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COMBINATION OF LOCALIZATION TECHNIQUES FOR MOBILE SENSOR NETWORK FOR PRECISE LOCALIZATION*

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Abstract. A precise localization is required in order to maximize the usage of Mobile Sensor Network. As well, mobile robots also need a precise localization mechanism for the same reason. In this paper, we showed a combination of various localization mechanisms for precise localization in three different levels. Localization can be classified in three big categories: wide area and long distance localization with low accuracy, medium area and distance localization with medium accuracy, and small area short distance localization with high accuracy. In order to present localization methods, traditional map building technologies such as grid maps or topological maps can be used. We implemented mobile sensor vehicles and composed mobile sensor network with three levels of localization techniques. Each mobile sensor vehicles act as a mobile sensor node with the facilities such as autonomous driving, obstacle detection and avoidance, map building, communication via wireless network, image processing, extensibility of multiple heterogeneous sensors, and so on. For localization, each mobile sensor vehicle has abilities of the location awareness by mobility trajectory based localization, RSSI based localization and computer vision based localization. With this set of mobile sensor network, we have the possibility to demonstrate various localization mechanisms and their effectiveness. In this paper, the result of computer vision based localization, sensor mobility trail based localization and RSSI based localization will be presented.

Key words: localization, mobile sensor network, RSSI, dead-reckoning, computer vision

1. Introduction. The researches on Mobile Sensor Network (MSN) have been plenty worldwide. For MSN, there could be a lot of valuable application with attached sensors as well as capabilities such as locomotion, environmental information sensing, dead-reckoning, and so on. For such applications, usual requirements have been acknowledged with localization of each sensor node and formation of the whole sensor network. In this research we are going to discuss about localization techniques for Mobile Sensor Vehicle (MSV) which can compose MSN. In addition, we will discuss a construction of MSN as well as required functionalities of each MSN. For the precise localization we may analyze human actions for localization. For long distance and huge area localization, humans call to their counterpart and identify counterpart's location by talking each other. From the conversation, only a rough location can be identified. Thus we guess long distance localization only allows rough, inaccurate information of location but it is sufficient to confine a region for more precise localization. For medium distance and medium area localization, human moves by transportation methods but eventually walks in order to localize. While walking, humans build a conceptual map for the local geographic information or they already have knowledge around the area, i. e. they already built maps. This sort of medium distance localization requires relatively more precise localization information than long distance localization as precise as, at least, for walking, i. e. autonomous driving.

For short distance and small area localization, humans detect counterparts by use of visual or aural information, i. e. they find their friends by their eyes. This sort of localization deduces precise information than other two sort of localization.

Thus, we can conclude and mimic the human localization with mobile sensor networks. Even though it depends on techniques and environments of the usage of MSN, we can categorize the localization technique according to its area or distance.

There have been variety forms of Mobile Sensor Nodes which utilizes various techniques of localizations such as RSSI, GPS, Raider, Laser, Camera, and so on [1] [2]. One of the most prominent one, an RSSI based localization, usually measures radio signal strength and it works well with popular network devices. Moreover, an 802.11 device based software approach can be realize easily as we did in this paper. However, RSSI method is prone to be fragile with a presence of obstacles or so which will diminish or attenuate radio signal strength. In a short distance, RSSI signals usually is too high that nullify accurate localization thus it is good for long distance, low accurate localization.

By mimicking human actions for localization we can choose RSSI for mobile sensors while wireless telephones for human and trajectory based tracking, so called INS (Inertial Nautical System), as human walking. Of course, map building techniques are required for MSV as well as humans. For human visual localization, we can choose

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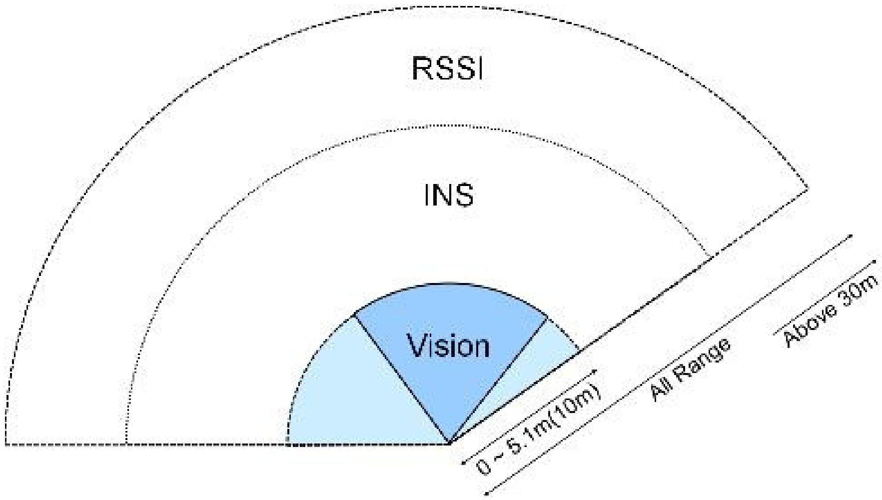

Fig. 1.1. *Categorization of Localization Techniques*

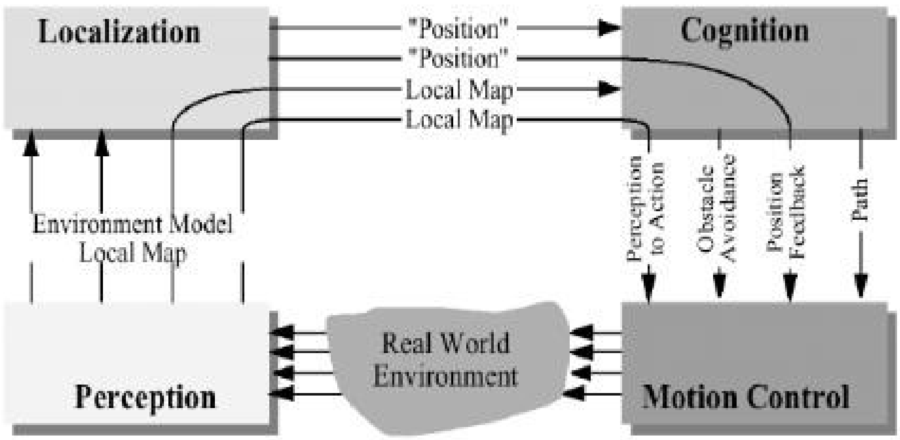

Fig. 1.2. *Relative Techniques for Localization*

a localization technique based on computer vision. Thus we conclude and categorize localization techniques in three big categories as shown in figure 1.1 so that we can choose proper localization mechanisms for its usage.

And in order to fulfill the localization, not only localization techniques but also techniques of cognition, motion control, and perception are tightly related as shown in figure 1.2. We must express idea of this paper in terms of these concepts of cognition, motion control, perception and localization.

This paper is organized as follows. In section 2 we will discuss localization method that have been researched. The following section 3 we will analyze the requirement for MSV, the hardware design of MSV, and equipments for localization, and we will discuss software capabilities of MSV software and will show software components to fully control our MSV including software for MSN itself, monitoring program, map building features, and other related topics. Then section 4 will shows the approaches of computer vision based localization for small area, short distance precise localization. In section 5, our approach and methodology for mobility trajectory based localization for medium distance localization will be discussed. In Section 6 RSSI (Radio Signal Strength Identification) based localization will be presented based on 802.11 devices with software modification. Finally section 7 will conclude this paper with possible future research topics.

