A Study on the Implementation of RFID-based Autonomous Navigation System for Robotic Cellular Phone(RCP)

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Abstract: Industrial and economical importance of CP(Cellular Phone) is growing rapidly. Combined with IT technology, CP is currently one of the most attractive technologies for all. However, unless we find a breakthrough to the technology, its growth may slow down soon. RT(Robot Technology) is considered one of the most promising next generation technology. Unlike the industrial robot of the past, today's robots require advanced technologies, such as soft computing, human-friendly interface, interaction technique, speech recognition, object recognition, and many others. In this study, we present a new technological concept named RCP(Robotic Cellular Phone), which combines RT & CP, in the vision of opening a new direction to the advance of CP, IT, and RT all together. RCP consists of 3 sub-modules. They are $RCP^{Mobility}$, $RCP^{Interaction}$, and $RCP^{Integration}$. $\mathrm{RCP}^{\mathrm{Mobility}}$ is the main focus of this paper. It is an autonomous navigation system that combines RT mobility with CP. Through $\mathrm{RCP}^{\mathrm{Mobility}}$, we should be able to provide CP with robotic functionalities such as auto-charging and real-world robotic entertainments. Eventually, CP may become a robotic pet to the human being. $\mathrm{RCP}^{\mathrm{Mobility}}$ consists of various controllers. Two of the main controllers are *trajectory controller* and *self-localization controller*. While Trajectory Controller is responsible for the *wheel-based navigation* of RCP, Self-Localization Controller provides localization information of the moving RCP. With the coordinate information acquired from *RFID-based self-localization controller*, Trajectory Controller refines RCP's movement to achieve better RCP navigations. In this paper, a prototype system we developed for $\mathrm{RCP}^{\mathrm{Mobility}}$ is presented. We describe overall structure of the system and provide experimental results of the RCP navigation.

Keywords: $RCP^{Mobility}$, *wheel-based navigation, trajectory controller, RFID-based self-localization controller*

1. INTRODUCTION

Robotic Cellular Phone(RCP) consists of 3 technological sub-modules called $\mathrm{RCP}^{\mathrm{Mobility}}$, $\mathrm{RCP}^{\mathrm{Interaction}}$, and $\mathrm{RCP}^{\mathrm{Intergration}}$. $\mathrm{RCP}^{\mathrm{Mobility}}$ takes care of human-friendly robotic movements of CP. $\mathrm{RCP}^{\mathrm{Interaction}}$ plays a role of modeling human emotion into the robotic CP. Through $\mathrm{RCP}^{\mathrm{Intergration}}$, these two sub-modules are combined to produce various communication and robot oriented applications. We have developed a prototype of RCP by making it more downsized and intelligent, and reported the work in several articles [1-3]. In this paper, we specifically focus on $\mathrm{RCP}^{\mathrm{Mobility}}$ and report our most recent efforts made for the development of the sub-module. $\mathrm{RCP}^{\mathrm{Mobility}}$ is an autonomous navigation and human-friendly motion system that combines RT mobility with CP. Through $\mathrm{RCP}^{\mathrm{Mobility}}$, we should be able to provide CP with robotic functionalities such as auto-charging and real-world robotic entertainments. With such functionalities, we may open up a possibility of making CP not just a personal communication device of today, but a companion robot to the human-being of the future.

$\mathrm{RCP}^{\mathrm{Mobility}}$ consists of various controllers. Two of the main controllers are trajectory controller and self-localization controller. While trajectory controller is responsible for the wheel-based navigation of RCP, self-localization controller provides coordinate information of the moving RCP. For the robotic movement of RCP, a pair of navigational wheels is installed on RCP. Its movement is controlled by a D.C. operated small size motor. Power needed for the motor is acquired from the CP battery. With the coordinate information acquired from the RFID-based self-localization controller, trajectory controller refines RCP movements to achieve better navigation.

