IEEE International Symposium on Industrial Electronics (ISIE 2009)
Seoul Olympic Parktel, Seoul, Korea July 5-8, 2009

Position Estimation for Mobile Robot Using In-plane 3-Axis IMU and Active Beacon

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***Abstract*- In most cases, indoor environment is unstable because of floor condition, obstacles and room noise. So, to elevate accuracy of robot position data at unstable condition, a robot navigation system needs to apply diverse sensor fusion methods. This paper presents a navigation system consisting of a MEMS-based digital in-plane 3-axis IMU (Inertial Measurement Unit), an active beacon system and an odometer to obtain more precise robot position data and to monitor robot movement in real-time. Two accelerometers and one gyroscope compensate the non-systematic errors of an odometer and perceive collision, bounce and slippage. Besides, fusing data of an IMU and an odometer can provide robot position data when an active beacon is losing its signal. When relative robot position data is unreliable, an active beacon system provides the absolute position data of the robot. To reduce noise of input sensors signal, low-pass filter and Kalman filter are applied. The sensor data from an in-plane 3-axis IMU, an odometer and an active beacon system are combined to obtain a precise navigation system. Results from two experiments in a real environment show that accuracy of robot position is elevated and that robot position data is not lost irrespective of robot's environment.**

I. INTRODUCTION

A fundamental requirement for a mobile robot is its ability to localize itself with respect to its environment [1]. Robot navigation in an ideal condition is stable system and does not have position errors. However, in indoor condition, ground is slippery and uneven, and many obstacles change robot position and orientation. So, many researchers have developed a variety of sensors and techniques for mobile robot position estimation [2]. In most robot positioning systems, relative and absolute position estimation techniques are employed together [3]. Absolute position means that the currently calculated position does not depend on the previous positions. GPS (Global Positioning System), active beacon system and landmark belong to absolute positioning. The GPS, one being a representative sensor of absolute positioning, has no accumulation of drift errors, however it has relatively low output rate. It is expensive and can not be used for indoors [4-5]. The active beacon system provides accurate position data with minimal processing, but has low output rate [6-8]. The landmark, a low cost system, gives a robot's absolute position and orientation of robot's head. But it loses robot's position information without enough landmarks for navigation [9-10]. On the other side, for a relative positioning system, the distance and angle data depend on previous data. Commonly used relative positioning systems are odometer, ultra sonic sensor, laser sensor and INS (Inertial Navigation Systems) [2, 11-12]. Odometer is widely used method for determining the relative position of a mobile robot. The advantages of odometer are that it can be used indoors, and output rate is faster than absolute positioning sensors. Moreover, UMBmark (University of Michigan Benchmark) test compensates odometric error, so robot has a more accurate position data [13]. The advantages of INS, which usually consists of accelerometers and gyroscopes, are that it can be operated any where, indoors or outdoors, and output rate is faster than GPS or active beacon system. Besides, INS is a self-contained device which requires no external electromagnetic signals. Thus, INS does not have the signal coverage problem found in GPS [3]. However, the odometer has non-systematic errors when a robot moves on the slippery or rugged roads. In the INS case, because of the bias drift problem, these errors would be accumulated and the accuracy deteriorates with time due to integration [3]. The robot uses ultrasonic sensor, infrared sensor or laser sensor to avoid obstacles or to create a map of its local environment [14-16]. But, to build a map, the robot must explore its environments. As ultrasonic or infrared signal are refracted from many obstacles, it can not communicate clearly when a robot meets a glass, water, room noise and so on [12]. Specially, all sorts of noises interrupt ultrasonic sensor signal flows.

In order to overcome disadvantages of positioning systems, many sensor fusion research methods have been developed. Using two accelerometers and the odometer, low level sensor fusion were developed [17]. With two accelerometers and three gyroscopes, the mobile robot attitude estimation was developed [1]. An optic gyroscope is combined with encoders to compensate position error [18]. An integrated GPS and gyroscope-free INS system is designed to achieve stable long-term navigation [19]. Using the inertial sensors, the odometer and the D-GPS, road vehicle state estimation has been done [20]. Sensor Integration of Sonar and 2D Laser Range Finder has been developed to overcome the disadvantages of each sensor and to progress path planning ability [21].