2. Related Works. There have been a lot of researches regarding mobile sensor localization. In this section, we will discuss past researches and our idea concentrating techniques with RSSI, vision and trajectory-tracking. This works are not restricted on mobile sensors only but also related to robot technology.

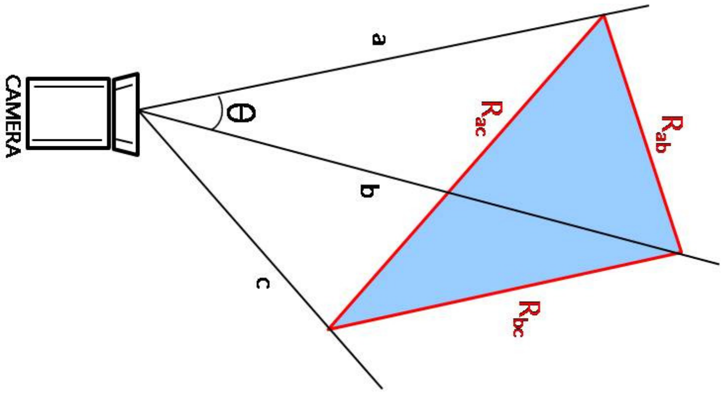

FIG. 2.1. *Calculation of distance from Camera Lens to Vertex of triangle ABC*

2.1. RSSI based Localization. Radio Signal Strength Identification is one of the known solutions for distance measure. It requires wireless network device for mobile sensors and extra features.

We use 802. 11 network devices which have wide popularity. In addition we need communication between mobile sensors thus 802.11 networking devices are popular solutions for us. RSSI features for 802.11 device networks are required features in order to implement physical layer of CSMA/CA networking [14]. However RSSI based distance measure is very prone to radio signal attenuation and thus has low accuracy. And it has some restriction that once it is a data transfer modes, it cannot switched to API mode instantly. It implies the restricted realtimeness for RSSI based localization. Manufactures of 802.11 devices usually provide their arbitrary method for RSSI [11]. In this paper, we will demonstrate our MSV successfully does long distance, low accurate localization only with commercial 802.11 devices and networking software embedded on MSVs.

2.2. Computer Vision based Approach. There are very few researches on localizations by use of computer vision technology. There have been the previous results regarding mobile sensor vehicle control, obstacle detection and so on.

Matsummoto et al. [15] used multiple cameras in order to control mobile robots. In their research, cameras are installed on their working space instead of mobile vehicle itself. Their whole system is consisted of mobile robots and multiple cameras and this helps the search of proper path of robots. Keyes et al. [16] researched various camera options such as lens type, camera type, camera locations and so on. They also used multiple cameras to obtain more precise information.

In this paper we will provide MSV with multiple cameras in order to accomplish short distance, high accurate localization. However, a single MSV cannot locate its location precisely. The ultimate localization can only be done with the cooperation of nodes in MSN.

The first requirement for localization is to identify the location of colleague MSV as a base point. For this purpose, we prepared three facilities for each MSV. Each MSV can estimate its location by trajectory trail. Moreover, each MSV can identify other colleague MSV with their infrared LED signal. In addition, this location information can be communicated by wireless network device equipped with each MSV.

Of course, a camera or a set of cameras are installed on an MSV in order to identify colleague MSVs. This set of cameras has infrared filters in order to diminish the effect of extra light noise in operating environment.

2.2.1. Location Determination Problem. With a set of camera, the required information for localization is collected from the view of cameras. For example, an infrared LED light can be a parameter to calculate the colleague's location. In this research, we applied two previous results. The first one is Sample Consensus(RANSAC) Method [5] and the second one is PnP Method [6] [7].

For RANSAC method, because of least square method, there is no possibility of wrong computation with gross error value. This is the major reason why we applied RANSAC method. In order to solve the problem of converting 3-dimensional view to 2-dimensional camera image, which has lost distance problem, we applied perspective-3-point (P3P) problem.

Figure 2.1 shows the basic principle of P3P problem. The gray triangle is composed by infrared LED installed on each MSV. Points A, B, C stand for each infrared LEDs and these vertices compose a triangle. The distance R_{ab}, R_{bc}, R_{ac} is known constants. From figure 2.1 we can drive the following very well-known

Fig. 3.1. *Driving Mechanism Outlook*

mathematical equation as shown in equation 2.1. The equation 2.1 is in closed form. The number of solutions from these equations will be up to eight. However, there are up to four positive roots.

$$
\begin{aligned}
{R_{ab}}^2 &= a^2 + b^2 - 2ab \cdot \cos\theta_{ab} \\
{R_{ac}}^2 &= a^2 + c^2 - 2ac \cdot \cos\theta_{ac} \\
{R_{bc}}^2 &= b^2 + c^2 - 2bc \cdot \cos\theta_{bc}
\end{aligned} \tag{2.1}
$$

With this P3P based method, we can only measure distances between observer and observed. For precise localization, we must identify angle of MSVs as well. Our MSV is equipped with digital compass in order to identify the angle of MSV based on magnetic poles. As predicted, digital compass also has its own error in angle measurement but is tolerable.

2.3. Autonomous Driving Robot and Dead-Reckoning. This sort of localization is usually due to military area. For example DARPA, USA invests on unmanned vehicle, and their aim is about 30% of army vehicle without human on board controller. Stanley by Stanford university [17], which earned first prize in competitions, are equipped with GPS, 6 DOF gyroscope and can calculate the speed of driving wheels. Those sensors information can be combined to locate the position of their unmanned vehicle. They used computer vision system with stereo camera and single camera, and laser distance meter, radar in order to get environmental information. Sandstorm from CMU [18] is equipped with laser distance meter as a major sensor. Topographical model can be obtained by laser lines and the speed of car can be calculated by the density of laser line. Gimbal on their vehicle can install long distance laser scanner with seven laser sensors. Shoulder-mounted sensors can calculate height information of topography. Two scanners on bumpers can obtain obstacle information. Long distance obstacles can be identified by radar.

Our MSV are equipped with RSSI devices, stereo cameras and other sensors for dead-reckoning. Apart from the examples of locomotive robots, these equipments are for accurate localization.

3. Mobile Sensor Vehicle. We developed MSV in order to experiment our localization method in real environment. Various versions of MSV are designed and implemented. The localization functions implemented on MSV are as follows:

- Long distance low accuracy localization by RSSI
- Medium distance medium accuracy localization by dead-reckoning tracking
- Short distance high accuracy localization by Stereo camera with computer vision.

In the following subsection we will discuss hardware and software of MSV respectively.

