An Integrated Location Method using Reference Landmarks for Dead Reckoning System

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Abstract— **Dead reckoning system is a promising solution for pedestrian location, which determines the user's location by using multiple built-in sensors in the wireless devices or wearable sensors (3-axis, magnetic, gyro) on the pedestrian. However, most location estimation methods in dead reckoning systems meet the problem of accumulated location errors due to magnetic field disturbances. Some existing methods solved the problem by forcing the user to take the phone in a fixed gesture. However, they are not practical for the users in daily life and also accumulate errors with time flying. To solve the above problem, in this paper, we propose a new method to integrate wireless time-of-arrival landmark signals into dead reckoning system. The proposed method utilizes the hearable Time Difference of Arrival signals from the LMs, which are placed in the known locations to help correct the accumulated location estimation errors in dead reckoning systems. We evaluate the location estimation error with the proposed method when different number of reference LMs is placed and compare with location estimation in a dead reckoning system. Simulation results show that location estimation errors drop when different number of reference LMs are used.**

Keywords- dead reckoning system; integrated location method; mobile phone built-in sensors (3-axis, magnetic, gyro); TDOA landmarks.

I. INTRODUCTION

Recently, mobile devices are widely spreading. The location information of mobile devices is expected to be used in many new services, such as friend finding, shopping guide, etc. Many mobile phones have GPS receivers, but some services should be provided in the situations where the function of GPS receivers is not available, such as indoor areas, underground areas and complicated urban districts with a lot of buildings.

Many studies have investigated indoor location technologies, and some services based on time difference of arrival (TDOA) [1-4], wifi access points [5] are available today. However, providing many sensors with localization hardware (e.g., GPS) is expensive in terms of cost and energy consumption [6-7]. A more reasonable solution to the localization problem is to allow mobile phones to have their step information at all times, and allow users to infer information from these sensors [8-11]. Recently, mobile phones with built-in sensors (e.g., 3-axis, magnetic, gyro sensors, etc) have been widely spreading. These sensors help providing a lot of user's information that can be used in a location system: arm swing detection, step count estimation, direction estimation and step length estimation. Swing detection, step count estimation, direction estimation and step length estimation. Therefore, relative location systems- DR systems offer a promising solution [12-15]. Dead reckoning (DR) systems use sensors (e.g., accelerometer and gyroscope) to determine the user's current location without external infrastructures, they derive the characteristics of human such as the number of steps, step length, and direction.

However, most location estimation methods in DR systems meet the problem of accumulated location errors due to magnetic field disturbances. Existing works solved the problem by using the following methods: required the user to input their step size before the location estimation [12-13]; forced the user to mount the mobile phone in a fix gesture on his/her body [14]. Obviously, the first one is not accurate once the users step into crowded environment, user's step size is changed into smaller ones; and the second one brings inconvenience to the users. Taking these into considerations, in this paper, we propose a new method to correct the accumulated estimation errors. The proposed method integrates wireless TDOA LMs signals (LMs are placed in known places) into location estimation in a dead reckoning system. Once the user walks near the transmission range of a TDOA LM, the TDOA signal information are received, and the accumulated errors are compensated with the received ranges.

The paper is organized as follows. Section II briefly describes dead reckoning system. Section III presents the proposed integration location system. Section IV illustrates the details of the proposed integrated method. Section V compares simulation results of the proposed method and the dead reckoning location method. Finally, Section VI concludes the paper.

II. DEAD RECKONING SYSTEM

A. System Overview

In a pedestrian navigation system, it is necessary to locate the position of the user in any environment. Dead reckoning location system is such a system that can estimate the user's location based on a previously determined location, without external infrastructures. For this reason, a self-contained

