Robotica (2011) volume 29, pp. 757–765. © Cambridge University Press 2010
doi:10.1017/S0263574710000536

Localization of a high-speed mobile robot using global features

Seungkeun Cho and Jangmyung Lee*

School of Electrical Engineering, Pusan National University, Pusan 609-735, Korea

(Received in Final Form: August 6, 2010. First published online: October 14, 2010)

SUMMARY

A new localization algorithm is proposed for a fast moving mobile robot, which utilizes only one beacon and the global features of the differential-driving mobile robot. It takes a relatively long time to localize a mobile robot with active beacon sensors, since the distance to the beacon is measured based on the traveling time of the ultrasonic signal. When the mobile robot is moving slowly, the measurement time does not yield a high error. At a higher speed, however, the localization error becomes too large for the mobile robot to be located accurately. Therefore, in high-speed mobile robot operations, instead of using two or more active beacons, only one active beacon and the global features of the mobile robot are used to localize the mobile robot. The two global features are the radius and center of the rotational motion for the differential-driving mobile robot, which generally describe the motion of, and are used for the trace prediction of, a mobile robot. In high-speed operations, the localizer finds the intersection point of this predicted trace and the circle, which is centered at the beacon whose radius is the distance between the mobile robot and the beacon. This new approach overcomes the large localization error caused by the high speed of the mobile robot. The performance of the new localization algorithm is verified through experiments with a high-speed mobile robot.

KEYWORDS: Localization; Differential-driving mobile robot; Active beacon; Global features.

1. Introduction

Since the initial application to factory automation, robots have become more and more popular for public services and home automation. For service applications, mobile robots should be able to recognize their own position precisely.[1,2] The recognition by the robot of its position is vital for planning its path from the starting point to the target while avoiding obstacles.[3] Therefore, the precise localization of the mobile robot is one of the most important issues in the field of robotics. Localization schemes have been widely investigated in various fields. These localization schemes are classified into two categories: relative and absolute position estimation. Typically, relative position estimation is done by the encoders and gyros used for the mobile robots. This relative position estimation is easy and inexpensive to implement. However, with increasing driving distance, the accumulative error becomes larger, thus making precise localization more difficult. Also, the artificial kidnapping of the mobile robot may cause it to lose track of its location.[4,5] The absolute location obtained using global positioning system (GPS), vision sensors, and ultrasonic sensors may resolve the problems of the relative position estimation. Vision-based localization is very sensitive to the illumination and environmental colors. It also requires heavy computation to obtain the three-dimensional (3D) information with high resolution.[6–8] GPS-based localization does not work in tunnels or buildings and, thus, requires the installation of extra transceivers.[9,10] There is also an interesting research article[11] on multirobot localization for applications such as transportation, rescue, scout, and spacecraft.

The localization errors for these schemes are dependent on the velocity of the mobile robot.[12] When the mobile robot is stationary or moving slowly, this localization error is small enough to be ignored. When the mobile robot is moving fast; however, the localization error becomes large, since the mobile robot moves to another place while the localization process is being performed. That is, the estimated location becomes the position where the mobile robot was located in the past or includes a large error component.

This paper proposes a novel algorithm to reduce the localization error for fast moving mobile robots. To reduce the sampling period, only one beacon is utilized for the localization process. In this research, the distance to the beacon and the history of the motion provide clues to the precise localization. Section 2 introduces the operation and composition of the iGS (indoor Global-Positioning System), which is a localizer formed by the radio frequency (RF) and ultrasonic sensor. Section 3 proposes the new localization algorithm with the iGS. Section 4 describes the experiments performed to verify the effectiveness of the algorithm. Finally, Section 5 concludes the contribution of this research.

2. Indoor Location using iGS (Indoor GPS System)

2.1. Composition

For the localization of the mobile robot, the iGS system developed by Ninety Corp. is utilized. The iGS is composed of a localizer and several beacons. Figure 1 illustrates the localization system for the mobile robot. The basic unit of the mobile robot motion space is a block, which has three beacons on the ceiling to provide the distance data for the 3D localization. Each beacon has an RF receiver and an ultrasonic transmitter circuit with a microprocessor.

* Corresponding author. E-mail: jangmlee@hanmail.net

https://doi.org/10.1017/S0263574710000536 Published online by Cambridge University Press

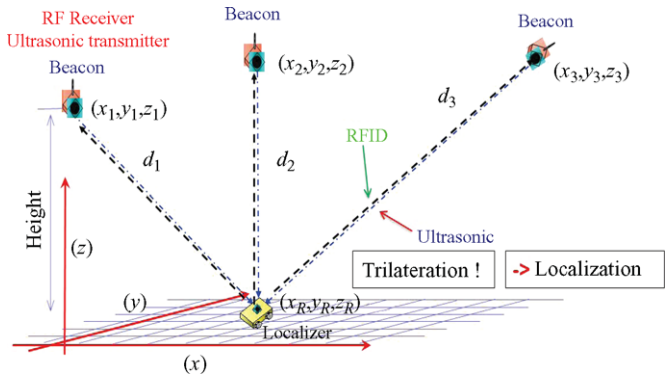


Fig. 1. Arrangement of the iGS.

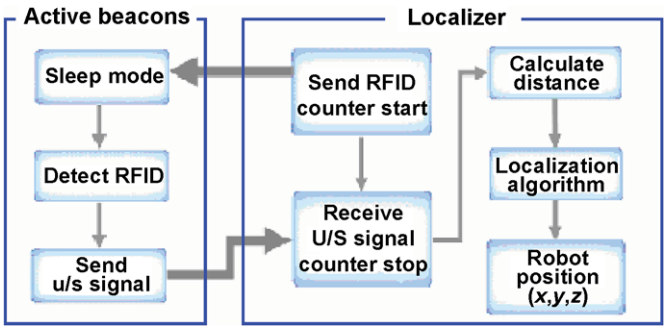


Fig. 2. Operating sequence of the iGS.

The localizer, which is installed on the mobile robot, has an RF transmitter and an ultrasonic signal receiver with a digital signal processor (DSP) to determine the distance to the beacons and to localize the mobile robot by trilateration.[13] This localizer also has a communication circuit to send the location information to the remote operator.