3.1. Hardware. MSV is actually a mobile sensor node for MSN. Each MSV can move autonomously and can identify obstacles. They can communicate each other by 802.11 networking devices. The chassis of MSV are composed of aluminum composite with high durability and lightweight. The main driving mechanism

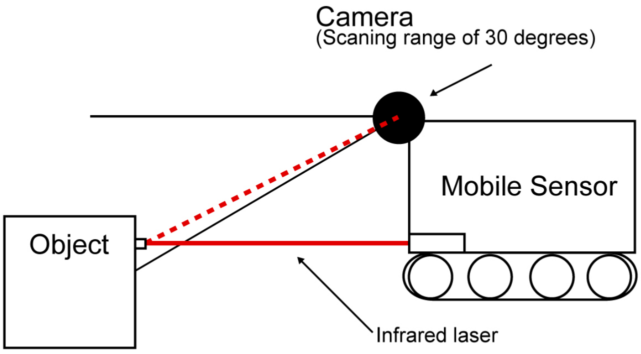

Fig. 3.2. *Obstacle Detection Mechanism*

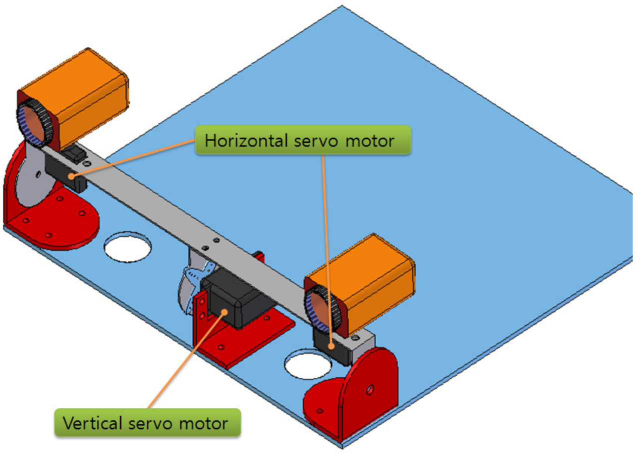

Fig. 3.3. *Stereo Eye System*

is caterpillar composed of three wheels, L-type rubber belt, gears as shown in figure 3.1. The adoption of caterpillar is for minimization of driving errors. There are a lot of rooms to install additional sensor hardware. With digital compass equipped on the top of MSV, the accurate vehicle location can be sensed. This angular information can help exact localization of MSVs. The design concepts of MSV are as follows.

- Autonomous mobility
- Extensibility of equipped sensors
- Precise movement and mobility trail

And MSV characteristics as a node of mobile sensor network are as follows:

- Self identification and colleague identification with various methods
- Wireless communication
- Digital Compass

For autonomous driving, MSV must identify obstacles and avoid them. We use an infrared laser and cameras with infrared filter. IR laser is constantly lighting in parallel to round. Camera looks down grounds in a degree of 30 which is determined by experiments. The concept of this obstacle detection is depicted in figure 3.2. Obstacle reflects IR laser and sensed by camera [5, 7]. The obstacles with reflected IR will be detected as white lines. This obstacle detection will be used by local map building as shown in section 5.1.

For short distance obstacles within the dead angle of camera, ultrasonic sensors are located under the MSV and in front of MSV. For computer vision based localization, MSVs are equipped with stereo eyes as shown in figure 3.3. Three servo motors can control two cameras independently. This stereo camera system can be used not only for localization but also for obstacle detection with diminished dead angle. There are three infrared LEDs mounted in the front of MSV. These LEDs are for computer vision based localization.

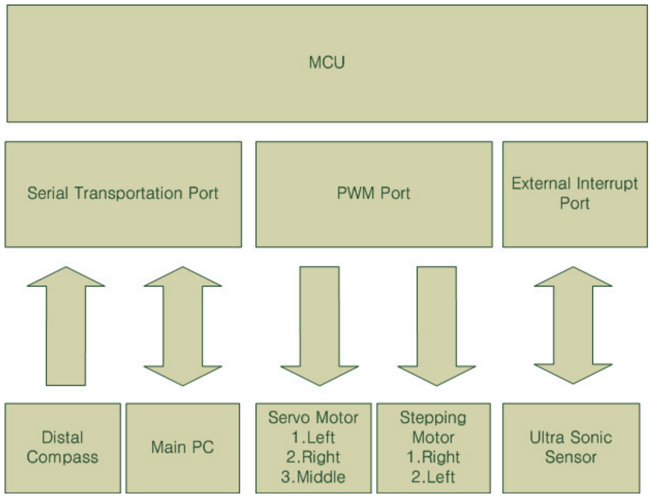

FIG. 3.4. *Hardware Structure*

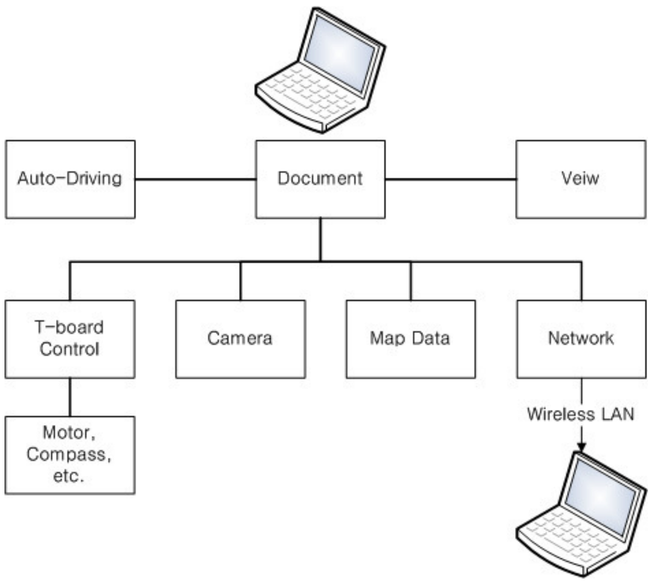

FIG. 3.5. *Software Structure*

For hardware construction, we need micro controller unit, a serial communication port, a PWM port, an interrupt port in order to control motors and communicate with sensors. Figure 3.4 shows the conceptual structure of MSV hardware.

3.2. Software. Software for MSV operations is required in a form of embedded software. Figure 3.5 shows required facility and their structure for MSV software.

Total part of software can be divided into five categories. One of the roles of software is to convert sensor information into driving information. Information for driving can be obtained via serial communication from T-board (MCU) with driving information and angular information.

The location of MSV is constantly updated with the moving distance and updated angle. Camera class provides obstacle information as well as basic information for map building. Map building class builds a map with the information from T-board class and camera class. These maps are required for autonomous locomotion and localization. Network class provides networking functionalities between MSVs.

We implement core software based on multi threads. There is document class, which provides organic data flow between classes. Thus the major role of MSV software is as follows.