In this study, we describe details on the $\mathrm{RCP}^{\mathrm{Mobility}}$ development. Especially, we suggest and implement a new localization method based on RFID. Using RFID sensing, RCP is now free from the line-of-sight problem that could not be avoided with commonly used sensors such as razor and ultrasonic. More specifically, we describe our implementation of a prototype RCP equipped with a small RFID reader and wheel-based navigation modules. We also provide details on the development of an in-door navigation floor installed with RFID tags which provide coordinate information of RCP during its navigation. We then provide experimental results of the RCP navigation. By analyzing performances of navigations, we also provide a way of determining the effectiveness of various RFID tag arrangements.

2. AUTONOMOUS NAVIGATION OF RCP

For the robotic movement of RCP, a pair of wheels is installed on RCP. Their movements are controlled by a D.C. operated small size motor. Two most important components of the RCP’s autonomous navigational system are trajectory controller and self-localization controller. The former is responsible for guiding RCP along the dynamically generated navigation path, considering many important navigation factors, such as the speed and the current coordinate of the moving RCP. The latter is responsible for generating localization (coordinate) information of the moving RCP by taking advantages of external sensors. Localization information generated by the controller is fed back to trajectory controller, so that it is used to compensate error accumulated during the wheel-based RCP navigation. With the information, trajectory controller calculates updated details of continuing navigations, such as path, speed, and posture of RCP.

In this paper we suggest a new way of implementing RCP localization using RFID tags. There have been a few attempts of applying RFID technology in robot localizations [4-5]. It seems a valuable replacement to the conventional sensing technologies such as laser and ultrasonic sensing, because it is free from the line-of-sight problem most other sensing techniques are having trouble with. However, there is a problem applying RFID sensing in the same way other methods are used for localization, because the triangulation of the conventional localization does not work with RFID. For this to work, the distance between a sensor and a sensed object needs to be accurately measured, but today’s RFID technology does not provide enough accuracy in the distance measurement. The best result so far, even after applying statistical filters such as Monte-Carlo, gives an average error of 0.77 feet in localization, which is not quite acceptable to the robot navigation [5].

Therefore, in our implementation, we place an RFID reader (with an RF antenna installed internally) onto RCP and prepare a floor installed with a number of RFID tags, each of which possesses coordinate information of itself. With such a setting, RCP may acquire quite accurate coordinates during navigations, because the localization error depends only on dimensions of the tag and the reader, not on the distance between them. Real-time updates of the RCP coordinates are possible as the RCP navigates through the floor, so that overall performance of the RCP navigation will be enhanced.

This is not the first application of RFID tag installed floor to the navigation. There is the NaviGeta project [4] which utilizes RFID floor, on which a person navigates wearing shoes equipped with an RFID reader. However, this study does not address the issue on how and how many tags we should distribute to the floor to achieve effective navigations. In this study, we not only implement an RCP navigation system based on RFID, but also suggest a way to determine the efficiency of tag arrangement and tag granularities for the RFID floor.

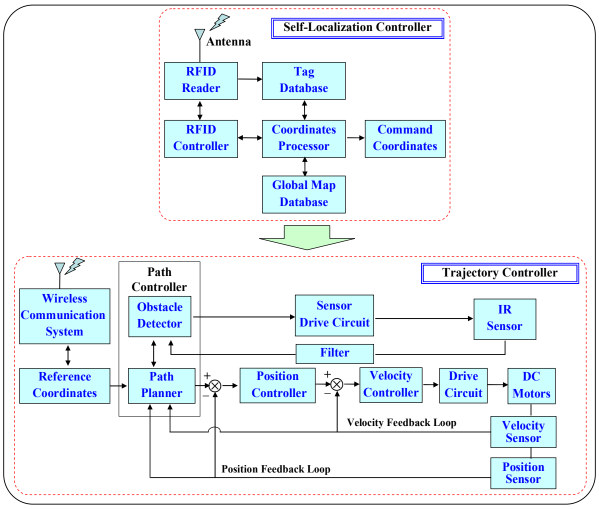


Fig. 1 Diagram for the RCP navigation control

Fig. 1 is a diagram for an overall RCP navigation control. The top of the diagram is self-localization controller. A tag ID detected by the RFID reader is looked up in the global map (location) database, and it is converted into the coordinate information of RCP on the floor. Then the positional information is fed into trajectory controller shown on the bottom of the diagram. At path planner, a modified path to the target is calculated and this information is fed into the position controller. In this controller, a new speed value for the RCP is determined. Velocity controller then controls the velocity of the motors attached to wheels according to this speed value. Path planner not only relies on the localization information from self-localization controller, but also monitors the speed of wheels and the position of the RCP as in the ordinary wheel-based navigation. Path planner uses the information together to complement the error accumulated during the navigation.

