Door-Opening Control of a Service Robot Using the Multifingered Robot Hand

Woojin Chung, *Member, IEEE*, Changju Rhee, Youngbo Shim, Hyungjin Lee, and Shinsuk Park

***Abstract*—Service robots are spreading their application areas to human coexisting real environments. However, it is still difficult to find an autonomous robot that is capable of manipulation services in a real environment. The three major difficulties of manipulation service can be summarized as follows: 1) unstructured human-centered environment; 2) limited resources in a robot; and 3) uncertainties in real environments. This paper deals with the autonomous manipulation task by a service robot in human coexisting environment. We focus on a door-opening problem. In this paper, we concentrate on three issues from the viewpoint of service-robot applications. The first issue is to estimate kinematic parameters by using an active-sensing strategy to overcome uncertainties in a real environment. The second issue is to provide an integrated strategy of motion coordination for door-opening control. This paper discusses the role assignment of each subsystem that depends on the physical characteristics. The third issue is to use the fingertip-contact forces to estimate the external force from a doorknob, instead of using an additional high-cost force sensor at the wrist. The proposed scheme is shown to be useful through experimental results.**

***Index Terms*—Door-opening control, mobile manipulator, multifingered robot hand, parameter estimation, service robot.**

I. Introduction

RECENTLY, an emerging issue in the field of robotics has been the development of autonomous service robots toward commercialization. Service robots are now spreading their areas of application to real human–robot coexistence environments. Some recent robotic applications can be found in [1]–[3]. Some mobile robots have realized successful practical applications, such as floor cleaning, visitor guidance, and patrolling. However, it is still difficult to find an autonomous robot that provides manipulation services in a real environment. The three major difficulties of manipulation services can be summarized as follows.

1) Unstructured human-centered environment. In conventional industrial robotic applications, the robot's work environment is prepared to support robotic operations. However, the modification of a human–robot coexistence environment is difficult, mainly because the environment is designed for humans, not for robots. As a result, robotic adaptation to human-centered unstructured environments becomes extremely difficult.
2) Limited resources in a robot. To obtain sufficient information for successful manipulation services, several sensors are required. In addition, the dexterity of manipulation accompanies complicated mechanisms. However, the available sensors and mechanisms with which stand-alone mobile robots are equipped are extremely limited in practice. In general, we cannot use sufficient resources due to the requisite cost and space for installation. Therefore, an appropriate design and control strategy for maximally exploiting available resources is essential for survival in a real environment.
3) Uncertainties in real environments. A real environment provides a lot of uncertainties. For examples, uncertainties include wheel slippage, sensing errors, or modeling errors of a robot arm. Overcoming uncertainties is the ultimate challenge of an autonomous robot.

There have been a number of studies on service robots with mobile-manipulation capabilities. Yamamoto and Yun [4] proposed kinematic/dynamic manipulability to resolve the redundancy in motion planning and analysis for mobile manipulators. In other studies on mobile manipulation, zero-moment point was proposed as a measure for mobile-manipulator systems performing heavy-load transferring tasks [5], [6]. In addition, there have been studies on the stable motion control of a mobile manipulator under unknown external-force application from the environment [7], [8]. Since the mobile manipulation may involve direct contacts with humans in a human-populated environment, it should be compliant enough to guarantee human safety [9], [10].

This paper deals with the autonomous manipulation task that is performed by a mobile-manipulator type of service robotic system in a human–robot coexistence environment. We focus on a door-opening problem. Door-opening control is one of the most difficult tasks of manipulation because the manipulator makes contact with the environment. Our robot is a mobile platform that is equipped with a 6-DOF robotic manipulator and

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W. Chung and S. Park are with the Department of Mechanical Engineering, Korea University, Seoul 136-713, Korea (e-mail: smartrobot@korea.ac.kr; drsspark@korea.ac.kr).

C. Rhee is with the Photolithography Group, Production Base Technology Department, Productivity Research Institute, LG Electronics, Inc., Seoul 150-721, Korea (e-mail: changju.rhee@gmail.com).

Y. Shim is with the Mechatronics and Manufacturing Research Center, Samsung Electronics, Suwon 443-742, Korea (e-mail: ddalbo.shim@samsung.com).

H. Lee is with the Productivity Research Institute, LG Electronics, Inc., Seoul 150-721, Korea (e-mail: hjlee337@lge.com).

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a multifingered hand. To carry out a door opening, position- and force-control problems should be solved. Furthermore, a hand, a manipulator, and a mobile robot should be controlled by an integrated coordinative motion control scheme. In this paper, we clarify the major difficulties of the door-opening problem and propose an integrated control strategy that is applicable in a real environment.

Many researchers investigated on the door-opening control [11], [12]. Kim *et al.* [13] introduced a service robot capable of door opening using compliance control. They employed rather-cheap force sensors for door-opening control. Kobayashi *et al.* [14] has been developing a series of rescue robots named Utility Mobile Robots for Search, since the Great Hanshin-Awaji earthquake in 1995. In their recent version, they implemented a door-opening system using compliant mechanisms. Klingbeil *et al.* [15] developed a vision-based learning algorithm capable of opening various types of doors without prior knowledge of the doors. They reported the success rate of door opening to be larger than 90% with the proposed algorithm. Nagatani and Yuta [16] presented a general approach for the door-opening strategy. It is assumed that the position and the radius of the door are known for opening a door by pushing. A mobile robot moves along a straight reference path. Compliance was applied on the basis of the incremental joint motion that was computed from the inverse Jacobian. To measure the external force, a six-axis force sensor was installed at the wrist of the manipulator [17]. For a manipulator and a mobile robot, 225 target sets of reference trajectories were planned offline prior to movement. Nagatani and Yuta [18] applied the concept of action primitives to deal with discrete behaviors. Images from a vision camera that was mounted on the wrist were obtained to measure the position of the doorknob. These approaches can be understood as the application of conventional compliance control schemes to the door-opening problem. It is assumed that a robotic hand takes a tight hold of a knob, and then, a robotic arm opens the door through compliance control.

Niemeyer and Slotine [19] proposed a simple method by which the system can automatically follow the path of least resistance when the manipulator motion is externally constrained, for example, during door opening. This approach does not require the kinematic model of an object. However, the velocity resolution should be sufficiently high. Under joint backlashes, the method is difficult to implement due to the error in the estimation of the direction of movement. Another door-opening control was presented for a mobile robot called ROMAN, wherein Hanebeck *et al.* [20] presented an overview of a service robot and a module representation. However, with regard to [20], it is difficult to ascertain the detailed control strategy for practical service tasks.

Petersson *et al.* [21] presented the high-level control of a mobile manipulator by relaxing the force control. The use of a hybrid dynamic system is proposed for complicated tasks such as door opening. They demonstrated the intelligent control architecture by finding the doorknob through visual tracking for estimating the parameters for opening the door [22]. They also employed an additional wrist force sensor and applied compliance control schemes. A difference between Nagatani and Yuta's work and the work of Petersson *et al.* is that, in the latter, the mobile robot moves along the estimated arc, and the manipulator configuration remains almost unchanged.

Khatib *et al.* [23], [24] considered a mobile-manipulator system as a macro–micro manipulator and proposed effective dynamic-behavior models on the basis of this concept. Basically, a mobile manipulator is modeled as a 9-DOF robotic system. Including Khatib's work, many of the previous studies on mobile manipulation focus on motion-control problems, rather than deal with uncertainties and application issues for service robots.