- Autonomous driving
- Motor control and driving distance identification

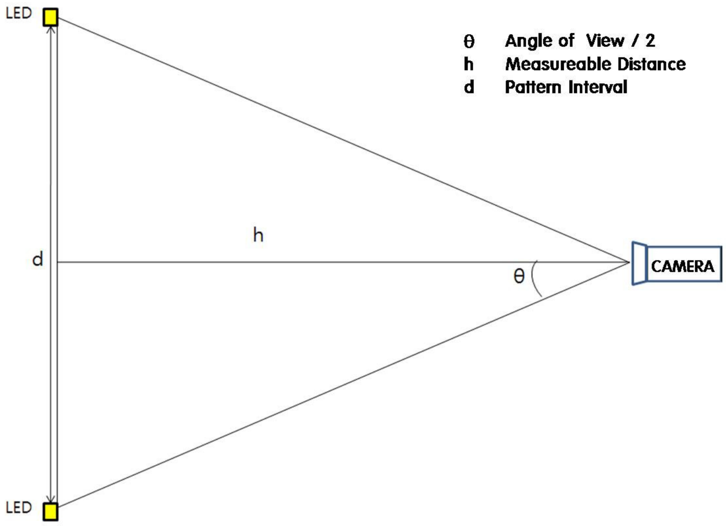

Fig. 4.1. *Correlation of LED pattern interval and measurable minimum distance*

Fig. 4.2. *Frond view of MSV*

- Communication with MCU (T-board)
- Obstacle detection
- Map building
- Internetworking
- User interface dialog (Monitoring Program)

Monitoring program is a user interface between MSV and user. Monitoring program shows MSV condition, camera view, driving information, map built, and other sensor information. It also provides manual operation functionality of MSV.

4. Computer Vision based Accurate Localization.

4.1. Sensor Equipment and Experimental Environment. Each MSV has a set of Infrared LED (IR-LED) in a form of triangle and the lengths of edges are all 30 centimeters. The IR lights from these LEDs can be viewed by stereo camera system from other colleague MSV. The stereo eye system as shown in figure 3.3 has two cameras. Three servo motors controls two stereo eyes vertically and horizontally.

TABLE 4.1
IR-LED specifications

MODEL NO.	Half Angle	Peak Wavelegnth
SI5315-H	$\pm 30°$	950nm
OPE5685	$\pm 22°$	850nm
OPE5194WK	$\pm 10°$	940nm
TLN201	$\pm 7°$	880nm
EL-1KL5	$\pm 5°$	940nm

The stereo cameras are equipped with IR filters. The front view of MSV for these equipments is as shown in figure 4.2. Three IR-LEDs forms a triangle and a stereo camera system are also presented.

With fixed length of triangle edges, i. e. interval between IR-LED, is fixed by 30 centimeters. Therefore by using P3P method, the distance between camera and MSVs with IR-LED triangle can be calculated. Embedded software for each MSV has a realtime part for P3P solution. The software also shows the image from stereo camera as a part of P3P solution.

The ideal situation starts by estimating the angle between two cameras. Once camera direction is fixed, we can estimate angles between tracked object and cameras, however, MSV can move every direction which causes difficulties to measure that angle. Moreover, if these cameras have pan-tilt functionalities, it is impossible to measure such an angle in real time.

Another method with P3P technique is to assume the distance to the object. The distance to object and the scale of triangle in camera view is proportional inversely thus the size of LED triangle can be a starting point to estimate the distance to obstacles. We decided to standardize the reduced scale of LED triangle in order to estimate distance to objects. The basic concept of this method is depicted in figure 4.1 and will be discussed further in the subsection 4.3.

This approach has limits of camera visibility, i. e. objects beyond visibility cannot be identified. However, two other localization methods will be presented in the following sections for beyond sight localization. In addition with the help of digital compass, we can measure the direction of each MSV. The combination of this information can achieve short distance accuracy for localization.

4.2. Preliminary Experiment for Equipment Setup. We conduct preliminary experiment in order to choose optimal device for computer vision based localization. The first purpose of this experiment is to select the best LED in order to increase the range of localization. Our past result showed 250 centimeter of localization range however our aim is to enlarge the range to 400 centimeters or farther.

We choose five infrared light emitting diodes with typical characteristics. We first concentrated on the visible angle of LED lights since we assumed wider visible angle guarantees the clearer identification of LED light and more precise localization.

Table 4.1 shows the specifications of various IR-LEDs with visible angle and peak wavelength. The major reason why we choose those IR-LEDs are as follows:

- Smaller half angle of LED enables long distance tracking however increases invisibility from the side.
- Larger half angle of LED enables tracking from the side however decreases tracking distance.

With infrared filter equipped cameras we planned experiments to evaluate the LEDs for vision based localization. Table 4.2 show the result of visible distance and visibility of IR-LEDs. Twelve experiments have been made and average values are shown. From the specifications of IR-LEDs, 5 volts DC voltage is supplied for the experiment.

Among five IR-LEDs, two showed stable visibility and acceptable visibility distance. Between these two candidates, we finally choose the best LED of MODEL NO.SI5313-H since it has the widest half angle as well with reasonable visibility distance.

4.3. Main Experiments for Computer Vision based Localization. Figure 4.1 shows the relationship between LED triangle size (d) and distance from camera to LED triangle (h). The relation between d and h