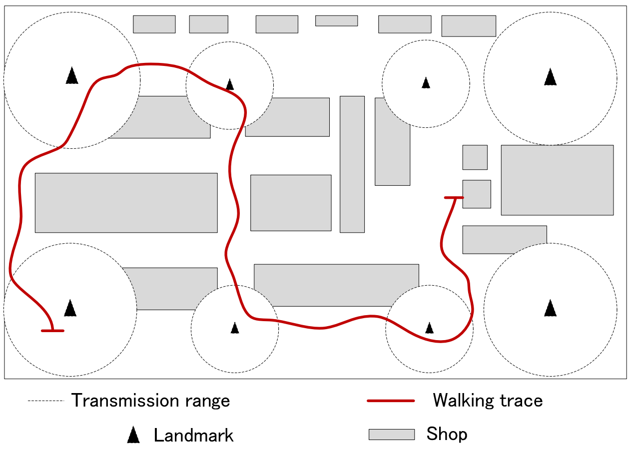

Figure 1. Integrated location system

navigation system based on a dead reckoning principle is ofinterest. To locate the position of the user, distance and heading from a known origin have to be measured at an acceptable level of accuracy [14-15]. In a pedestrian navigation system, an electronic pedometer can be used to count the number of steps, which can be combined with the step size for obtaining the distance traveled. In addition, a terrestrial magnetic compass can be used as a heading sensor.

B. *Problem in Dead Reckoning System*

The dead reckoning system is dependent upon the accuracy of measured distance and heading and the accuracy of the known origin. Recently, mobile phones with built-in sensors (e.g., 3-axis, magnetic, gyro sensors, etc) have been widely spreading. These sensors help providing a lot of user's information that can be used in a dead reckoning location system. The current relative location of the user is calculated as movement in an estimated direction, based on the step length estimated from the last position at each estimated step. However, most studies on dead reckoning system accumulated estimation errors, which greatly reduced location accuracy.

Apart from sensor measurement noise, the main factors that have effect on the estimation accuracy are step size error and direction bias error. The step size error is the difference between the actual step size and the predetermined step size entered by the user. Although the exact step size is not necessary for the distance calculation, the average step size over a short period has to be measured. The reason for this is that the step size of the user may vary according to the environment; for example, the step size of the user is shorter when the user is walking in a crowded area. Hence, the predetermined step size cannot be used effectively for the distance measurement. The direction bias error is a result of several causes such as magnetic declination and body offset [2, 8]. In a clean environment, the total bias can be changed slowly over a long period and may need to be re-calibrated occasionally. Therefore, how to alleviate the accumulated location errors is the challenging issue. We solve this problem by introducing the reference TDOA LMs in the system to alleviate the accumulated estimation errors. The details are described in the next sections.

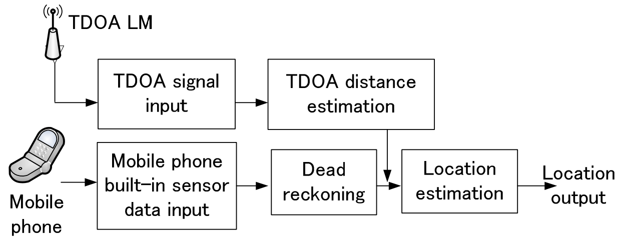

Figure 2. System architecture

III. INTEGRATED LOCATION SYSTEM

A. *Requirements and Scope*

Our method is to develop an integrated location method using some reference LMs and mobile phone built-in sensors. The requirements and scope are as follows,

- Commercial mobile phones with built-in sensors (3-axis, magnetic, gyro sensors).
- Reference LMs located at known places, e.g., the intersections or corners of the road.
- Location estimation should be compensated when the user received TDOA signals from LMs, accuracy guaranteed even in a magnetically noisy environment.

B. *System Architecuture*

The integrated location system is shown in Figure 1. It includes some reference LMs (RF/acoustic signals deployed at some known locations) which are deployed at the corners or intersections of shops. The transmission range of each LM is different based on the space of the corners and intersections of shops. The user walks in the room, and the walking trace is shown in red line. The system architecture is shown in Figure 2, which constitutes mobile phones with built-in (3-axis accelerometer / magnetic / gyro) sensors and TDOA LMs. Each LM broadcasts its ID and location periodically. The number of steps is counted by detecting the peaks of acceleration in the same way as a typical pedometer and the orientation of a mobile phone with the sensors is found in the same way as an electronic compass. The step size and the compass bias were calculated from step size average and compass bias average of the last 100 seconds. In location correction part, the mobile phone corrects its location, by using information from TDOA signals [14-15].

