Indoor Localization and Navigation for a Mobile Robot Equipped with Rotating Ultrasonic Sensors Using a Smartphone as the Robot's Brain

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***Abstract*— Identifying the exact current location of a robot is a fundamental prerequisite for successful robot navigation. To precisely localize a robot, one popular way is to use particle filters that estimate the posterior probabilistic density of a robot's state space. But this Bayesian recursion approach is computationally expensive. Most microcontrollers in a small mobile robot cannot afford it. We propose to use a smartphone as a robot's brain in which heavy-duty computations take place whereas an embedded microcontroller on the robot processes rudimentary sensors such as ultrasonic and touch sensors. In our design, a smarphone is wirelessly connected to a robot via Bluetooth by which distance measurements from the robot are sent to the smartphone. Then the smartphone takes responsible for computationally expensive operations like executing the particle filter algorithm. Also we propose to use rotating ultrasonic sensors to reduce the number of sensors needed as well as time of distant measurements. In this paper, we designed a mobile robot and its control architecture to demonstrate that the robot can navigate indoor environment while avoiding obstacles and localize its current position. Several experiments were conducted to show feasibility of the rotating sensors and a smartphone brain for a mobile robot.**

***Index Terms*— mobile robot, smartphone, localization, navigation, particle filter, ultrasonic sensor.**

I. INTRODUCTION

The demand of indoor autonomous mobile robots has increased for last few decades. Commercial success of cleaning robots is a good example of such high-demand. In 2012 about three million service robots for personal and domestic use were sold according to the International Federation of Robotics (IFR) [1]. The IFR prospects about 22 million units of service robots for personal use to be sold during the period 2013 to 2016.

There have been many approaches in indoor localization and navigation for a mobile robot for last couples of decades. To be autonomous, a robot must be able to identify its exact current position. Based on the knowledge the robot is aware of how to proceed to arrive at a goal position. To enhance robot localization, high-quality sensors such as laser scanners and 3D cameras are preferable. But most microcontrollers in a small robot cannot afford the computation required to process such high-fidelity sensor data. In this paper we propose to use a rotating ultrasonic range sensor to measure distance to the walls and detect obstacles. With its Bluetooth wireless connectivity to the robot a smartphone can be used as robot's brain in which all heavy-duty computations are executed. State-of-the-art smartphones outperform a few year old laptop computers not to mention all the high performance sensors in a smartphone including a multi-million pixel camera, an ambient light sensor, an accelerometer, a pressure sensor, a temperature sensor, a GPS, a gyroscope, and many more. With a proper connectivity and communication methods to a robot a smartphone is capable of being the robot brain.

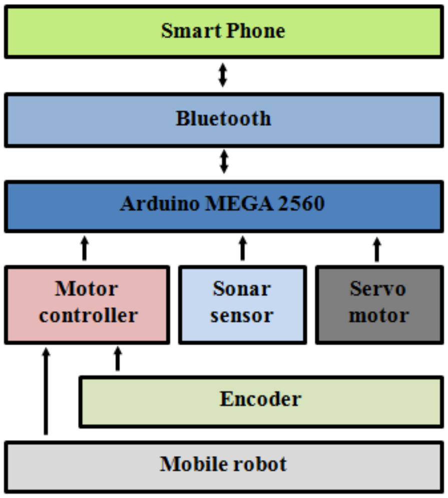


Figure 1. Block diagram of the robot using a smartphone as its brain

The block diagram in Fig. 1 shows the overall design of the robot and its components. A smartphone is in charge of processing complex algorithm that requires heavy-duty computations. A microcontroller powered by Arduino [2] is only responsible to control DC motors for four wheels and a servo motor for rotating ultrasonic sensors. The smartphone wirelessly communicates with the microcontroller through Bluetooth technology. Higher level commands such as setting a goal position and starting navigation are from the smartphone to the microcontroller. Obstacle detection and distance measurement using ultrasonic range sensors are executed by the microcontroller. The measurement data are sent to the smartphone to calculate the probability of the robot location in the next step.