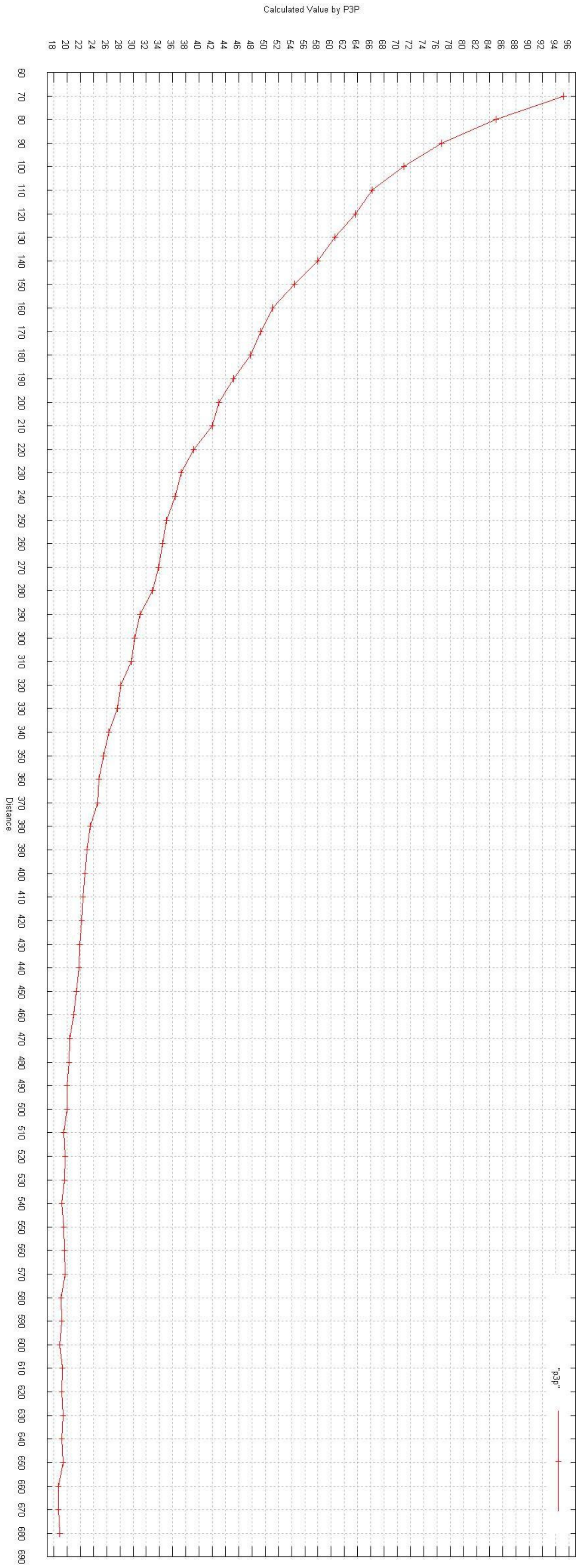

Fig. 4.3. *Relative size of triangle calculated by P3P on actual distance*

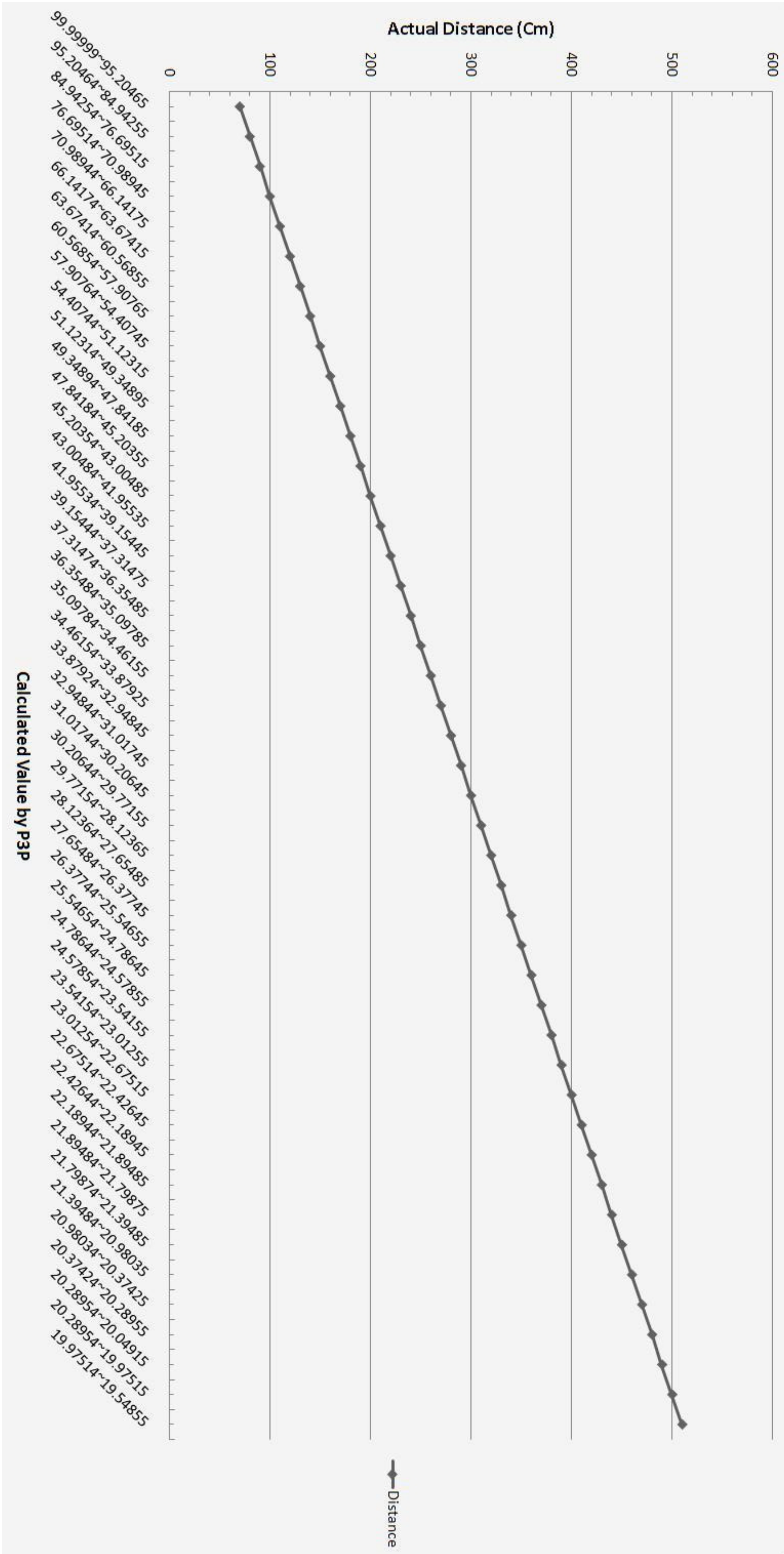

Fig. 4.4. *Actual distance calculated from measured relative distance*

Table 4.2
IR-LED Visibility Experiments

MODEL NO.	Max Length	Visible Angle	Visibility
SI5315-H	500cm	±60°	Stable
OPE5685	490cm	±45°	Somewhat Unstable
OPE5194WK	520cm	±35°	Most Stable
TLN201	510cm	±20°	Unstable
EL-1KL5	450cm	±10°	Indiscriminable

can be directly drawn from the following equation 4.1

$$\tan\theta = \frac{d}{2h}$$
$$\theta = \arctan\frac{d}{2h} \tag{4.1}$$

Most of cameras has angle of view in $54° \sim 60°$. Since we used camera with angle of view in 60°, from the equation 4.1 we can solve ratio about $h : d = 1 : 1.08$. The actual value of d is 30 centimeter for our experiment.

Thus we can summarize the following:

- High angle of view camera can increase minimum measure distance.
- With narrow LED pattern interval, we can decrease actual distance h but practically meaningless.
- With wider LED pattern interval, we can increase actual distance but dependent on MSV size.

From the experiments, we can identify the vision based localization is effective within the range from 30 centimeters to 520 centimeters with our LogiTech CAM camera. The 30 centimeter lower bound is due to the 30 centimeter interval of LED triangle edges. The 520 centimeter upper bound is due to the visible sight capability of LogiTech CAM camera. Thus 520 centimeter would be a maximum distance of computer vision based localization. However it is still meaningful since we can achieve very high accuracy in localization with these cheap, low grade cameras. The other idea for more localization distance is to use cameras with higher resolution.

From our experiments, we identified the correlation between actual distance from camera to colleague MSV and size of LED triangles in camera view. The results can be translated into graphical form as shown in figure 4.3.

From figure 4.3 the result shows the fluctuation of results with more than 500 centimeters which makes localization unstable. For applications which require the error range of 20 centimeters, we can use the results to 520 centimeters. Since our aim is to keep localization errors within the range of 10 centimeters, we decided to discard results more than 400 centimeters.

4.4. Experimental Result. From our experiment in the previous subsections we will provide the final result of computer vision based localization in this subsection. Figure 4.4 shows graphical version of final result.

Apart from the results in previous section, this figure shows actual distance up to 500 centimeters. From figure 4.3 we can observe errors in calculated values of P3P for more than 500 centimeter distance. These errors is due to the resolution limit of CAM camera which is 640×480. Even a small noise can vary actual distance of ten centimeters in the distance more than 500 centimeters.

Thus we conclude the accurate localization by computer vision can be done in the range of 70 centimeters to 500 centimeters with our camera equipments. For the localization in more than 500 centimeters, localization based on MSV trajectory tracking will be effective. In addition, for the localization in more than 30 meters, localization based on RSSI will be effective 6. Of course, the location information can be broadcasted and be used by the members of MSN in order to build maps, to correct location errors and so on.