C. *Reference TDOA LMs*

The reference LMs use TDOA ranging method, which are based on the time difference of arrival between radio and acoustic signals. TDOA ranging utilizes the fact that two signals propagate at different speeds: an instantaneously at short distances for radio waves, and approximately 340m/s for sound. The TDOA LMs operate as follow; the sender broadcasts a radio message followed by an acoustic signal (chirp) with a known frequency signature. The mobile phone receives the radio message by starting to listen the chip using

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Table 1. Definitions

Definitions:
r_{LM}- maximum transmission range of a LM;
r_{TDOA}- received TDOA signal distance from a LM;
Intersection- arcs of a circle of a radiu r_{TDOA} centered at LM by roads which locates within the circle.
(x_k, y_k)- LM_k location;
(x_{est}, y_{est})- mobile phone location estimated by DR method;
d_{est}- the distance between (x_{est}, y_{est}) and (x_k, y_k);
(x_{mk}, y_{mk})- centroid location of intersection m within LM_k;
($x_{cross,ij}$, $y_{cross,ij}$)- location of the road's cross-point i and j;

integrated RF reader [15]. Once the mobile phone detects the radio message, it estimates the distance by computing the difference in arrival time of the radio and acoustic signals. As an example, the MCS410CA Cricket mote can be used as the TDOA reference LM [1]. The Cricket Mote includes all of the standard MICA2 hardware and an ultrasound transmitter and receiver. This device uses the combination of RF and ultrasound technologies to establish differential time of arrival and hence linear range estimates [16]. The Cricket mote works at a frequency in the 433MHz band, but the frequency can be fine tuned within several megahertz either at compile time or runtime [17].

For the mobile phone users, Wireless Dynamics has announced a device called the iCarte that will add both RFID and NFC capabilities to the iPhone, which can be used for the users to receive RF signals [18].

IV. INTEGRATED LOCATION METHOD

As discussed in Section II, there are several sources of errors in the dead reckoning system, mainly as step error and direction error. Most existing methods solved the problem by using the following methods: required the user to input their step size before the location estimation; forced the user to mount the mobile phone in a special position on his/her body. Obviously, these methods accumulate estimation errors with time flying. The first one is not very accurate once the users step into crowded environment, they may change their step size into smaller ones; and the second one brings inconvenience to the users. Taking these into considerations, we propose an integrated location method utilizing the received TDOA range from reference locations to correct the accumulated estimation errors.

There are two parts in the proposed integrated location method. The first part is that, when TDOA LM signal is not available, the location is estimated using the method in a DR system [15]. The second part is that, when the TDOA LM signal is available, the received TDOA signal will be incorporated in the estimation process. We will describe the detail steps of the whole method, and two parts in the following subsections. Table 1 shows the definitions that are used in the paper.