In following sections, relevant studies will be discussed. Then the design and implementation details will follow the discussions. To demonstrate the practicality and effectiveness of our robot design several experiments will be shown. The experimental results show that the layered control architecture using a smartphone as the robot's brain with rotating sensors is a valid approach to balance the quality and affordability of a mobile robot.

II. RELATED WORKS

A laptop has been a popular processor unit for mobile robot [3]-[6]. As the processor of smartphones becomes faster and the size of the memory becomes larger, smartphones have been gaining popularity as a processing unit for a mobile robot. As far as the performance of smartphones is sufficiently strong, smartphones have many obvious advantages against traditional laptops. The small size and light-weight are evident benefits. Heavy load of a laptop requires more battery power that must be saved as much as possible for a mobile robot. For the reason, small mobile robots are restricted from using complex algorithms requiring heavy-duty computations. Smartphones are not just comparable processing unit with laptops. All the high performance sensors in a smartphone are incomparable with a laptop. Due to the reasons many researchers started using smartphones as part of mobile robots. A remote control system of a mobile robot was proposed using Bluetooth with a smartphone and its performance was evaluated in [7]. A camera in a smartphone was used to detect landmarks such as QR code for localization and navigation of mobile robot in [8]. Sensors of a smartphone were used in mobile robot navigation in [9]-[11]. Unlike other approaches mentioned above, the proposed system in this paper utilizes a smartphone as a main processor, the brain of a robot, to process computationally expensive tasks.

Ultrasonic sensors have been a popular measurement tool due to the simplicity and affordability. A line feature based SLAM was proposed using ultrasonic sensors for a mobile robot in [12] in which seven IR sensors are separately installed with a 30 degree in front of the robot to measure distance for SLAM. A hierarchical algorithm for indoor mobile robot localization was suggested using RFID sensor in [13] in which nine ultrasonic sensors were used. A navigation method was introduced for a tour guide robot in [14]. In front of the robot eight ultrasonic sensors were installed. Unlike these approaches we articulated the number of sensors and angles/distances between them. Our design is to use only four ultrasonic sensors that are placed on a plane on top of a servo motor in perpendicular each other. The details will be given in the following sections.

III. METHODOLOGY

Hardware components including the robot chassis, motors, ultrasonic sensors, Bluetooth module, and the Smartphone will be presented with design details of the robotics platform in this section.

A. Layered Control Structure using a Smartphone as the Brain of a Robot

A two-layer control structure was designed and used. The lower layer is responsible for relatively simple tasks that include processing sensor readings and controlling motors. The higher layer is in charge of processing tasks that need heavy-duty computations. Bluetooth wireless technology is a bridge to connect the two layers. See Fig. 1 for more details on hierarchy of control structure.

The Nexus 4 smartphone [15] was used as a robot's brain. The Atmega328 based Arduino MEGA microcontroller is in charge of controlling motors and reading ultrasonic sensors. The mobile robot platform that we used is Rover 5 platform and 333 CPR quadrature encoders are operated by the ROB-11593 motor controller [16]. A pack of four ultrasonic range sensors called HC-SR04 [17] was placed on a board on top of a servo motor. Four sensors are positioned in 90 degree angular distance so that they are perpendicular each other. The sensor reading will be used to measurement distance for particle filters and detect obstacles for navigation of our mobile robot. The Bluetooth module called HC-06 [18] is used for wireless communication between the microcontroller and the smartphone. The actual robot is shown in Fig. 2.