5. Mobility Trail based Localization.

5.1. Map Building. Map building is one of the core parts of medium distance localization as well as for other distances and areas. The result of localization must be presented on local map and therefore be

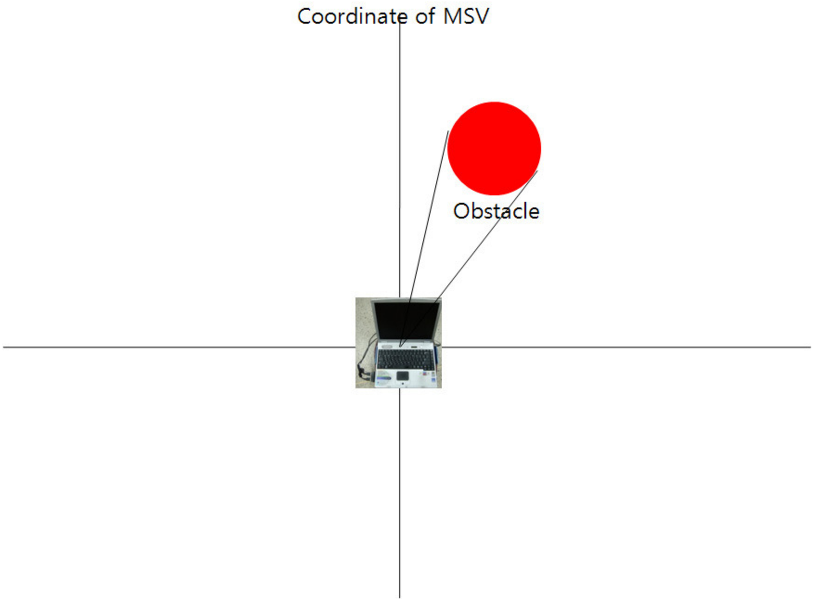

Fig. 5.1. *Relative Coordinate*

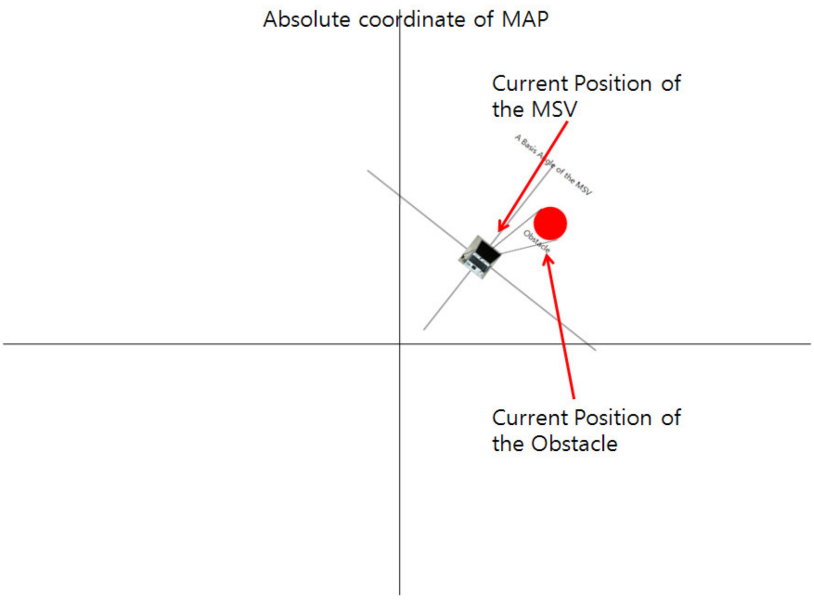

Fig. 5.2. *Absolute Coordinate*

transferred to global map. MSVs communicate with each other in order to combine local maps into global maps. The following information will be shown on a map.

- Untapped territory
- Territory with obstacle
- Territory with MSV
- Tapped territory
- Totally unknown territory

For map building we must consider relative coordinate and absolute coordinate. For example, obstacle information identified by MSV is in a form of relative coordinate. In relative coordinates, the very front of MSV is in angle 0 as shown in figure 5.1. This coordinate must be transformed into absolute coordinate as shown in figure 5.2 and therefore can be a part of map.

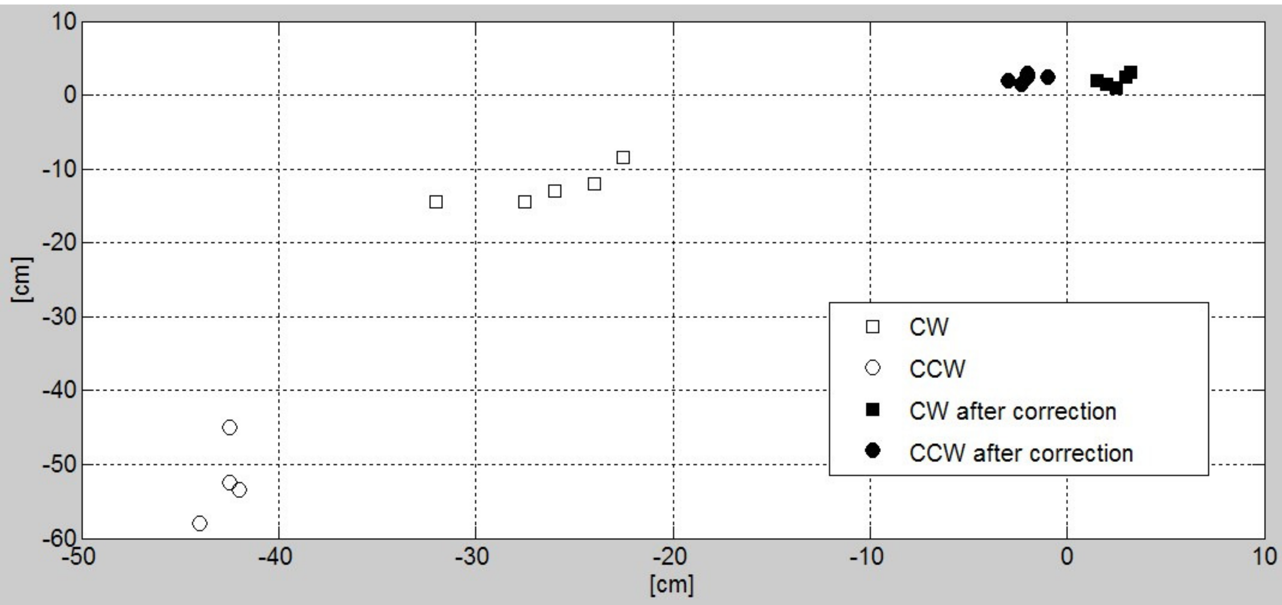

FIG. 5.3. *Result of UMBmark*

TABLE 5.1
COMPARISON BETWEEN GRID MAP AND TOPOLOGICAL MAP

MAPS	Grid MAP	Topological MAP
Advs.	Precise presentation of geography of environment Ease of algorithm design: environmental modeling, path finding, localization by map-matching	Simple presentation of environment and simple path planning Tolerance of low accuracy mobile sensors Natural interface to users
Disadvs.	Difficulty in path planning Requirement of large memory and computation Poor interface to symbolic problem solver	Impossibility of large map building with inaccurate, partial information Difficulties in map-matching: difficulties in calculation of pivot sensor value Difficulties in dealing complex environment

Local map is usually in a form of grid map. However in case of global map with huge capacities, grid map is very inefficient. Therefore we will use topological map for global map as presented by Kuipers and Bynn [6]. Thrun [8] presented a hybrid approach of both maps and we will consider it as our ultimate format of global map. Table 5.1 compares advantages and disadvantages of grid and topological map.