2.2. *Detailed operation*

The operation of the iGS as shown in Fig. 2 can be described by the following two steps: (1) The localizer measures the time of freight (TOF) to the specific beacons and (2) the trilateration measurement for the final position calculation of the mobile robot.[13,14] First of all, the localizer sends out the radio-frequency identification (RFID) for a specific beacon, whose absolute position information is known *a priori*, and simultaneously turns on the counter starting from zero. The beacons around the localizer may receive the RFID to check whether it matches its own ID. The beacon, which succeeds in the matching process immediately, sends out an ultrasonic signal to the localizer. When the localizer receives the ultrasonic signal, it stops counting. Therefore, the counter value represents the traveling times of the RFID and ultrasonic signal. There exists some constant time delay in the beacon, which can be directly eliminated from the counter value. Therefore, the counter value is used for the calculation of the distance between the localizer and the beacon. The traveling time is represented by

$$t_T = n \times T_c - t_d, \tag{1}$$

where T_c is the timer period, n is the counter value, and t_d is the time delay in the beacon for the ID matching process, which is constant and can be measured empirically.

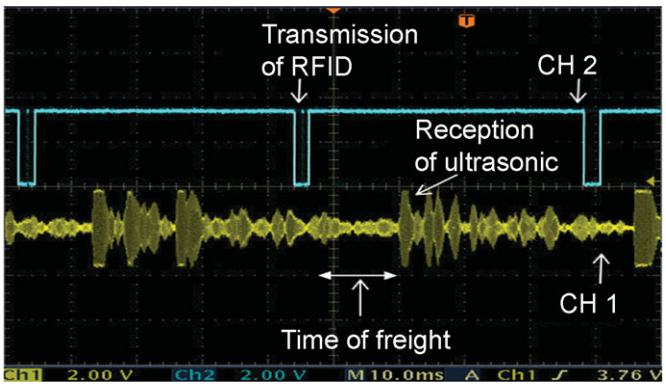


Fig. 3. Measurement of TOF.

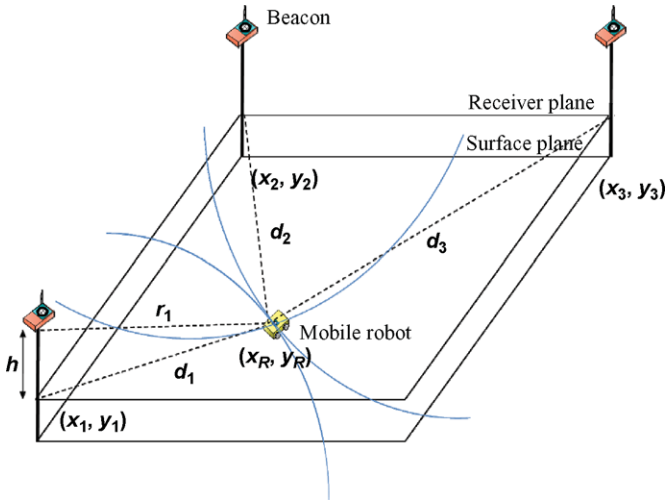


Fig. 4. Localization of the mobile robot by trilateration.

Now, the distance to the beacon can be obtained by multiplying the velocity by the traveling time of the ultrasonic signal as

$$r[m] = v[\mathrm{m/s}]t_T[\mathrm{s}] \tag{2}$$

where $v[\mathrm{m/s}] = 331.5 + 0.6 \times T[^\circ\mathrm{C}]$ is a function of the room temperature, T. Note that the RFID traveling time is ignored, since the speed of the RF signal is a lot faster than that of the ultrasonic signal. For precise measurement, the localizer carries a temperature sensor on the main board.

Figure 3 shows the RFID signal (above, CH2) and the ultrasonic signal (below, CH1) caught on the oscilloscope. The TOF, which is measured by the counter, is represented by the arrow interval.

Figure 4 illustrates the trilateration scheme. The measured distance, r, is changed to the distance value, d, on the plane with a known height of the ceiling, h.

$$d = \sqrt{r^2 - h^2}. \tag{3}$$

This distance, d, is now used to draw a circle on the plane on which the mobile robot may be located. If there are distance data, d_1, d_2, and d_3 with the three beacon locations, (x_1, y_1), (x_2, y_2), and (x_3, y_3), three circle equations are

https://doi.org/10.1017/S0263574710000536 Published online by Cambridge University Press

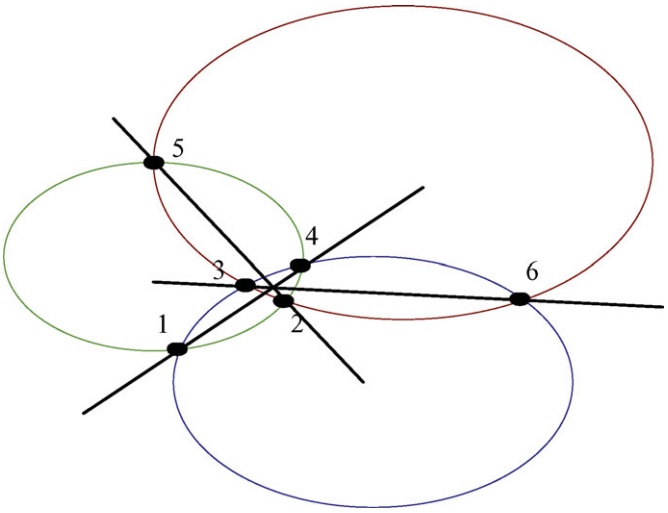


Fig. 5. Minimization of localization error.

obtained to locate the mobile robot.

$$\begin{bmatrix} (x_R - x_1)^2 + (y_R - y_1)^2 \\ (x_R - x_2)^2 + (y_R - y_2)^2 \\ (x_R - x_3)^2 + (y_R - y_3)^2 \end{bmatrix} = \begin{bmatrix} d_1^2 \\ d_2^2 \\ d_3^2 \end{bmatrix}. \quad (4)$$

The intersection of these three circles provides the location of the mobile robot, (x_R, y_R).[14,15]

Notice that there are two unknowns, (x_R, y_R). Therefore, the two equations obtained for the two beacons in (4) are sufficient to obtain the location of the mobile robot in an indoor environment, which is flat and has a constant height. This redundant beacon is also very useful for the robustness of the system. If the matched beacon does not send out the ultrasonic signal within a limited time, this beacon can be assumed to be faulty and can henceforth be ignored. Since there are four beacons situated at each corner of the room, even if one or two beacons are faulty, the localization process can still be successfully accomplished.