Brooks *et al.* [25] reported the development of a mobile-manipulator system, called CARDEA. The system is composed of a base mechanism for locomotion that uses a Segway and a manipulator. The manipulator has a 15-DOF robotic arm that is designed with a series elastic actuator to explore behavior-based methods of mobile and dexterous manipulation in an unstructured environment. Through virtual spring models, human-like compliance was obtained, and the results were experimentally verified. The work in [25] can be understood as a solution that uses a specially designed sophisticated mechanical hardware.

Our door-opening control scheme offers original contributions in relation to prior research. Instead of using the wrist force sensor, we utilize the information from the fingertip-contact force sensor of the multifingered robotic hand. Moreover, an integrated strategy for estimating kinematic parameters is developed on the basis of the active-sensing scheme. A part of this paper was introduced in [26], which was the starting point of this paper.

In this paper, we concentrate on three issues from the viewpoint of service-robot applications. The first issue is to estimate kinematic parameters by the use of an active-sensing strategy. An increase in the number of sensors adds complexity and increases costs. Therefore, we propose active sensing for maximally utilizing limited resources.

The second issue is to provide an integrated strategy of motion coordination. The Public Service Robot (PSR1) is composed of three subsystems, which are a robotic hand, a robotic arm, and a mobile robot. These components have different mechanical characteristics in terms of the workspace, bandwidth, and accuracy. This paper discusses the role assignment and coordination of heterogeneous robot components.

The third issue is to use the fingertip-contact force sensor of the robotic hand, instead of using high-cost force sensor at the wrist. A prevailing approach for estimating the external force is to use a six-axis force sensor at the wrist of the manipulator. In this paper, an external force is estimated by using the fingertip-contact force of the three-fingered robotic hand. The presented experimental results clearly show the effectiveness of the proposed scheme.

The rest of this paper is organized as follows. In Section II, our robotic platform, PSR1, is presented. The developed multifingered robotic hand plays a dominant role in door-opening control. In Section III, the integrated control strategy of door opening is described. After a brief introduction to the door-opening scenario, a kinematic-parameter estimation scheme is explained. Experimental results are discussed in Section IV. Some concluding remarks are presented in Section V.

Fig. 1. PSR1 robot system.

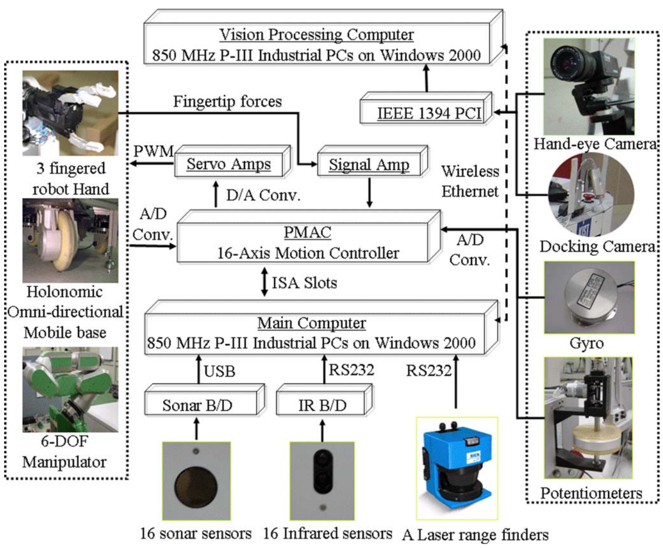


Fig. 2. Hardware architecture of the PSR1 robot system.

II. PSR1 Robot System

An autonomous service-robot platform PSR1 has been developed, as shown in Fig. 1. The robot is a modular, reconfigurable, and fully autonomous system. It is composed of a holonomic omnidirectional mobile platform and a 6-DOF robotic manipulator that is equipped with a multifingered robot hand.

The overall hardware configuration of the PSR1 system is shown in Fig. 2. A laser range finder is installed for navigation. An eye-in-hand camera system is installed at the manipulator wrist to recognize objects for manipulation. In order to obtain real-time control performance of the low-level control, the commercialized motion-board PMAC system is adopted. It controls all 14 servomotors and provides a sensor interface. The PC and PMAC are connected through a serial communication.

The mobile platform is designed to have omnidirectional mobility. Two active caster modules and two passive casters are equipped to achieve holonomic omnidirectional movement. A 6-DOF robot manipulator is developed, and a special design is employed to keep the arm folded during navigation. Since the robot operates in human-centered environment, it is advantageous for the robot to possess humanlike physical dimensions. Therefore, the length of the upper arm link was 330 mm and that of the forearm link was 370 mm. The attachment configuration to the mobile robot was carefully designed under the consideration of the manipulator workspace.

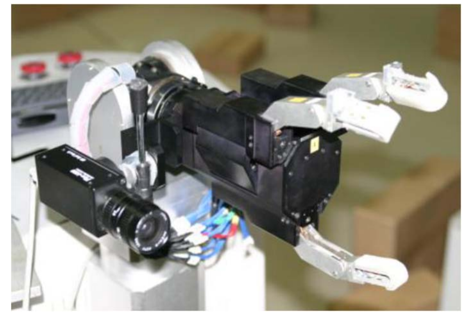


Fig. 3. Prototype of the multifingered robot hand with a CCD camera.

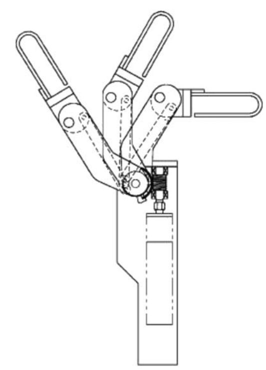


Fig. 4. Curling motion of the finger.

Fig. 3 shows the prototype of the three-fingered robot hand. The hand is compact, and it is capable of grasping various objects. Each finger consists of one active and one passive joint. The first joint of each finger is driven by a dc servomotor using the worm gear. The second joint is passively driven by the four-bar linkage mechanism, and the second joint angle is dependent on the first joint. The passive-joint design is motivated by a human's finger. In the case of human, the third joint of an index finger is passively driven by the second joint. The physical dimensions were designed on the basis of the workspace analysis of the human hand. Through numerical simulations, optimal link parameters to achieve humanlike finger motions were derived. The optimal length of the base link is 50 mm and that of the distal link is 60 mm.

Fig. 4 shows the curling motion of the finger. The working range of the active joint is 70° and that of the passive joint is 120°. The maximum joint angular velocity of the first joint is 13.3°/s. The maximum continuous fingertip force is 22.3 N. The kinematic design parameters of the finger were carefully determined to handle objects with various shapes such as cylinder, block, paper, and doorknobs. The thumb is fixed on the palm. The other two fingers make a symmetrical lateral motion for grasping objects with various shapes. A parallel four-bar linkage mechanism is used to change the distance between two fingers.