With mobility trajectory tracking, medium range localization can be implemented by use of local map. Each MSV moves autonomously and build its own local map. In the following subsection, we will discuss error corrections of mobility tracking based approach which is essential to guarantee the accuracy of localization.

5.2. Dead-Reckoning. For the medium distance localization, we decided to utilize mobility trail. We define the range of medium distance between 4 meters and 40 meters since our vision based short distance localization covers within the range of 5 meters and RSSI based long distance localization is effective outside the range of 30 meters. Our aim is to trail the mobility of MSV and to record the trail on the local map with reasonable accuracy for medium distance localization. Every driving mechanism for mobile sensors or even mobile robots has mechanical errors and it is impossible to avoid such errors practically. We can summarize the cause of driving errors as followings:

- The difference between the sizes of two (left and right) wheels
- The distortion of wheel radius, i. e. the distance between average radius and nominal radius
- The wheel misalignment

- The uncertainty about the effective wheelbase
- The restricted resolution of driving motors (usually step motors)

Usually those errors are cumulated and final result will be void without proper error correction technique. However, in order to cope with those location errors due to mechanical errors, a method of dead-reckoning have been widely used and we also adopt such technique as well. Dead-reckoning is a methodology that calculates the moving distance of two wheels of MSV and derives the relative location from the origin of MSV.

Among the various versions of Dead-reckoning techniques, we used UMBmark technique from University of Michigan [4]. UMBmark analyzes driving mechanism errors and minimized the effect of driving errors. UMBmark analyzes the result of MSV driving in a certain distance and compensates mechanical errors of MSV driving mechanism. The driving results of rectangular course, both in clockwise(CW) and counter-clockwise(CCW), and then analyzed.

Two error characteristics are classified in Rotation angle error and Wheel mismatch error. Rotational angle errors are for the difference between actual wheel sizes and theoretical design sizes of wheels. Due to rotational angle errors, CCW driving after CW driving shows larger errors as usual. For example, actual wheel size bigger than designed wheel size results in insufficient rotation at corners and then rotational angle errors are cumulated for the whole driving. The following equation summarizes the rotational angle error which is depicted in [4].

$$E_d = \frac{D_R}{D_L}$$

where D_R is diameter of left wheel and D_R is diameter of right wheel. In short, E_d is a ration between diameters of left wheel and right wheel.

Wheel mismatch errors are from wheelbase mismatch. This error causes skews in straight driving. With wheel mismatch error, the error characteristic of CW driving is opposite to CCW driving. The following equation summarizes the wheel size error which is depicted in [4].

$$E_b = \frac{90^\circ}{90^\circ - \alpha}$$

where α is a value of rotational angle error. E_b stands for a ration between ideal and practical errors in rotation, i. e. wheel base error.

Mechanical errors are systematical errors and therefore can be predicted and analyzed, while non-mechanical errors cannot be predicted because non-mechanical errors are due to the driving environment. Non-mechanical errors are classified as follows:

- Uneven driving floor or ground
- Unpredicted obstacle on driving course
- Slipping while driving

We applied UMBmark to our MSV and the following subsection shows the result.

5.3. Driving Error Correction of MSV. We composed a set of experiment for MSV driving in order to apply UMBmark. The driving experiments have been made on the flat and usual floor with the rectangular driving course of 4 × 4 meters. As shown in [4] both CW and CCW driving have been made and error values have been measured. These error values are incorporated in our software system and MPU controllers.

With the following equations from [4] we can find the error value for error correction.

$$b_{actual} = E_b \times b_{nominal}$$

where b_{actual} is an actual wheelbase and $b_{nominal}$ is a measured wheelbase.

$$\Delta U_{L,R} = c_{L,R} \times c_m \times N_{L,R}$$

Where U is actual driving distance, N is the number of pulses of the encoder, and c_m is the coefficient to convert pulse per centimeters.

Our experimental result with driving location correction by UMBmark dead-reckoning mechanism is shown in figure 5.3. Circled dotes are result from CCW driving and rectangular dotes are from CW driving. Empty

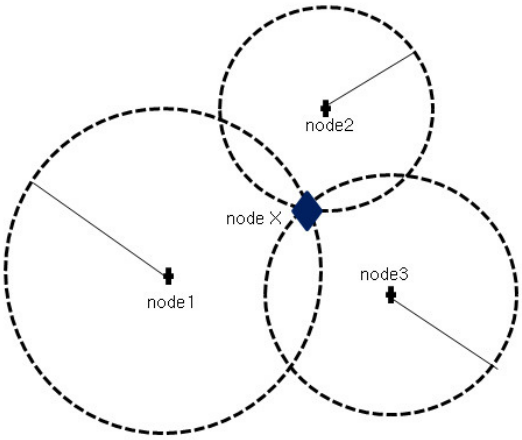

Fig. 5.4. *Triangulation With RSSI Measurement*

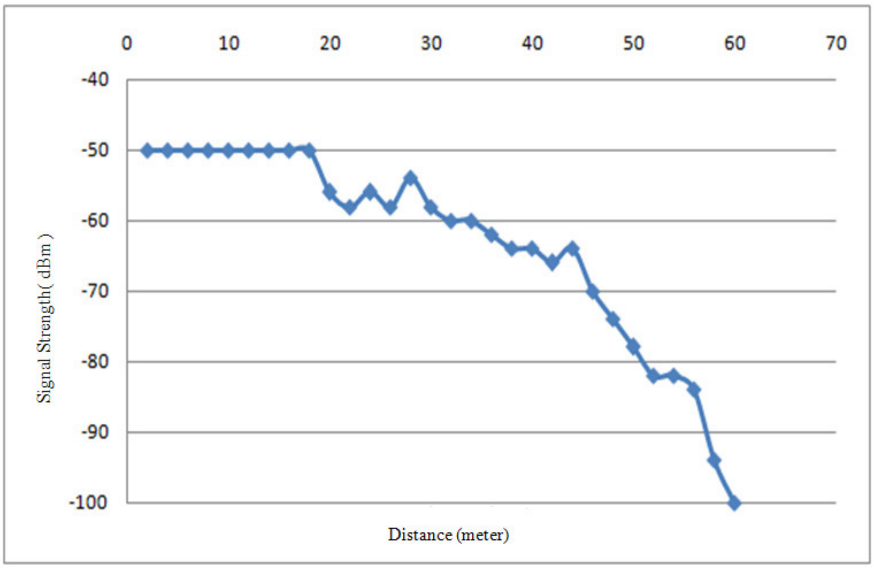

Fig. 5.5. *RSSI values According To Distance*

dotes are of uncorrected driving results while filled dotes are of driving results with UMBmark in 16 meter driving experiment. Note that the origin of MSV (starting point) at the coordinate (0,0) are at the upper right part of the figure. Without dead-reckoning technology, MSV returns to erroneous point than the origin point, at the left part of the figure. This MSV tends to show more errors with CW driving. With the application of UMBmark technique, we achieved faithful result within 10 centimeters of error range in total. Directional errors are within the range of 3 centimeters from the origin. Since our approach is for mechanical driving errors, non-mechanical errors can be avoided and thus we will introduce real-time correction of driving with the help of digital compass for the future researches. Thus it is possible to mention that the trail of MSV is in the correct location within the errors of 10cm in our experimental environments.

