Simulation Study on a Method to Localize Four Mobile Robots Based on Triangular Formation

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ABSTRACT

Localization of mobile robots is crucial to the deployment of robots in real-world applications. With infrastructure-based technologies, such as global positioning system (GPS) and indoor positioning system (IPS), robot localization is relatively straightforward. However, the extra cost to maintain the infrastructure can be problematic for certain applications. Other methods, such as dead reckoning and simultaneous localization and mapping (SLAM), have also been actively studied, despite the fact that they do not employ these infrastructure-based technologies. However, in such methods, the accumulated errors are still detrimental. Moreover, the SLAM method is hardly used in pattern-less environments, such as in totally open space. In this paper, we propose a localization method for mobile robots based on cooperative formation. The system does not need positioning infrastructures or existing maps. The concept of the proposed localization method is similar to that of localization methods, which are based on infrastructures: first, three mobile robots build a triangular formation, then, they are fixed at their locations, and the robot team accomplish their beacon-as task, as if it were an infrastructure-based localization system. The last robot is a moving robot, as it moves to the next vertex while localizing itself. The positioning error of the proposed system is much lower than the errors caused by dead reckoning or SLAM algorithms without loop matching method, because the error of the proposed system is not continuously accumulated over time. The performance of the proposed system is compared to the performance of the odometry-based localization method and the SLAM algorithm. Simulations demonstrate that the localization method proposed by us produces less positioning errors than the odometry-based method and the SLAM algorithm.

INTRODUCTION

Localization has been an important problem for achieving autonomy of mobile robots (Leonard and Durrant-Whyte, 1991). In fact, even though a high quality controller is implemented, when a robot has wrong information about the position, it cannot reach the desired point. Thus, the localization system has occupied a significant portion of the cost involved on the construction of mobile robots, when the aim is to achieve high accuracy of the positioning system. In the particular case of outdoor environments where Global Positioning Systems (GPS) are available, the position and heading information of the Unmanned Ground Vehicles (UGV) and the Unmanned Aerial Vehicles (UAV) can be acquired by GPS (Misra and Enge, 2001). These positioning systems use information from the infrastructure, whose position is accurately described. As such, these systems, which are based on the infrastructures, have provided the exact position of the robots. However, to acquire the position of the robot should depend on the infrastructure, and not on onboard systems; it implies that, if there are no infrastructure facilities, or if they are destroyed (e.g., the case of disaster, war, mine, etc.), it is impossible for the robots to acquire position information. For example, GPS is vulnerable to radio frequency interference (Chen et al., 2012; Seo et al., 2011a) and ionospheric scintillation (Seo and Walter, 2014; Seo et al., 2011b). Thus, a large body of research on the localization of mobile robots without GPS has been done.

Dead reckoning has been a common method to estimate the position of mobile robot, using an inertial navigation system composed of inertia sensors and wheel encoders (Borenstein and Feng, 1994; Cho et al., 2011). However, in the dead reckoning system, as the position of the mobile robot is estimated via integrations of the accelerations and velocities, the position estimation errors are accumulated.

To overcome this drawback of the dead reckoning system, map-based localization algorithms have been researched (Filliat and Meyer, 2003; Dissanayake et al., 2003). With map-based algorithms, the mobile robots can measure the environmental information against the map information that the mobile robot already received, using various sensors, such as image sensor, RADAR, and laser scanner. However, in unknown environments, the whole map of every region that mobile robot should explore is hardly collected.

Simultaneous Location and Mapping (SLAM) has been proposed to enable the operation of mobile robots at an unknown location and in an unknown environment (Thrun et al., 2005; Durrant and Bailey, 2006). Because mobile robots can handle both mapping and localization during their operation, the SLAM has been broadly employed in unmanned systems. However, the position error of the mobile robot can be accumulated during operation without a loop matching method (Newman et al., 2005; Williams et al., 2009). Mobile robots need to return to positions where they have already passed through in order to reduce localization errors. Moreover, sensors utilized for SLAM still have limitations, such as the environmental information being detected only in the visible area.

Cooperative systems have been proposed to overcome the limitations of the detectable area (Grocholsky et al., 2006; Kwon et al., 2015). As UAVs present the advantage of dynamic field of view (FOV), UAV-UGV cooperative systems can provide information relative to a wider area to UGVs. In (Garzon et al., 2013; Kim et al., 2013; Kim et al., 2014), obstacle mapping and navigation systems for UGVs with support of UAVs are proposed. The purpose of those researches is not to decide the accurate position of the robots, but to determine the approximate location of the obstacles.

Thus, we propose a triangular formation mechanism for the localization of a multiple robot system, without the infrastructures of the positioning system nor the expensive sensory data.

In our system, three robots organize and maintain a triangular formation to accomplish the task as beacons for the moving robot. The other moving robot can move to the position that constructs a new triangular formation, while it acquires position information from the robots in the triangular formation. To move the entire system, keeping the triangular formation, at the same time, the robots keep building new triangles. The moving patterns and the movements of the entire system are similar to those of the walking pattern of a four-legged robot. By means of this moving pattern, which has the shape of the triangle, whereas the robots are in an unknown environment without infrastructure facilities, it is possible that the positioning methods based on the infrastructures are implemented using the onboard positioning sensors, such as communication Recieved Signal Strength Indicator (RSSI) measurement sensors and vision systems.

The remainder of this paper is organized as follows. The details of how the robotic system operates to build a triangular formation are explained in the triangular formation section. A few examples regarding the localization of the robotic system are proposed in the localization section. In order to demonstrate the feasibility of the proposed system, simulation results are presented in the simulation section. Finally, the conclusions of this research are given.

