Paper:

Home-Use Object Transfer/Storage Robot System with Compliant Strategy and Mechanism

(Commodities Management and its Extended Application of Daily Life Support for the Elderly)

Rui Fukui, Taketoshi Mori, and Tomomasa Sato

Department of Mechano-Informatics, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan
E-mail: fukui@ra-laboratory.com, tmori@ics.t.u-tokyo.ac.jp, tomomasasato@jcom.home.ne.jp
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This research describes the strategy and mechanism design methodology to realize a robot system that transfers and stores daily use objects in our living space. Unlike industrial applications, there are three specific problems in the home application: (1) variation of living environment, (2) diversity of daily use objects, (3) dispersion of human activity. First, we presented a concept of strategic compliance as a basic solution for these problems and extracted three fundamental functions (regulation, assist/enforce, and navigation) for the strategy. Second, we aimed to realize a robust robot motion by introducing adequate mechanisms which are suitable for the strategy. The mechanisms are; (1) passive mechanical compliance and (2) object constraint methodology with "caging." As an actual prototype system, a home-use logistical support robot system implemented with those strategies and mechanisms is constructed. By experiments, validity of the presented methodology was confirmed. In addition to the domestic logistical application, we considered applying the proposed system to the elderly people support, and developed prototypes of supporting instruments; lavatory and refrigerator containers. The basic design of the instruments is also introduced.

Keywords: intelligent environment, home robot, manipulation, compliance, caging

1. Introduction

In recent years, more and more people are obliged to live in environments abundant with commodities and information. While living environments in urban cities are worsening in terms of living areas and costs, consumers are exposed to a flood of information on commodities to encourage them into shopping with a result of overflowing commodities. This in turn takes people more and more effort and time in their storage and management. This research is aimed to develop a robot system (home-use logistical support robot system) to help solve various problems over the abundance of commodities in particular.

In general, robot systems are expected to have the following advantages to provide fundamental solutions to the above-mentioned problems: (1) commodities could be handled and stored in a way and mechanism that is not possible with human beings, for example, commodities could be stored in high places, under the roof or under the floor, which are normally not available to human beings for storage, to achieve a high spatial efficiency; and (2) unlike ambiguous human memories, external storage equipment would enable us to use commodity management information technologies which are free from memory obscurity.

The robot system to be developed in this research could also be applied to daily life support of the elderly who would find it physically difficult to gain access to commodities as they get older and physically deteriorated. This paper therefore elaborates on the feasibilities in use of the proposed robot system for daily life support of the elderly.

In order to realize such robot systems, it is essential to work out proper strategies for the entire system to overcome numerous problems as well as to refine element technologies for the robot. In this research, therefore, we first discuss what strategies would be effective to realize such systems, and then develop mechanical and informational element technologies to achieve such strategies.

This paper consists of the following sections.

Section 2 first summarizes the robot-specific problems in transferring and storing commodities in the living environments and then discuss three major strategies and technologies that will be required to overcome such problems.

Section 3 describes the construction of home-use logistical support robot system using the above-mentioned three major strategies and technologies, as well as the basic performance test results for the system components.

Section 4 describes the tasks that can be made possible by coordinating the system components with each other and presents the integrated experimental results.

Section 5 discusses possible applications of the developed robot system to nursing care and support of the elderly in transferring and storing commodities.

Section 6 concludes this paper.

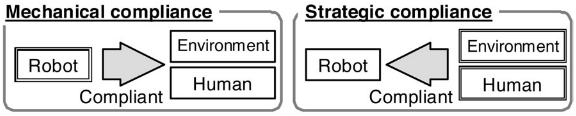


Fig. 1. Difference between mechanical and strategic compliance.

2. Robots to Transfer and Store Commodities in Living Environments

2.1. Problems Specific to Living Environments and Three Major Strategies and Technologies

Although at present, there are about 350,000 industrial robots operating in the production fields in Japan, there are very few robots intended to operate in the living environments other than Roomba manufactured by iRobot Inc., let alone commercially available robots capable of handling commodities except for several experimental robots [1–7]. Absence of robots intended for use in the living environments is due to the following reasons which are not applied to the production fields:

- variation of living environments,
- diversity of objects for daily use,
- dispersion of human activities.