Practically, it is not usual to have a unique intersection point because of the errors in the distance measurement. The error may come from the ultrasonic sensor itself, the A/D resolution of the receive circuit, or the measurement of the TOF, which is sensitive to the signal reflected from some obstacles. To resolve this problem, three straight lines are obtained by connecting the two intersecting points of each of the three pairs of circles, as shown in Fig. 5. This is the most popular method of reducing the localization error by means of trilateration.[16]

3. Position Recognition Algorithm Based on Global Feature

3.1. Error analysis for a moving robot

The existence of a localization error for a moving robot is inevitable, since it takes some time for the localizer to receive the necessary signals and to process the data to obtain the location information. When the mobile robot is moving fast, this error becomes larger. The time required

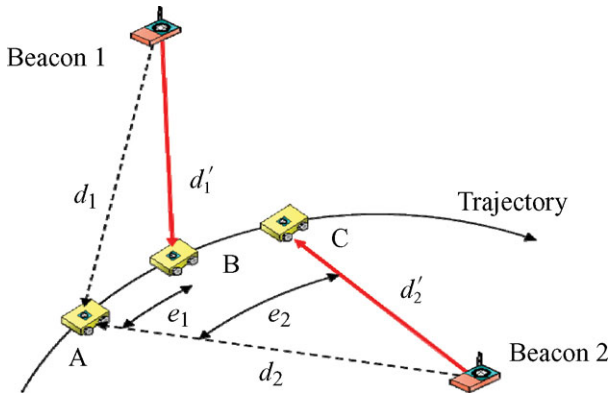


Fig. 6. Position error induced by fast robot motion.

for each localization is composed of four time slots: (1) The RFID transmission time from the localizer to the beacon to find the desired beacon, (2) the traveling time of the ultrasonic signal (TOF) from the matched beacon to the localizer, (3) the coordinate calculation time using the distance data at the localizer by trilateration, and (4) the transmission time of the position data to the user. Among these four components, the ultrasonic TOF is dominant, since the RFID has almost the same speed as light and the DSP processors are fast enough for these simple computations. Especially, when the mobile robot is moving fast, during the time in which the ultrasonic signal travels from the beacon at 340 m/s at room temperature to the localizer on the robot, the robot has already moved to another place.

Figure 6 illustrates the position error induced by fast robot motion. The mobile robot starts to recognize its own position at location A and transmits the RFID for beacon 1. Since it is moving, it receives the ultrasonic signal from beacon 1 when it arrives at location B. For the localization of the robot on a plane, at least two distances to the beacons are necessary. Therefore, the localizer may try to get the distance information from beacon 2. However, when the ultrasonic signal arrives at the localizer, the mobile robot has already moved to location C. The distances d_1 and d_2 are the initial values, but the real values are d_1' and d_2'. Therefore, in the localization process, there exists an inevitable error, which can be represented by

$$e_n = d_n - d_n'. \quad (5)$$

Notice that if more beacons are used for the localization process, a larger localization error occurs. However, if one beacon is used for localization, the distance datum is correct at the moment of receipt. That is, at location B, d_1' is the correct distance to beacon 1, which can be used to obtain the precise location with the global features of the mobile robot's motion.

3.2. Motion characteristics of differential-driving mobile robot

The motion of the differential-driving mobile robot is determined by the velocities of the two wheels.[17,18] The motion can be generalized as a curved motion, which has an instantaneous center of curvature (ICC) and rotation radius,

https://doi.org/10.1017/S0263574710000536 Published online by Cambridge University Press

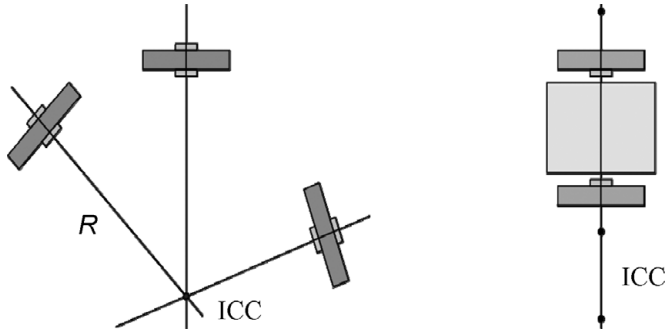


Fig. 7. Instantaneous center of curvature, ICC.

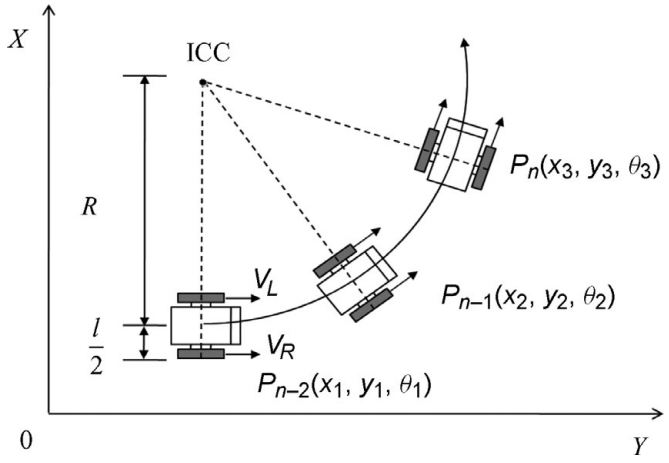


Fig. 8. Single curvature motion of a mobile robot.