TRIANGULAR FORMATION

The positioning system proposed in this paper is based on multiple robots, and is achieved by building the triangular formation. Three robots, which organize the shape of the triangle, perform the task of the beacon. From these beacon robots, the moving robot acquires position information. The proposed system is depicted in figure 1.

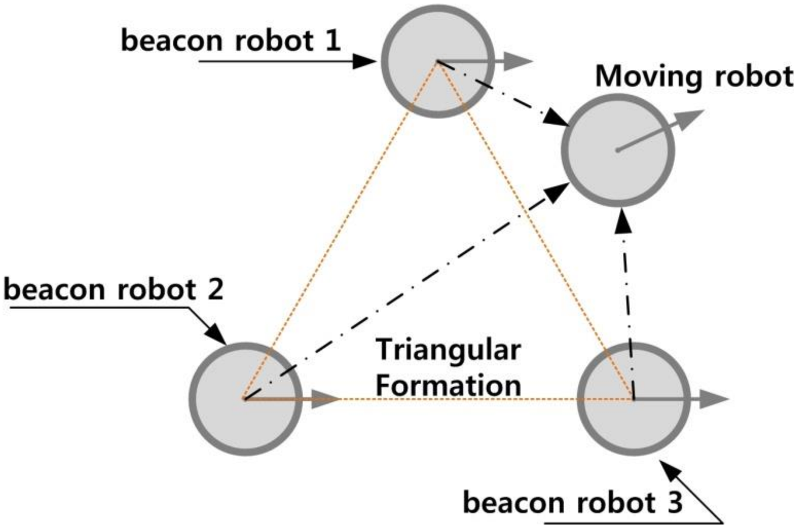


Figure 1. Localization system based on the triangular formation (orange dash lines: triangular formation and dash-dot arrow: calculated position by acquired distance information).

As shown in figure 1, beacon robots 1 to 3 build a fixed triangular formation that provides localization information. The system operates similarly to infrastructure-based localization systems. Moreover, it is shown in figure 1 that the moving robot is independent on the odometry, because it acquires position information from the other robots; it has the instantaneous position error, unlike dead reckoning, which is based on the odometry and presents integrated error along the time. Nevertheless, when the triangular formation is repeated to move the entire system, the position errors of the robots are accumulated by a summation along the number of formation changes, not by integration along the time. This localization system is achieved by the following process. Three beacon robots construct the triangular formation, and the moving robot acquires position information from the beacon robots. In order to repeat the triangular formation using four robots, a formation with two connected triangles is proposed, as depicted in figure 2.

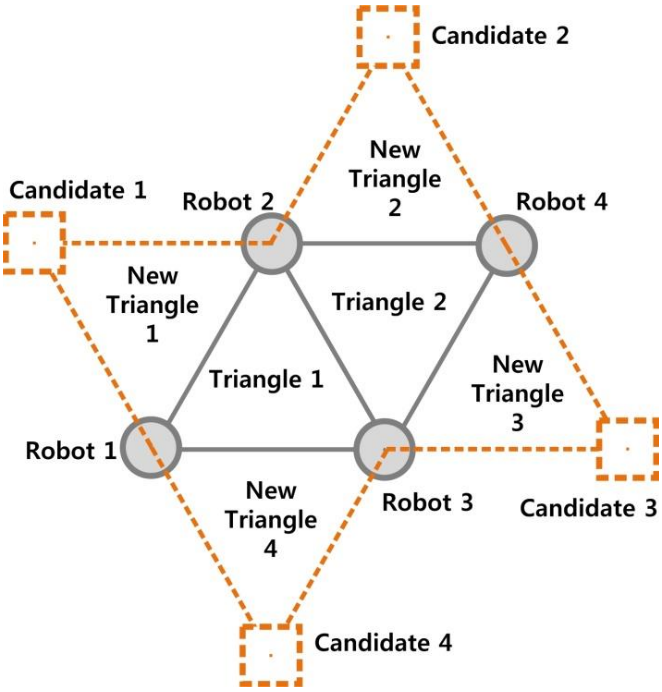


Figure 2. Formation with two connected triangles

In figure 2, the circles are the robots in the triangular formation, the dotted squares are candidate positions, where the other adjacent triangle can be generated by the moving robot, and the dotted lines show the new adjacent triangles, which are generated by the moving robot. Considering the formation of four robots, which is organized by two connected triangles, which are triangles 1 and 2 in figure 2, four new triangles 1-4, sharing the sides of triangles 1 and 2, can be generated by a movement of the moving robot toward one of the candidates 1-4. When the moving robot in figure 1 reaches a desired position, selected in four candidate positions in figure 2, a new triangular formation with two triangles is organized. By repeating this process where a new triangle, sharing side with the current triangles, is generated, the proposed triangular formation can move. Because this moving pattern can be similar to walking patterns of the four-legged robots, the moving pattern of the proposed triangular formation can be explained by walking locomotion.

To achieve an objective that makes the entire system move in an unknown environment, while position information of the robots are acquired, moving patterns of whole system are as follow. One robot should be selected to assign the moving task. Note that the robots which can be assigned the moving task are the robots which do not share the two triangles (e.g., robots 1 and 4 in figure 2), because a newly generated triangle should share the side of one of the current triangles. Regarding the desired moving direction of the entire formation, one robot between robots 1 and 4 is selected. If we determined the moving direction of the formation, then a candidate position among the candidates 1-4, shown in figure 2, is selected. For example, in the cases that the formation moves toward the left side, upper side, downside, and right side, the candidates 1, 2, 3, and 4 are selected as the desired position to generate the new triangle, respectively. After choosing a candidate position, the moving task is assigned to the robots, such that the farthest robot from the selected candidate is chosen. For example, in figure 2, when the formation moves left, candidate 1 is selected as the desired position, then, from this selection of the desired position, robot 4, the farthest from candidate 1, is assigned the moving task. This process of choosing the desired position among the candidates and moving a robot to the next target position to build triangles is repeated, as the whole system moves to the global target point. As can be seen in figure 2, the triangular formation can move in four directions, by choosing a candidate.