To cope with these issues, we propose the concept of strategic compliance. It is already well recognized that it is essential to properly control forces and flexibilities of the robots when they are used in contact with environments [8]. In this paper, compliance refers to flexibility or compliant performance of robots; as shown in **Fig. 1**, in the mechanical compliance, robots are supposed to comply with environments and humans, while in the strategic compliance, environments including humans are supposed to comply with robots.

Strategic compliance, which has been inspired by the concepts of intelligent environments and structuralizing of robot's working environments [9, 10], should be a concept not only to help enhance the functions of robots but also improve the quality of services provided by robots by streamlining working environments and schemes for robots.[1] Such flexibilities in strategy can only take effect when it is combined with mechanical flexibilities of robots, and making mechanical compliance is one of the major technologies we address in this research.

In this research of home-use object transfer/storage robot systems, on the other hand, we also need to address the problems involved in manipulation of objects although difficulties may be abated by implementation of various strategies. People have focused on the closure problem as a measure for stability in grasping by robotic manipulators [11, 12]. As a major technology, we also address how to compose such closures that will conform to the proposed strategies in order to improve robustness in the task of transferring and storing objects.

In the following sections, we take up strategic compliance, mechanical compliance and closure in that order.

1. Unlike conventional robots adapting wholly to humans, this strategy is flexible in the sense that humans and environments cooperate with robots.

Table 1. Analysis of automobile history and extraction of key strategies.

History of environmental arrangement for automobile	Generalization of arrangement	**Basic function of strategies**
(1) Establishment of traffic rules (Left-hand traffic, Separation of walk way and road way)	Establishment of basic rules in machine motion area	**Regulation** (1) Task regulation (2) Role regulation (3) Space regulation
(2) Pavement of road	Configuration of environments that support machine capability	**Assist**
(3) Installation of signal, traffic sign and white line	Promotion of rule or law compliance	**Navigation**
(4) Construction of high way	Configuration of environments that elicit machine potential	**Assist, Enforce**

2.2. Strategic Compliance

We can extract essential strategic requirements to introduce robots from analysis of automobile history [13], which is one of the indispensable machines in today's life. Our analysis of automobile history is summarized in **Table 1**, from which we have picked out as fundamental functions for strategic compliance (1) task-, role- and space-regulations; (2) assist and enforce; (3) navigation.

(1) Task-, role- and space-regulations would be tantamount to defining what and how robots should handle and how humans should respond to them. If we view robots as an automatic machine, we need to first define the requirement specifications before development. The strategic function plays a role of clarifying the standing positions of robots and humans through definition of the requirement specifications.

(2) The function of assist and enforce is an approach to determine the performance of the machine based on considerations for operating environments of the machine rather than solely on the machine itself. As the relationship between automobiles and pavement surfaces clearly demonstrates, we are likely to demand unnecessarily high performance of machines if performance of the machine is to be evaluated without regard to operating environments. In this sense, this strategic function is meant to optimize the desired performance specifications.

(3) The function of navigation is a strategic function designed to actively navigate humans into the machinery approach. As pedestrians following traffic signals secure the safety performance of automobiles, this is an approach to realize such performance with human assistance that would not be possible with machine capabilities alone. While environments support robots in the function of assist and enforce, it is humans who assist robots in the function of navigation.

Now, we will discuss specifically how these fundamental functions work to solve various problems specific to living environments.

In addressing the issue of diversity in objects for daily life, the minimum unit of objects to be handled by robots is set to one 'container case' rather than individual pieces of commodities. This is intended for task-regulations as well as role-regulations in which humans deliver and receive commodities to and from containers and robots handle such containers. Implementation of this strategy helps simplify the functions and specifications required for robots by clearly defining the relationship between humans and robots in handling household commodities. From the viewpoint of robot manipulation, handling of limited commodities would lead to a new advantage that new technologies could be introduced that would not be adopted in pursuit of general versatility.

Next, in order for robots to be able to respond to variations in living environments, we have constructed and equipped the containers specified in the task-regulations in a way that robots will find it physically and intelligently easy to handle. More specifically, markers are provided to enable robot sensors to extract steady amounts of features; guides are provided to the construction so that mechanical compliance performance can be extracted exactly as implemented in robots. These provisions will ensure achievement of robustness against environmental changes which used to be absent in the previous home-use robots. Moreover, commodities accommodated in the containers are tagged with RFIDs for identification purposes, which corresponds with the strategy of assist and enforce.