R. Figure 7 illustrates the ICC and R. The ICC can be obtained by extending the center lines of the wheels, and it changes according to the velocity ratio between the two wheels.[19,20] The rotation radius, R, is also determined by the velocity ratio between the two wheels and is equal to infinity when the two wheels have the same velocities. It has been reported that a smaller R causes a lot of slippage of the wheels on the ground.[21,22] Therefore, if possible, it is better to use a larger R to reach a certain position precisely. Therefore, a single curvature path is desirable for precise curved motion.[21]

Since the mobile robot follows a curved path, which can be classified by ICC and R, its location can be estimated by referring to the past trajectory. In this paper, the instantaneous trajectory of the mobile robot is predicted based on its motion characteristics, ICC and R. Practically, the path of a differential mobile robot can be described as a sequence of single curvature paths, as shown in Fig. 8. Theoretically, when there are two position data, ($P_{n-1}(x_1, y_1, \theta_1)$ and $P_n(x_2, y_2, \theta_2)$), from the past trace, the single curvature specified by ICC and R can be estimated.[22–24] To increase the accuracy, that is to reduce the estimation error, several points are utilized for the estimation of ICC and R in real experiments.

In this paper, instead of using two beacon data to identify the position, the global features of the mobile robot's motion are utilized to estimate its current position with a beacon datum giving the distance to the beacon. To obtain the global features of ICC and R, the three consecutive coordinates, P_{n-2}, P_{n-1}, and P_n are used, as shown in Fig. 8. The estimated

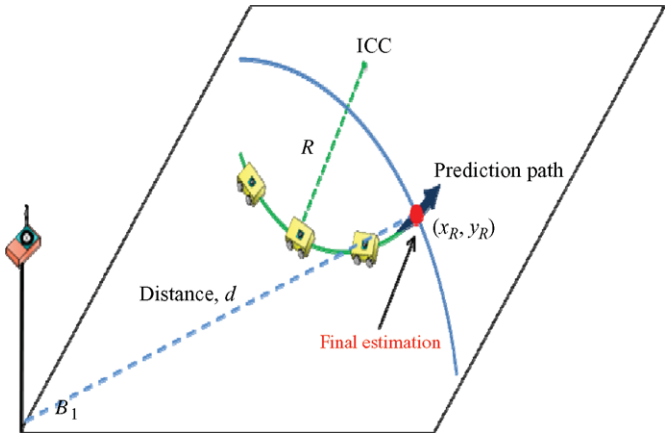


Fig. 9. Position estimation with global features and one beacon.

trace forms a circle centered at ICC with radius R. Since the mobile robot is expected to be on this circle, its location can be determined by calculating the intersection with the circle centered at the beacon with radius d, as shown in Fig. 9.

ICC and R are obtained from the coordinates of P_{n-2}, P_{n-1}, and P_n, which form a circle, which is represented by the following matrix equation

$$M \begin{bmatrix} a \\ b \\ c \end{bmatrix} = N, \tag{6}$$

where

$$M = \begin{bmatrix} 2x_1 & 2y_1 & 1 \\ 2x_2 & 2y_2 & 1 \\ 2x_3 & 2y_3 & 1 \end{bmatrix}, \quad N = \begin{bmatrix} -\left(x_1^2 + y_1^2\right) \\ -\left(x_2^2 + y_2^2\right) \\ -\left(x_3^2 + y_3^2\right) \end{bmatrix},$$

(x_1, y_1), (x_2, y_2), and (x_3, y_3) represent the coordinates of the points, P_{n-2}, P_{n-1}, and P_n, respectively.

By solving (6), the coefficients of the circle can be obtained as

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = M^{-1}N. \tag{7}$$

The coordinates of the ICC, $(x_{\text{icc}}, y_{\text{icc}})$, are obtained now as

$$(x_{\text{icc}}, y_{\text{icc}}) = (-a, -b). \tag{8}$$

The radius R is also easily derived as

$$R = \sqrt{a^2 + b^2 - c}. \tag{9}$$

Figure 9 illustrates the motion of the mobile robot on a single curvature with ICC and R and shows how its current position can be estimated from the intersection of two circles: one is the circle representing the mobile robot's motion, and the other is the circle drawn from the beacon with the radius of d. Representing the two circles as f_1 and f_2, the estimated coordinates of the mobile robot can be represented by

$$f_1(\text{ICC}, R) \perp f_2(B_1, d) = (x_R, y_R), \tag{10}$$

https://doi.org/10.1017/S0263574710000536 Published online by Cambridge University Press

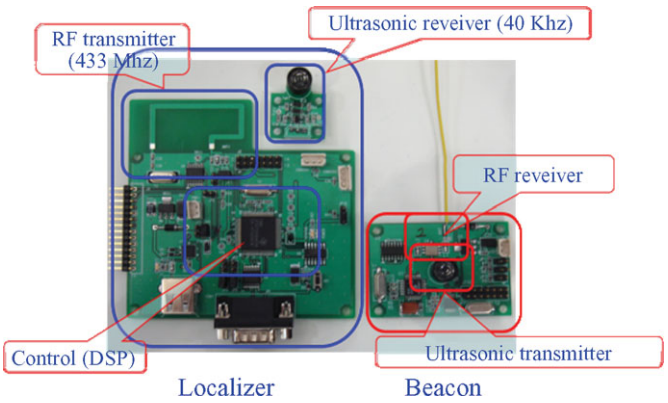


Fig. 10. The localizer and beacon.

where B_1, the coordinates of the beacon, is the center of circle f_2. Through this simple and reliable algorithm, the position estimation cycle is minimized. As a result, the localization process becomes very precise even for a fast moving mobile robot.

4. Experiment and Results

4.1. Experimental environment

Figure 10 illustrates the iGS, which is composed of a localizer and a few beacons. For the high-speed localizer, a TMS320LF2406A of TI Corp. is used and an rfPIC12F675F of Microchip Corp. is used for the control of the RF signal in the 433 MHz band. To reduce the power consumption at the active beacon, which should wait for signals at all times, an MSP430F1101A of TI Corp. which has a sleep mode for power saving is used to build the beacon. An AR/T40-10R of Nippon Ceramic Corp. is used as the ultrasonic signal generator and detector in the 40 kHz band.

For the high-speed mobile robot, DC motors (Max. 500 r/m, model: IG42GM, D& J. Corp.) are used to achieve a maximum speed of 15 km/h. To drive these motors, a dsPIC30F4012 of Microchip Corp. is used and is remotely controlled through infrared wireless communication. The localizer sends the finally estimated position to the remote user through the Brutus wireless communication system. The monitor programs for the user were developed on a PC using QT Library 3.3.8, which enables the real-time monitoring of the robot motion on the 2D map, as shown in Fig. 11.