LOCALIZATION

This section shows examples of localization methods that can be employed with the proposed triangular formation in unknown environments. As stated above, a localization system, similar to infrastructure-based positioning systems, can be implemented. That means that the infrastructure of the positioning system is constructed instantly by the beacon robots, keeping the triangular formation. Thus, in this paper, we consider two localization methods in the ensuing sub-sections: RSSI-based localization and an artificial marker-based localization method.

RSSI-based Localization

Several studies have been conducted with the objective of identifying device locations using RSSI. RSSI measurement can be accomplished via WiFi, BLE, ZigBee, etc. (Huang et al., 2015; Chen et al., 2016; Kuo et al., 2016). In RSSI-based localization, the following well-known propagation model is utilized: (Patwari et al., 2003).

$$P(dBm) = P_0(dBm) - 10n_p \log_{10}(d/d_0) + X_\sigma, \tag{1}$$

where $P(dBm)$ is the received power from the beacon in decibel milliwatt, $P_0(dBm)$ is the received power at a reference distance d_0 in decibel milliwatt, n_p is a path loss parameter representing the condition of the environment, d is the distance between the receiver and the beacon, and X_σ is a random variable for the noise in $P(dBm)$. In the proposed localization system, based on triangular formation, the receiver, which is a moving robot, moves in the formation of an open space, with the aid of the collision avoidance algorithm. Thus, we assume that there is no shadowing effect, and that the path loss exponent and the received power noise are trivial.

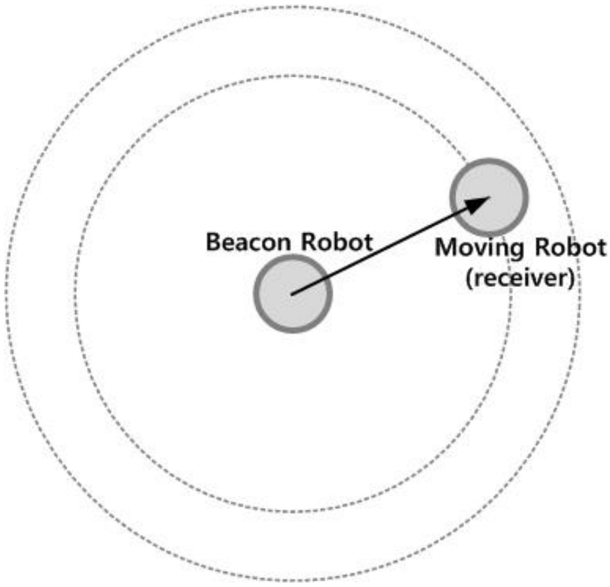


Figure 3. Localization of the moving robot using RSSI: Signal propagation from the beacon robot to the moving robot.

The propagation signal of RSSI is shown in figure 3. In general, three beacon robots are sufficient to calculate the location of the receiver robot with the RSSI-based localization algorithm. The trilateral algorithm, which comprises maximum likelihood estimation, least squares, or Kalman filter, is utilized to get the location of the receiver, using three RSSIs, which can be converted to the distances between the receiver and the beacons.

The location coordination of the beacon robots and of the moving robot are $B_i = (x_{Bi}, y_{Bi})$ and $M = (x, y)$, respectively; i is 1, 2, and 3, because the proposed triangular formation needs three beacon robots. During the moving operation, the coordination of the moving robot is calculated as follows (Chen et al., 2016):

$$\begin{aligned} (x - x_{B1})^2 + (y - y_{B1})^2 = d_1^{\ 2}, \\ (x - x_{B2})^2 + (y - y_{B2})^2 = d_2^{\ 2}, \\ (x - x_{B3})^2 + (y - y_{B3})^2 = d_3^{\ 2}. \end{aligned} \tag{2}$$

From the three formulas in (2), the location of the moving robot can be calculated as:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 2(x_{B3} - x_{B1}) & 2(y_{B3} - y_{B1}) \\ 2(x_{B3} - x_{B2}) & 2(y_{B3} - y_{B2}) \end{bmatrix}^{-1} \cdot \begin{bmatrix} x_{B3}^2 - x_{B1}^2 + y_{B3}^2 - y_{B1}^2 + d_1^2 - d_3^2 \\ x_{B3}^2 - x_{B1}^2 + y_{B3}^2 - y_{B2}^2 + d_2^2 - d_3^2 \end{bmatrix}. \tag{3}$$

Figure 4 presents the localization method using RSSI measurement.