2.1 Development of Trajectory Controller

In order to control the movement of RCP for navigations, RCP must be based on the wheel-based navigation. Therefore, we installed two wheels on the rear part of the RCP, which are operated by CP battery powered motors. Fig. 2 depicts the logical flow of trajectory controller which is responsible for the wheel-based navigation of RCP. Through information acquired from various components, such as communication system, self-localization controller, application targets, and external sensors, trajectory controller updates the path and the speed of RCP. It constantly monitors the speed and the position of the RCP in a loop, so that constant compensation of error occurred during the navigation is conducted in a real-time fashion.

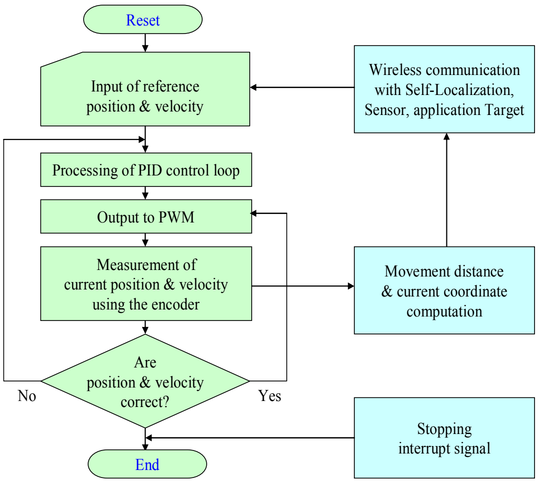


Fig. 2 Logical flowchart for trajectory controller

For the wheel-based navigation of RCP, we should be able to find out the current position of the RCP and be able to control its movement. Therefore, we need a kinematical analysis on the RCP movement. In this implementation of the wheel-based navigation, we used a robot model with two wheels. It is one of the simplest ways of implementing wheel-based robot, and its kinematical diagram is shown in Fig. 3. We can derive a kinematical model of RCP from this diagram. RCP’s speed at the contact point of the wheel with the floor under the non-slipping condition is given in Eq. (1).

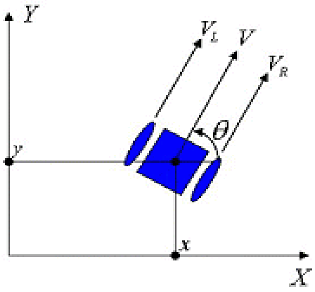


Fig. 3 RCP with two wheels

$$V_R = r\omega_R \quad , \quad V_L = r\omega_L \tag{1}$$

$$\omega = \frac{V_R - V_L}{L} = r\frac{\omega_R - \omega_L}{L} \tag{2}$$

$$v = \frac{V_R + V_L}{2} = \gamma\frac{\omega_R + \omega_L}{2} \tag{3}$$

ω_R, ω_L : Angular velocities of wheels

v : Linear velocity of RCP, ω : Angular velocity of RCP

r: Radius of the wheel, L : Distance between two wheels

Therefore, the relationship between $[P_x \quad P_y \quad \theta]^T$ and $[v \quad \omega]^T$ can be expresses as a kinematical formula:

$$\begin{bmatrix} P_x \\ P_y \\ \theta \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{4}$$

Note that in Eq. (4) we have two motors for RCP control, but we have three degrees of freedom for the direction and angle to the destination. This is because we have an extra steering wheel not associated with any motor. Therefore, a constraint occurs when we want to change RCP's current posture into a new one. However, if we take advantage of the non-slipping condition, which implies the vertical velocity to the wheel is 0 at the contact point of wheel with the floor, we can derive a non-holonomic constraint:

$$H \bullet P = [\sin\theta \; -\cos\theta] \begin{bmatrix} P_x \\ P_y \end{bmatrix} = P_x \sin\theta - P_y \cos\theta = 0 \tag{5}$$