4.1.1. Evaluation of the position error according to the speed. Three accurate experiments are performed to verify the relation between the position error and the speed. The room size is 2.5 m × 3 m, and there is no obstacle, which may reflect the ultrasonic signal. The temperature is measured and compensated for when calculating the propagation speed of the ultrasonic signal. Two beacons are installed and used for the localization process, since two data are sufficient to locate a mobile robot moving in a room with a flat floor.[21]

The first experiment is performed in the stationary state by using two beacons, following the conventional approach. That is, the mobile robot is stopped at a specific location, while the localization process is performed. The error data

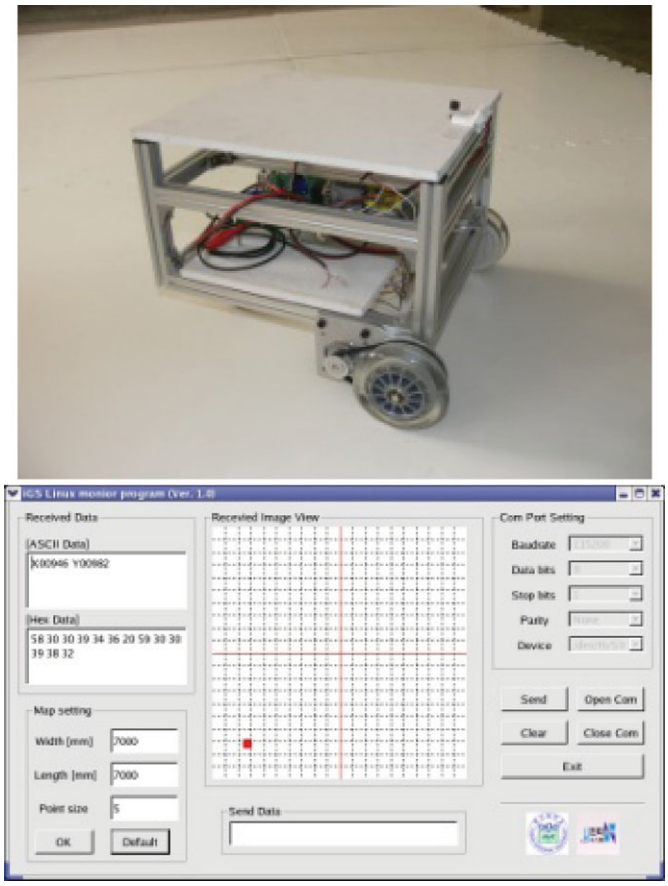


Fig. 11. Mobile robot and monitor program based on Linux OS.

represent the accuracy of the iGS, which is smaller than 2 cm, as shown in Fig. 12(a). Figure 12(b) and (c) shows the position recognition data when the mobile robot is moving at speeds of 1.23 and 3.96 Km/h, respectively. As the speed increases, the estimated trace increasingly deviates from the real trajectory. That is, the localization error of the mobile robot increases with increasing speed.

Figure 13 compares the errors for the three cases, viz., stationary, 1.23 and 3.96 Km/h. It is very clear that the position estimation error increases with increasing speed. When the mobile robot is moving fast, the measurement value becomes smaller, since the total travel time of the mobile robot becomes shorter. Therefore, it is necessary to develop a new localization algorithm, which has a short cycle time for the measurement process. Even though it is not directly proportional to the speed, the error at high speed is increased approximately two times.

4.2. Experiments with the novel algorithm

To evaluate the proposed algorithm, the velocity of the mobile robot is adjusted in a planned manner, as shown in Fig. 14. In the period of t_0-t_1, the robot increases its speed linearly. In this period, the localization is done using two beacons. In the high-speed period from A to B, the proposed algorithm is evaluated by comparing the proposed algorithm with the conventional approach. To show the effect clearly, the speed is kept at 13 km/h during the period t_1-t_2, where only one beacon and the motion characteristics of the mobile

https://doi.org/10.1017/S0263574710000536 Published online by Cambridge University Press