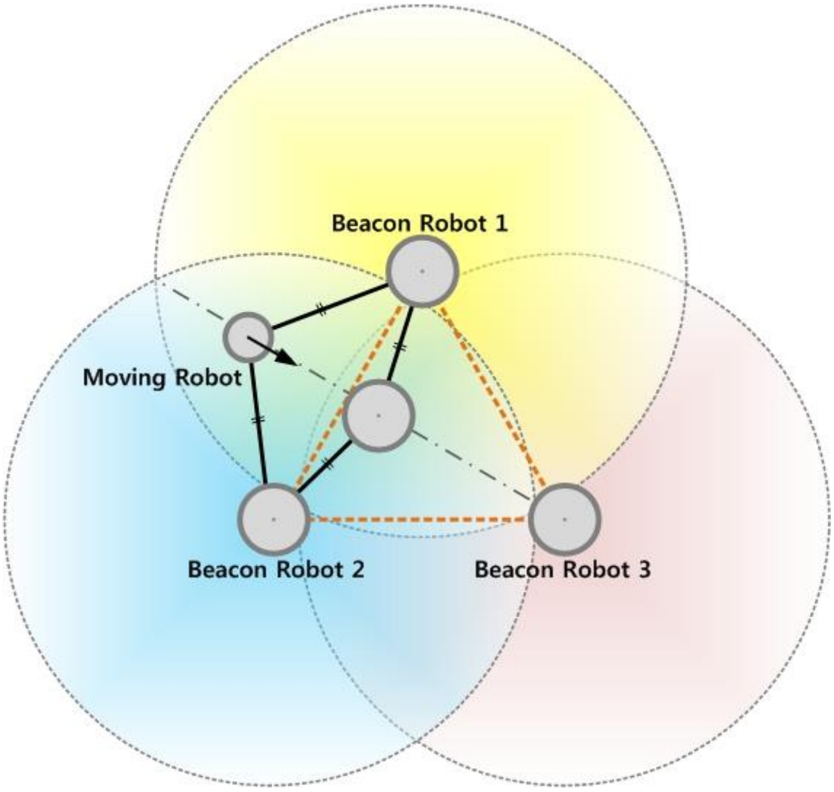


Figure 4. Localization of the moving robot using RSSI: operation of the moving robot that calculates the location using three RSSIs from the beacon robots.

In figure 4, the moving robot monitors the distance to each beacon robot repeatedly, while moving toward the local destination in the triangular formation. The distances can be calculated using the measured signal strength. When the beacon robots set the triangular formation, they decide the distances from each other. The moving robot measures half of the distance to each of two beacon robots, and recognizes that it is located in the center of the first two-beacon robot pair. Then, the moving robot moves to the next destination.

Artificial Marker-based Localization

Artificial markers can also be used to calculate the location of moving robots (Rudol et al., 2010; Lee et al., 2013; Kim et al., 2014). Figure 5 depicts a multi-robot system that uses cameras to detect artificial markers. If the intrinsic and extrinsic parameters of the camera on the robot are known, the rotation matrices R and the translation matrices T can be calculated (Kim et al., 2014).

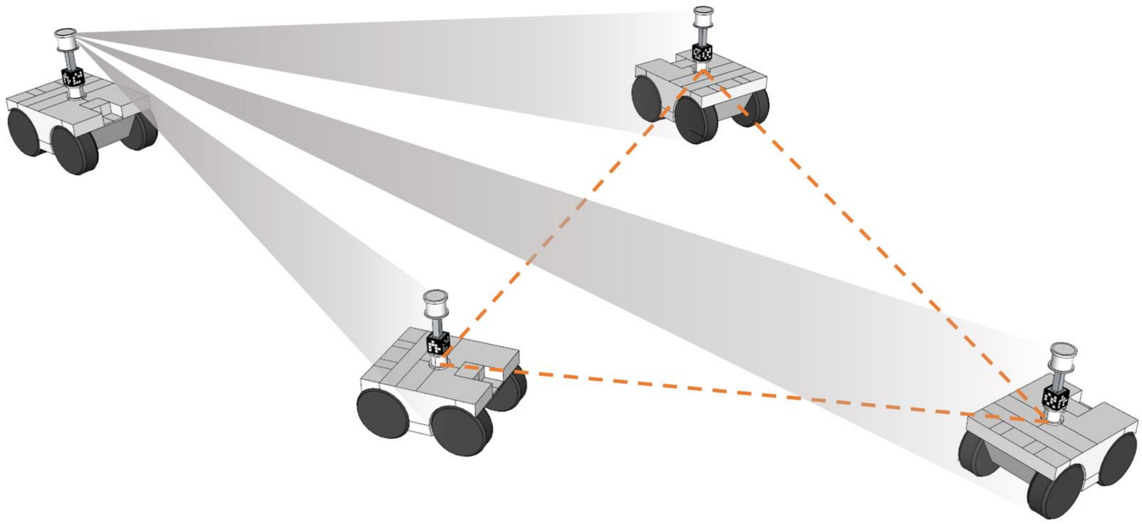
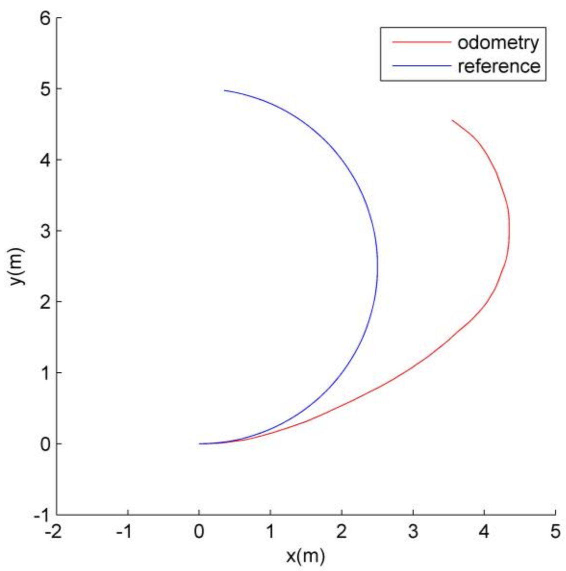