Here, H is a unit vector vertical to the floor. Eq. (5) can be simplified as $\tan\theta = P_y / P_x$. This implies that the direction of movement of RCP at a certain point of the navigation has to be the same as the angular direction θ of the moving RCP. Velocities of wheels (V_L and V_R) are linearly proportional to the distance from ICR (instantaneous center of rotation) to r_1 and r_2 as they are shown in Fig. 4.

$$V_L : r_1 = V_R : r_2 \tag{6}$$

$$V_L \Big/ \left(R - \frac{L}{2}\right) = V_R \Big/ \left(R + \frac{L}{2}\right) \tag{7}$$

$$R = \frac{L}{2}\frac{V_R + V_L}{V_R - V_L} \tag{8}$$

R : Radius in the RCP rotation

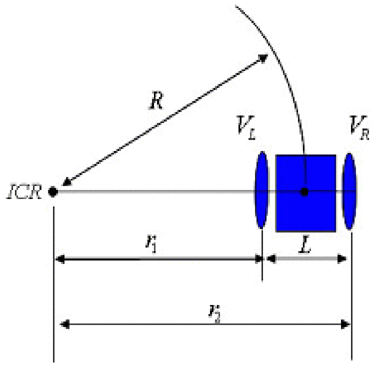


Fig. 4 Calculation of instantaneous center of rotation (ICR)

According to Eq. (8), RCP moves straight when $R = \infty$ and $V_R = V_L$. It spins around when $R = 0$ and $V_R = -V_L$.

2.2 Development of Self-Localization Controller

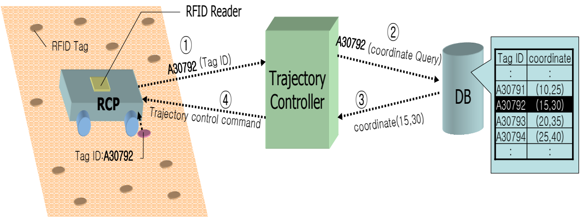
For the autonomous navigation of RCP, the role of trajectory controller is important because it actually controls the movement of RCP. However, trajectory controller needs localization information of the moving RCP in order to complement errors accumulated during the wheel-based navigation. Therefore, another very important issue in the autonomous navigation is to give RCP an ability to identify its own coordinates during navigation. Self-localization controller developed for RCP plays such a role.

In order to implement self-localization controller for RCP, we adopted the RFID technology. Not like other conventional sensors, RFID readers do not suffer from the line-of-sight problem. It can trivially provide ID information of the sensed objects as well, so that the technology is very well suited for many ubiquitous computing application such as the robot navigation we are interested in the study.

In this section, we describe our RFID-based implementation of self-localization controller and suggest a way of improving the effectiveness of navigation by varying RFID tag arrangements on the floor.

2.2.1 Structure and Operation of the Controller

In this implementation, we make RCP know of its own coordinate through RFID sensing. For the purpose, we place a small RFID reader integrated with an RF antenna onto RCP. On the in-door floor, where the navigation is to take place, we place multiple RFID tags and associate each tag (tag ID) with a coordinate. This information is then stored into the back-end DB. During an actual navigation, as the RCP detects a tag, its ID is converted back to a coordinate at the DB, and it is fed back to the trajectory controller for further control of the RCP navigation. Fig. 5 shows overall structure and procedures involved in the control.



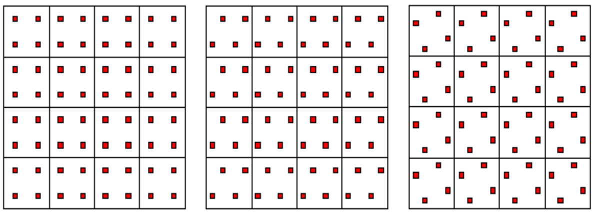
Tag ID	coordinate
:	:
A30791	(10,25)
A30792	(15,30)
A30793	(20,35)
A30794	(25,40)
:	:

Fig. 5 Structure of self-localization controller

2.2.2 Tag Arrangement

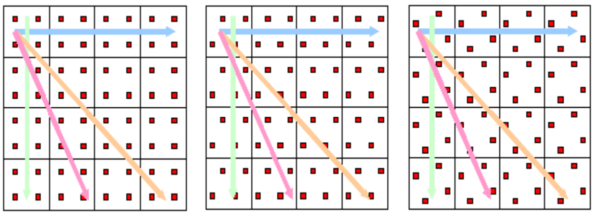
There may be many sensible ways of placing RFID tags to the floor. However, it may be easier to prepare tiles of the same fashion and assemble them to produce a navigational floor. This is the way we prepare an in-door floor in this implementation, so that once we decide on the tag arrangement for one tile, the rest of the floor construction is easy. The simplest way of arranging RFID tags on a tile is to place 4 tags in a square manner as is shown in Fig. 6(a).

Another way might be the one suggested in [4]. Fig. 6(b) shows such an arrangement. The rational behind this is that, with the arraignment in Fig. 6(a), there are higher possibilities of missing tag detections during navigation. However, as we can see from Fig. 7(a) and 7(b), possibilities of missing tags in both cases are same. Therefore, we suggest the "tilted-square" placement of tags as is shown in Fig. 6(c). As we can see from Fig. 7(c), this has the lowest possibility of missing tag detections during navigation. Any straight-line movement of RCP will be easily detected with such an arrangement.



(a) Square (b) Parallelogram (c) Tilted-Square

Fig. 6 Various tag arrangement method



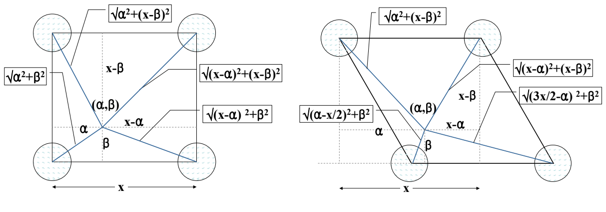
(a) Square (b) Parallelogram (c) Tilted-Square

Fig. 7 Possible misses of tag detection

2.2.3 Effectiveness of the Navigation

In the navigation suggested above, the more tags we place on the floor, the better the tag encountering possibility will be. That is to say, with more tags on the floor, we have a better chance of encountering tags in the navigation, so that the coordinate information of RCP can be updated more often. Since we can compensate the error accumulated by the wheel-based navigation more often in this case, RCP will navigate better in overall. However, in reality, we cannot afford to place more than necessary amount of tags to the floor, because the tag price is still too expensive (about 50cents per tag) for a large volume of tags needed for the navigation floor. Therefore, it is desired to place only the minimum number of tags to the floor for the required degree of performance. To do this, we need a mechanism to analyze the relationship between the tag granularities and the effectiveness of navigation.

Even with the same number of tags, there might be RCP performance differences depending on the way tags are arranged on the floor. To back up such speculation, let us look into Fig. 8(a) and 8(b). From a random position (α,β), sum of the distances to four neighboring tags are different. The difference in total is plotted in Fig. 9. Here, we consider 10cm×10cm tiles having four RFID tags each. When α is less than or equal to 7, the parallelogram arrangement resulted in shorter distance than the square arrangement. With the α value of 8-9, the performance was reversed as it is shown in the figure. Therefore, it is worth investigating which tag arrangements and granularities are the best for the floor. For this purpose, we developed a simulation program for the RCP navigation on RFID floors. We defined the error in the navigation and use it to compare the effectiveness of various tag arrangements and granularities.



(a) Square (b) Parallelogram

Fig. 8 Distances from a to four neighboring tags

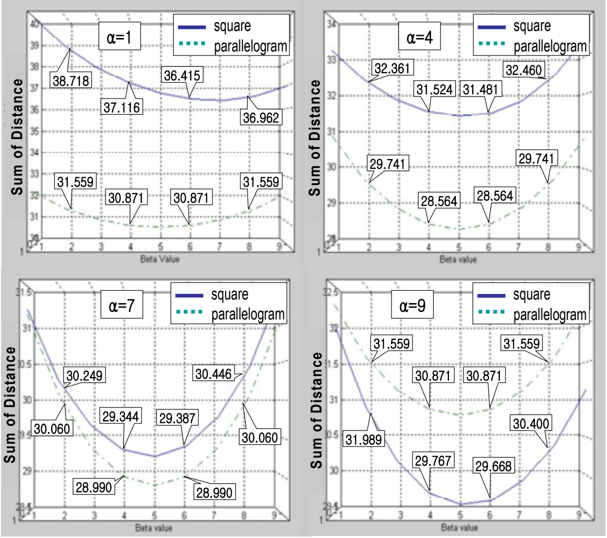


Fig. 9 Comparison of the sum of distances for "Square" and "Parallelogram" tag arrangements

