Flexible Docking Mechanism with Error-Compensation Capability for Auto Recharging System of Mobile Robot

Se-gon Roh, Jae Hoon Park, Young Hoon Lee, Young Kouk Song, Kwang Woong Yang, Moosung Choi, Hong-Seok Kim, Hogil Lee, and Hyouk Ryeol Choi*

Abstract: The docking and recharging system for a mobile robot must guarantee the ability to perform its tasks continuously without human intervention. This paper proposes two docking mechanisms with localization error-compensation capability for an auto recharging system. The mechanisms use friction forces or magnetic forces between the docking parts of the robot and those of the docking station. It is a structure to improve the allowance ranges of lateral and directional docking offsets, in which the robot is able to dock into the docking station. In this paper, auto-recharging system and the features of the proposed mechanisms are verified with experimental results using simple homing method.

1. INTRODUCTION

Recently, mobile robots have begun to perform more various and important tasks in place of humans such as cleaning, guiding, entertainment, surgery, and security. However, robots can be useless without a concern for the energy problem. Many researches on energy conservation of mobile robots have been conducted. The Mars rover Sojourner [1] used solar power while SlugBot [2] converted various organic resources such as slugs to a form of energy that is useful to a robotic system. Although some methods exist for energy conservation of mobile robots, a docking station remains widely used for recharging as most modern robots use batteries for their energy resources [8-13]. At the docking station, the mobile robot can attach the connectors between a battery and a station charger for recharging. The first research on

docking stations was performed by Walter [3] in 1948. He used two mobile robots, Elsie and Elmer, which used light to find their way to a hutch where their power supplies were installed. Researches have also been conducted on docking mechanisms for security mobile robots, cleaning robots, rescue robots [4,5,16]. Silverman developed a docking mechanism with two degrees of freedom to increase the tolerance for docking error [6]. Recently, the use of a docking station has even been adapted to several commercial cleaning robots. However, all docking stations which have been suggested by researchers and then commercialized suffer from the following three significant problems: (i) the low error tolerance of the docking mechanism, (ii) the low adaptability of the docking mechanism for various mobile robots as most docking mechanisms are specifically designed to match the shape and size of their own robots, (iii) the requirement for the mobile robot to be shut down during recharging, turned on by the user and returned to the previous task after full recharging. These are impediments to the development of mobile robots as independent systems able to perform tasks continuously without external assistance.

In this paper, we present docking mechanisms with high error compliance, flexibility, and capability of auto-recharging in order to overcome the three obstacles detailed above. The docking mechanisms were designed using friction forces or magnetic forces between the docking parts of the docking module and the docking station. In addition, we suggest an auto recharging system that uses a Solid State Relay (SSR) to control the power transmission. The system enables the mobile robot to operate all its modules except the mobile module during the recharging period and to

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undock autonomously after full recharging. The paper is structured as follows. Section 2 explains the mobile robot platform to which the docking system is attached and the auto-recharging system. Section 3 describes the proposed mechanisms. The experimental investigation of the mechanism is discussed in Section 4, and the conclusions are presented in Section 5.

2. MOBILE ROBOT PLATFORM

2.1. Mobile robot hardware

The mobile robot platform for which the proposed docking module is adapted to is shown in Fig. 1. This mobile robot has two wheels and a caster with a suspension mechanism.
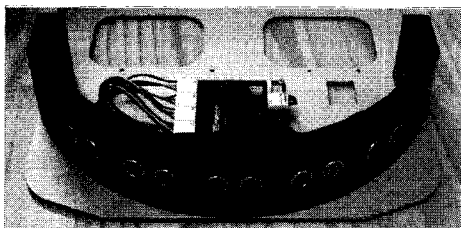
As shown in Fig. 2, the robot has a single board computer (SBC), a control panel, a sonar sensor
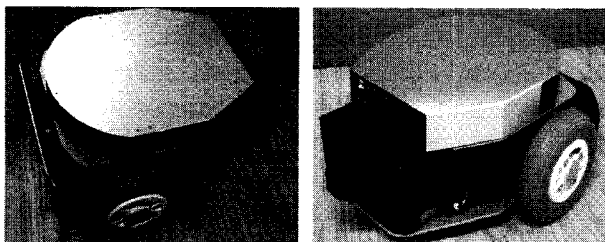
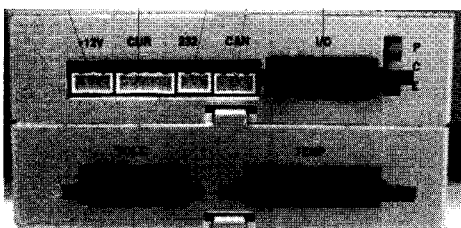(a) Front view.   (b) Rear view.