As a final measure, we have implemented the strategic function of navigation, in which, to reduce dispersion of human activities in the living environments, physical guides or informational guides by sounds or light are provided in places (facilities) where both humans and robots may have access opportunities to the same objects (containers), so that container cases which have been manipulated by humans should be easy for robots to handle.

The problems to be encountered in the living environments, their solutions and the fundamental strategic compliance functions are given in **Table 2** to summarize the above-mentioned studies.

Table 2. Home-use specific problems, solutions, and strategies.

Problems	Solutions	Basic function of strategies
Variation of living environment	Environmental arrangement for stable measurement	Assist, Enforce
	Cooperation of multiple equipments	Role regulation
	Arrangement of a specific space where robots can concentrate on their task	Space regulation
Diversity of daily use objects	Definition of robotsí operation target as a container (Not objects themselves)	Task & Role regulation
	Installing special structure or informative equipment to the container	Assist, Enforce
	Each object is equipped with RFID tag	Assist, Enforce
Dispersion of human activity	Mechanical or informative navigation of human casual motion	Navigation, Role regulation

2.3. Mechanical Compliance

Mechanical compliance can be realized in the following three forms:

(1) Passive compliance by means of passive mechanical elements such as springs, is a typical method of Remote Center Compliance (RCC) analyzed in detail by Whitney et al. [14]. Recent approaches on the performance of robots are more and more focused on the importance of passive mechanical elements for the learning performance of robots [15] or on incorporation of spring elements in the robot mechanism to enable robots to co-act with humans [16–18], in order to realize performances that would not be realized through learning or controls alone.

(2) Active compliance integrated approach, generally known as coarse-fine manipulation [19], is an approach by means of high-accuracy and short-stroke actuators fitted at the tip of general-purpose manipulators for large operating regions to realize high-accuracy motions at the robot's hands or to control the contact forces of robots with the environments. Detailed experiments and analyses made by Tsuda et al. [20] provide important findings on the active compliance integrated approach as well as on the passive compliance designs.

(3) Active compliance distributed approach is an approach by means of controlling joints of general-purpose manipulators to realize the desired compliant performance at the robot's hands. Various researches have focused on the performance at the robot's hands and on the methods to control the robot's joints [21, 22].

With the proven robust fail-safe technologies in the industrial applications taken into full account, this research aims to achieve smooth contacts of robots with the environments through the passive mechanical compliance. Specifically, we have implemented passive mechanical flexibilities in the robots to carry container cases (see Section 3.2) in order to realize robust handling of containers.

2.4. Geometrical Designing and Closure

Geometrical designing takes the longest time in the general machine designing work. With drawings, engineers become engaged in designing the shapes, layouts, etc. of the components for their optimization to achieve the required functions. On the other hand, grasp and manipulation of objects are addressed as problems to be solved by quasi-statics or dynamics. If it is possible to realize grasp conditions primarily in the geometrical designs, it would enable engineers to study the manipulation problems in the "drawing" process familiar to engineers, which would produce very large benefits. Form closure [23], a well-known geometric constraint, is said

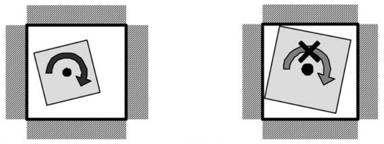


Fig. 2. Difference between object closure and GOC.

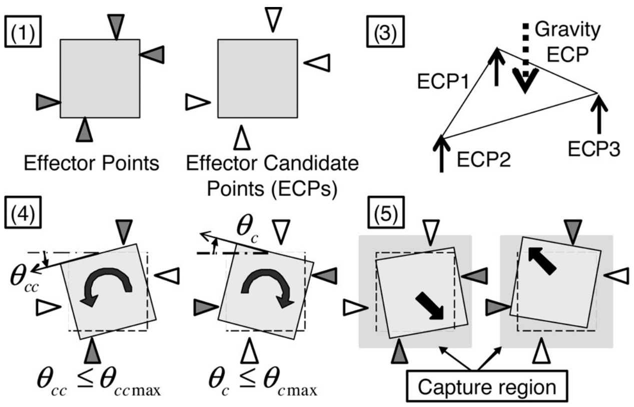


Fig. 3. Conceptual diagram of GOC conditions.

to have duality with force closure as dynamic constraint, so that form closure may not be genuine geometric constraint. On the other hand, object closure [24] proposed by Wang et al. realizes a caging which allows objects to move within the constraint; if robots can output sufficiently large reaction forces against objects to be transferred, grasping conditions can adequately be reproduced through geometrical designs alone. Object closure can be defined as follows:

$$\begin{cases} C_{free.obj} \neq \emptyset \\ C_{free.obj} \neq q_{obj} \\ C_{free.obj} \cap C_{free.inf} = \emptyset \end{cases} \quad \text{. . . . . (1)}$$

where $C_{free.obj}$ denotes six-dimensional configuration space (C-Space), q_{obj}, configuration of the existing object, and $C_{free.inf}$, C-space where objects in infinite distance can freely move.