2.2.4 Performance Factors

As RCP recognizes tags during the navigation, it knows its current position. It adjusts its posture and the navigational path as needed and continues on its navigation. In order to analyze RCP's navigational efficiencies, we developed a simulation program. The output of the simulation is the time it takes to travel from a given departure point to a given destination. The time it takes is the sum of straight line movement time at each successive point it goes through, plus the time it takes to adjust its posture at each tag. However, the movement is all depends on the arrangement of tags on the floor. Therefore, we may define RCP navigation time as:

$$T(\chi_0,\chi_n,e_i)=\sum_{i=0}^{n-1}\{tm(\chi_i,\chi_{i+1})+tr(\chi_i,\chi_n)\} \qquad (9)$$

Where,

$T(\chi_s,\chi_d,e_i)$: Time it takes navigating from χ_s to χ_d under the floor arrangement of e_i

$tm(\chi_a,\chi_b)$: Time for a straight-line movement from χ_a to χ_b

$tr(\chi_a,\chi_b)$: Time for adjusting posture from χ_a for χ_b

χ_s or χ_0 : Departing point

χ_d or χ_n : Destination point

$\chi_1\cdots\chi_{n-1}$: Locations of successive tags encountered during navigation

By subtracting the straight-line movement time between the departure point and the destination point from Eq. (9), we may be able to define the navigation error of certain navigation. The navigational error $E(\chi_s,\chi_d,e_i)$ can be defined as:

$$E(\chi_s,\chi_d,e_i)=T(\chi_s,\chi_d,e_i)-tm(\chi_s,\chi_d) \qquad (10)$$

Using the definition of navigational error in Equation (10) and varying the arrangements and granularities of the tags, our research group is in the process of analyzing the effectiveness of various RFID tag arrangements through the simulation. In order to increase the reliability of the simulation, we use thousands of randomly generated departure-destination pairs. We accumulate errors for each floor arrangements e_i and use the mean values of E for performance comparison of each tag arrangement e_i.

3. EXPERIMENTS AND RESULTS

3.1 Development of the RCP Navigation Module

Selection of an appropriate motor for RCP is the very first thing we need to do for the construction of an RCP. RCP needs to be portable so that there are several constraints on the motor, such as the weight and size. Other constraints to consider are the torque, power consumption, and rotational velocity of the motor. Especially, we have to take into account the fact that the power consumption of the motor depends on what kind of battery it uses, such as Li-Ion and Li-Polymer.

RCP motor needs not be a fast one. Namely, the rotational velocity of the motor is not important, because RCP does not have to navigate fast. However, for the RCP navigation and flipping movement of the cover, we need a certain level of motor torque. The torque depends on the weight of RCP and the friction coefficient of the wheel and the floor. For example, when RCP weights 0.1kg, and the friction coefficient of the wheel and the floor is 0.4, and the radius of the wheel axes is 0.01cm, the minimum necessary torque τ_G can be calculated as in Eq. (11). For the size of a motor including a gear and an encoder, less than 5cm in length is desirable.

$$\tau_G = \frac{1}{2} \times F \times R = \frac{1}{2} \times \mu \times m \times g \times R_0 \qquad (11)$$

$$\tau_G = \frac{1}{2} \times 0.4 \times 0.1kg \times 9.8 \,{}^{m}\!/_{s^2} \times 0.0001m = 0.0196\,mNm$$