This paper has introduced a technique to obtain the robot positioning using a 3-axis IMU, an encoder, and an active beacon system in mobile robot. To introduce this navigation system, in this paper, the following topics will be discussed: First part, robot and sensors system, focuses on a robot platform and each sensor characteristics. Second part,

978-1-4244-4349-9/09/$25.00 ©2009 IEEE

algorithm, presents system modeling and sensor signals flow. Third part, experiments and result, describes Linux GUI software and two experiments for verifying a robot navigation system, and also contains results and analysis. Finally, conclusion part summarizes characteristics of navigation system and test results.

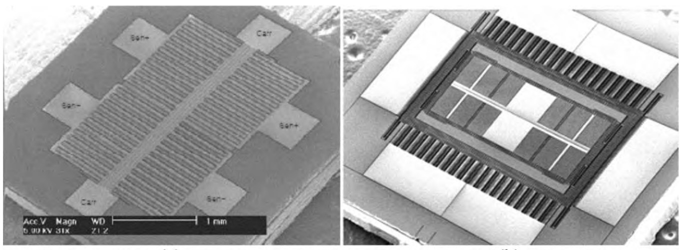
II. Sensors System

A. *Inertial Navigation System*

Recent advances in micro-machining technology have made the design and fabrication of MEMS (Microelectromechanical Systems) sensors more affordable [19]. It can be fabricated in large quantities by batch process, so MEMS sensors cost has decreased. Also, demand of small size and diversity function than the conventional ones can be made various types and high performance MEMS sensors. This development of MEMS technology leads the advent of huge changes such as micro robotics and intelligent navigation systems [12]. The core MEMS technology of robot navigation is accelerometer and gyroscope. Fig.1 (a) shows the x/y-axis accelerometer. And (b) shows the z-axis gyroscope. These MEMS inertial sensors are fabricated by the SBM (Sacrificial Bulk Micromachining) process [22-23]. The advantages of this process are high-aspect-ratio and footing-free fabrication. The characteristics of the inertial sensors, made by SBM process, are high performance, high yield and high reliability. The accelerometer measures acceleration by the capacitance change when the external force is applied. And the gyroscope measures angular velocity by the capacitance change when the rotation is applied [24]. Fig.2 shows in-plane 3-axis IMU module and Fig.3 shows system configuration diagram of the 3-axis IMU Module. The width, length and height of this system are 3 cm, 3 cm, and 0.8 cm. The sensing circuits and the packaged inertial sensor are on the single PCB. Each sensor signal outputs digital interface such as RS232C. The specification of accelerometers and gyroscope are given below in Table I.

TABLE I
SPECIFICATION OF ACCELEROMETER AND GYROSCOPE

Accelerometer (x/y-axis)		Gyroscope (z-axis)	
Dynamic range	10 g	Dynamic range	180 deg/s
Nonlinearity	± 0.8 %FSO	Nonlinearity	± 0.4 %FSO
Sensitivity	326 count/g	Sensitivity	296 count/deg/s
Bias-instability	700 μg	Bias-instability	0.02 deg/s



(a) (b)

Fig. 1. (a) Fabricated x/y-axis accelerometer and (b) Fabricated z-axis gyroscope. These sensors are fabricated by SBM process.

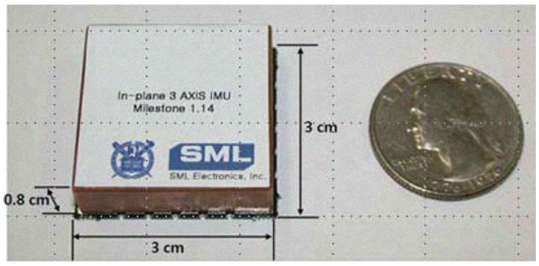


Fig. 2. In-plane 3-axis IMU Module. This IMU Module is composed two accelerometers and gyroscope.