Figure 5. The artificial marker-based localization system

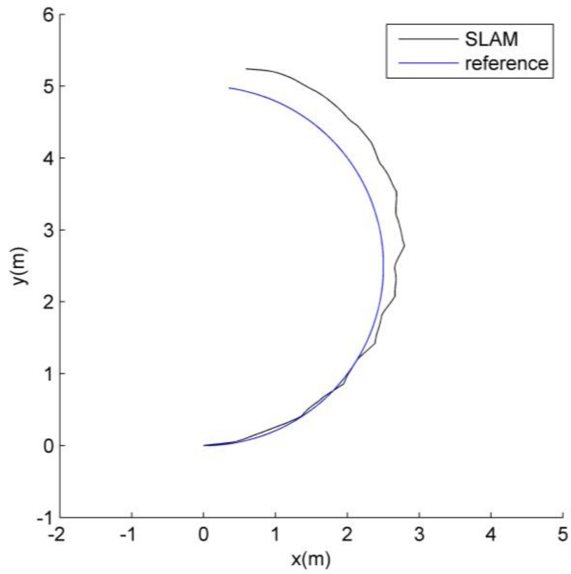
In figure 5, it is shown that the cameras installed on the moving robot can detect artificial markers around the robot. With three different information about the relative position, the moving robot can continue to maneuver through the path generated previously. When the moving robot reaches the local destination position, it stops at that position, and composes a new triangular formation with two other robots located nearby.

SIMULATION

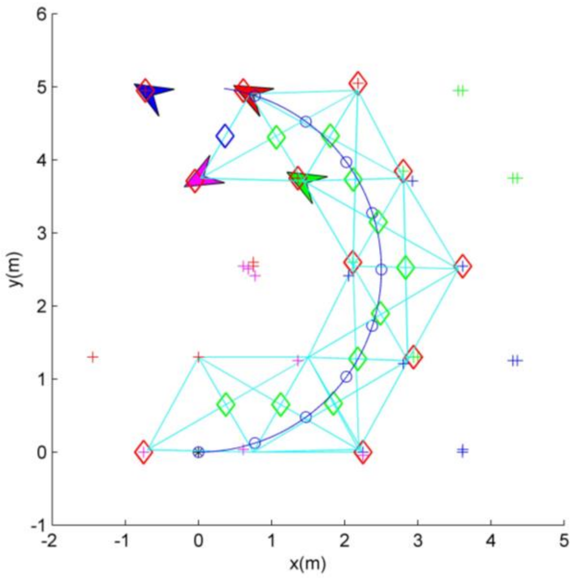
In this section, simulation results are provided in order to prove the feasibility of the proposed triangular formation system. A traditional SLAM algorithm and an odometry method are implemented, and both are compared to the proposed system. The simulation scenario that is set for the robotic system moves along a half circle. In this scenario, the odometry method and the SLAM algorithm follows the referenced waypoints, while the proposed system generates their own waypoints for the four robots.



(a)



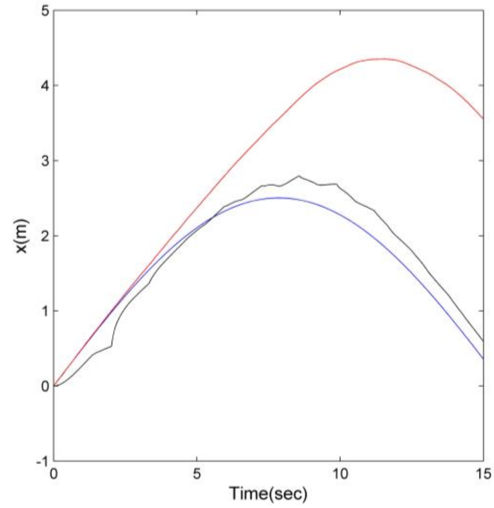
(b)

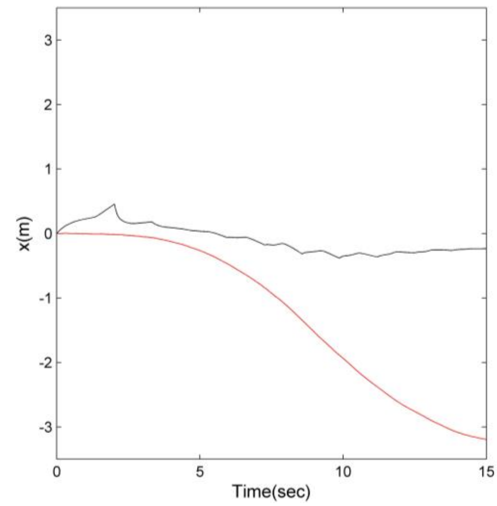


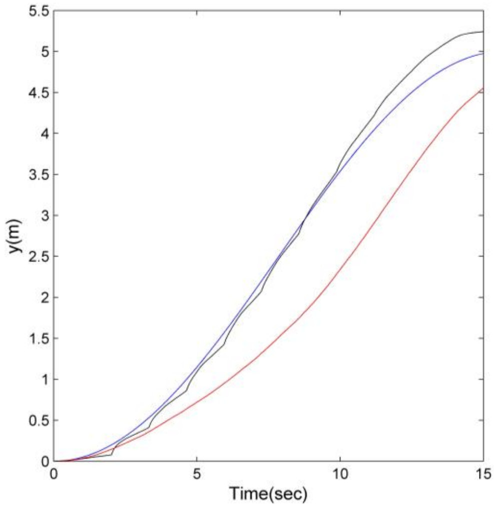
(c)

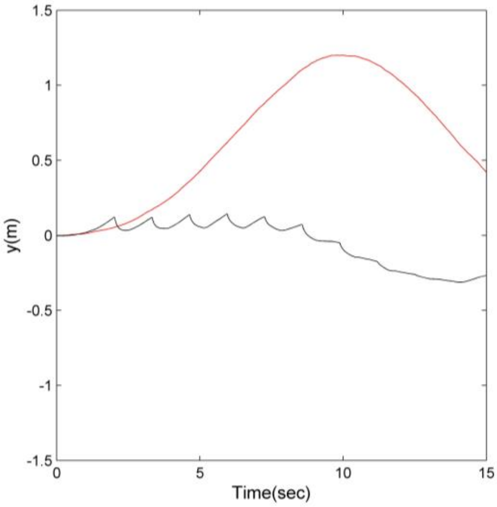
Figure 6. Localization trace calculated by each algorithm: (**a**) odometry method, (**b**) SLAM algorithm without loop matching, (**c**) proposed triangular formation algorithm.