Object closure, which allows objects to take arbitrary postures as shown in **Fig. 2(A)** and which is represented in the C-space, may not be suitable for geometrical designing of the transfer task with drawings. We therefore make Geometric Object Closure (GOC), as shown in **Fig. 2(B)**, by restricting the postures of objects within certain limits and by rewriting the object closure as follows so that we can confirm it with the drawings. **Fig. 3** is a conceptual diagram of GOC conditions.

(1) Objects are allowed to move within the specified region. In other words, all effector points do not always need to be in contact. Such effector points are called effector candidate points.

(2) Positional constraint by frictions decrease stability in grasping and is not counted as an effector candidate point.

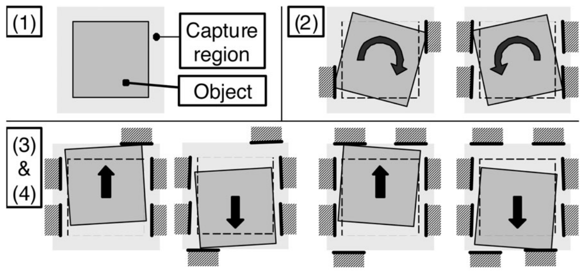


Fig. 4. A drawing procedure example for GOC.

(3) Reviews should be made in the gravitational and non-gravitational (horizontal) directions separately as far as possible. In the gravitational direction, gravity shall be regarded as an effector candidate point.

(4) If objects make 3-degree-of-freedom rotational movements within the specified region, there shall be two or more effector candidate points acting within the allowable posture limits irrespective of rotational directions.

(5) If objects which take the postures within the allowable limits in the specified region make 3-degree-of-freedom translational movements, there shall be one or more effector candidate points acting in the region irrespective of translational directions.

Caging is constructed by the following drawing procedures (**Fig. 4**):

(1) Caging region is set.

(2) Draw up possible postures of objects within the region and establish a constraining structure so that such postures should be within the allowable limits.

(3) Create step sizes in the allowable posture limits to draw up the postures of the objects in each step size.

(4) Check if there are any effector candidate points by moving the objects in translational motion within the region that does not interfere with the constraining structure. Add constraining structures if necessary.

In the drawing process, use of Computer Aided Design (CAD) software with the function to check interference will facilitate the work. As in the case of reviews in the configuration space, step sizes should be established with great care, for too-large step sizes may fail to detect frustrated caging closures. This GOC is used to improve robustness in container handling in the home-use automated container warehouse as referred to in Section 3.3.

3. Construction of Home-Use Logistical Support Robot System

In this section, we describe the construction for home-use logistical support robot system incorporating the three major strategic technologies mentioned in the preceding

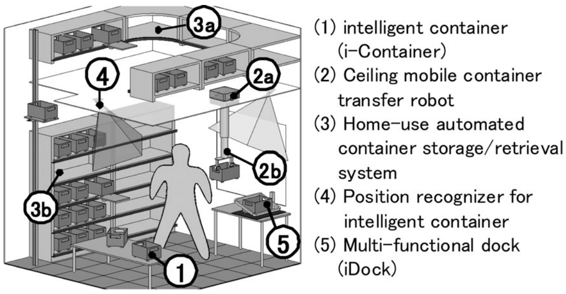


Fig. 5. Logistical support robot system in a living space.

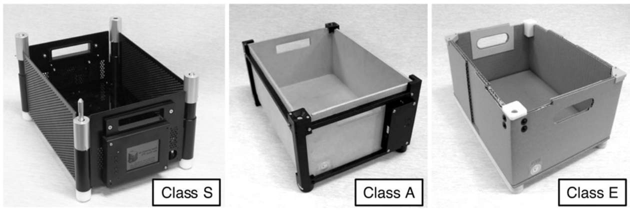


Fig. 6. Snapshot of the intelligent containers.