Fig. 1. Mobile robot platform.

(a) Ultra sonic module.

(b) Control panel.

Power   Current RS232 CAN   External I/O

*Voltage input from battery Temperature input from battery*

(c) BMS.

Fig. 2. Hardware components of the robot.

module, an IR sensor module, a lithium-polymer battery pack, a battery management system (BMS), and space for the docking module. To perform obstacle avoidance and navigation, SBC can communicate with a sonar sensor module, an IR sensor module using CAN, and RS232. The LCD display which shows battery condition, connectors such as USB, and a power switch are located on the control panel for the user's robot control (see Fig. 2(b)). Five ultra sonic sensors (Davantech, SFR04) are controlled by the sonar sensor module which obtains signals from a maximum of sixteen sonar sensors. Thirteen IR sensors in the IR sensor module consist of ten GP2Y0A02YK (range: 200mm~500mm) for omni-directional detection of objects and three GP2D120 (range: 40mm~300mm) for detection of ground height. BMS checks the battery condition and sends a data to SBC with CAN or RS232 (see Fig. 2(c). The acquired data are battery voltage, current, and temperature. BMS can monitor a maximum of eight cells. The power of the adapted lithium polymer battery is 244.2W (22.2V, 11Ah).

2.2. Auto recharging system

An auto recharging system must guarantee that the mobile robot can remain active even when charging, docking and undocking. The proposed auto recharging system was developed based on the concept of the SSR controlling the power transmission [7]. The control board gets the battery condition data from SBC and BMS by CAN communication, and decides the recharging time. Fig. 3(a) shows the power transmission of the auto-recharging system. When the mobile robot is operating generally without battery shortage, the mobile robot's power is supplied by battery through SSR 3. Two control boards shown in Fig. 3(b) are attached to the docking module and the docking station, respectively. The boards control auto recharging, CAN communication, and IR signals of the docking module and the docking station. The docking success is decided by the control board 1 of the docking module and the control board 2 of the docking station, using a 5V signal line. Auto recharging consists of three steps. When physical docking has been accomplished in step 1, the mobile robot operates by the external power from the docking station. Then, the control boards turn on SSR 1 and 4. Therefore, although both the battery power and the external power from SMPS are provided to the mobile robot, the robot only receives the external power because the SMPS voltage is higher than the battery's and a diode protects the counter current of the external power supplied to the battery. Then control board 1 turns off SSR3 after a few seconds. In step 2, the control boards turn on SSR 5 and 2 in order to charge the battery by the charger. Therefore, the mobile robot operates on the external power while the battery is

24V Charging & Battery
24V External Power
5V
Signal Line
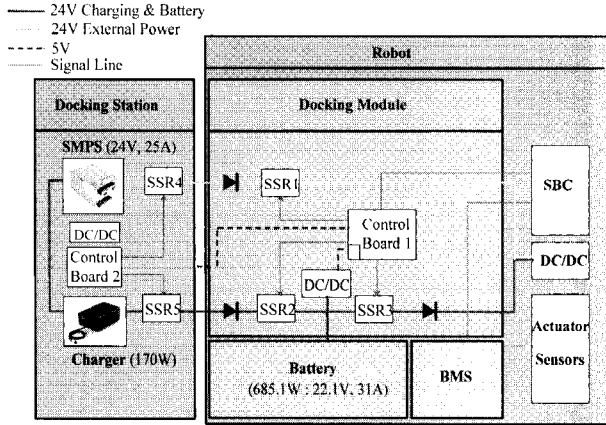
(a) Power transmission.
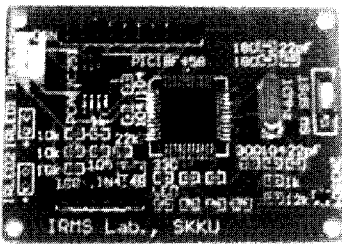
(b) Control board for IR LED and auto recharging.