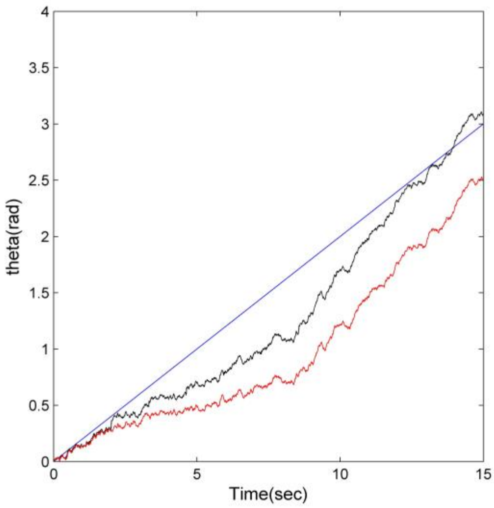
In figure 6, the blue curves in each plot are the desired trajectory of the robot, the red curve in (a) is the trajectory calculated by odometry, and the black curve in (b) is the trajectory calculated using the SLAM algorithm without loop matching. The diamonds in figure 6(c) are the positions that the moving robots calculate as destinations during operation, and the crosses are the waypoint candidates for the moving robot. The cyan lines show the triangular formations formed by the set of robots. The error on the trajectory, calculated by odometry information, accumulated over time.


x(m)
Time(sec)
(a)


x(m)
Time(sec)
(d)


y(m)
Time(sec)
(b)


y(m)
Time(sec)
(e)


theta(rad)
Time(sec)
(c)

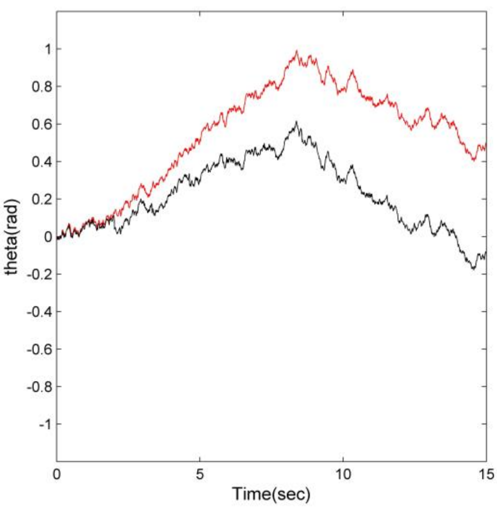

theta(rad)
Time(sec)
(f)

Figure 7. Position and error accumulated during operation: (**a**–**c**) position of x, y, and heading angle of the robot with odometry method (red lines), SLAM (black lines), and reference (blue lines). (**d**–**f**) position error accumulated with odometry method (red lines) and SLAM (black lines).

Figure 7 shows the position errors generated while the SLAM algorithm and the odometry method adapted to the moving robot. The position error regarding the odometry method accumulated continually during the operation, because it cannot compensate the initial error, and, therefore, the error is added to the control values, which are the speed and the angular velocity. The SLAM algorithm exhibits much better performance, but it is still limited in performance when the system cannot operate the loop matching method, owing to the fact that the error accumulates. The position and heading angle error of the proposed localization system, along the same target trajectory as in figure 6, are depicted in figures 8 to 10.