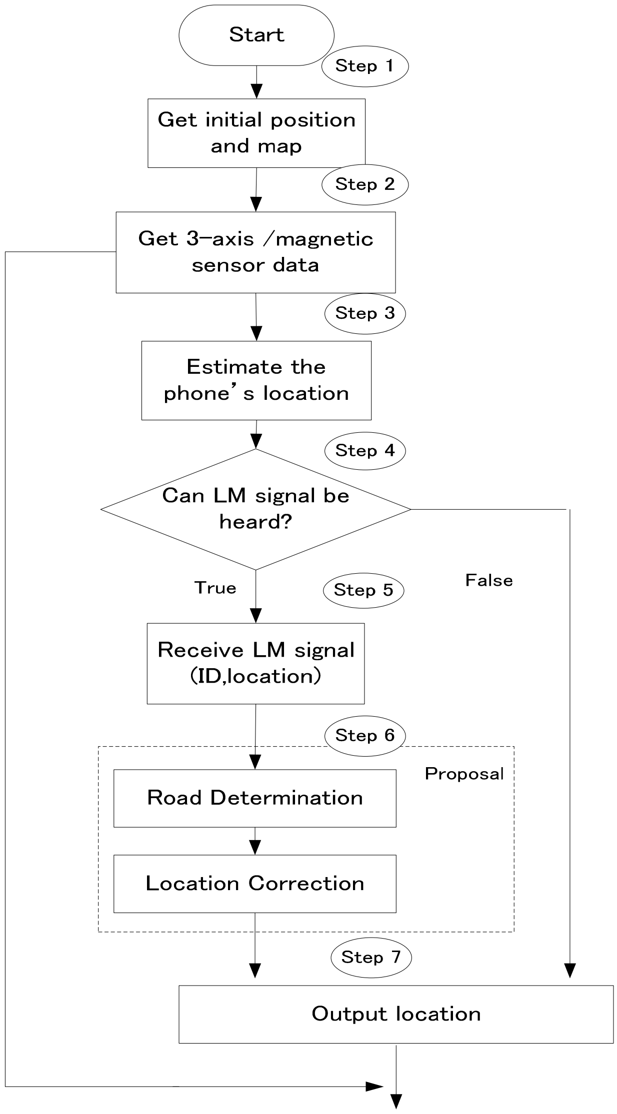

Figure 3. The flowchart of the proposed method

A. *Overview of the Proposed Method*

The following describes the detail steps of the overall method. The flowchart is illustrated in Figure 3.

[Step 1] Get initial location from the nearest LM.
[Step 2] Get 3-axis/magnetic/gyro sensor information from the mobile phone.
[Step 3] Estimate current mobile phone's location by using the method in a DR system [15].
[Step 4] Receive signals from LMs, and record LM's ID, and location.
[Step 5] Check if LM signals can be heard. If LM signal can be heard, go to step 5; if LM signals cannot be heard, go to step 6.
[Step 6] Stop location estimation by DR method. Estimate the mobile phone's location by using the following method, then go to step 7.
[Step 7] Location output.

B. Road Determination

As the LMs locate at the corners or the intersections of the roads, once the user receives TDOA signals, we need determine the direction of the user's road first. There are two cases for road determination:

-Case 1: (x_{est}, y_{est}) is on a single road
The signal road is determined as the current road.
e.g., (x_{est}, y_{est}) is on road 1-> road 1 is its current road.
-Case 2: (x_{est}, y_{est}) is on several roads (inside the transmission range of a LM)
e.g., (x_{est}, y_{est}) is on road 1,2,3
[step 1] Calculate the distance between the current location and the centroids of those roads.
e.g., (x_{est}, y_{est}) is on roads 1,2, and 3. Calculates the distance d_{11}, d_{21}, d_{31}, for (x_{est}, y_{est}) with (x_{11}, y_{11}), (x_{21}, y_{21}), and (x_{31}, y_{31}).
[step 2] Sort the calculated distance. The road with the shortest calculated distance is determined as current road.
e.g., $d_{11}< d_{21}<d_{31}$, then road 1 is current road.

C. Location Correction

Once the user receives TDOA signals from the reference LMs, the user should locate in the transmission range of the reference LMs. We have determined the user's road in the previous subsection. However, the user's location estimated by a DR system may be different from the transmission range of the heard LM, due to accumulated errors [17-18]. Therefore, we discuss the location correction based on the estimation differences between DR location and received LM ranges. Three cases are studied: within hearable TDOA ranges; within twice TDOA ranges; and out of twice TDOA ranges. Figure 4 shows the detail of the studied scenario.