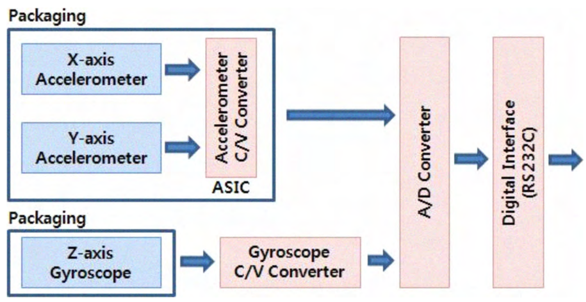


Fig. 3. System configuration diagram of the In-plane 3-axis IMU Module

B. *Active Beacon System*

Compared with GPS, active beacon system provides an economical and accurate solution for the indoor environment [25]. To detect the absolute position of mobile robot, the active beacon system is composed of four transmitters, called beacons, two ultrasonic sensors and a tag as shown in Fig. 4 and Fig. 5. Four beacons are attached below a ceiling, and two ultrasonic sensors and one tag are mounted on head of mobile robot.

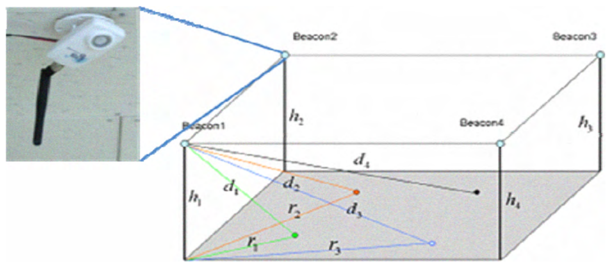


Fig. 4. Transmitters attached below ceiling at four points. The active beacon calculate robot position using triangulation technique

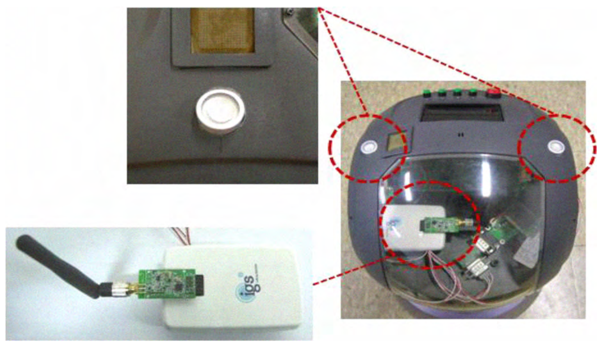


Fig. 5. Fixed two ultrasonic sensors and a tag on the mobile robot

Periodically, the two ultrasonic sensors send omni-directional ultrasonic signal, and the tag transmits an RF (radio frequency) signal to each beacon. Each beacon receives ultrasonic signal and RF signal. Then, each beacon measures the time of flight for ultrasonic signal and calculates distance between beacon and mobile robot. Finally, each beacon sends distance data to the tag through RF signal, and using triangulation technique, the tag calculates a robot's set of coordinates which is composed of x, y coordinates and orientation of robot head [26]. The specifications of active beacon system are given below in Table II.

TABLE II
SPECIFICATION OF ACTIVE BEACON SYSTEM

Size (mm)	Beacon	35 x 68 x 18	RF transmission	2.4~2.485 GHz
	Tag	90 x 58 x 17	Update Time	100 ms
	Sonar	35 x 35 x 15	Data Channel	128 channel
Voltage (DC V)	Beacon	3.3 ±5%	Detection Range	5m x 5m x 2.5m
	Tag	5~15	Accuracy	±10cm, ±2°

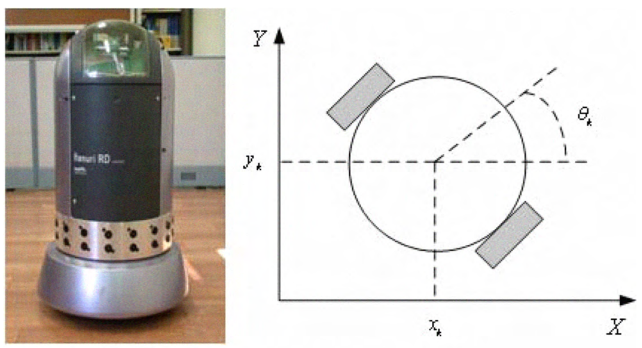
C. *Odometer*

Mostly, mobile robots use an odometer for robot navigation system. It allows very high sampling rates and provides good short-term accuracy and has low cost. However, odometer has unpredictable errors. There are two fundamental types of odometric errors: systematic errors and non-systematic errors. Systematic errors are caused by kinematic imperfections of the robot, for example, unequal wheel diameters or uncertainty about the exact wheelbase. Non-systematic errors are those that result from the interaction of the floor with the wheels, for instance, wheel slippage or bumps [12]. To overcome systematic error, UMBmark has been proposed [13]. But, this method has limitations that each robot platform must perform the UMBmark test. For compensating non-systematic errors, it needs to fusion sensors data and to design a robust system.