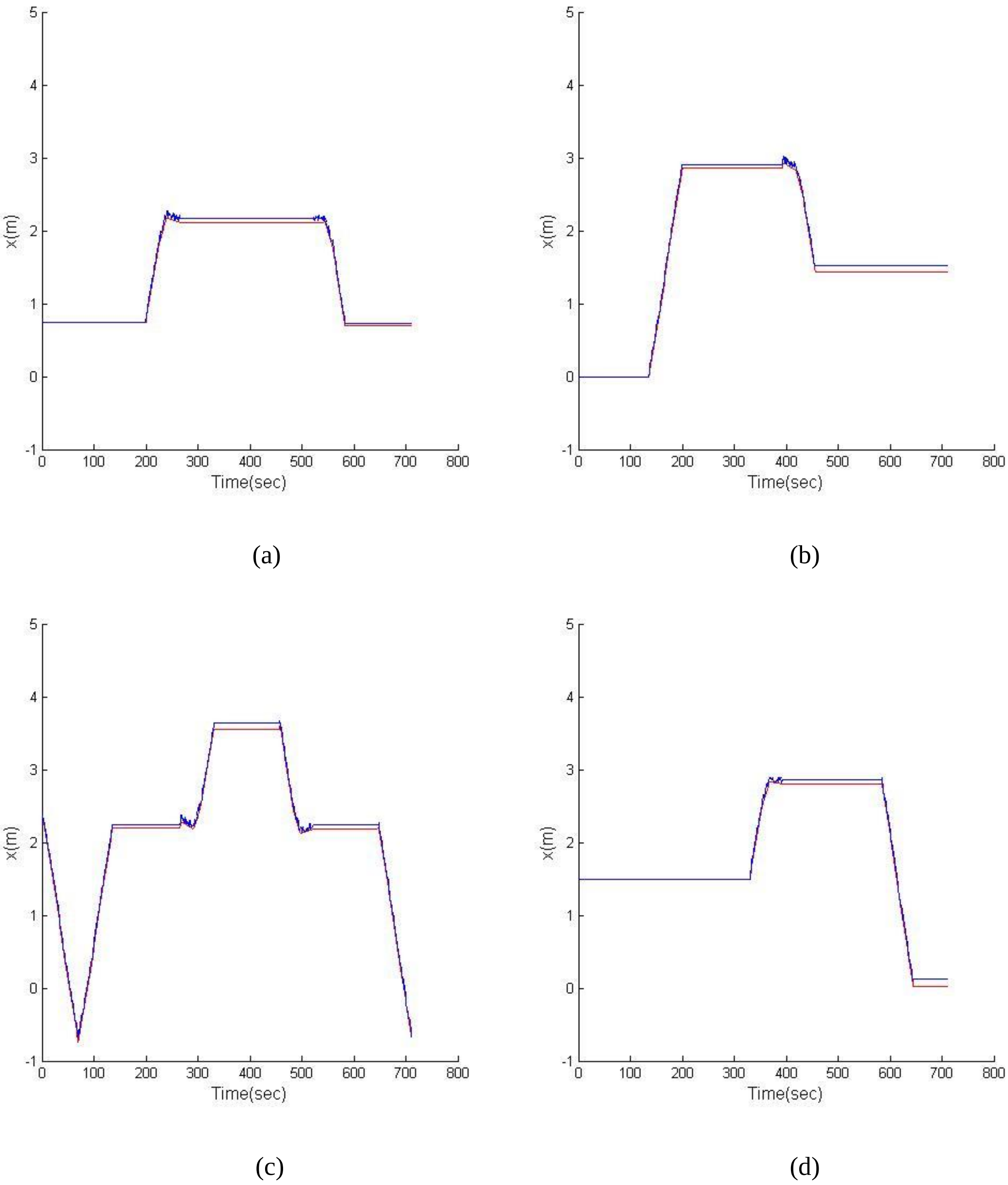
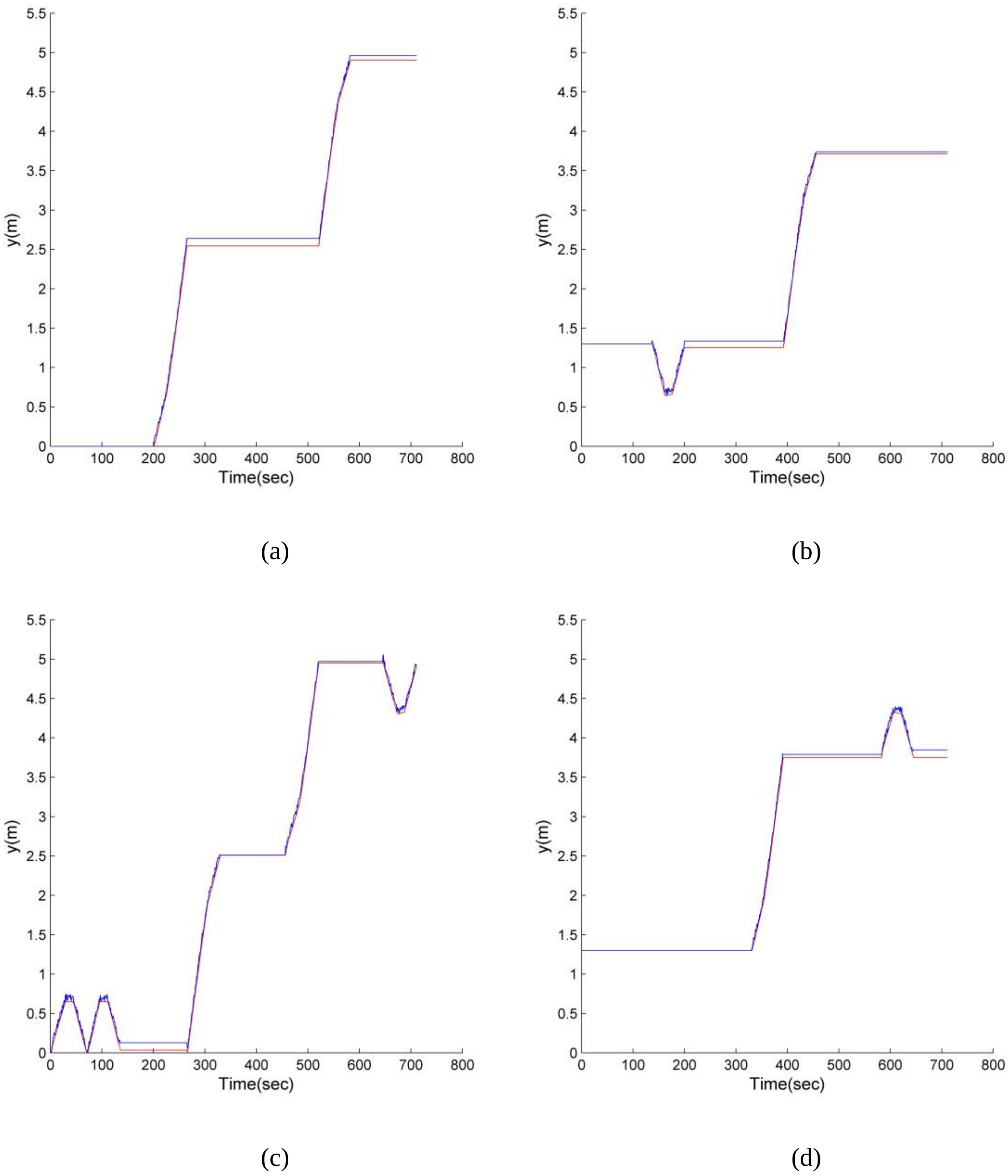


Figure 8. Ground truth position (red lines) and estimated position (blue lines) of the robots in the proposed triangular formation method: (**a**) position of robot 1 within x-coordinate, (**b**) position of robot 2 within x-coordinate, (**c**) position of robot 3 within x-coordinate, (**d**) position of robot 4 within x-coordinate.