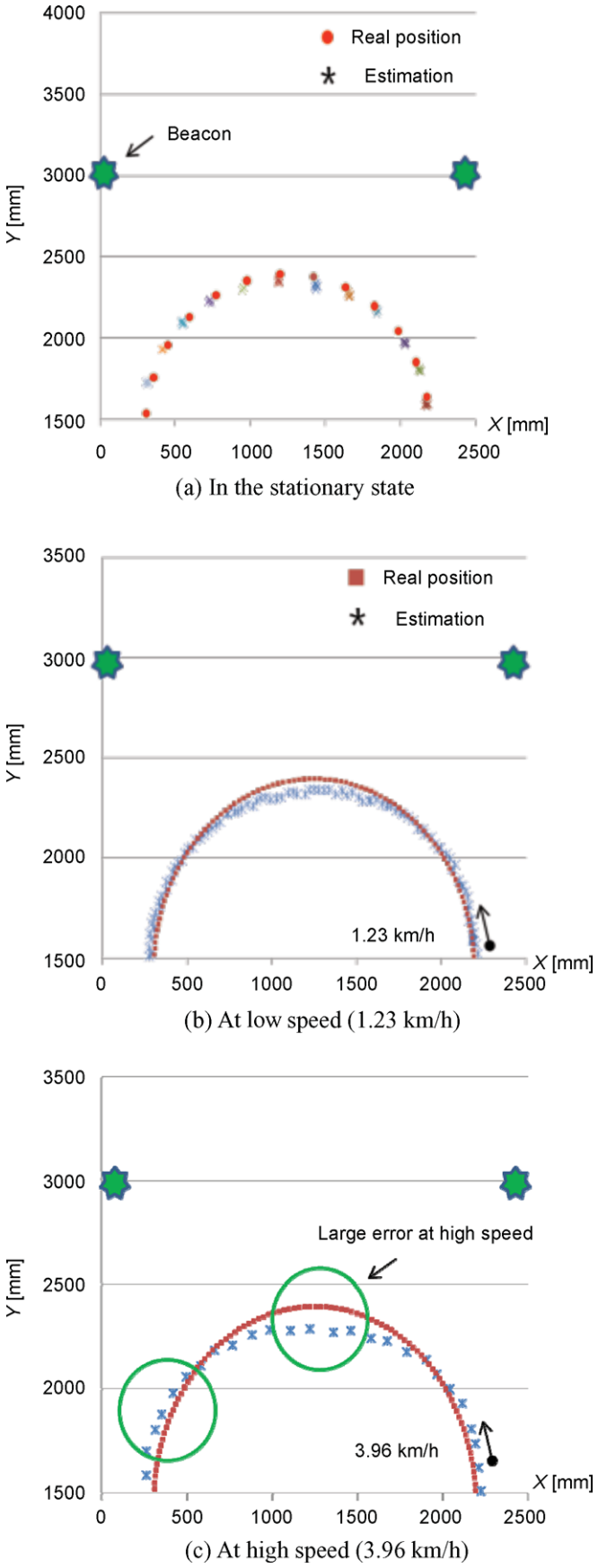


Fig. 12. Position error as a function of the speed of the mobile robot. (a) In the stationary state. (b) At low speed (1.23 km/h). (c) At high speed (3.96 km/h).

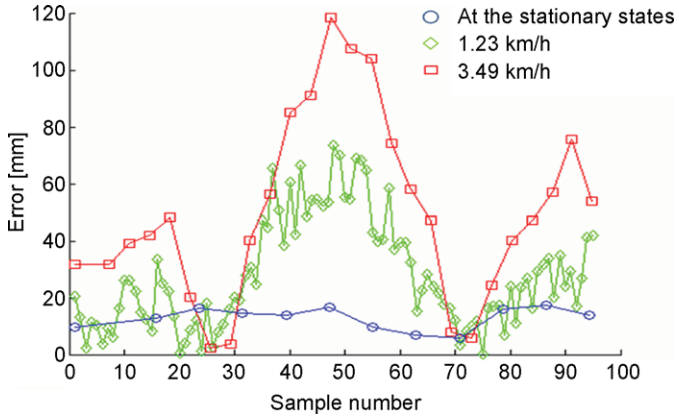


Fig. 13. Comparison of position error in three cases.

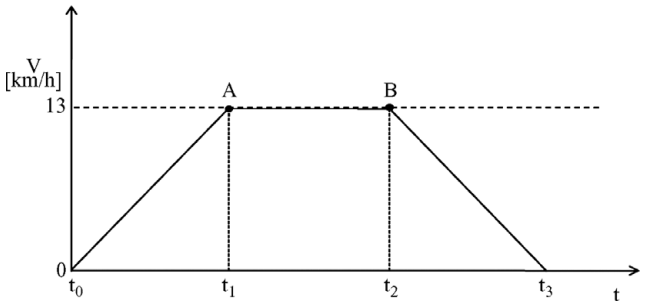


Fig. 14. Velocity planning of the mobile robot.

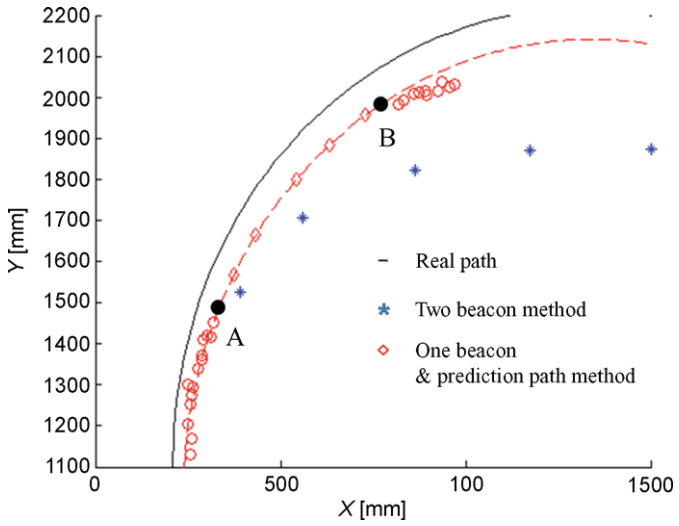


Fig. 15. Experimental comparison of the proposed algorithm and the conventional approach (curved motion).

robot, ICC and R, are used for its localization. After t_2, the position estimation is done using two beacons again, since the speed becomes slower. The velocity of the mobile robot is calculated as the differential value of the position data at every moment of position estimation by the microprocessor.

Figures 15 and 17 show the experimental comparisons of the proposed and conventional approaches for curved and straight-line motions, respectively. In the high-speed region from A to B, the proposed algorithm is applied for the position estimation. To obtain the global features, ICC and R, from the past coordinates of the mobile robot, several datasets are utilized instead of two sets. In practice, there

https://doi.org/10.1017/S0263574710000536 Published online by Cambridge University Press

Table I. Comparison of position error and estimation result of ICC and R in high-speed curve motion, [cm].

Error	Average	Maximum	ICC	X	Y	R (Radius)
Without algorithm	14.7	22.7	Theoretical	133	111	113
With algorithm	7.5	8.2	Estimated	134.1	103.8	110.2

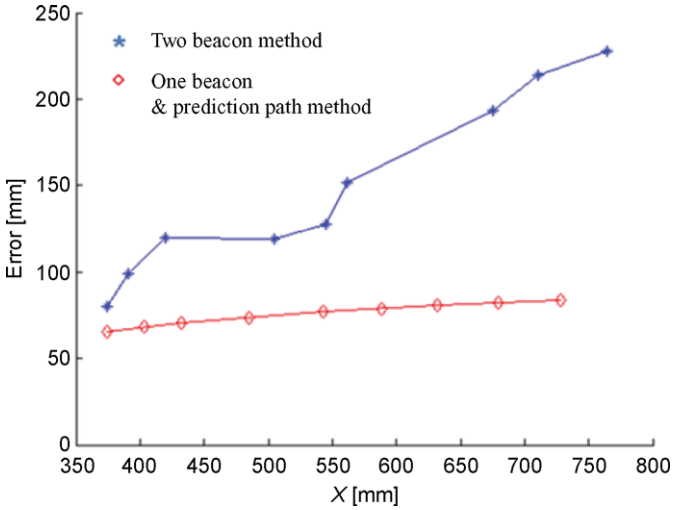


Fig. 16. Comparison of estimation errors (curve motion).

are intrinsic sensor errors and noises from the environment to consider. To overcome these errors, several datasets are utilized to estimate ICC and R by the least squares method.