Fig. 5 shows the widest configuration of the fingers when viewed from the top of the robot hand toward the palm. At this time, the distance between the two fingers is 99 mm. A pair

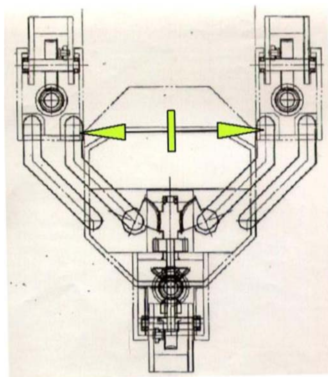


Fig. 5. Symmetrical lateral motion.

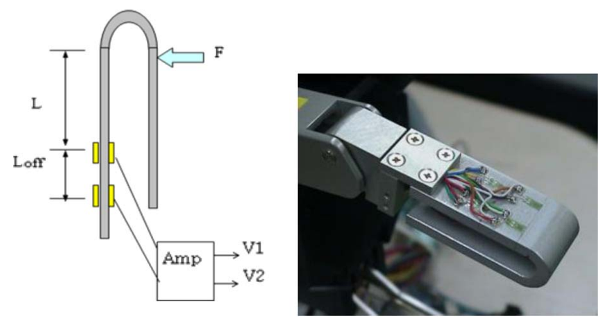


Fig. 6. Fingertip sensor system for estimating the contact force and the contact position.

of worm gears symmetrically drives both left and right linkage mechanisms.

The embedded force sensor using strain gauges is designed to measure the fingertip force and the contact position even if the force is applied to an arbitrary position of the distal link. The sensor consists of eight strain gauges that are attached to the surface of the distal link, as shown in Fig. 6. We can measure the output voltages of the bridge circuit, which are proportional to the bending moment of the cantilever. Once output voltages V_1 and V_2 are obtained, then contact distance L and contact force F are obtained as follows:

$$L = \frac{V_2 L_{\text{off}}}{V_2 - V_1} \qquad F = \frac{V_2 - V_1}{K L_{\text{off}}} \tag{1}$$

where K is determined by the amplification gain and the gauge factor. The details of the finger design are shown in [27]–[29]. PSR systems and the scope of research are introduced in [30]–[32].

III. Door-Opening Control

A. Overview of Proposed Door-Opening Control Strategy

The major purpose of this section is to clarify how to control and coordinate the behaviors of each robotic component. We first analyze the physical characteristics of the components. Table I represents the functional categorization. For example, if we consider the workspace, the motion range of the arm is larger than that of the robot hand but smaller than that of the mobile base. In addition, the robotic hand is suitable for high speed and fine motion when compared to the robotic arm. On

TABLE I
Functional Categorization of Subsystems

	HAND	ARM	MOBILE
Main function	Grasping	Manipulation	Moving
Workspace dimension	10~20 cm	Smaller than 1.3 m	Unlimited
Weight	1 kg	25 ~ 30 kg	Over 100 kg
Positioning accuracy	5 mm	10 ~ 30 mm	Over 100 mm
Cycle time of motion control	480 μs	25~50 ms	100 ~ 200 ms

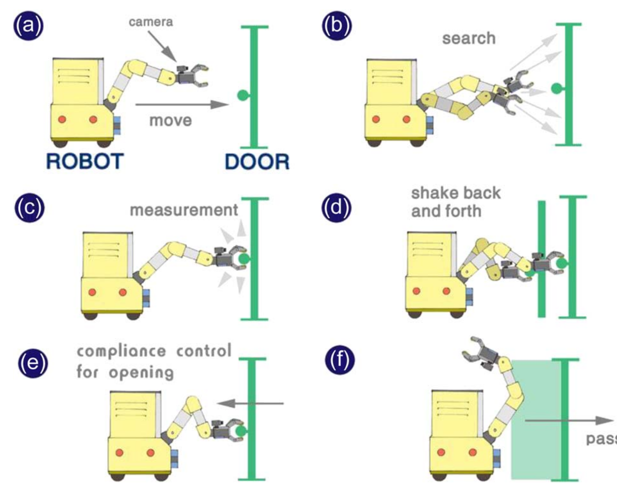


Fig. 7. Scenario for passing through the door.

the other hand, a mobile base has relatively slow response and inaccurate motion. Table I clearly shows that an appropriate role assignment is essential. Basically, the operations that require fast and small-scale motion are assigned to the hand, while large-scale motion is carried out by the mobile-base and arm components.

Fig. 7 shows a description of the scenario of our door-opening process. The shape of a doorknob is limited to a cylindrical one. A brief explanation of each phase is given as follows.

Phase A) First, the mobile robot moves to the desired position in front of the door by using the navigation capability. The maximum positioning error is about 200 mm. In fact, the error range is acceptable for most indoor-navigation purposes. However, the range is not narrow enough for the grasp of a doorknob.

Phase B) To overcome the positioning errors of the mobile robot, the robot measures the doorknob position by using a charge-coupled device (CCD) monovision camera that is mounted on the wrist of the hand. However, the accuracy of the vision system depends on the light condition. The system also has inherent errors (about 20 mm), which may result in failures in grasping. A firm grasp of a doorknob is also difficult due to the positioning error of the manipulator.

Phase C) To assure a firm grasp at the appropriate position, the robotic hand estimates the shape of the doorknob by repeatedly touching the knob and measuring the fingertip forces. Based on the measured data, the hand

TABLE II
ROLE ASSIGNMENT OF COMPONENTS

Phase	Action	HAND	ARM	MOBILE
A	Moving	Idle	Idle	
B	Searching	Idle	Position control	Idle
C	Measuring	Position/force control	Position control	Idle
D	Pulling	Grasp force control, Position measurement	Position control	Idle
E	Opening	Grasp force control	Position/force control	Idle
F	Passing	Position control	Position control	Position control

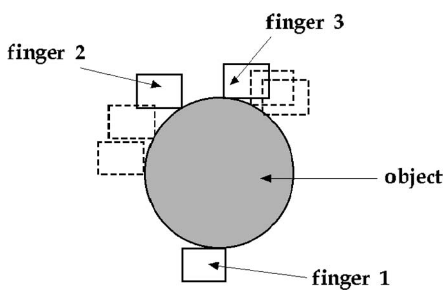


Fig. 8. Shape detection of an object through touching.

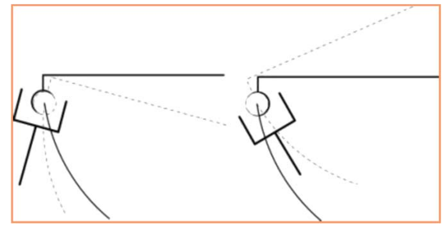


Fig. 9. Illustration of different configurations for grasping.

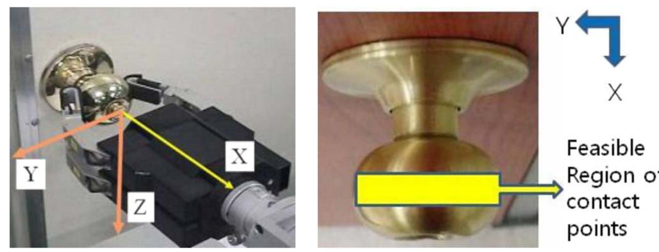


Fig. 10. Definition of the global coordinate system.