Fig. 3. Circuit of auto-recharging system.

simultaneously being charged by the charger. BMS is continually checking the battery condition during step 2 which allows control board 1 to decide the full charging state of the battery. The last step is carried out in reverse order of the previous steps 1 and 2, and then the mobile robot exits from the docking station and returns to its previous task.

2.3. Mobile robot software

The operating system of the mobile robot is RT Linux 3.1 based on Linux Kernel 2.4.20. Since the main functions of each module are developed in the form of Application Programming Interface (API) in Table 1, the auto-recharging module can be adapted easily to other mobile robots [7].

Table 1. API (Application Program Interface).

| Module	API	Function
Mobile Module	turnInDegree(int d)	Turn to d degree direction at current position
	goTo(float x, float y, float d)	Go to new position (x, y, d)
	stop(void)	Stop moving
	setPosition(float x, float y, float d)	Set current position and posture(x, y, d)
	VelTurn(int d)	Turn to d degree using velocity control
	VelGo(int Lvel, int Rvel)	Set Left and right wheel velocity
	VelStop(void)	Stop controlling velocity
Ultra sonic Module	getSensorData(void)	Get sonar data
Infrared Module	getIRData(void)	Get IR data
Auto recharging Module	getVoltage(void)	Get battery voltage value
	getCurrent(void)	Get battery current value
	getLEDData(void)	Get IR LED data
	startAutocharging(void)	Start auto charge
	stopCharging(void)	Stop auto chage
	startExternalPower(void)	Start external power supply
	stopExternalPower(void)	Stop external power supply

3. DOCKING MECHANISM

3.1. Prototype I

The prototype I of the docking mechanism was designed based on remote center compliance (RCC) [14,15]. The peg of the docking station in Fig. 4(a) is docked into the matching hole of the mobile robot's docking module shown in Fig. 4(b). The peg contains the external power, charging power, and ground connectors. A charger, Switching Mode Power Supply (SMPS) for external power, an IR sensor control board, and a DC/DC converter are installed in the docking station. The peg of the docking station can not only move vertically and horizontally but also rotate in any direction. These processes are all operated on the same plane. The shapes of the peg and the chamfered hole of the docking module were designed by using a friction cone. The docking module, which is attached to the mobile robot's rear part, consists of a chamfered hole, an auto recharging circuit, and solenoids. The chamfer guides the peg of the docking station into the hole using friction.

Generally, even in the case of successful docking between the docking module and docking station, the docking parts can be separated because of disturbance from the user or the reaction force against the approaching force of the mobile robot. The solenoids push the connectors of the docking module onto the connectors of the peg, and hold the peg, as shown in Fig. 5. Consequently, the connectors of the docking station and the docking module can maintain their contact.
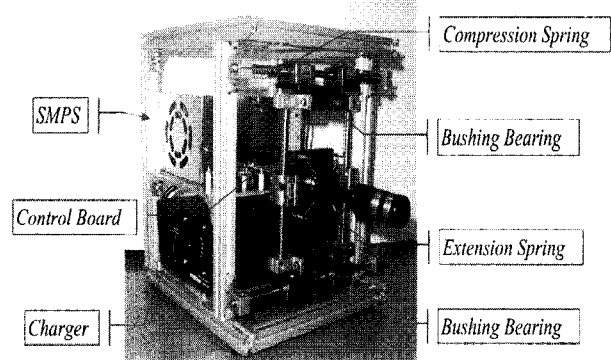
(a) Docking station.
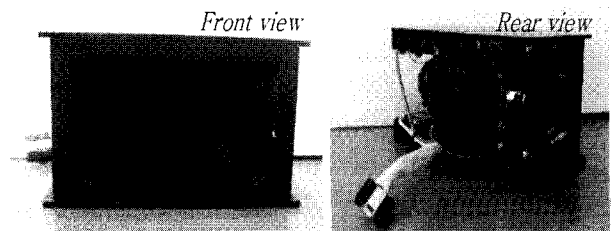
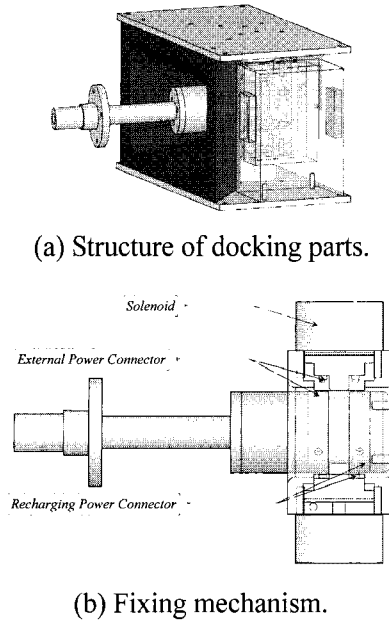(b) Docking module of robot.