III. ALGORISM

A. *Robot modeling*

In this paper, We will focus on differential drive robots like the Hanuri-RD platform as shown Fig. 6-(a). To calculate relative robot position, Hanuri-RD platform has to make mobile robot model as shown Fig. 6-(b). Kinetic representation



(a) (b)

Fig. 6. (a) Hanuri-RD robot platform (b) Differential drive robot model

of a two wheel mobile robot that moves in a 2D plane is shown below eq.(1) [11].

$$\begin{bmatrix} x_{k+1} \\ y_{k+1} \\ \theta_{k+1} \end{bmatrix} = \begin{bmatrix} x_k \\ y_k \\ \theta_k \end{bmatrix} + \begin{bmatrix} v_k \cos\theta_k \Delta t \\ v_k \sin\theta_k \Delta t \\ \Omega_k \Delta t \end{bmatrix} \tag{1}$$

x_k : x-axis robot position y_k : y-axis robot position
θ_k : Heading orientation Δt : Sampling time
v_k : Velocity of robot Ω_k : Angular velocity of robot

The Velocity of robot and angle of robot head are expressed below eq.(2) and eq.(3). This data can be calculated by x-axis acceleration a_x, y-axis acceleration a_y and z-axis gyroscope Ω_z. Eq.(2) and eq.(3) is substituted for eq.(1).

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = \begin{bmatrix} \int a_x dt \\ \int a_y dt \end{bmatrix} \tag{2}$$

$$v_k = \sqrt{{v_x}^2 + {v_y}^2}, \quad \Omega_k = \Omega_z \tag{3}$$

a_x : x-axis acceleration a_y : y-axis acceleration
v_x : x-axis velocity v_y : y-axis velocity
Ω_z : z-axis angular velocity

B. *Filter*

Acceleration signal and gyroscope signal form the IMU contains noise and drift effects. And the active beacon system have noise signal. Moreover, the IMU signal error is accumulated, when the IMU signal integrates. So, to reduce noise, sensor signals from the IMU and active beacon system are filtered using low-pass filter and Kalman filter. In case of the IMU, accumulation errors of integration of signal should be removed using active beacon data. To apply Kalman filter, eq.(1) transforms Jacobian matrix as shown eq.(4). Eq.(5) shows Kalman filter algorithm [27].

$$A_k = \begin{bmatrix} 1 & 0 & -v_k \sin\theta_k \Delta t \\ 0 & 1 & v_k \cos\theta_k \Delta t \\ 0 & 0 & \Omega_k \Delta t \end{bmatrix} \tag{4}$$

$$\begin{aligned} &\hat{x}_k^- = A\,\hat{x}_{k-1}^+ \\ &P_k^- = A_{k-1} P_{k-1}^+ A_{k-1}^T + Q_k \\ &K_k = P_k^- H_k^T [H_k P_k^- H_k^T + R_k]^{-1} \\ &\hat{x}_k^+ = \hat{x}_k^- + K_k[(z_k - z_{k-1}) - H\,\hat{x}_k^-] \\ &P_k = (I - K_k H_k) P_k^- \end{aligned} \tag{5}$$

x_k : Robot position matrix K_k : Kalman filter gain
z_k : Measurement R_k : Process noise covariance
P_k : Error covariance Q_k : Measurement error covariance

C. *Compensation of non-systematic error*

The odometric systematic error can be compensated by using UMBmark test. However, to overcome non-systematic error, we suggest following process as shown Fig. 7. Position of the mobile robot is based on the IMU data and the encoder data. Preferably, low pass filter is applied to the accelerometers and the gyroscope to remove high frequency noise. Rotation angle is then calculated using the z-axis gyroscope. Calculated