Figure 16 compares the position estimation errors of the proposed algorithm and the conventional approach in the region from A to B. On the curved motion, the conventional approach has an average error of 14.7 cm and maximum error of 22.7 cm. However, the proposed algorithm has an average error of 7.5 cm and maximum error of 8.2 cm. The maximum error is reduced to 33% of that in the conventional approach, which is a remarkable improvement. The theoretical values of ICC and R on the curved motion are ICC = [133, 111 cm] and $R = 113$ cm. In the experiment, these values are evaluated as ICC = [134.1, 103.8 cm] and $R = 110.2$ cm and utilized for the localization. As shown in Fig. 15, the estimated trajectory of the mobile robot is very close to the real trajectory, which is recorded by the CCD camera.

Table I shows the improvement of the position estimation error obtained with the proposed algorithm. It also shows the estimated ICC and R, which represent the motion characteristics of the mobile robot.

Figure 17 shows the straight-line motion along the x-axis, where the y coordinates of ICC and R are theoretically equal to infinity. The estimated values in the real experiments are ICC = [208.8, 12,860.1 cm] and $R = 13,003.6$ cm, which are large enough to be considered as infinity, considering the size of the experimental room, 2.5m × 3m. Therefore, the motion characteristics defined by ICC and R can be utilized

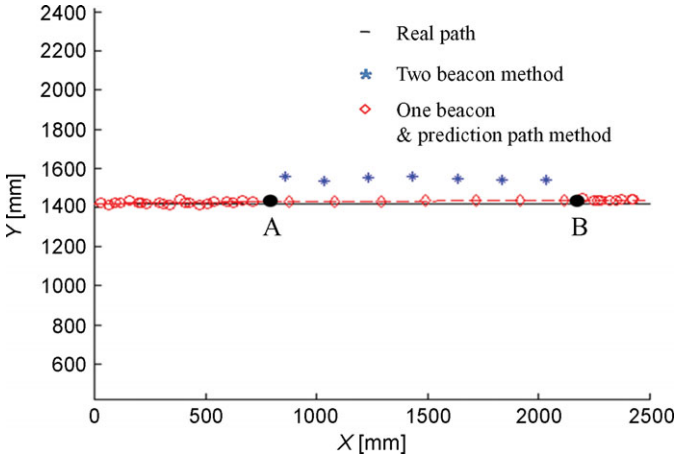


Fig. 17. Experimental comparison of the proposed algorithm and conventional approach (straight line).

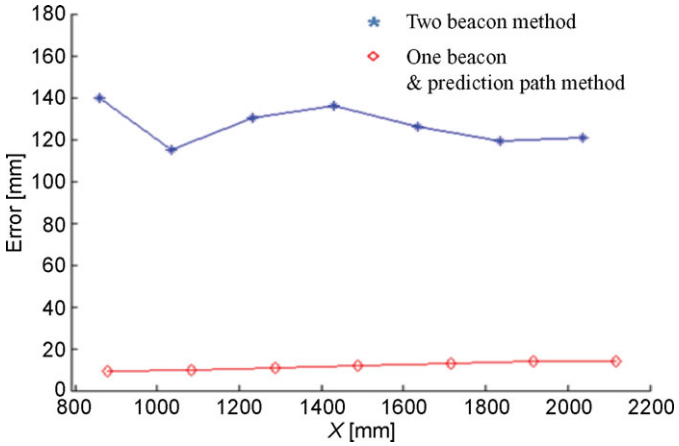


Fig. 18. Comparison of estimation errors (straight line).

even for the localization of a mobile robot moving on a straight line. Figure 18 compares the position estimation errors of the proposed algorithm and the conventional approach in the region from A to B. In the straight-line motion, the conventional approach has an average error of 12.6 cm and maximum error of 14.0 cm. However, the proposed algorithm has an average error of 1.1 cm and maximum error of 1.4 cm. The maximum error is reduced to 10% of that in the conventional approach, which is a considerable improvement. It is observed that the motion characteristics featured by ICC and R are suitable even for characterizing straight-line motion.

Practically, ICC and R do not change rapidly. There is a mechanical constraint, which prevents the curvature from changing rapidly for differential-driving mobile robots. Also, when the curvature changes rapidly, the slippage of the wheels becomes large in practice. Therefore, in the path planning of the mobile robot, a bigger R is desirable so as not to cause a large amount of slippage. To overcome this shortcoming of the differential-driving mobile robot, omnidirectional mobile robots have been developed recently. However, they[25] are not as popular as differential-driving mobile robots, since their wheel structure is bulky and expensive.

https://doi.org/10.1017/S0263574710000536 Published online by Cambridge University Press

Table II. Comparison of position error and estimation result of ICC and R in high-speed straight-line motion, [cm].

Error	Average	Maximum	ICC	X	Y	R (Radius)
Without algorithm	12.6	14.0	Theoretic	151	∞	∞
With algorithm	1.1	1.4	Estimated	208.8	12,860	13,003

Table II summarizes the improvement of the position estimation error obtained with the proposed algorithm. It also shows the estimated ICC and R, which represent the motion characteristics of the mobile robot.

In this paper, a dynamic localization algorithm is proposed where only one beacon and the global features are used to localize the mobile robot instead of using two or more beacons. In this algorithm, the sampling period of the localization is reduced by half, by using just one beacon, and the error caused by the movement of the mobile robot is reduced. This means that this scheme is very effective for fast moving mobile robots. It also makes stable position estimation possible when only one beacon signal is usable for the localization process on account of obstacles or reflected ultrasonic signals.

5. Conclusions

This paper demonstrates a novel approach to reduce the position estimation error for the indoor localization system, iGS, where the position of a fast moving mobile robot is estimated by means of RFID/ultrasonic sensors. Many studies have been conducted to improve the localization accuracy for slowly moving mobile robots. However, fast moving mobile robots are currently required to operate over a wide area to perform various tasks, which demands a precise and reliable position estimation scheme. It is shown that the localization error of the mobile robot is proportional to the speed by conducting real experiments. Based on this observation, to improve the localization accuracy, the measurement cycle is minimized by using only one beacon at a time. The global features of the differential-driving mobile robot are used for the localization process with the beacon data. The global features are derived from a single curvature path, which can be defined as the center point, ICC, and rotation radius, R, along which the mobile robot is moving. With these features, the future path of the mobile robot can be estimated by extending the current path. This scheme is applicable to situations in which only one beacon is effective for localization because of the existence of obstacles, which block the paths of the other ultrasonic signals for a short time. In practice, this scheme does not require any special equipment or extra hardware, which ensures its usability for commercial purposes.