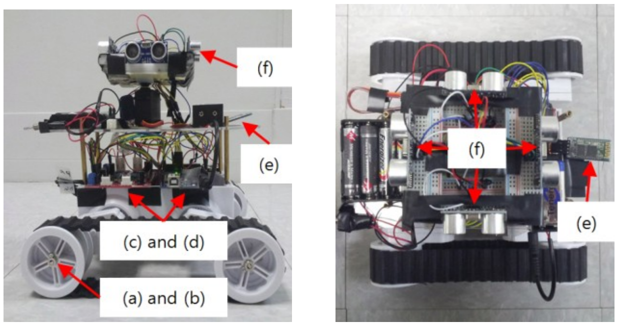


Figure 2. Lateral view of the mobile robot (left) and a bird eye's view (right). (a) rover 5 with (b) 333 CPR encoder, (c) ROB-11593 motor shieild, (d) Arduino MEGA, (e) HC-06 Bluetooth module chip, (f) ultrasonic sensor HC-SR04

B. Path Plan

To make the mobile robot navigate, we used A-star algorithm [19] that calculates the shortest path in a map. The algorithm does not calculate bigger g-value than current g-value [20] to reduce the calculation time. After a path of mobile robot is calculated, a smoothing algorithm is applied to the calculated path. The smoothing process is shown in (1).

$$\begin{aligned} y_1 &= y_1 + \alpha\,(x_0 + x_2 - 2y_1) \\ y_1 &= y_1 + \beta\,(x_1 - y_1) \end{aligned} \tag{1}$$

where x_0, x_1 and x_2 are current position, next position and position after next each. The smoothing algorithm iteratively applies to update equations to the waypoints on our path. The terms α and β control a level of smooth path or a level of original path. Fig. 3 shows an original path and a smooth one.

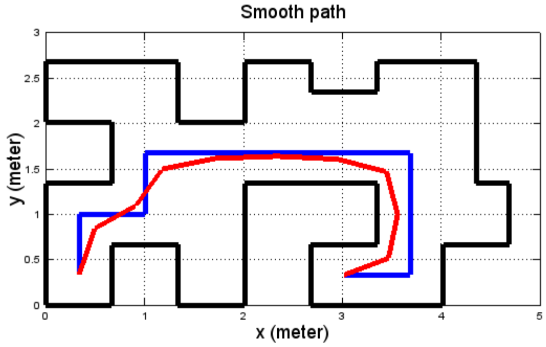


Figure 3. Smooth path planning. The solid line in red is the original path and the blue solid line is the smooth path.

When the robot detects an obstacle on the planned path, the path planning must be done at from the current position to the goal position (Fig. 4).

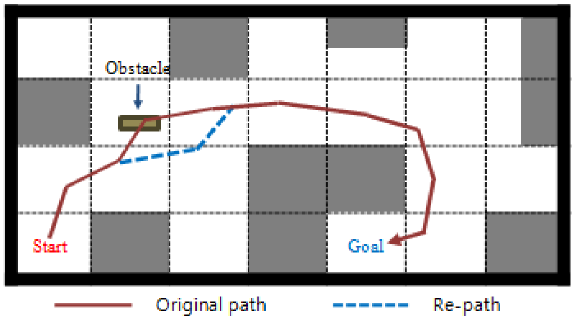


Figure 4. Avoding obstacle and new path planning.

C. *Particle Filters*

In the past decade, particle filters or Sequential Monte Carlo (SMC) has been applied to mobile robot localization [21][22]. Particle filters estimate the posterior probabilities of unobservable state variables from sensor measurements.

Each particle with weights that is the likelihood of the stats is approximated by particle filter. After motion and measurement are updated, the particles are re-sampled by its own weight value. Through repetition of re-sampling, all particles converge into one cluster. As a result, the mobile robot can predict own position by particles. All complex process is handled by a smartphone such as calculating a number of particles. After processing a complex process, a smartphone send commands such as measuring distance and moving robot to Arduino MEGA through the Bluetooth connection.

Four ultrasonic sensors are attached to a servo motor for measurement update of particle filters. The servo motor rotates from 0 to 90 degree with 30 degree interval as shown in Fig. 5. Thereby, it is possible to cover 360 degree. This reduces the scanning time as well as the number of sensors. The number of sensors may be reduced but the scanning time will be increased, and vice versa. The servo motor rotates in 30 degree interval. Twelve distance values from four ultrasonic sensors are obtained. Each sensor reads three times on one scanning session. 30 degree was chosen to reduce interference from neighboring sensors emitting ultra sound.

