global coordinate of the tester and the ASC is less than 2m, the approaching procedure will stop. The ASC keeps giving announcement to draw attention of the tester until the target is found successfully. The experiment result is shown in Fig. 9. The blue solid line and the red dashed line represent the trajectory of the ASC and the tester, respectively.

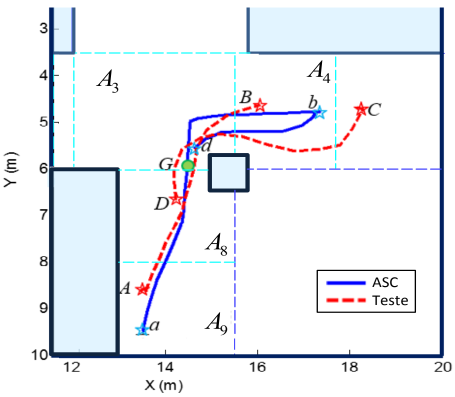

Fig. 9 Target tester approaching

The ASC lost its tester at position G marked by a green/light gray circle, but the position of the tester is at red/black star B. Then ASC stops and tries to find the tester. The approximate location of the tester with a blind node BN_1 is known by the customer localization algorithm in section III. B, and the location of the ASC is estimated by the ASC localization algorithm. Therefore, by using the known map and the positions of the ASC and the tester, the ASC can navigate to the tester by following the preplanned trajectory from the ASC to tester. The approaching trajectory of the ASC is from G to the blue/light gray star b. When the tester founds the ASC at the position C, then it restarts the human tracking process. After the ASC finds the target tester, the trajectory of ASC depends on the target tester's trajectory, as marked by the line connecting points b and d.

From experiment 2, it is seen that based on Zigbee WSN system, the proposed two localization method provides reasonable real time global coordinate to the ASC and the tester. As a result, the ASC performs locating and approaching the lost tester successfully.

V. Conclusion

An active shopping cart system is proposed in this work. A new automatic shopping cart is designed to provide its mobility and implement customer tracking function. Combining the Zigbee wireless sensor network based localization system and the laser range finder based human tracking technique, we could offer a technological support for providing automatic and intelligence services to customers in a shopping mall environment. Through experiments, we demonstrated that the ASC was able to locate and keep following the lost target customer by using the wireless sensor network and self-navigation algorithm. It is believed that this technique will assist special populations who cannot conducted shopping alone in the shopping mall environment.

Acknowledgements

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