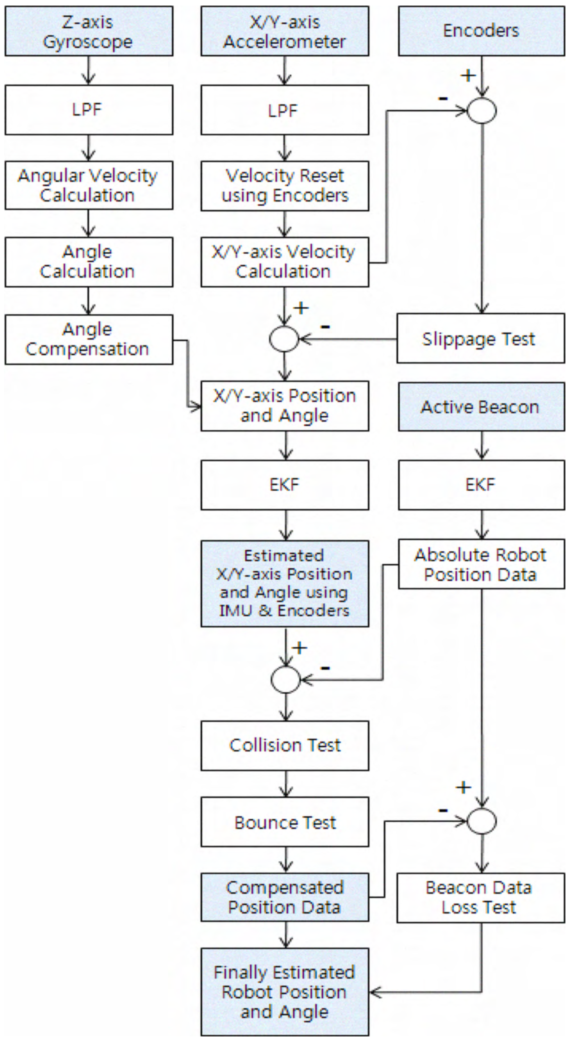


Fig. 7. Signal processing algorithm flow chart to compensate non-systematic error using the IMU, odometer and active beacon

angle from the gyroscope is used for compensation of angle from the encoders. Velocity is calculated from the x/y-axis accelerometers. At this time, if difference between IMU data and encoder data is measured lager than mean difference value, robot substitutes the IMU data for the encoder data. Kalman filter is applied in order to achieve estimated position and angle. After this, we determine robot position data.

However, when the mobile robot crosses an obstacle, wheel slippage or irregular movement of the robot is possible. If collision or bounce came over the mobile robot, the accelerometer signal appears in specific form. The process detects specific signal form of accelerometer. Immediately after the robot movement's end, the robot position data is replaced by active beacon data. When the mobile robot passes through under a table or a plate glass, the robot loses its position data. In this case, the robot takes combination data of the IMU and encoders. Then, if active beacon data normally receives, the robot modifies position data using the active beacon.

IV. Experiments and Result

To qualify our robot navigation system, we have made a monitoring program and designed two experiments.

A. Robot position monitoring program

The robot platform is Linux-based embedded system which it can communicate with the host PC by wireless network interface. Fig. 8 is Linux-based robot position monitoring GUI (Graphic User Interface) program. It is coded by GTK+ 2.0. This program can be divided into control part, IMU signal part and position map part. Control part can control the robot motion. When the robot moves around, we can see real-time two graphs: IMU signals and robot's route. And lower of position map part displays robot position data from encoders, an active beacon, combining between encoders and the IMU, and fusing all sensors. From this program, we can check up the robot current position.

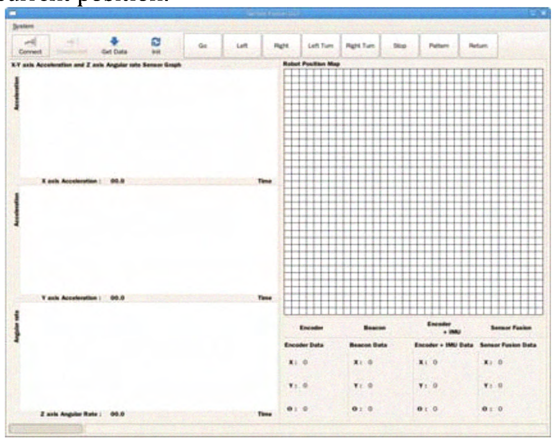


Fig. 8. Linux-based robot position monitoring GUI program

B. Below plate glass passage test

First experiment is below plate glass passage test. When beacon signal passes through a glass, an active beacon loses its data or gets abnormal sensor signal. Nevertheless, the mobile robot has to get position data. This test shows whether the mobile robot keep up position data or not.