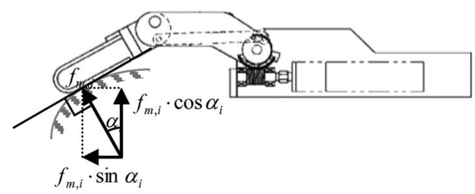


Fig. 11. Fingertip force at the contact point.

calculates the geometric shape of the doorknob with respect to the hand coordinates. After detecting the shape of the doorknob, the robotic hand moves to a central position of the doorknob for stable grasping. The resultant positional error of this active sensing through touching was less than 5 mm from our experiments; this will be explained in Section IV.

Phase D) In this phase, the robot searches for the positions of door hinges relative to itself by measuring the fingertip forces while slightly pulling the doorknob. The knob position is estimated by a fingertip movement, by the maintenance of a desired constant grasping force. The position of a door hinge can be computed from the measured trajectory of the knob. From the estimated geometric configuration of a door, the entire reference trajectory of the manipulator can be generated. To simplify the problem, we assume that the size and direction of opening of the door are known. Steps C) and D) are designed by the imitation of the behavior of a human when s/he tries to find out the exact position of a doorknob and tightly grasps it in the absence of lighting. Generally, the human behavior includes three basic functions, which are as follows: exploring, restraining an object, and manipulating the object.

Phase E) Since there are errors in the estimation of the trajectory and the positioning of the manipulator, a force controller is simultaneously adopted along with a position controller. A force controller guarantees safe manipulation by preventing excessive contact force at the fingertip. We exploited fingertip-contact force sensors for measuring external forces, whereas most conventional door-opening schemes use a force sensor at the wrist. Although the fingertip force sensors were originally developed for the stable grasping of an object, we also used the sensors for measuring external forces. This is an illustration of our efficient use of the limited resources that are available.

Table II summarizes the resultant role assignment of hardware components throughout the earlier door-opening scenario. It can be seen that each component serves totally different functions depending on the control phases.

B. *Sensing Schemes for Kinematic-Parameter Estimation*

In this section, we describe two kinds of online kinematic-parameter estimations through active-sensing schemes. The first is to estimate the center position of the doorknob for the stable grasping of the doorknob by the multifingered hand. The other is to estimate the hinge position of the door by the pattern of hand–arm coordination. By the estimation of the hinge position of the door, a reference trajectory of the doorknob can be computed.

A multifingered robotic hand grasps the doorknob after the approximate location is found out through the visual information from the camera. A kinematic-parameter estimation is subdivided into two problems. One is to find out the center position of the doorknob by groping for it. This is similar to the case where a person gropes around in a dark room for detecting the shape of an object by touching. Fig. 8 shows a conceptual illustration of shape detection through touch. Once the object shape is detected, a robotic hand can be moved to the most desirable configuration for grasping.

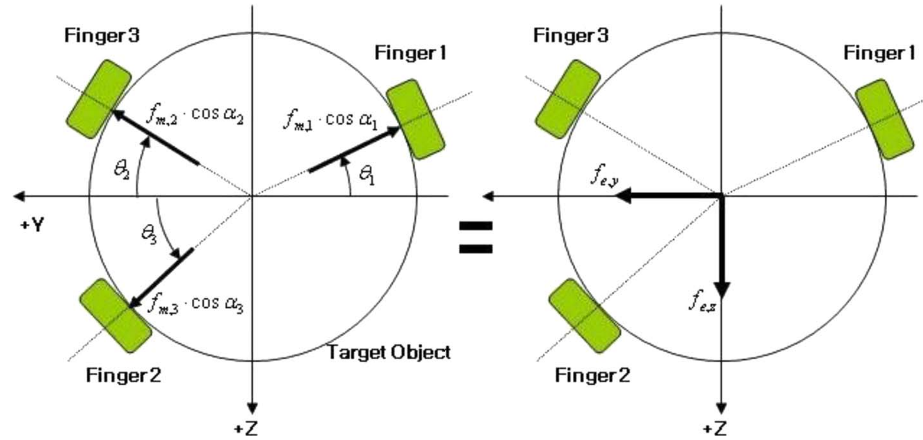


Fig. 12. Fingertip force equilibrium on the local Y–Z plane.

The second estimation problem is to find out the reference trajectory of the doorknob. This problem is equivalent to finding out the position of the door hinge when the door size is known. Fig. 9 shows that the robot can hold the doorknob from different configurations. Therefore, the estimation of the trajectory of the end-effector is required in practice. Once the hand successfully grasps a doorknob, the manipulator slowly pulls and pushes the doorknob by open-loop position control. The hand performs explicit force control to maintain a constant desired grasping force between the fingers and the doorknob. As a result, the finger-joint angles are changed with respect to the trajectory of the doorknob. Appropriate calibration of the fingertip position leads us to the estimation of the doorknob trajectory.

C. Door Opening Under Application of Hybrid Position/Force Control

We show the definition of the global coordinate system in Fig. 10. At the initial stage, the local coordinate of the hand is located at the same configuration with the global coordinate system. The experimental motion of the hand and the arm will be shown with respect to the global coordinate system in Fig. 10. The pulling motion is applied to the direction of positive X. Force control of fingers is carried out in Y–Z plane.

In the experiment, it is assumed that the contact points draw a circle in the Y–Z plane. In order to assure a stable grasp, the allowable region of the contact points should be located in the narrow region on the doorknob, as shown in Fig. 10. The width of the feasible region of contact points in Fig. 10 is only 10 mm. Therefore, the grasp problem can be considered in the Y–Z plane.

In phase E), the robot hand firmly grasps the doorknob. The manipulator pulls the doorknob under the application of the hybrid force/position control scheme in [33]. The control objective of phase E) is to pull a door while minimizing the external forces exerted to the fingers. Therefore, the robot arm should be controlled to track the estimated target trajectory of the end-effector. In addition, the external forces exerted from the door to the fingers should not exceed the allowable limit.

Fig. 11 shows the contact force and its components for one finger. $f_{m,i}$ is the contact force at ith fingertip, and α_i is the angle between the ith contact force and the local Y–Z plane. Fig. 12 shows the force equilibrium of contact forces in the local Y–Z plane. Since the operating speed of the robot arm is slow, the following static equilibrium conditions are considered:

$$\begin{aligned} f_{e,x} &= -f_{m,1}\sin\alpha_1 - f_{m,2}\sin\alpha_2 - f_{m,3}\sin\alpha_3 \\ f_{e,y} &= -f_{m,1}\cos\alpha_1\cdot\cos\theta_1 + f_{m,2}\cos\alpha_2\cdot\cos\theta_2 \\ &\quad + f_{m,3}\cos\alpha_3\cdot\cos\theta_3 \\ f_{e,z} &= -f_{m,1}\cos\alpha_1\cdot\sin\theta_1 - f_{m,2}\cos\alpha_2\cdot\sin\theta_2 \\ &\quad + f_{m,3}\cos\alpha_3\cdot\sin\theta_3. \end{aligned} \tag{2}$$

$F = (F_X, F_Y, F_Z)^{\mathrm{T}}$ is the reaction force to the hand. F_X is assumed to be zero because our scope is limited to the local Y–Z plane. If F is too large, the robot arm should be driven to the direction of F. Since our control hardware allows only position control of joints, target pose of the end-effector should be derived in order to compensate F

$$\Delta\overline{p} = (\Delta x_e, \Delta y_e, \Delta z_e)^{\mathrm{T}} = K_p \cdot \Delta F \tag{3}$$

where

$$K_p = \mathrm{diag}(k_{p,x}, k_{p,y}, k_{p,z}) \in R^{3\times3} : \text{force-position gain.}$$

Equation (3) gives the small displacement vector of the hand to compensate $\overline{f}_e$. Since $\Delta\overline{p}$ is defined in the local Y–Z plane of the hand, the joint space-displacement vector should be computed as $\Delta\overline{p} = J\cdot\Delta\overline{q}$, where $\Delta\overline{q} \in R^{6\times1}$, $J \in R^{3\times6}$: Jacobian.