Fig. 4. Prototype I.

(a) Structure of docking parts.

(b) Fixing mechanism.

Fig. 5. Connection of docking parts of the prototype I.

3.2. Prototype II

The proposed docking mechanism of the prototype II was developed based on the idea that the docking mechanism should be a passive system without

(a) Docking parts of docking station.

(b) Docking parts of docking module.

(c) Docking motion.
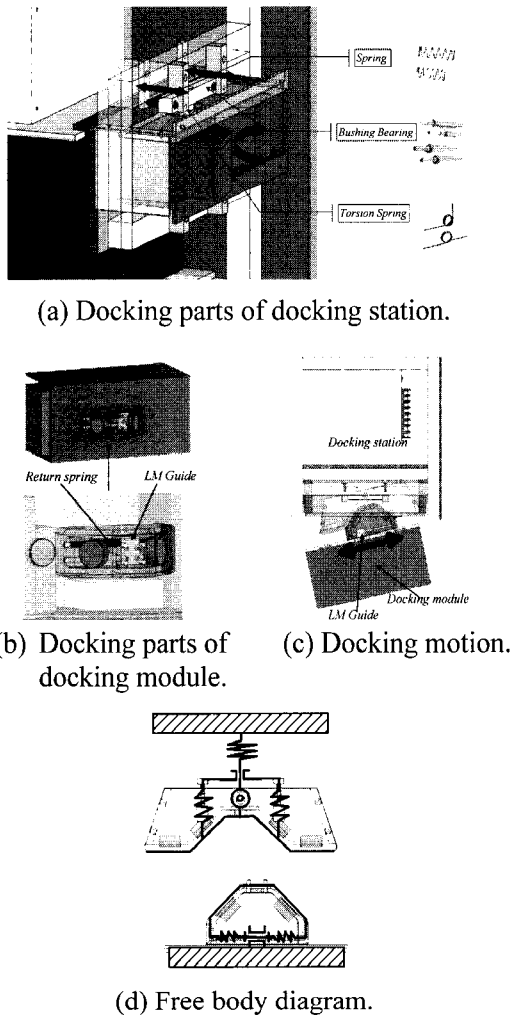

(d) Free body diagram.

Fig. 6. Docking mechanism of prototype I.

actuators. The prototype II uses magnets for supporting docking. Magnetic forces guarantee the error compensation between the docking parts of the docking station and the docking module of the mobile robot. Furthermore, friction between the docking parts can be slight due to the magnetic forces between docking parts (see Fig. 6).

As shown in Fig. 7, when the mobile robot has an error distance only, magnetic forces act such as in case 1, while magnetic forces act when both error distance and angle occur such as in case 2. Attractive force and repulsive force make the docking parts of the docking module toward the center of the docking station, after which the docking part of the docking station rotates to the direction of the docking module and moves toward the docking module. Furthermore, the use of magnetic force in this mechanism helps the contact maintenance of connectors during a charging period. The attractive force of the mechanism was designed with the minimum value required to pull the weight of the docking part of the docking station. Therefore, the mobile robot can undock easily even if there is an attractive force between the docking station and the mobile robot's docking module. The shape of the docking parts was designed based on the friction cone which allows successful compensation of the error even in the absence of sufficient friction force to move the docking part.
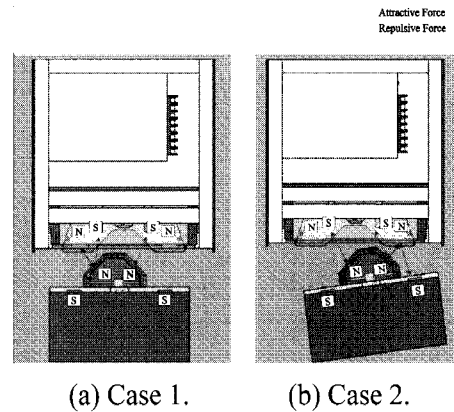

(a) Case 1.   (b) Case 2.

Fig. 7. Interaction between docking module and docking station.