The robot is programmed to traverse a path as shown Fig. 9. First, the robot moves straight 1m and rotates 90 degrees to counterclockwise direction. After the robot moves from side to side, the robot goes to center position. Finally, it moves straight

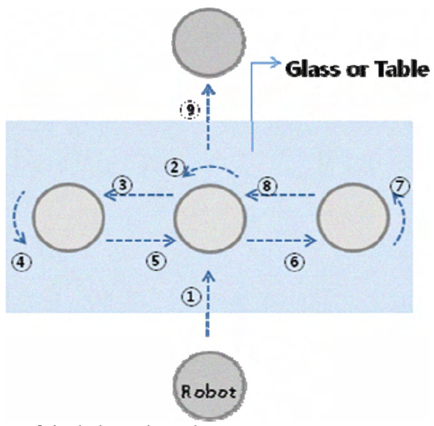


Fig. 9. Procedure of the below plate glass passage test

1m and gets out of the plate glass.

In Fig. 10, the position map describes the robot moving path at two conditions. The dotted line is using only active beacon data case. And the solid line is substitution case using the IMU and odometer. Before the robot goes to the plate glass, position error cannot be found in all these cases. Using only active beacon, it lost beacon signal or transforms to abnormal signal at below the plate glass. Then the robot has correct position data after the robot escapes the plate glass. But, replaced the IMU and the encoder case, it always maintains the robot position data. So, combined data of the IMU and encoders find out how to cover a loss of active beacon.

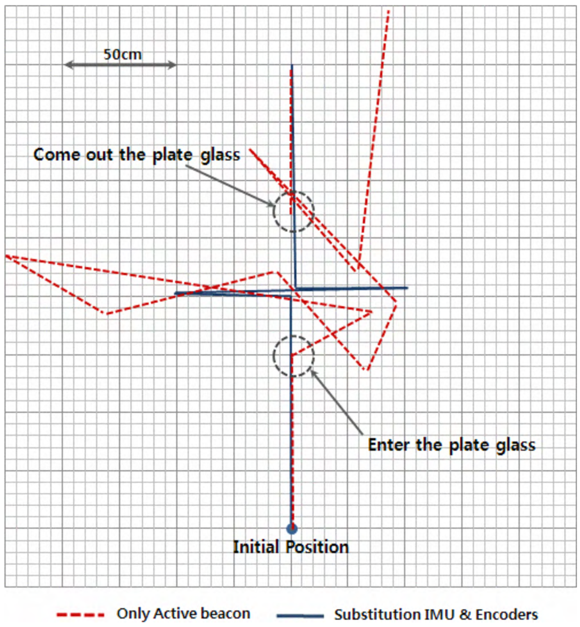
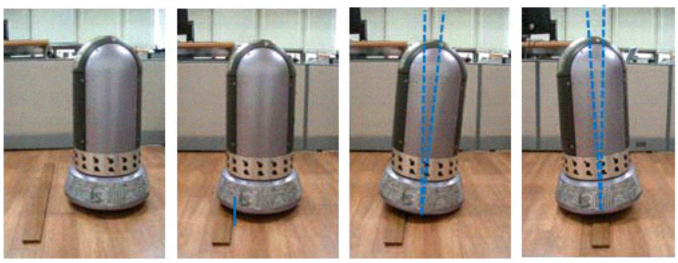


Fig. 10. The robot moving path in the position map of GUI program, when the robot passes the plate glass

C. *Obstacle crossing test*

The second experiment is obstacle crossing test. In this test, our signal processing algorithm shows a robust navigation system, when collision or bounce occurs.

The robot moves straight 1 m and crosses an obstacle of height 1cm, then once more moves straight 1 m as shown Fig. 11. First, the robot runs into an obstacle, process detected a collision signal. While the robot crosses the obstacle, it leans to the backward and frontward. And then, it has known a bounce signal. Using these signals, we detect a collision and a bounce.



(a) (b) (c) (d)

Fig. 11. (a) ready for crossing an obstacle, (b) collision, (c) and (d) it is tilt the robot forward and backward. Our algorithm checks a collision and bounce.