6. RSSI based Long Distance and Wide Area Localization. Our MSV are equipped with homogeneous 802.11 networking devices with RSSI facilities. With distance information we can do triangulation with at least three nodes and one anchor. Our monitoring station with monitoring program can act as an anchor. The 802.11 networking devices can be switched to AP (Access Point) mode so that each MSN can act as AP. With software modification that utilizes 802.11 device RSSI features, we can achieve RSSI based localization for our MSN.

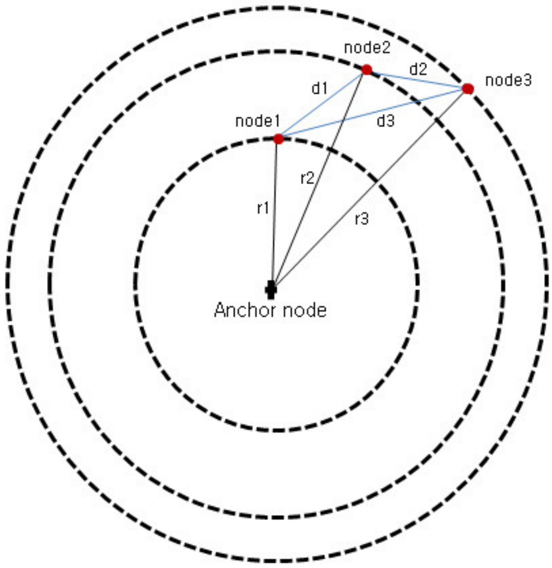

Fig. 5.6. *Relation Between One Fixed Anchor And Mobile Sensor Vehicles*

The unit of RSSI is in dBm (-50dBm $\sim$ -100dBm) and it designates distances between specified MSVs. As already mentioned, the RSSI value is very affective by environments, and we obtain error rate of 10 $\sim$ 15% in specific distance. The RSSI value is very sensitive with hardware vendor and the direction of AP [9]. Our experimental environment is as follows.

- Wide open area
- Intel Wireless LAN 2100 3B Mini PC Adapter
- WRAPI software model [11]
- One fixed anchor as monitoring station

For the calibration of our RSSI device, a set of experiment has been conducted and the results are shown in figure 5.5.

We can find within the distance of 20 meter, RSSI is no more useful for distance measure since the signal strength is too high. Our experiments shows RSSI based localization is useful more than 35m distance. The values are within error range of 15% by experiment. This is the main reason why we choose RSSI based localization for long distance, low accuracy localization.

From the distance information from RSSI sensing, we can do triangulation as shown in figure 5.4. For actual implementation, we have one fixed anchor and can do more precise localization with a known anchor coordinate as shown in figure 5.6. The figures show three mobile nodes one anchor node. The distance obtained from circle $r1, r2, r3$ can be obtained from RSSI values. Thus with this environment we can triangulate the coordinate node X from the intersection of circles drawn by node 1, node 2, and node 3 [12] [13].

Thus from the distance which can be obtained from RSSI values, let the distance be di from radius of circle ri The following algorithm 2 shows a procedure to find coordinates of each MSV with provided distance information by RSSI.

Figure 6.1 shows a final result in RSSI based localization. The x-axis stands for actual distance between MSVs and y-axis shows a distance calculated by algorithm 2. As we predicted the RSSI based localization is useful with the distance more than 30 meters. On the range where RSSI based localization is effective, we can see errors between actual distance and calculated distance. We believe it is tolerable since we have another method of localization with more accuracy within the distance of 30 meters. Of course, the distance information is not a sufficient condition for localization. The other information of direction of MSV can be obtained by digital compass on each MSV. Thus we implemented long distance, low accuracy localization.

Algorithm 2 Localization of Sensor Nodes with RSSI Measurement

```
Input : d1, d2, d3, r1, r2, r3
//Distance d1, d2, d3
//Circle r1, r2, r3
Output :  SolutionList
LinkedList SolutionList
//Mobile Sensor Node Coordinates

for (each (x1,y1) on Circle r1)
{
 for (each (x2,y2) on Circle r2)
 {
  if (d1 ==
    distance between (x1,y1) and (x2,y2))
   {
    for(each (x3,y3) on Circle r3)
    {
     if (d2 ==
      distance between (x2,y2) and (x3,x3))
     {
      if (d3 ==
      distance between (x3,y3) and (x1,y1))
      {
       SolutionList =
        Coordinate (x1,y1),(x2,y2),(x3,y3)
}}}}}}
```

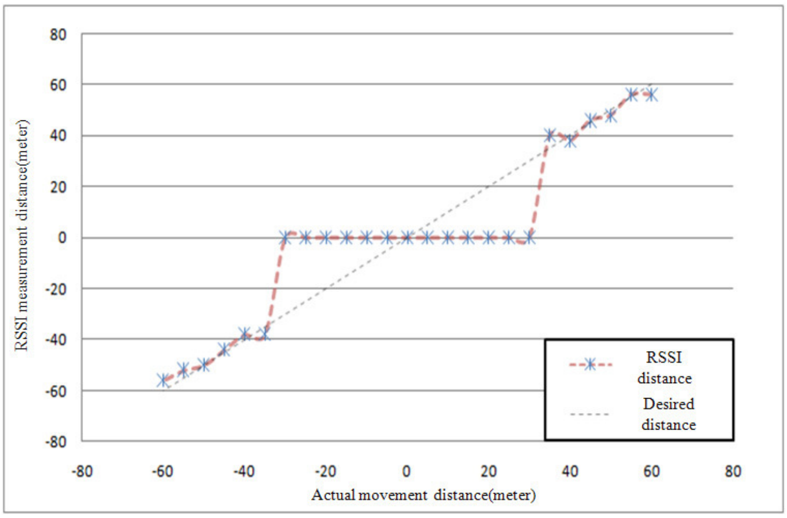

Fig. 6.1. *Actual and RSSI based Distance*

7. Conclusions. Of the localization methodologies for mobile sensor network, we combined three different categories of localization methodology. In addition for the experiment, we implemented mobile sensor vehicle as a node of mobile sensor network. We showed brief description of our mobile sensor vehicle including hardware and software functionalities. A computer vision based approach has been presented for the small area localization with a considerable range of preciseness. The driving mechanism hardware and software cooperate with each other and naturally achieve localization based on trajectory-tracking with the help of local map building, which is a medium distance and medium accuracy localization. The result of localization can be presented on local maps and eventually be merger into global maps. In addition we showed RSSI based localization. The long distance, low accuracy localization can be implemented by commercial 802.11 networking devices only with software but without any other specific hardware device..

From these three levels of localization, we believe that we implemented useful localization system and will do more research using this platform. For example multiple MSV can cooperate and communicate each other and then a formation based on localization can be made. A smooth transition between these localization information for specific environment or application with probability model is our next goal to achieve.

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