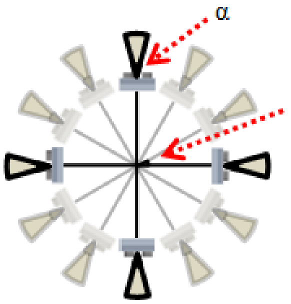


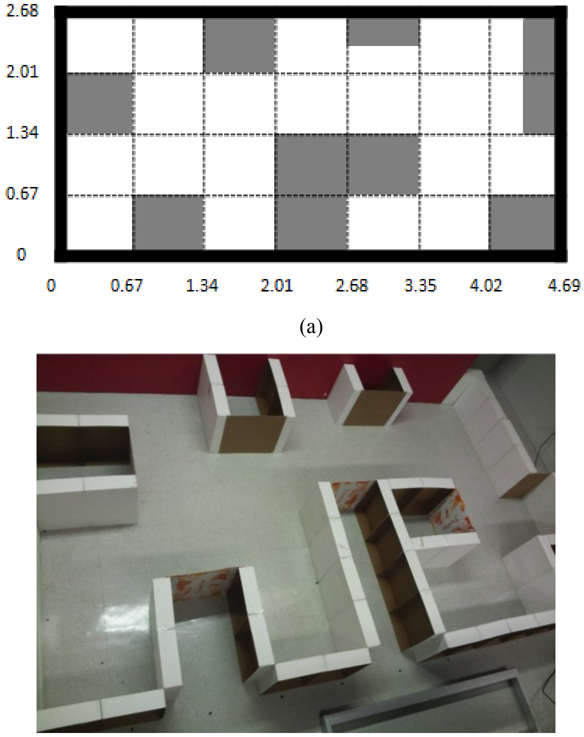
Figure 5. Four ultrasonic sensors are used with one servo motor for particle filter. Each sensor measures distance frome 0 degree to 90 degree with 30 degree interval. $\alpha = 30°$ and $\beta = 30°$

When an ultrasonic sensor does not receive its own reflected sound signal after emitting sonar beam, the sensor reading is absolutely not reliable. In this case we exclude it from measurement data. The reason is that these wrong readings will disturb the particle re-sampling process since the weight of a particle is calculated based on the difference between actual sensor readings and the map data.

The robot cannot identify its location with high certainty in early steps since the probability of the location is evenly spread in state-space. We used variance of particles (*x*, *y*, *theta*) as a threshold to determine a moment when localization is reliable enough to adjust the robot's location. The experimental results will be presented in the following section

IV. EXPERIMENTAL RESULTS

Our approaches described above have been implemented and validated using a mobile robotic platform with a smartphone and a rotating ultrasonic sensor package.

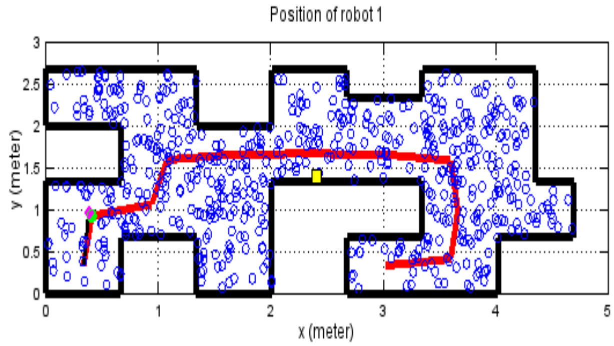


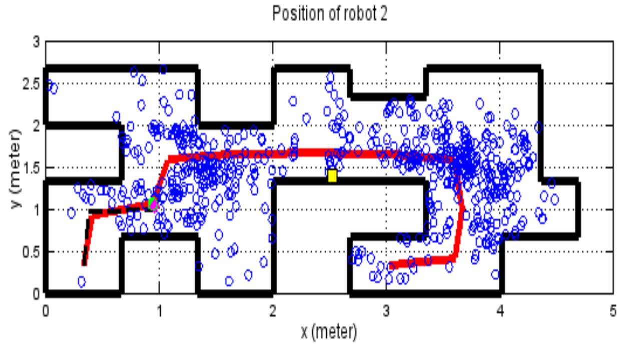
(a)