-Case 1: $d_{est} < r_{LM}$
[Step 1] List the user's possible intersection(s) ($i=1,\ldots,N$) based on the past location (last three steps, t-3,t-2,t-1,t).
e.g.,
road 1 at time t-1, t-2, t-3 -> possible intersection is 1.
road 3 at time t-3, t-2, road 1 at time 1 -> possible intersection is 1,3.
[Step 2] Estimate the output location using the intersection's location obtained in step 1 and the estimated location (x_{est}, y_{est}).

$$x_{out} = \frac{1}{\mathrm{N}+1}\left(x_{est} + \sum_{\mathrm{i}=1}^{\mathrm{N}} x_{ik}\right) \tag{1}$$

$$y_{out} = \frac{1}{\mathrm{N}+1}\left(y_{est} + \sum_{\mathrm{i}=1}^{\mathrm{N}} y_{ik}\right) \tag{2}$$

[step 3] If (x_{out}, y_{out}) is on the map, then outputs it. If (x_{out}, y_{out}) is not on the map, then go to step 4.
[step 4] Calculate the distance between the location (x_{out}, y_{out}) and the centroids of those roads.
e.g., calculates the distance d_{11}, d_{21}, d_{31}, d_{41} between (x_{out}, y_{out}) and the (x_{11}, y_{11}), (x_{21}, y_{21}), (x_{31}, y_{31}) (x_{41}, y_{41}).

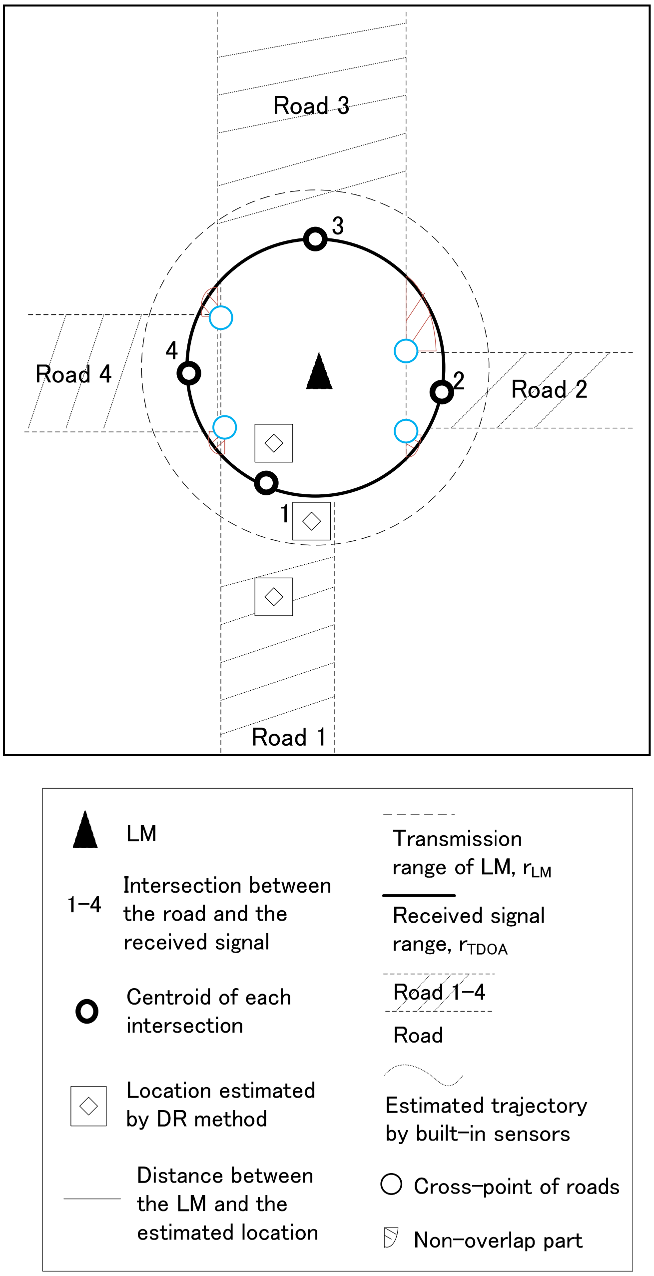

Figure 4. Study scenario

[step 5] Sort the calculated distances, and find the intersections with two shortest distances
e.g., the calculated result is as $d_{11}< d_{41}< d_{31} <d_{21,}$ then intersections 1 and 4 are two intersections founded;
[step 6] Estimate and output the location by using the cross-point between the two intersections, $x_{out}=x_{cross,ij}$, $y_{out}=y_{cross,ij}$ e.g., $x_{out}=x_{cross,ij}$, $y_{out}=y_{cross,ij}$