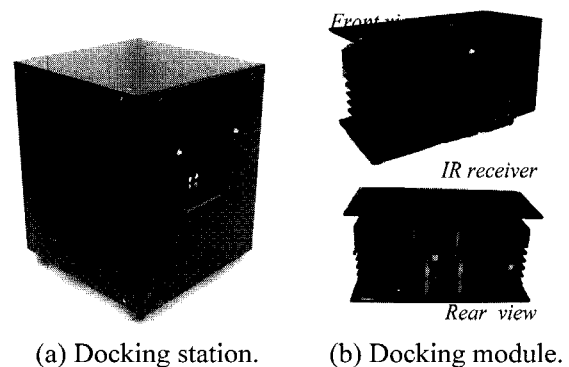(a) Docking station.   (b) Docking module.

Fig. 8. Prototype II.

The docking station shown in Fig. 8(a) has two SSR components, two diodes, four connectors, SMPS for external power, charger, two IR emitters for docking, a DC/DC converter, a control board, etc. Fig. 8(b) shows the docking module with three SSR components, three diodes, one IR receiver for docking, four connectors, a control board, etc.

4. EXPERIMENTS

4.1. Homing algorithm

This section presents a scheme for the homing of a mobile robot. Vision technology is a powerful tool for homing. However, since a vision system places a heavy demand on the robot's processing system, it cannot be suitable for a general homing method. IR LED has advantages including being cheap, easy to handle, and easily applied to mobile robot applications, compared to the other methods. The proposed homing system is composed of IR LED emitters and a receiver (radiation pattern: uni-directional, maximum reading range: 3m, sensible angle: 30°). As shown in Fig. 9(a), the mobile robot performs its homing procedure using the signals from IR LED emitters in the docking station. The two emitters in the docking station send different signals to the mobile robot every 2ms synchronously, as shown in Fig. 9(b).

The homing and docking experiment was performed in the environment shown in Fig. 10. Since
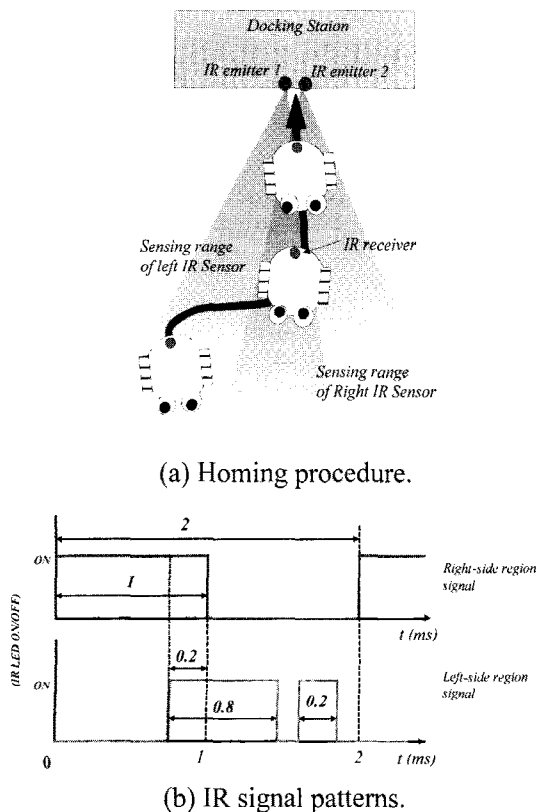
the proposed mechanism can reduce the dependency of the robot control using the excessive system resource and can allow easy docking using only mechanical configuration, the homing algorithm can be simple. The mobile robot wanders and tries to dock into the docking station by using some docking procedures.

Fig. 11 shows the procedure of the docking experiment. In step 1, the mobile robot searches for the docking station by using the sonar sensors and the IR sensors of the robots for localization. In steps 2~4, the mobile robot moves to in front of the docking station. In step 5, the mobile robot turns 180 degrees to orientate the docking module toward the docking station by using the signals of the docking module's IR receiver and the docking station's IR emitters. These two signals are overlapped in the center area, thereby enabling it to detect regions such as right, left, and the central area for the docking station and thus
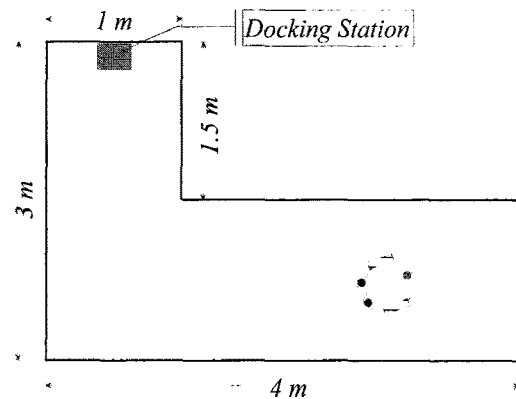

Fig. 10. Experimental environment.