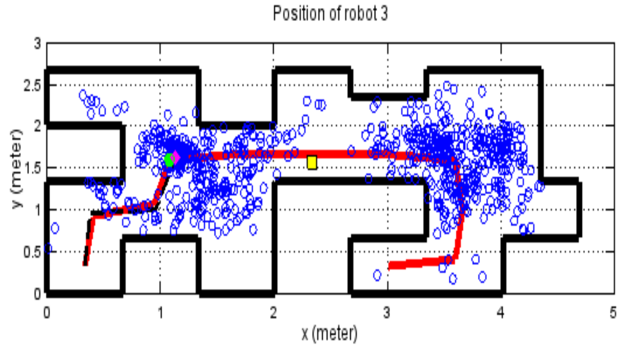
(b)

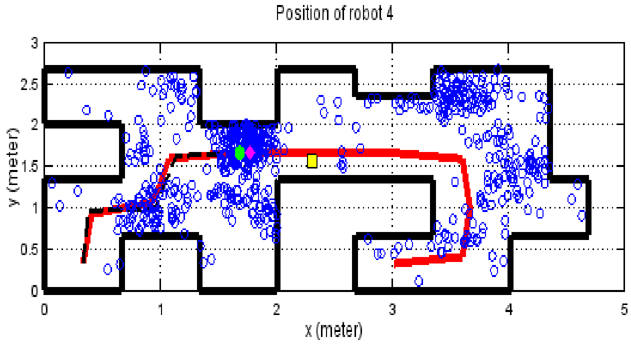
Figure 6. Map environment for navigating and localizign our mobile robot. Each size of gird is 0.67m by 0.67m. (a) occupancy grid map (b) the actual environment.

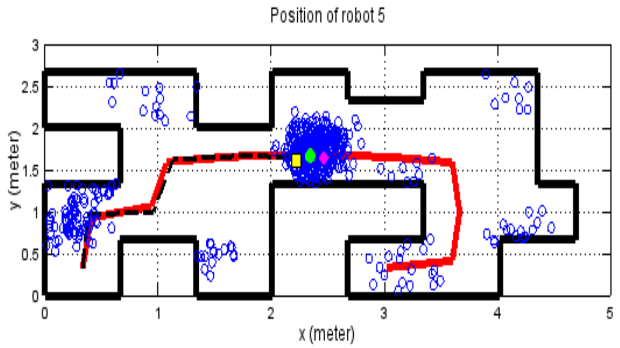
A two-dimensional occupancy gird map generated for the particle filters is shown in Fig. 6. The size of the environment is 4.69m by 2.68m. Fig. 7 shows that our mobile robot smoothly navigates to the goal point in the shortest path and localizes its own position using particle filter. If variances of particles are smaller than threshold (0.1) then we can conclude that most particles are gathered into one cluster. This mean the robot has high certainty on its location. A number of particles are spread in the map as shown in Fig. 7 position of robot 1. Four ultrasonic sensors equipped with servo motor read twelve distance values for measurement update. After motion and measurements update, each particle has different weight by re-sampling. All particles converge one cluster through the iteration of motion and measurement update. As a result, our mobile robot can safely reach to the goal position by continuous localization.