After the robot stops, it estimates the robot orientation and the robot movement distance from sensor's estimated position to real estimated position and observes the robot motion path. This experiment also has been done using only the odometer case and mounted IMU module and the active beacon system case. Each case is experimented five times. Fig. 12 shows the robot moving path at two conditions. The dotted line is using only data from encoders. The solid line is to compensate the odometric error using sensor data from the IMU and the active beacon system. All these cases do not find error before the robot meets the obstacle. But, using data from only encoders for navigation, when robot crosses obstacle, robot has not only huge distance error but also direction error. These errors are represented in the Table III below. e_n is a distance error and θ_n is a direction error at encoder case Also, e_c is distance error and θ_c is direction error using the IMU and active beacon case. On the other hand, combining data from IMU and active beacon system case, the robot does not lose the robot's current position and the direction of robot head. The accuracy of robot position data is within less than 5.3 cm.

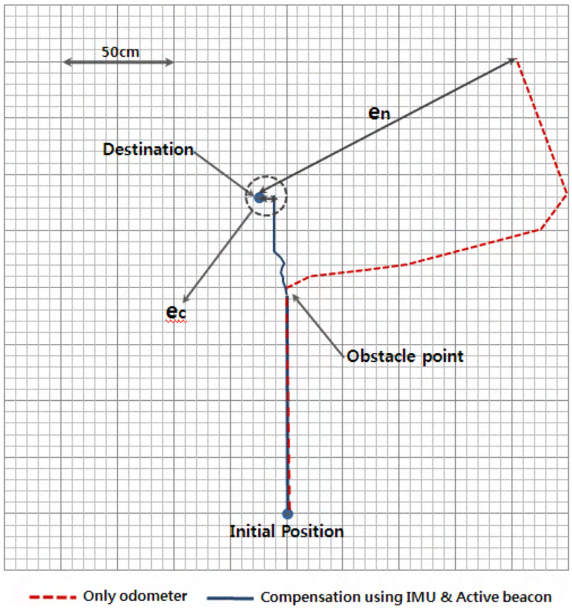


Fig. 12. The robot moving path in the robot position map part of GUI program, when the robot crosses the obstacle.

TABLE III

DISTANCE AND DIRECTION ERROR

Only encoder case		Combining IMU & Beacon case	
e_n (cm)	θ_n (deg)	e_c (cm)	θ_c (deg)
270	138	4.7	5
132	76	5.3	-3
219	-93	5.0	4
98	151	3.8	1
103	69	4.9	-3

e_n : distance error using the encoder case

θ_n : direction error using the encoder case

e_c : distance error using the IMU & the active beacon case

θ_c : direction error using the IMU & the active beacon case

V. CONCLUSION

This paper has introduced a technique to obtain the accurate robot positioning using a 3-axis IMU, an encoder, and an active beacon system in mobile robot. Specifically, the 3-axis IMU module is MEMS-based, digital interface, and in-plane type. The in-plane 3-axis IMU is constituted of x/y-accelerometers and a z-axis gyroscope. The x/y-axis accelerometers are used for distance estimation, and the z-axis gyroscope is used for angle estimation. And the IMU detects the collision and bounce using specific abnormal signal. The active beacon system is constituted of four transmitters, two ultrasonic sensors and one tag. The active beacon system is used for absolute position estimation. Because of two ultrasonic sensors, the active beacon system can calculate rotation angle of the robot. To reduce noise of input sensors signal, low-pass filter and Kalman filter are applied. Using only odometer case cannot prevent non-systematic errors, which is wheel slippage or irregular movement of the robot. In this case, slippage of the encoders is compensated using IMU data, and the accumulation error problems of the IMU are compensated using the active beacon system data. Also, when the active beacon loses its signal, combining data of the IMU and the encoders covers. Two experiments are presented to qualify our robot positioning system. Results from two experiments in a real environment show that accuracy of robot position is elevated and that robot position data is not lost irrespective of robot's environment using a combining sensor data from the IMU, the odometer and the active beacon system. And Thus, combining sensor data from the odometer, the in-plane 3-axis IMU and the active beacon system yielded a satisfactory navigation system and showed possibility of real-time monitoring.

ACKNOWLEDGMENT

This work was supported by the IT R&D program of MKE/IITA. [2008-F-037-01, Development of HRI Solutions and Core Chipsets for u-Robot]

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