(a) Homing procedure.

(b) IR signal patterns.

Fig. 9. Homing mechanism using IR LED.

Step 1

Step 4

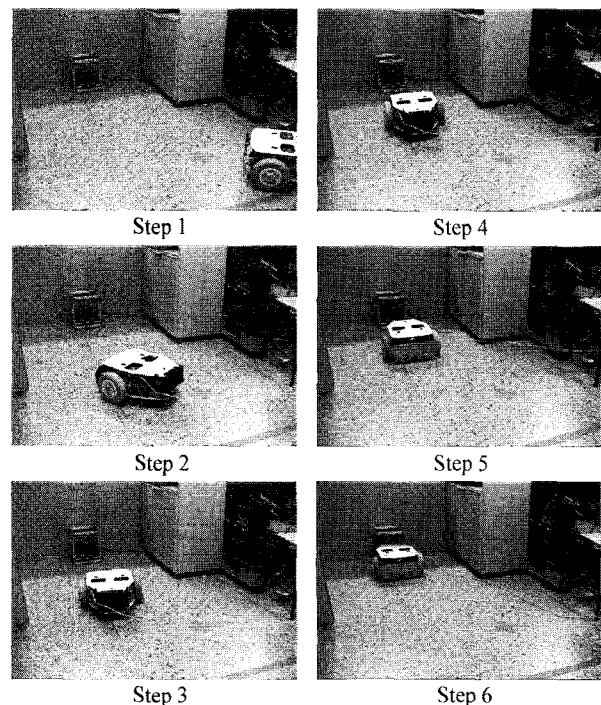Step 2

Step 5

Step 3

Step 6

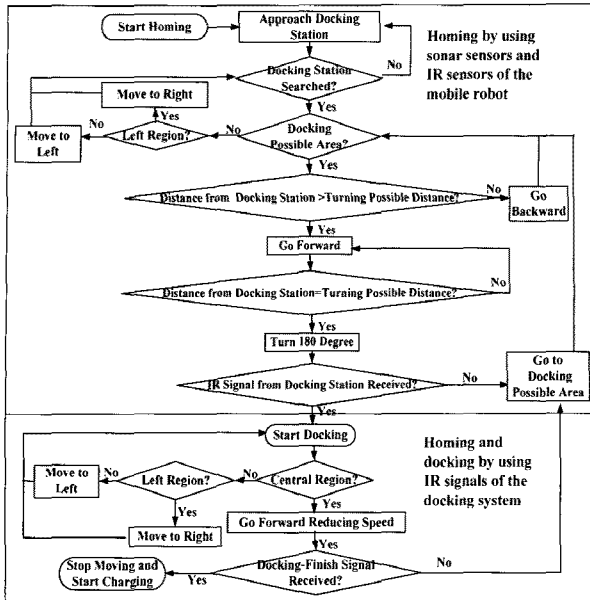Fig. 11. Homing and docking experiment.

Fig. 12. Flowchart of homing and docking.

move to the central region for docking. The mobile robot decides whether it turns right or left, based on its location relative to the docking station. The mobile robot then proceeds to the docking station and turns 180 degrees in order to connect the docking module attached to the back face to the docking station. Finally, the mobile robot docks using the docking mechanism and starts recharging in step 6. The flowchart illustrated in Fig. 12 shows the algorithm for homing and docking in detail.