The final step is to add $\Delta\overline{q}$ to the reference door-opening trajectory. Since there are many candidate solutions in $\Delta\overline{q}$, the minimum norm solution is adopted by the use of as follows:

$$\Delta\overline{q} = J^{\mathrm{T}}\cdot(J\cdot J^{\mathrm{T}})^{-1}. \tag{4}$$

The optimal solution is closest to the originally computed reference path. The proposed control scheme is summarized in the block diagram shown in Fig. 13.

IV. Experimental Result

The proposed strategy was experimentally tested on the PSR1 platform. Experiments were carried out in an office environment. The mobile robot reached in front of the door after

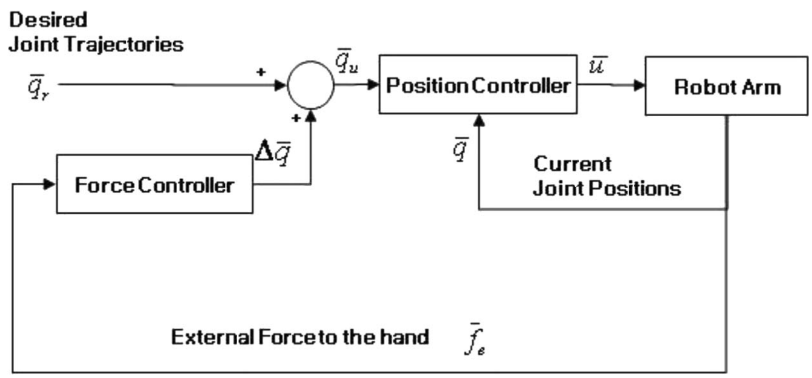


Fig. 13. Block diagram of hybrid force/position control strategy.

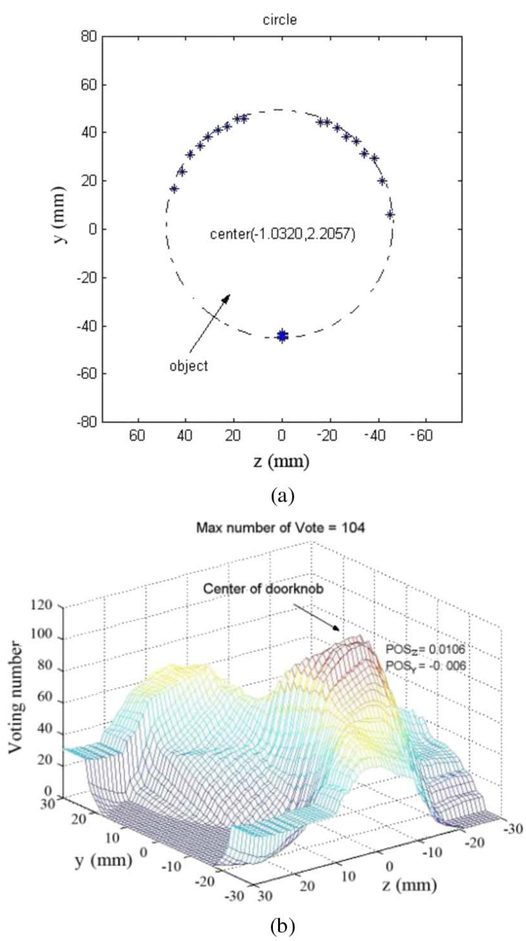


Fig. 14. Result of shape detection through touching. (a) Shape detection through multiple touching of a circular object. (The dotted points represent the positions of fingertip contact.) (b) Voting result through the Hough transform for estimating the center.

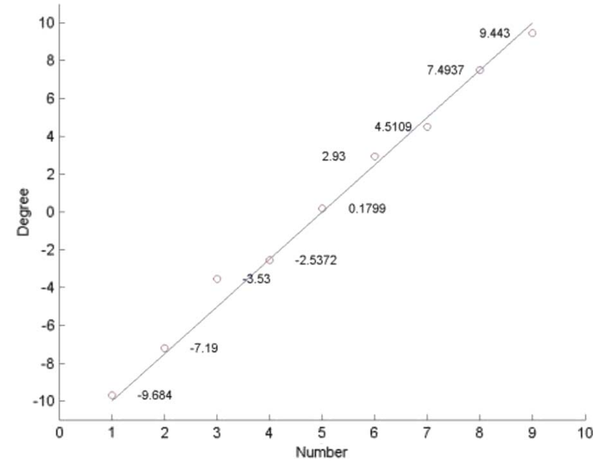


Fig. 15. Experimental results of the estimation of door orientation.

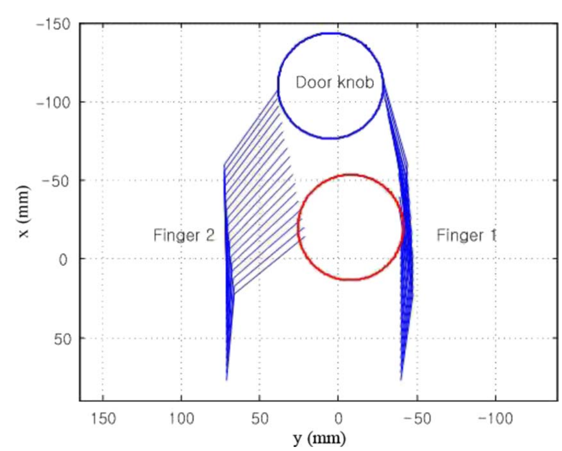


Fig. 16. Experimental finger motions in R^2 during the pulling trial motion.

completing phase A) of the proposed scenario shown in Fig. 7. Then, the approximate pose of the doorknob was estimated on the basis of the visual information from the eye-in-hand camera.

In phase C) of the proposed scenario shown in Fig. 7, the fingertip-contact points draw the circular shape of the doorknob. In order to estimate the center of a circle, the Hough transform is carried out. Fig. 14(a) shows that the circular object can be detected through multiple touching. The nominal diameter of the circle is initially given (46.5 mm). From the result of the Hough transform, the estimated center point is $[z, y] = [-1.0, 2.2]$.

Once the center is obtained, the least square method is applied to estimate the diameter of the contact point circle. The estimation result of a diameter was 47.1 mm. If the robot fails to make contacts in the feasible region in Fig. 10, the least square estimation of the contact circle diameter shows great difference with the nominal diameter. In such cases, the robot should repeat phase B).