Fig. 10 shows a prototype RCP we developed in this study. It is equipped with a graphical LCD, infrared sensors, wireless communication modules, and a driver IC that controls two D.C. motors. For the RCP's power source, we used a 3.7V Li-Ion battery commonly available for CPs. We used an AVR ATmega 128(8MIPS) 8-bit CPU from ATMEL for the RCP processor. For the external appearance and unit mountings, we designed and crafted a shell case using an RP (Rapid Prototyping) machine and a 2D engraving machine. Fig. 11(a) through 11(c) show the components needed for the development of Self-Localization Controller. For the RFID reader we used an "M1" reader from Skyetek (dimension: 38mm×40mm; read range: 100mm), which is integrated with an internal RF antenna. Tags are 13.56MHz passive RFID tags (Dimension: 14mm×31mm) from Texas Instrument. For the navigation floor, we prepared our own foamax tiles (dimension: 200mm×200mm×5mm).

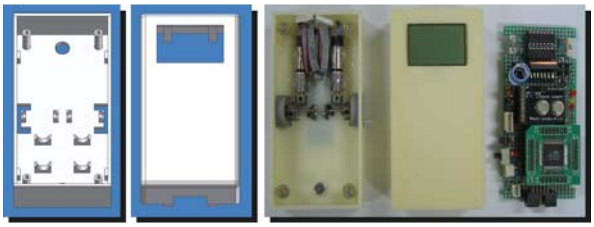


Fig. 10 Wheel based navigation system of RCP

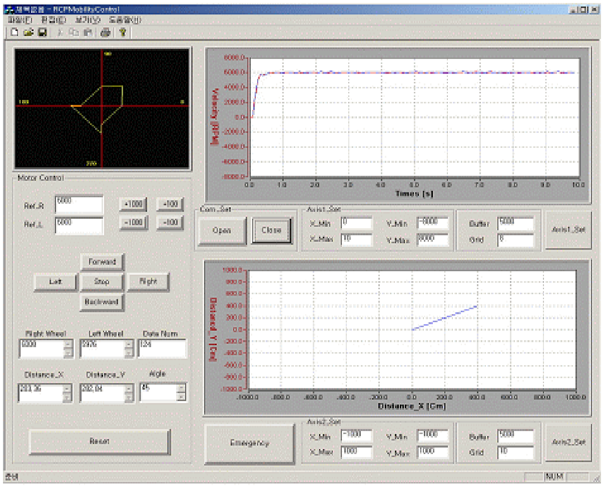
(a) RFID reader (b) RFID Tag (c) Floor tile

Fig.11 Components of the RFID self-localization controller

3.2 Experimental Results on the RCP Navigation

In the wheel-based navigation system, techniques on identifying RCP's position and an efficient guidance to the destination is important. Therefore, a fine-grained velocity control to the D.C. motor should be possible, along with an ability to circumvent obstacles in the navigation. In this implementation, infrared sensors are used for the obstacle detection and for measuring distance to objects. Through the PI control, we implemented the velocity control of the motor. We used H-Bridge structured motor driver in which the reverse rotation of motor is possible. Also, by filtering signals of infrared sensors through a 12bit AD converter, the existence and the distance to obstacles could be accurately identified.

Fig. 12 shows a program we developed, which can monitor RCP's velocity, position, and posture in real-time. Input velocity and destination for this program are transmitted to the RCP through a wireless communication. This triggers RCP navigation. Fig. 12 depicts navigation results from a starting point to a destination with the motor speed of 6000RPM for 10 seconds, for the movement of 400cm.



Ref_R 6000
Ref_L 6000
Right Wheel 6000
Data Num 124
Angle 45
X_Min 0
X_Max 10
Y_Min -8000
Y_Max 8000
Buffer 5000
X_Min -1000
X_Max 1000
Y_Min -1000
Y_Max 1000
Buffer 5000
Grid 10

Fig. 12 Monitor program for the RCP trajectory controller

A simulation program for testing the effectiveness of various tag arrangements of the RCP is shown in Fig. 13. In this program, users may specify various navigational parameters. Some of more important parameters are:

- Tag arrangements
  "Square", "Parallelogram", "Tilted Square", and "Random" arrangements can be chosen.
- Tag granularities
  Four tags per tile in all cases. By adjusting the size of the tile (hence the distance between tags), we can control the tag granularity.
- Read range of the tag and the reader
  Users may define these values. Because there are so many different types of tags and readers in the market, we wanted to make this simulation as general as possible. It is not only applicable to our RCP project, but also should be useful to the construction of RFID floors of many other USN applications.
- Other parameters
  Users may also specify values for departure/destination coordinates, RCP velocity, posture adjustment time, and the angular error-rate of wheels.