4.2. Experimental results and discussion

To evaluate the proposed docking mechanisms, we located the mobile robot such that an error distance (case 1) and an error angle (case 2) from the docking station occurred as shown in Fig. 13. The mobile robot approached the docking station in step 1 and then the peg was inserted into the hole by the chamfer. Finally docking was achieved in both cases as shown in step 4. Prototype II was evaluated in the same manner as prototype I, as shown in Fig. 14. The mobile robot is placed at the location with lateral docking error (case 1) and the position with directional docking error (case 2) from the docking station. The mobile robot approaches the docking station in step 1 and then the docking part of the docking station rotated to the direction of the approaching angle of the docking part of the docking module (step 2). In step 3, the docking part of the docking module was maneuvered to the center of the docking station by the attractive and repulsive forces of the magnets. The docking part of the docking station then rotated to the direction of the approaching angle of the mobile robot and finally moved forward to attach to the docking part of the docking module (step 4). Barely any friction occurred between the docking parts because the docking part's movements
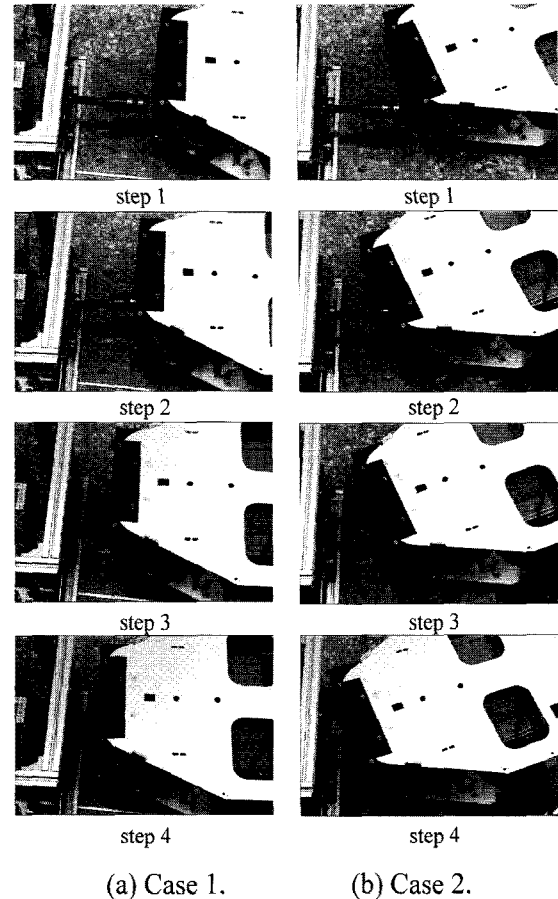

(a) Case 1.   (b) Case 2.

Fig. 13. Docking experiment of the prototype I.

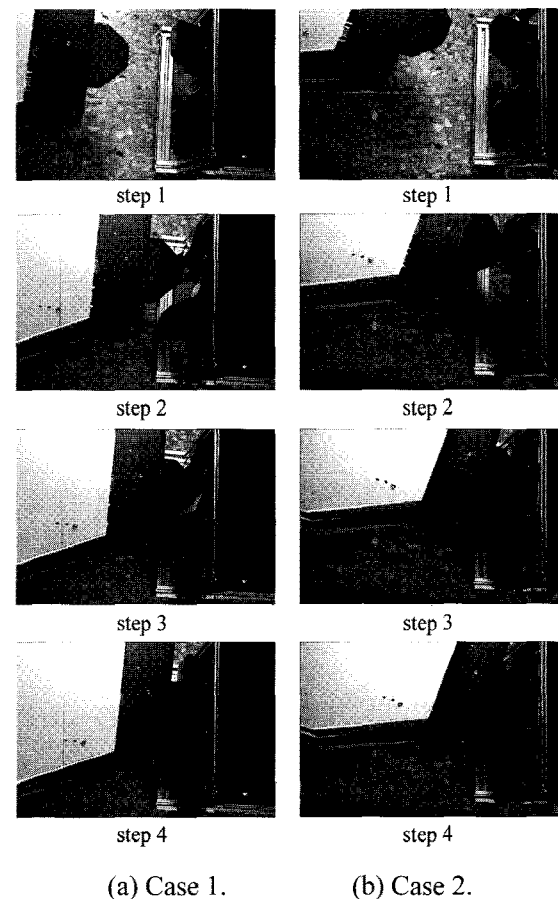(a) Case 1.   (b) Case 2.

Fig. 14. Docking experiment of the prototype II.

were guided by magnetic rather than friction forces in order to compensate for the error.