Acknowledgment

This work was supported (in part Pusan National University Specialized Navigation/Localization Robot Technology Research Center) by the Ministry of Knowledge Economy under Human Resources Development Program for Convergence Robot Specialists.

References

1. D. Lee and W. Chung, "Discrete-status-based localization for indoor service robots," *Ind. Electron. IEEE Trans.* **53**(5), 1737–1746 (2006).
2. A. Talneau, S. Slempkes and A. Ougazzaden, "Multisensor fusion for simultaneous localization and map building," *Robot. Autom. IEEE Trans.* **17**(6), 908–914 (2001).
3. S. Garrido, L. Moreno, D. Blanco and M. L. Munoz, "Sensor-based global planning for mobile robot navigation," *Robotica* **25**(2), 189–199 (2007).
4. C.-C. Tsai, "A localization system of a mobile robot by fusing dead-reckoning and ultrasonic measurements," *Ind. Electron. IEEE Trans.* **47**(5), 1399–1404 (1998).
5. J. Borenstein and L. Feng, "Measurement and correction of systematic odometry errors in mobile robots," *Robot. Autom. IEEE Trans.* **12**, 869–880 (1996).
6. F. Donoso-aguirre, J.-P. Bustos-Salas, M. Torres-Torriti and A. Guesalaga, "Mobile robot localization using the Hausdorff distance," *Robotica* **26**(2), 129–141 (2008).
7. J. Wolf, W. Burgard and H. Burkhardt, "Robust vision-based localization by combining an image-retrieval system with Monte Carlo localization," *Robot. IEEE Trans.* **21**(2), 208–216 (2005).
8. F. Chenavier and J. Crowley, "Position Estimation for a Mobile Robot Using Vision and Odometry", *IEEE International Conference on Robotics and Automation* (1992) pp. 2588–2593.
9. J. Huang and H.-S. Tan, "A low-order DGPS-based vehicle positioning system under urban environment," *Mechatronics IEEE/ASME Trans.* **11**(5), 567–575 (2006).
10. V. Milanés, J. E. Naranjo, C. González, J. Alonso and T. de pedro, "Autonomous vehicle based in cooperative inertial systems," *Robotica* **26**(5), 627–633 (2008).
11. H. Chen, D. Sun and J. Yang, "Global localization of multirobot formations using ceiling vision SLAM strategy," *Mechatronics* **19**(5), 618–628 (Aug. 2009).
12. S. K. Cho, S. C. Shin and J. M. Lee, "A Dynamic Localization Algorithm for Mobile Robots using the iGS System," *Proceedings of the 2008 IEEE/ASME International Conference on Advanced Intelligent Mechatronics* (2008), pp. 734–739.
13. J. M. Yun, S. B. Kim and J. M. Lee, "Robust positioning a mobile robot with active Beacon sensors," *Knowl.-Based Int. Inf. Eng. Syst.* Part I, 890–897 (2006).
14. S. B. Kim and J. M. Lee, "Precise indoor localization system for a mobile robot using auto calibration algorithm," *Korean Robot. Soc.* **2**(1), 40–47 (2007).
15. D. E. Manolakis, "Efficient solution and performance analysis of 3-D position estimation by trilateration," *IEEE Trans. Aerosp. Electron. Syst.* **32**, 1239–1248 (1996).
16. S. S. Ghidary, T. Tani, T. Takamori and M. Hattori, "A New Home Robot Positioning System (HRPS) Using IR Switched Multiultrasonic Sensors," *Proceedings of the IEEE Conference on Systems, Man, and Cybernetics 1999 (SMC 1999)*, vol. 4 (1999) pp.737–741.
17. J. M. Lee, K. Son, M. C. Lee, J. W. Choi, S. H. Han, M. H. Lee, "Localization of a mobile robot using the image of a moving object," *Ind. Electron. IEEE Trans.* **50**(3), 612–619 (2003)
18. W. E. Dixon, D. M. Dawson, E. Zergeroglu and A. Behal, "Nonlinear Control of Wheeled Mobile Robots," **In**: *Lecture Notes in Control and Information Sciences*, vol. 262 (Springer Verlag, 2001).
19. W.-C. Chang and S.-A. Lee, "Autonomous Vision-Based Pose Control of Mobile Robots with Tele-Supervision," *IEEE*

https://doi.org/10.1017/S0263574710000536 Published online by Cambridge University Press

International Conference on Control Applications (2004), pp. 1049–1054.
20. T.-H. S. Li, S.-J. Chang and W. Tong, "Fuzzy target tracking control of autonomous mobile robots by using infrared sensors," *IEEE Trans. Fuzzy Syst.* **12**(4), 491–501 (2004).
21. S. S. Han, B. S. Choi and J. M. Lee, "A precise curved motion planning for a differential driving mobile robot," *Mechatronics* **18**(9), 1–9 (2008).
22. S. Wei and M. Zefran, "Smooth Path Planning and Control for Mobile Robots," *IEEE Conference on Networking, Sensing and Control* (2005), pp. 894–899.
23. W.-C. Chang and S.-A. Lee, "Autonomous Vision-Based Pose Control of Mobile Robots with Tele-Supervision," *IEEE International Conference on Control Applications* (2004), pp. 1049–1054.
24. S. Han, H. S. Lim and J. M. Lee "An efficient localization scheme for a differential-driving mobile robot based on RFID system," *Ind. Electron. IEEE Trans.* **54**, 1–8 (2007).
25. H.-C. Huang and C.-C. Tsai, "Simultaneous tracking and stabilization of an omnidirectional mobile robot in polar coordinates: a unified control approach," *Robotica* **27**(3), 447–458 (May 2009).

https://doi.org/10.1017/S0263574710000536 Published online by Cambridge University Press