-Case 2: $r_{LM} < d_{est}<2\, r_{LM}$
[Step 1] Calculate the distance between the estimated location and the centroids of all the intersections, d_1,d_2,d_3,d_4;

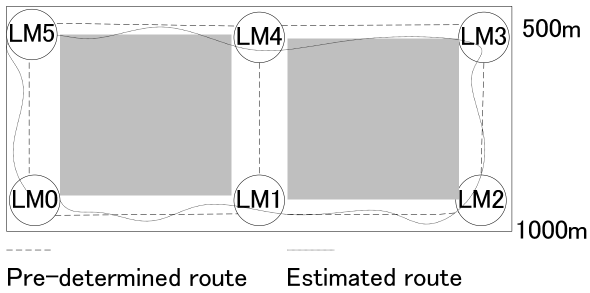

Figure 5. Simulation scenario

[Step 2] Sort the intersections in distance order, e.g., $d_1<d_4<d_2<d_3$, then 1<4<2<3;
[Step 3] Calculate the centroid on the arc between the shortest centroid and the second shortest centroid; and another centroid on the arc between the shortest centroid and the third shortest centroid,
e.g., (x_{141}, y_{141}) is the centroid on arc between (x_{11}, y_{11}) and (x_{41}, y_{41}). (x_{121}, y_{121}) is the centroid on arc between (x_{11}, y_{11}) and (x_{21}, y_{21}).
[Step 4] Calculate the centroid on the arc between the two centroids calculated from step 3; and output it, e.g., (x_{out} y_{out}) = centroid on the arc between (x_{121}, y_{121}) and (x_{141}, y_{141}).

-Case 3: $d_{est}>2r_{LM}$
[Step 1] Determine the intersection based on the user's current road; e.g., user is in road 1, then the current intersection is 1;
[Step 2] Select a random location from the intersection determined in step 1, and output it, e.g., (x_{random}, y_{random})∈intersection(x_{mk}, y_{mk}), then (x_{out}=x_{random}, y_{out}=y_{random}).

V. SIMULATION

In this section, simulations are performed to evaluate the performance of the proposed method.

A. Simulation Setup

The simulation is evaluated in Matlab. We consider a simulation area, where six reference LMs are placed at the corners in a simulation area of 1000x500m, as shown in Figure 5. The coordinates of each LM are: (10, 10), (500, 10), (990, 10), (10, 490), (500, 490), (990, 490). The transmission distance of a LM is assumed to be 15m. Considering wireless radio wave propagation which may cause serious uncertainty while measuring signals from LMs, the noise is added to the simulated transmission distance with Gauss distribution $N(0, 1^2)$. In the simulations, we do not consider to adaptively change LM coverage.

We simulate the user's walking trajectory using a random walk model. The user's step length uses built-in sensor data from references [2, 3]. The user's walking speed is selected between 0.6m/s~1.4m/s. The user's walking distance is obtained at each second; and step size is sampled at each second. The walking distance is considered with $\pm 10\%$ error [15]. Walking direction detection is considered within $\pm 30\%$ error [15].