In general, the error of visual pose estimation at phase B) is about 20 mm. In order to guarantee stable-grasping configurations, the positioning accuracy of the robot hand should be on the order of millimeters. The error of visual estimation at phase B) can be compensated through the estimation by

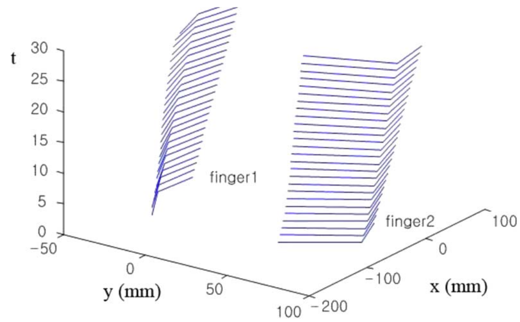


Fig. 17. Experimental finger motions in $R^2 \times t$ during the pulling trial motion.

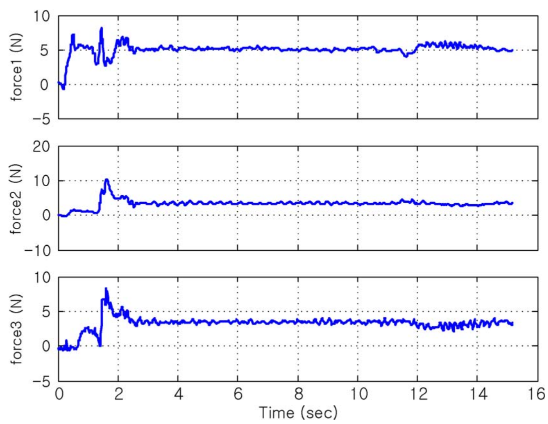


Fig. 18. Measured contact force during the pulling trial motion.

touching in phase C). The overall estimation error after phase C) could be decreased to the order of millimeters.

Pulling the door is a behavior that finds the relative position and orientation between the robot and the door. It is assumed that the initial orientation error after the mobile-robot positioning is less than $\pm 10^{\circ}$. Experiments were carried out nine times for different door orientations. Fig. 15 shows the results of door-hinge estimation for different orientations. The x-axis is the relative orientation between the door and the robot. Circles on the figure denote the estimated orientation. The straight line represents the real orientation. The resultant error of estimation is about $-0.5 \sim 1.5^{\circ}$. This fact implies that sufficient accuracy for computing the reference trajectory of the door opening was achieved.

Figs. 16 and 17 show the finger motions with respect to time. It is shown that the finger configuration is changed by following the doorknob trajectory in order to maintain stable configuration for grasping. Throughout the experiment, the desired maximum contact force of each finger is limited to 10 N. Fig. 18 shows the fingertip-contact forces during the experiment. In Fig. 18, the force1, force2, and force3 indicate measured contact forces from finger 1, finger 2, and finger 3, respectively. Suppose that the robot hand is the right hand of a human. Finger 1, finger 2, and finger 3 are the thumb, the index finger, and the middle finger, respectively. It is clear that the contact force is maintained within the desired limit.

In order to visualize the door-opening motion in phase E), the top view of the manipulator configurations are shown in Fig. 19. The manipulator pulls the doorknob from the initial configuration to the final configuration. There are three links

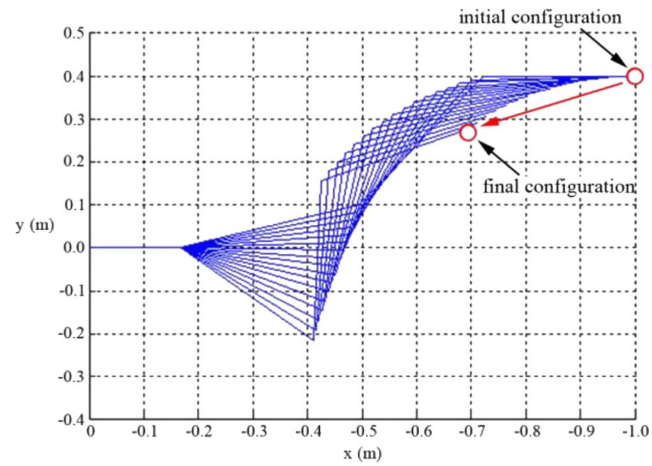


Fig. 19. Experimental result of manipulator configurations.

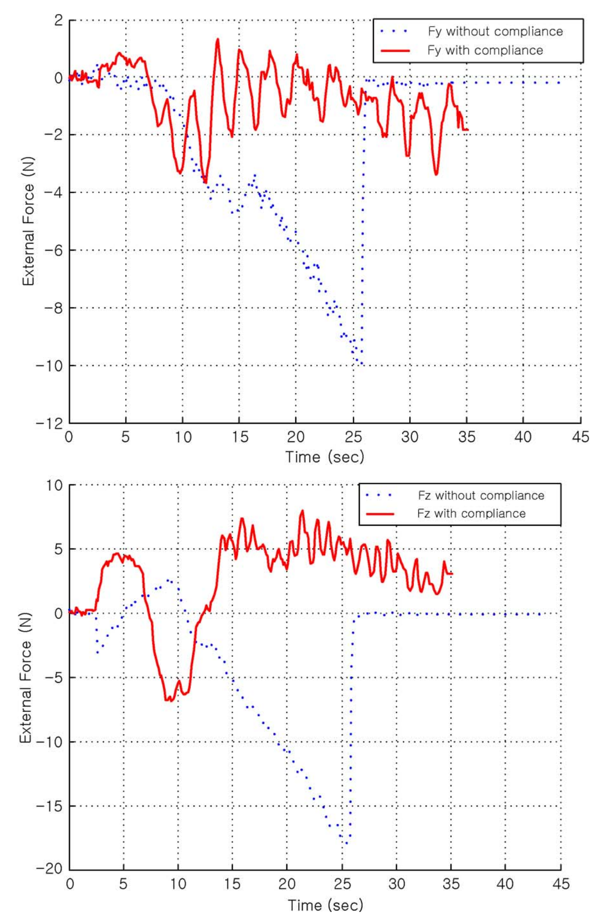


Fig. 20. Comparison of external forces with and without the compliance control.

in the projected image of the manipulator in Fig. 19. The three links are the upper arm link, the forearm link, and the hand. The moving distance of the doorknob was about 0.3 m, and the angle of door opening was about 25°.

In Fig. 20, the solid line shows the result of the measured external forces F_Y and F_Z at the fingertip with compliance control, and the dotted line shows the corresponding result under position control only. F_Y and F_Z were defined in Section III-C. Since the force control is carried out in Y–Z plane, it is required to maintain appropriate F_Y and F_Z during phase E).