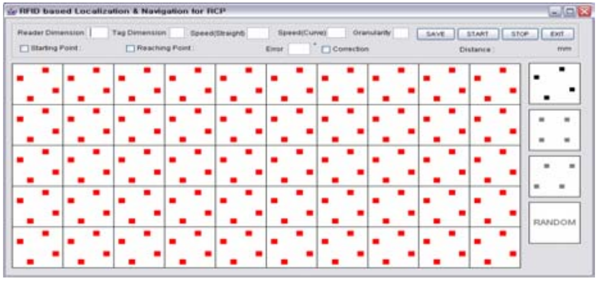


Fig. 13 Simulation program to analyze performance of self-localization controller on the RFID installed floor

Fig. 14 depicts an experimental navigation for the RCP auto-charging. The in-door is made of “Tilted Square” RFID floor and the RCP has an RFID reader mounted on it.

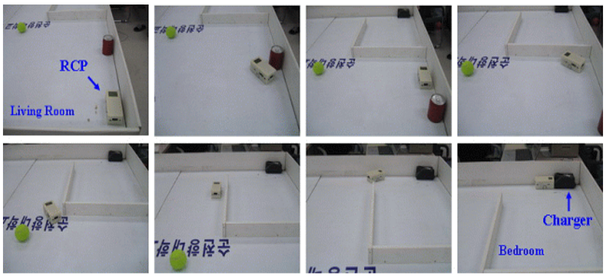


Fig. 14 Navigation for RCP auto-charging in the RFID in-door floor environment

In this experiment, the RCP navigates through a living room with walls and obstacles, and it gets to the bedroom where the battery charger is. It then performs a battery auto-charging. During the navigation, RCP recognizes RFID tags on the floor and obstacles, and uses them to correct its navigational error as well as for avoiding obstacles. RCP’s localization information generated by self-navigation controller is fed into trajectory controller, so that it refigures out an optimal path to the destination in real-time, and continues on guiding RCP through the new path. RCP paths are normally allocated near and along the wall, in order to better avoid a possible collision with a human. Besides the use of RFID, RCP uses 6 pairs of infrared sensor for measuring distance to the wall and obstacles, so that the collision avoidance feature of RCP is effectively implemented. In the region where the recognition of RFID tags is not performed, RCP uses dead-reckoning method in navigation. Once a tag is recognized, we could see RCP readjusting its own path and posture for the continuing navigation. In this experiment, we could successfully navigate the RCP to the destination, at which an autonomous charging of RCP battery is performed.

4. CONCLUSION

In this study we developed an autonomous navigation system of RCP by constructing two of its main modules called trajectory controller and self-localization controller. Trajectory controller is responsible for the wheel-based navigation of RCP, and self-localization controller provides localization information of the moving RCP. For the robotic movement of RCP, a pair of navigation wheels is installed on RCP. Its movement is controlled by a D.C. operated small size motor. Power supply needed for the motor is acquired from the CP battery. With the accurate positional information acquired from self-localization controller, trajectory controller refines RCP's movement to achieve better navigation. For the implementation of self-localization controller, we used RFID technology whose impact in USN application area is rapidly increasing. Not like other conventional sensors, RFID readers do not suffer the line-of-sight problem. It can trivially provide ID information of the sensed objects as well, so that we could better implement autonomous RCP navigation with RFID.

Wheel-based navigation module in RCP$^{\text{Mobility}}$ is in the process of a major revision. This time we are concentrating on module integration and performance enhancement. Once the second prototype of RCP is developed, we should be able to provide more reliable movements. The work reported in this paper presents a new technological concept which combines personal RT & CP, in the vision of providing a new direction to the advance of CP, IT, and RT all together. This kind of new idea is valuable to the current technology market where competition is getting tougher and harder throughout all over the world.

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