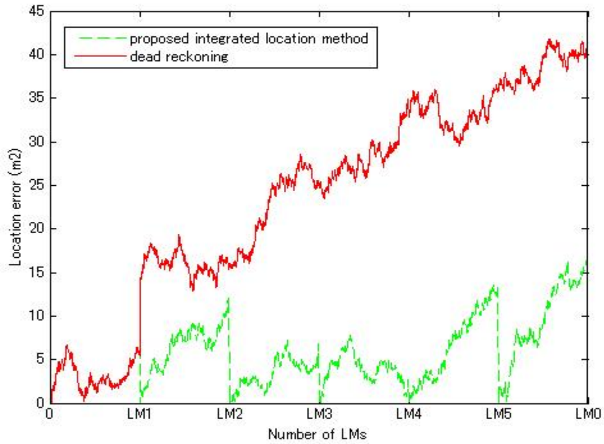

Figure 6(a). Location error, route 1

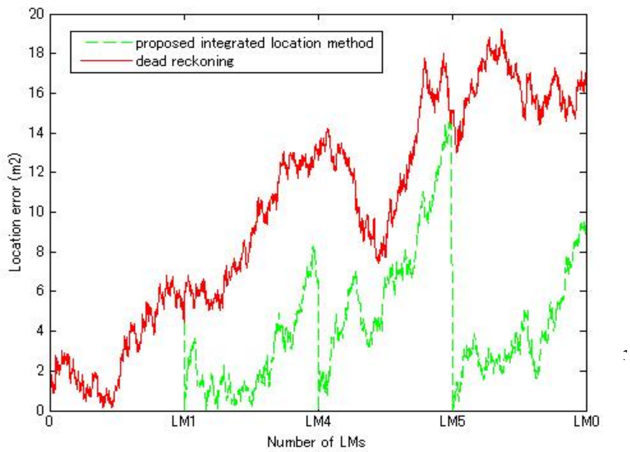

Figure 6(b). Location error, route 2

The goal of a wireless location system is to accurately locate a user. In the simulations, we evaluate the system performance using location error as the metric. Location error is defined as the difference between the user's pre-determined route and the estimated route. Two routes are studied in the simulation: route 1, LM0->LM1->LM2->LM3->LM4 ->LM5->LM0; and route 2, LM1->LM4->LM5->LM0. The location estimation method in the DR system [16] is used as a comparison method, represented as DR method. All the simulation results are the average of 10 runs.

B. Simulation Results

Figure 6 (a) shows the simulation results for location errors evaluated by two methods when the user is simulated to walk in route 1. From the figure, we see that DR method accumulates more location errors when the user walks in the direction of LM0->LM1->LM2->LM3->LM4 ->LM5->LM0. For instance, location error is about 15m^2 at LM1, 23m^2 at LM2, and about 40m^2 when the user comes back to LM0. Obviously, this is due to accumulated errors with time being.

From the same figure, we see that using the proposed integrated location method, location error drops obviously, which means better location accuracy for the mobile phone user. For example, the user accumulates about 12 m^2 errors before coming to LM2, and drops about $6m^2$ after receiving TDOA signals and re-estimating the location near LM2. Finally, the location error drops to 10 m^2 when the user goes back to LM0.

Figure 6 (a) shows the simulation results for location errors evaluated by two methods when the user is simulated to walk in route 2. Using DR method, location error is about 15 m^2 at LM4 and about 18 m^2 when the user goes back to LM0. Using the proposed integration method, location correction works when the user receives TDOA signal from each reference LM. The highest location error is about 14 m^2 that happens at LM5, and it quickly drops to 1~2 m^2. Finally location error is about 8~9 m^2 when the user comes back to LM0.

VI. CONCLUSION AND FUTURE WORK

In this paper, we proposed a new method to integrate wireless TDOA LM signals (TDOA LMs locate at several fixed locations) as reference location information into dead reckoning system. We evaluated the location estimation error when different number of reference LMs is used to compensate the accumulated location errors. Performance of the proposed method is compared with the location method in a DR system. Simulation results demonstrate that average $9m^{2\sim}25m^2$ location estimation error in a simulation area of 1000x500m can be obtained, verify the effectiveness of the proposed method. This level of location accuracy helps mothers locate their children more accurate and easier in a shopping mall. Map matching, implementation and evaluation of a practical system will be a part of our future work.

REFERENCES

[1] A.Smith, H.Balakrishnan, M. Goraczko, and N. Priyantha. "Tracking Moving Devices with the Cricket Location System". *In Proceeding of Mobisys 2004*.(2004)

[2] M. Rudafshani, and S. Datta. "Localization in Wireless Sensor Networks". *In Proceedings of IPSN 2007*, pp. 51-60.(2007)

[3] G.Zhang,S.Krishnan, F.Chin, and K.C.Chung. "UWB MultiCell Indoor Localization Experiment System with Adaptive TDOA Combination". *In Proceeding of VTC 2008-fall*.(2008)

[4] Lui, K.W.K., So, H.C., and Ma, W.-K. "Maximum A Posteriori Approach to Time-of-Arrival-Based Localization in Non-Line-of-Sight Environment". *IEEE Transactions on Vehicular Technology*,Vol. 59, Issue. 3, pp. 1517 - 1523, 2010 (2010).