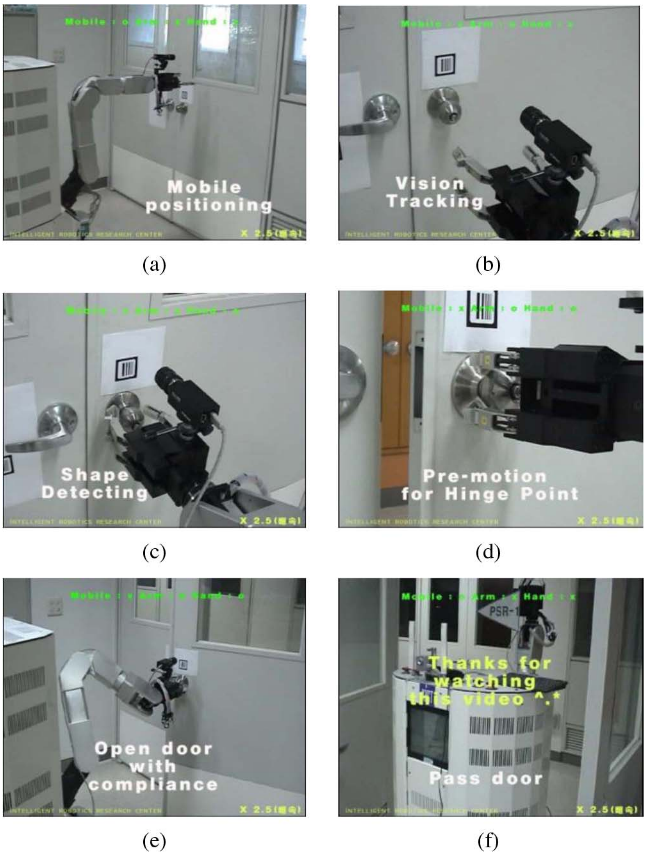


Fig. 21. Door-opening experiment with the proposed motion control strategy. (a) Mobile robot positioning. (b) Visual recognition. (c) Estimation of the knob shape. (d) Estimation of the hinge position. (e) Compliance control of the arm. (f) Passing through the door.

The dotted line shows that the use of position control only can cause an excessive reaction force at the fingertip due to the positional error. The robotic hand releases the doorknob in the case of excessive external force, i.e., 20 N or higher. The sources of failure include the error of trajectory estimation, the positioning error of the manipulator, and so forth. In order to deal with various uncertainties, the manipulator was controlled by applying the proposed compliance control scheme in Section III-C. From Fig. 20, it is clear that the maximum F_Y and F_Z under the proposed compliance control are smaller than 10 N. This result indicates that the robot fingers successfully grasp the doorknob throughout the motion without excessive reaction force from the door.

Fig. 21 shows the overview of the door-opening experiment. Each control scheme in Fig. 21(a)–(f) corresponds to the strategy in the proposed scenario which was presented in Section III-A. Fig. 21 shows the implementation of the scheme shown in Fig. 7. In practical applications, the door opening at phase E) is insufficient to open the door fully. Therefore, a heuristic motion control scheme to open the door was added between phases E) and F).

Before we developed the kinematic-parameter estimation schemes, the success rate of door-opening control was less than 50% due to accumulated errors. However, the overall success rate increased up to more than 90% after the application of the proposed estimation and control schemes. This result clearly shows the usefulness of the proposed methodologies.

V. Conclusion

In this paper, a control strategy for the procedure of opening a door by a mobile manipulator has been proposed. A mechanical design of a three-fingered robot hand is established, and the hand is adopted as a useful end-effector for door opening. An integrated strategy of motion coordination was presented on the basis of the investigation of each robotic component. A practical door-opening control was proposed, and the usefulness was verified through an experiment. The force and position control were successfully carried out through the contact force of a multifingered robotic hand, instead of using a wrist force sensor. Two active-sensing schemes were proposed in order to overcome various uncertainties in a real environment, and they were experimentally verified.

References

[1] R. C. Luo and K. L. Su, "Multilevel multisensor-based intelligent recharging system for mobile robot," *IEEE Trans. Ind. Electron.*, vol. 55, no. 1, pp. 270–279, Jan. 2008.

[2] F. J. Berenguer and F. M. Monasterio-Huelin, "Zappa, a quasi-passive biped walking robot with a tail: Modeling, behavior, and kinematic estimation using accelerometers," *IEEE Trans. Ind. Electron.*, vol. 55, no. 9, pp. 3281–3289, Sep. 2008.

[3] W. L. Xu, J.-S. Pap, and J. Bronlund, "Design of a biologically inspired parallel robot for foods chewing," *IEEE Trans. Ind. Electron.*, vol. 55, no. 2, pp. 832–841, Feb. 2008.

[4] Y. Yamamoto and X. Yun, "Unified analysis an mobility and manipulability of mobile manipulators," in *Proc. IEEE/RSJ Int. Conf. Robot. Autom.*, Detroit, MI, May 10–15, 1999, pp. 1200–1206.

[5] H. Todoroki, K. Yokoi, K. Komoriya, and R. Murata, "Development of an indoor mobile platform and its posture control," presented at the ROBOMECH Conf., Japan, 2000, 2P2-41-052.

[6] Q. Huang, K. Tanie, and S. Sugano, "Coordinated motion planning for a mobile manipulator considering stability and manipulation," *Int. J. Robot. Res.*, vol. 19, no. 8, pp. 732–742, Aug. 2000.

[7] F. Inoue and T. Murakami, "A motion control of mobile manipulator with external force," *IEEE/ASME Trans. Mechatronics*, vol. 6, no. 2, pp. 137–142, Jun. 2001.

[8] R. Jamisola, M. Ang, D. Oetomo, O. Khatib, T. Lim, and S. Lim, "The operational space formulation implementation to aircraft canopy polishing using a mobile manipulator," in *Proc. IEEE Int. Conf. Robot. Autom.*, Washington, DC, May 11–15, 2002, pp. 400–405.

[9] K. Suita, H. Ikeda, N. Tsuchida, and N. Sugimoto, "A failure-to-safety 'Kyozon' system with simple contact detection and stop capability for safe human–autonomous robot coexistence," in *Proc. IEEE Int. Conf. Robot. Autom.*, Nagoya, Japan, May 21–27, 1995, pp. 3089–3096.

[10] K. Inoue, T. Miyamoto, and Y. Okawa, "Impedance control of mobile manipulator with the stability to external force," in *Proc. IEEE Int. Conf. Intell. Robot. Autom.*, Osaka, Japan, Nov. 4–8, 1996, pp. 721–728.

[11] W. Chung, G. Kim, and M. Kim, "Development of the multi-functional indoor service robot PSR systems," *Auton. Robots*, vol. 22, no. 1, pp. 1–17, Jan. 2007.

[12] G. Liu, X. He, J. Yuan, S. Abdul, and A. A. Goldenberg, "Development of modular and reconfigurable robot with multiple working modes," in *Proc. IEEE/RSJ Int. Conf. Robot. Autom.*, Pasadena, CA, May 19–23, 2008, pp. 3502–3507.

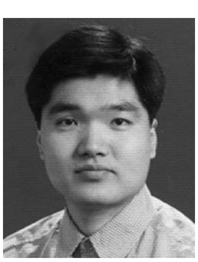
[13] D. Kim, J. Kang, C. Hwang, and K. Park, "Mobile robot for door opening in a house," in *Knowledge-Based Intelligent Information and Engineering Systems*, vol. 3215, LNAI. New York: Springer-Verlag, Oct. 2004, pp. 596–602.

[14] S. Kobayashi, Y. Kobayashi, Y. Yamamoto, T. Watanabe, Y. Ohtsubo, T. Inoue, M. Yasuda, and Y. Takamori, "Development of a door opening system on rescue robot for search 'UMRS-2007'," in *Proc. SICE Annu. Conf.*, Tokyo, Japan, Aug. 20–22, 2008, pp. 2062–2065.

[15] E. Klingbeil, A. Saxena, and A. Ng, "Learning to open new doors," presented at the Proc. AAAI 17th Annu. Robot Workshop Exhib., Chicago, IL, Jul. 13–17, 2008.

[16] K. Nagatani and S. Yuta, "Designing a behavior to open a door and to pass through a door-way using a mobile robot equipped with a manipulator," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Munich, Germany, Sep. 12–16, 1994, pp. 847–853.