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

Figure 9. Ground truth position (red lines) and estimated position (blue lines) of the robots in the proposed triangular formation method: (a) position of robot 1 within y-coordinate, (b) position of robot 2 within y-coordinate, (c) position of robot 3 within y-coordinate, (d) position of robot 4 within y-coordinate.

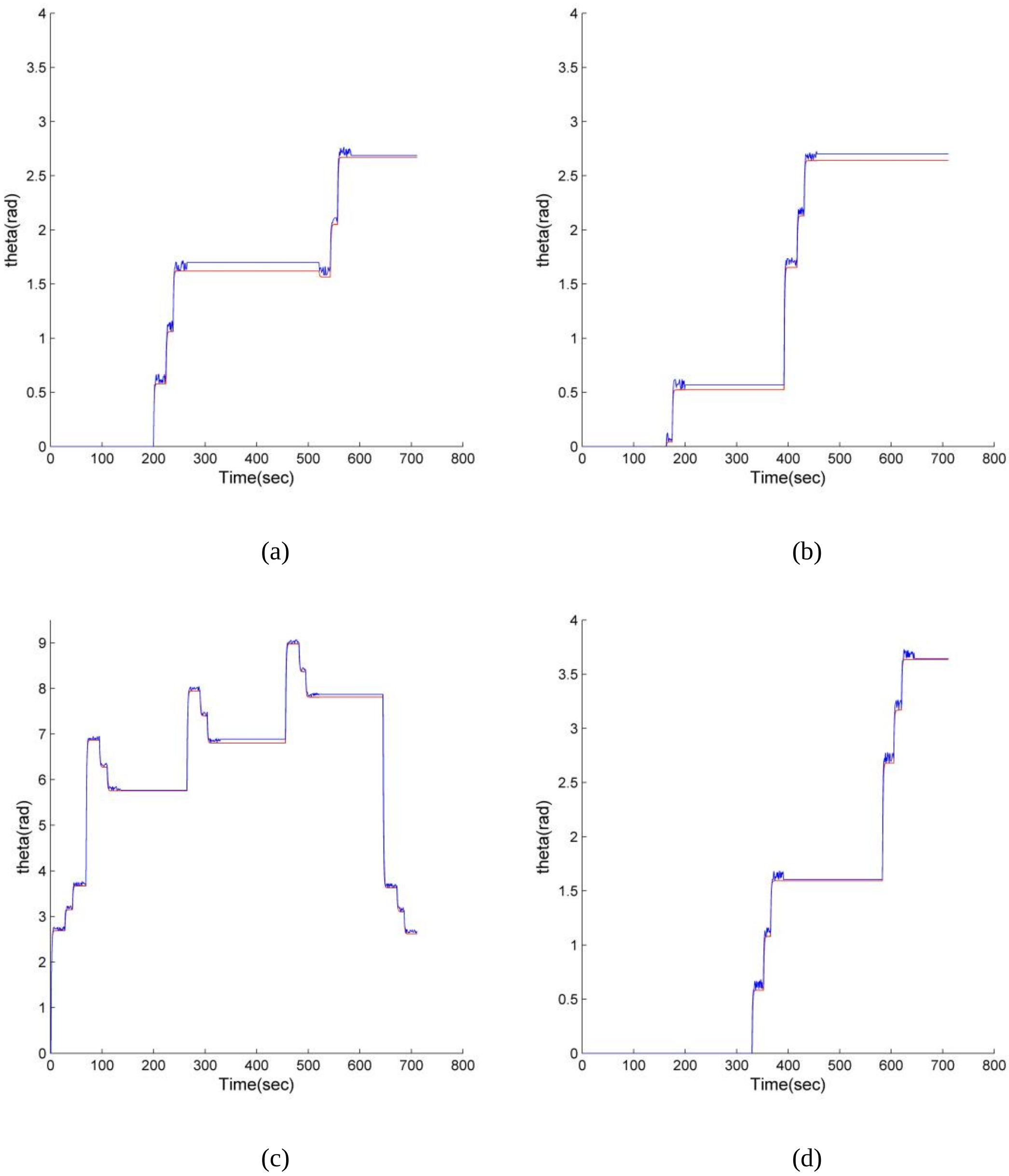


Figure 10. Ground truth position (red lines) and estimated position (blue lines) of the robots in the proposed triangular formation method: (**a**) heading angle of robot 1, (**b**) heading angle of robot 2, (**c**) heading angle of robot 3, (**d**) heading angle of robot 4

The position error and heading angle of the proposed system are much smaller than those obtained by the odometry method and by the SLAM algorithm. The errors originated by the proposed system did not accumulate over time, while the errors obtained by the other systems are integrated over time. The member robots, which act as beacon robots, are fixed during one moving robot maneuver through the formation, and they provide fixed position information, originating limited errors.

CONCLUSION

This paper proposes a triangular formation-based localization system. In the proposed system, at least three robots build a triangular formation in order to estimate the position of the moving robot. When three robots are fixed at the position that forms each vertex of the triangle, they are utilized as beacon robots. Thereafter, the fourth moving robot moves to the local destination, which will be part of the next triangle. The proposed system can be employed in GPS denied environments because it does not use any infrastructure, unlike GPS or indoor positioning system. The proposed system can also be operated in open space without landmarks, where other localization algorithms, such as the SLAM or map-based algorithms, cannot be operational. Moreover, the positioning error of the proposed system is much lower than by the odometry method or by the SLAM algorithm without loop matching.

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