[5] Koozyt, Inc.,: PlaceEngine, http://www.placeengine.com/, accessed May 17, (2010).

[6] M.J.Caruso, "Application of magnetoresistive sensors in navigation systems". *Sensors and Actuators*, SAE SP-1220, pp. 15-21, 1997. (1997)

[7] B., N., Schmidt, G., "Inertial sensor technology trends". *Sensors Journal, IEEE*, vol. 1, no. 4, pp. 332-339, (2001)

[8] G.Gartner, A.Frank, G.Retscher, "Pedestrian Navigation System in Mixed Indoor/Outdoor Environment". *Journal of. CORP*. pp24-27, 2004 (2004)

[9] M.Kourogi and T.Kurata, "Personal positioning based on walking locomotion analysis with self-contained sensosrs and a wearable camera". *In Proceeding of ISMAR 2003,* pp.103 (2003).

[10] R. Stirling, K.Fyfe, and G. Lachapelle. "Evaluation of a new method of heading estimation for pedestrian dead reckoning using shoe mounted sensors". *Journal.Navigation*. *Royal Society of Navigation*, *vol.58, no.1*,, pp31-45 (2005).

[11] S. H. Shin, C.G. Park, J.W. Kim, and H.S. Hong and J.M. Lee, "Adaptive Step Length Estimation Algorithm Using Low-Cost MEMS Inertial Sensors". *IEEE Sensors Applications System (SAS)*(2007).

[12] L.F, P.J. Antaklis, L.A. Montestruque, M.B. McMickell, M.Lemmon, Y.Sun, H.Fang, I.Koutroulis, M.Haenggi, M.Xie, and X.Xie. "Design of a wireless assisted pedestrian dead reckoning system". *The NavMote experience. IEEE Trans. Instrum*. Meas.,vol. 54, no. 6, pp. 2342-2358, (2005).

[13] U. Steinhoff and B.Schiele, "Dead reckoning from the pocket- An experimental study". *in Proceeding of PerCom 2010,* pp. 162-170, (2010).

[14] P.Pombinho, A.P. Afonso, and M.B.Carmo. "Indoor positioning using a mobile phone with an *integrated accelerometer and d*igitial compass". *INForum*, (2010).

[15] D. K, S. Muramatsu, T. Iwamoto, and H. Yokoyama, "Design and Implementation of Pedestrian Dead Reckoning System on a Mobile *Phone". IEICE Transactions on Information and Systems*, Vol. E94. No. 6, pp. 1137-1146, 2011.

[16] N. B. Priyantha, "The Cricket Indoor Location System PhD Thesis". *Massachusetts Institute of Technology*, June 2005.

[17] Y. Wang, S.Goddard, and L.C.Perez "A Study on the Cricket Location-Support System Communication Protocols". *in Proceeding of IEEE EIT 2007*, pp. 257-262, 2007.

[18] D. Etherington, "iCarte Turns the iPhone Into an RFID Reader", *http://gigaom.com/apple/icarte-turns-the-iphone-into-an-rfid-reader/* , Nov, 2009

[19] X. C. Xu, N. S. V. Rao, and S. Sahni, "A Computational Geometry Method for Localization using Differences of Distances". *ACM Trans. on Sensor networks*, Vol. 6, No. 2, pp. 10, Article. 10, 2010.

[20] S. Minamimoto, S. Fuji, H. Yamguchi, and T. Higashino, "Local Map Generation using Position and Communication History of Mobile node". *in Proceeding of IEEE percom*, pp. 2-10, 2010.

[21] Beauregard, "Omnidirectional pedestrian navigation for first responders". *in Proeedings of 4th Workshop on Positioning, Navigation and Communication*, pp. 33-36, 2007.