[17] K. Nagatani and S. Yuta, "An experiment on opening-door-behavior by an autonomous mobile robot with a manipulator," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Pittsburgh, PA, Aug. 5–9, 1995, pp. 45–50.
[18] K. Nagatani and S. Yuta, "Designing strategy and implementation of mobile manipulator control system for opening door," in *Proc. IEEE Int. Conf. Robot. Autom.*, Minneapolis, MN, Apr. 22–28, 1996, pp. 2828–2834.
[19] G. Niemeyer and J. J. E. Slotine, "A simple strategy for opening an unknown door," in *Proc. IEEE Int. Conf. Robot. Autom.*, Albuquerque, NM, Apr. 20–25, 1997, pp. 1448–1453.
[20] U. Hanebeck, C. Fischer, and G. Schmidt, "Roman: A mobile robotic assistant for indoor service applications," in *Proc. IEEE Int. Conf. Intell. Robots Syst.*, Grenoble, France, Sep. 7–11, 1997, pp. 518–525.
[21] L. Petersson, D. Austine, and D. Kragic, "High-level control of a mobile manipulator for door opening," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Takamatsu, Japan, Oct. 31–Nov. 5, 2000, pp. 2333–2338.
[22] L. Petersson, D. Austine, D. Kragic, and H. I. Christensen, "Towards an intelligent service robot system," in *Proc. Int. Conf. Intell. Auton. Syst.*, Venice, Italy, Jul. 25–27, 2000, pp. 704–709.
[23] O. Khatib, "Mobile manipulation: The robotic assistant," *J. Robot. Auton. Syst.*, vol. 26, no. 2/3, pp. 175–183, Feb. 1999.
[24] O. Khatib, K. Yokoi, O. Brock, K. Chang, and A. Casal, "Robots in human environment: Basic autonomous capabilities," *Int. J. Robot. Res.*, vol. 18, no. 7, pp. 684–696, Jul. 1999.
[25] [Online]. Available: http://www.ai.mit.edu/projects/cardea/index.shtml
[26] C. Rhee, Y. Shim, W. Chung, and M. Kim, "Door opening control using the multi-fingered robotic hand for the indoor service robot," in *Proc. IEEE/RSJ Int. Conf. Robot. Autom.*, New Orleans, LA, Apr. 26–May 1, 2004, pp. 4011–4016.
[27] W. Chung, M. Kim, B. Kang, C. Lee, and H. Lee, "Robot hand and robot hand finger," U.S. Patent 6 918 622, Jul. 19, 2005.
[28] W. Chung, M. Kim, B. Kang, C. Lee, and H. Lee, "Robot hand and robot hand finger," Japan Patent 3 721 354, Aug. 16, 2005.
[29] W. Chung, M. Kim, B. Kang, C. Lee, and H. Lee, "Multi-fingered robot hand," Korea Patent 10-2001-0069841, Sep. 2004.
[30] D. Lee and W. Chung, "Discrete status based localization for indoor service robots," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1737–1746, Oct. 2006.
[31] G. Kim and W. Chung, "Tripodal schematic control architecture for integration of multi-functional indoor service robots," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1723–1736, Oct. 2006.
[32] A. J. Schmid, N. Gorges, D. Göger, and H. Wörn, "Opening a door with a humanoid robot using multi-sensory tactile feedback," in *Proc. IEEE Int. Conf. Robot. Autom.*, Pasadena, CA, May 19–23, 2008, pp. 285–291.
[33] M. W. Spong and M. Vydyasagar, *Robot Dynamics and Control*. Hoboken, NJ: Wiley, 1989, pp. 255–256.



Woojin Chung (M'05) received the B.S. degree from the Department of Mechanical Design and Production Engineering, Seoul National University, Seoul, Korea, in 1993 and the M.S. and Ph.D. degrees from the Department of Mechano-Informatics, The University of Tokyo, Tokyo, Japan, in 1995 and 1998, respectively.

From 1998 to 2005, he was a Senior Research Scientist with the Korea Institute of Science and Technology, Seoul. Since 2005, he has been with the Department of Mechanical Engineering, Korea University, Seoul. His research interests include the design and control of nonholonomic underactuated mechanical systems, trailer-system design and control, and mobile-robot navigation.

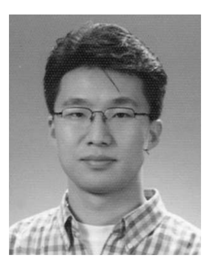
Dr. Chung was the recipient of the Excellent Paper Award from the Robotics Society of Japan in 1996 and the King-sun Fu Memorial Best Transactions Paper Award from the IEEE Robotics and Automation Society in 2002.

Changju Rhee received the B.S. degree from the Department of Mechanical Engineering, Wonkwang University, Iksan, Korea, in 1997 and the M.S. degree from the Department of Mechanical Engineering, Hanyang University, Seoul, Korea, in 2003.

From 2000 to 2004, he was a Research Scientist with the Korea Institute of Science and Technology, Seoul. Since 2004, he has been with the Photolithography Group, Production Base Technology Department, Productivity Research Institute, LG Electronics, Inc., Seoul, where he first joined as a Junior Research Engineer. His research interests include the design and control of mechanical systems and a system integration of intelligent systems.

Youngbo Shim was born in Incheon, Korea, in 1970. He received the B.S. and M.S. degrees from the Department of Mechanical Design and Production Engineering and the Ph.D. degree from the Schools of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Korea, in 1994, 1996, and 2002, respectively.

He was a Postdoctoral Researcher with the Advanced Robotics Research Center, Korea Institute of Science and Technology, Seoul, in 2002. In 2003, joined SAMSUNG Advanced Institute of Technology, where he was a Senior Researcher in the field of robot motion control. Since 2004, he has been with the Mechatronics and Manufacturing Research Center, Samsung Electronics, Suwon, Korea. His research interests include the design of robot mechanisms for human–robot interaction, particularly in terms of safety and the dynamic analysis and control of robot manipulators.



Hyungjin Lee was born in Seoul, Korea, in 1973. He received the B.S. degree in mechanical engineering from Kyunghee University, Seoul, in 2000 and the M.S. degree from the Department of Mechanical Engineering, Yonsei University, Seoul, in 2002.

From 1999 to 2001, he was a Research Scientist with the Advanced Robotics Research Center, Korea Institute of Science and Technology, Seoul. In 2002, he joined the Productivity Research Institute, LG Electronics, Inc., Seoul, where he is currently a Senior Research Engineer.

Shinsuk Park received the B.S. and M.S. degrees in mechanical design and production engineering from Seoul National University, Seoul, Korea, in 1989 and 1991, respectively, and the Ph.D. degree in mechanical engineering from Massachusetts Institute of Technology, Cambridge, in 1999.

From 2000 to 2002, he was a Postdoctoral Research Fellow with the Biorobotics Laboratory, Harvard University, Cambridge. From 2002 to 2004, he was a Visiting Assistant Professor with the Department of Mechanical Engineering, Keio University, Yokohama, Japan. He is currently an Associate Professor with the School of Mechanical Engineering, Korea University, Seoul. His research interests include dynamics systems and control and their applications to human–machine interface design and biomedical-engineering problems.