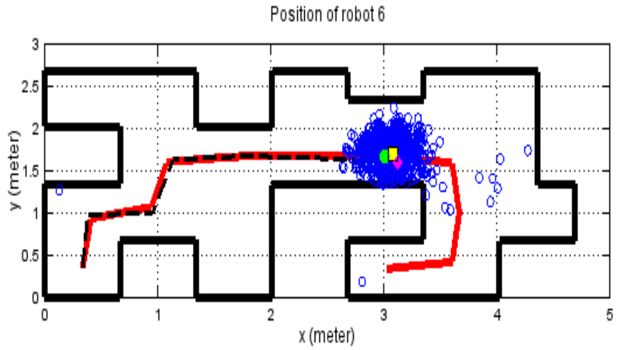

Position of robot 1

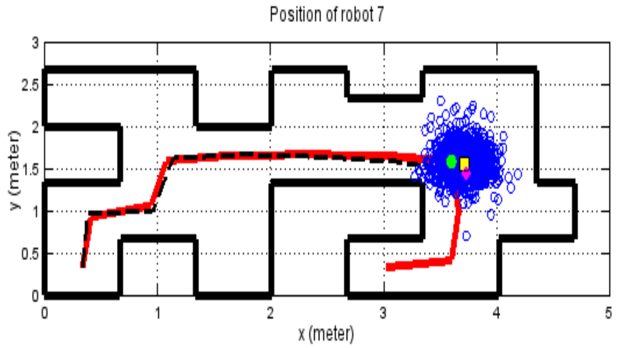

Position of robot 2

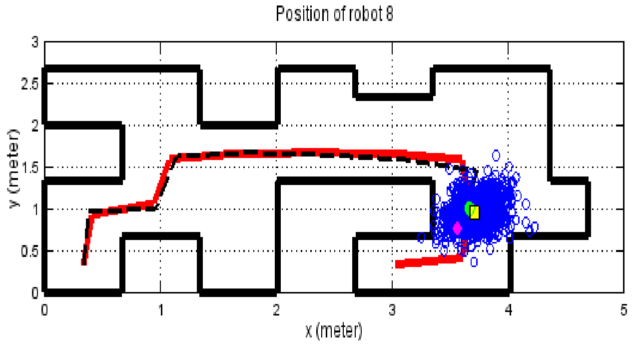

Position of robot 3

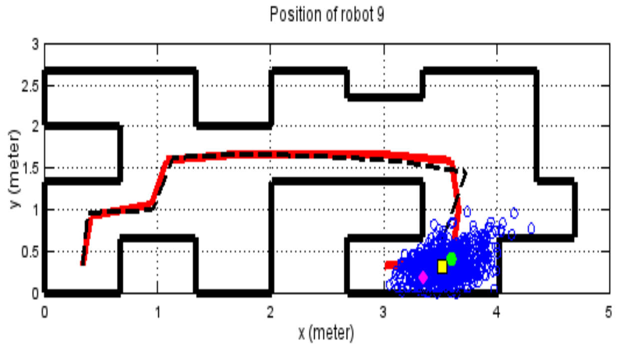

Position of robot 4


Position of robot 5


Position of robot 6


Position of robot 7


Position of robot 8


Position of robot 9

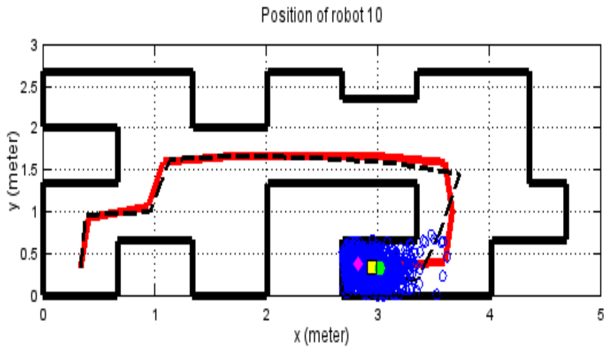
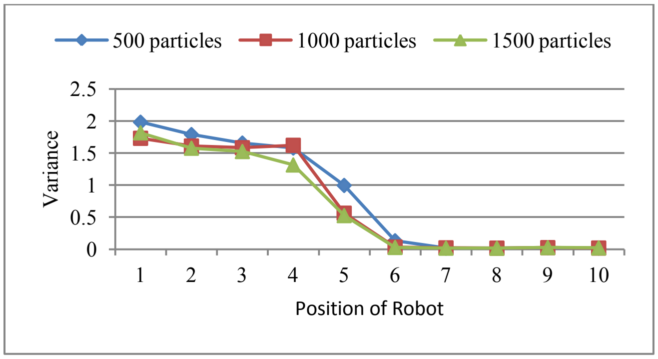