Figs. 15 and 16 show the docking success rate according to the mobile robot's error distance and error angle. Each experiment was performed ten times and each of the plotted graphs shows the average value of the experimental results. As shown in Figs. 15(a) and 15(b), the maximum and the minimum error tolerances of distance and angle within which the robot can dock the docking station by using the prototype I are about ±35mm and ±14°, respectively. In case of the prototype II, the maximum and the minimum error tolerances are about ±45mm and ±12°, respectively (see Fig 16). The maximum error tolerance for docking mainly depends on the sizes of the parts of the docking mechanism. In case of the prototype I, the docking chamfer of the docking module should be large and the peg of the docking station should be small to improve the error tolerance. Both the two prototypes have capabilities to compensate the localization error for docking and each has its own advantage. The structure of the prototype I is a general mechanism to be applied to various docking systems as well as mobile robots because it can compensate vertical, lateral, and directional errors. The prototype II is a mechanically simplified mechanism of the prototype I and its structure is more compacted by using magnetic force. It was designed to be suitable to indoor mobile robots rather than outdoor mobile robots. Since the ground of the indoor environment is even or flat, the robot requires capability to compensate just lateral and directional errors (except for the vertical error).
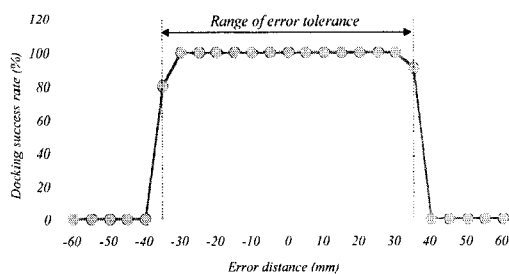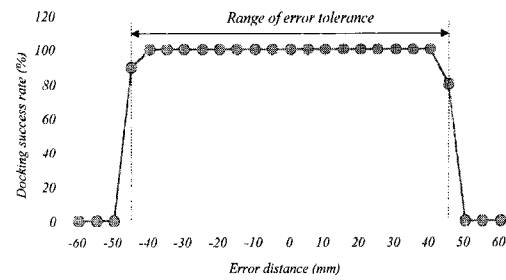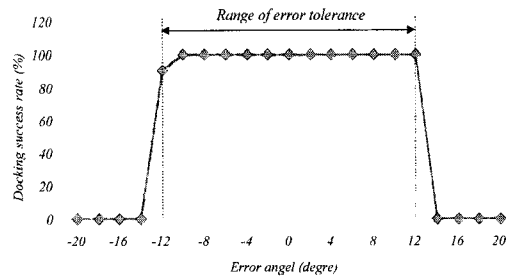

(a) Error distance.
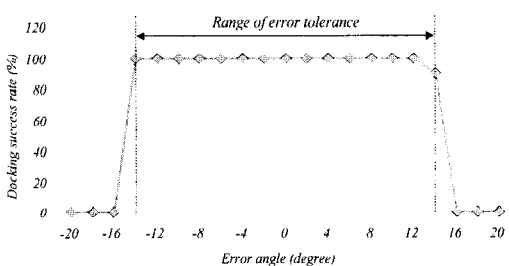
(b) Error angle.

Fig. 15. Docking success rate of the prototype I.

(a) Error distance.

(b) Error angle.

Fig. 16. Docking success rate of the prototype II.

5. CONCLUSIONS

In this paper, we have proposed a new docking mechanism for auto charging. In experiments, the proposed mechanism showed a sufficiently high ability to compensate for the approaching errors of the mobile robot. As robot technology advances and the robot market grows, robots will perform an increasingly wide range of important tasks which require the ability to operate continuously. Furthermore, security and service robots in public institutions need to be able to recharge and return to their tasks autonomously without interruption. Therefore, the auto recharging system has become an indispensable technology for mobile robot operation. Since the proposed system is based on modularization with a simple and practical mechanism allowing easy adaptation to other mobile robots, the authors believe that it can become a reference for the other robot researchers and developers.

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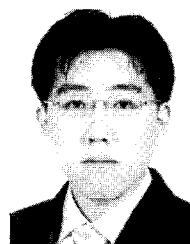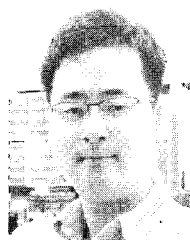

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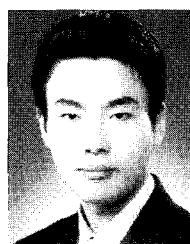

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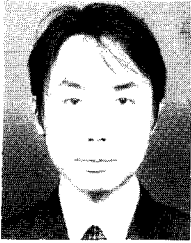
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