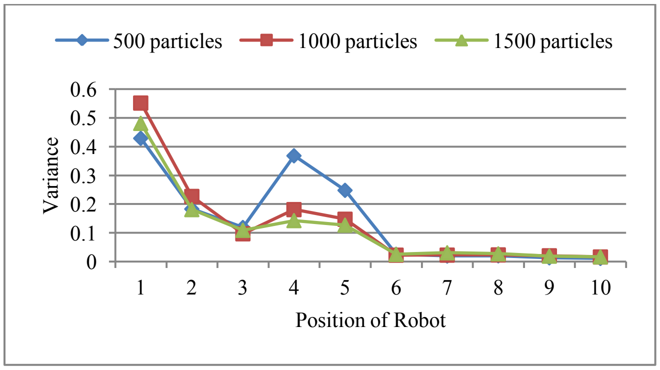
Figure 7. Experimental results of mobile robot localization using particle filter by ranmdom action. The bold red line and black dashed line are the true trajectory and acutual robot trajectory. Particles(blue circles), ideal position(green circle), acutual robot position (magenta diamond), and robot postion prediced by particles(yellow square)

V. DISCUSSION

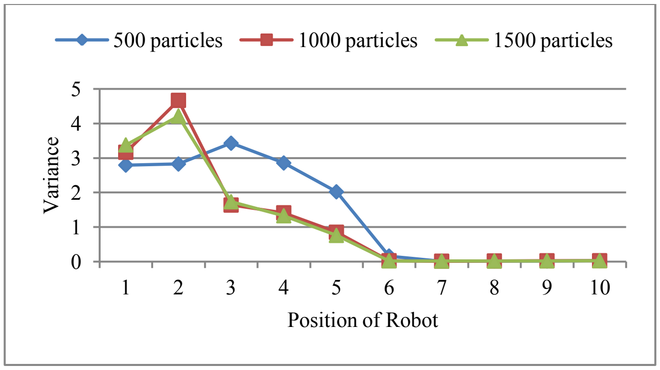
To determine an optimal number of particles we conducted experiments in three different environmental setups in which we used three different numbers of particles: 500, 1000, and 1500 particles. The experiment results show that the more particles the robot uses the quicker convergence to the threshold the robot can achieve (See Fig. 8). The result means that the robot can localize its own position in an earlier position, if more particles were used. But with more particles more computations are required to process the particles. According to these experiments in the environment that we prepared we can conclude that 1000 particles is a good choice since there is no significant difference between using 1000 and 1500 particles in terms of performance.



(a)



(b)



(c)

Figure 8. Variance of particles(x, y, theta) in each position using 500(blue diamond), 1000(red square), 1500 particles(green triangle). (a)variance of x-coordinate, (b)variance of y-coordinate, and (c)variance of theta

VI. CONCLUSION

In this paper we introduce a method of indoor localization and navigation for a mobile robot equipped with rotating ultrasonic range sensors as a measurement tool using a smartphone as the robot brain. The proposed approaches were validated by corresponding experimental results. By rotating ultrasonic range sensor package we were able to reduce the scanning time and the number of required sensors. We also proposed to use a smartphone as the robot's brain in which all heavy-duty computations are executed. We believe that the design of the proposed mobile robot with a rotating ultrasonic sensor package using a smartphone can be widely used in indoor autonomous mobile robot. We expect more affordable service robots can be developed with the proposed design.

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