Table 3. Specification of the intelligent containers.

	Class S (Daily use)	Class A (Weekly/Monthly use)	Class E (Long period storage)
Size, payload	370*270*188 [mm], maximum 5 [kg]		
Weight	2.8 [kg]	1.7 [kg]	1 [kg]
Grasping guide	POM tapered guide plate (Hole D11[mm], Taper angle 45 [deg])		
Fork insertion	Fork gap: 20.5 [mm], Fork width: 206 [mm]		
Position marker	Red LED 4 points; blinking 7.5 [Hz]		---
Wireless comm.	Bluetooth Ver2.0, Class2, Serial 57.6 [kbps]		---
Load sensor	Photo reflector type x4: each max range 6 [kg]		---
Main material	Aluminum (A5052)	ABS/MDF board	Cardboard/MDF board

section. Conceptual diagram of the system is shown in **Fig. 5**. The system consists of the following five components:

(1) Intelligent container (i-container): Intelligent containers act as interface between humans and robots and accommodate commodities [25].

(2) Ceiling mobile container transfer robot (ceiling mobile unit plus container handling unit): Ceiling mobile container transfer robots can move without much interference with humans and their flexible mechanism enables robust handling of containers [26, 27].

(3) Home-use automated container storage/retrieval system: This is a system which can achieve automated storage/retrieval motions and high spatial utilization efficiency without infringing on the human living space or styles [28].

(4) Container-position recognition system: This is a recognition and measurement system, covering various tasks from detection of the containers placed in the room to detailed positioning measurements of such containers, to achieve strategies for the role-regulation and assist and enforce.

(5) Multi-functional dock for i-containers (iDock): iDock provides a gateway in individual rooms for the home-use logistical support robot system and makes up for function deficiency in the inexpensive version of i-containers, to achieve the strategies for the role-regulation, navigation and assist and enforce.

Explanations on the container-position recognition system and multi-functional dock for i-containers (iDock) are omitted due to limitations of space in this paper; for details, please refer to References [29, 30].

The following sections describe the overviews of the subsystems and the basic performance test results.

3.1. Intelligent Containers (i-Containers)

In the home-use logistical support robot system, i-containers play a role of an “intermediate” to interface between the supports which users require robots and the ones which robots provide to users. In other words, users deliver to and receive from the robot system commodities through intermediation of i-containers, and the robot system satisfies the users’ requests for transfer/storage of commodities through handling of i-containers. In that sense, i-containers provide typical means to materialize the strategic compliances (task-regulation, role-regulation, and assist and enforce) of the system. We have developed three classes of i-containers according to the frequencies in use of the contents as shown in **Fig. 6**.

Intelligent containers have the following features: (1) containers are portable and storable in the same way as the container cases of A4 size which are commonly used at home (regulations); (2) contents of the containers are identified by reading the RFID tags affixed to them by the RFID tag readers which are implemented in the i-containers (Class S) or by a movable RFID tag reader of iDock [30] (Classes A and E) (assist) ; (3) connecting holes with tapered guides which are diagonally arranged on the upper surface of the containers serve to facilitate robot’s motions to grasp containers (enforce); (4) periodically blinking LEDs installed at the four corners of the upper surface of the containers serve to facilitate measurements of container positions and postures using a camera (assist). Specifications of the intelligent containers are given in **Table 3**.

3.2. Ceiling Mobile Container-Transfer Robots

Container-transfer robot consists of the ceiling mobile unit and the container handling unit. We have noticed availability of the ceiling space which is usually left unutilized so that robots can move along the ceiling surface and gain access to the living space only when necessary. This is an example of the strategic compliance for the space/region-regulations. For details of the mechanism, please refer to Reference [26].

In this section, we describe the container handling unit where passive mechanical compliance technologies are

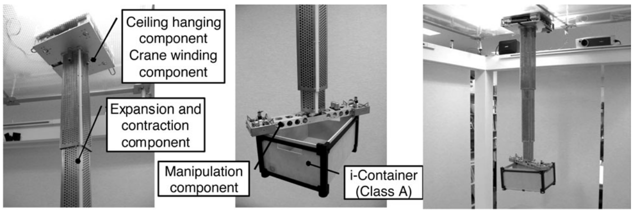


Fig. 7. Snapshot of the container handling unit.

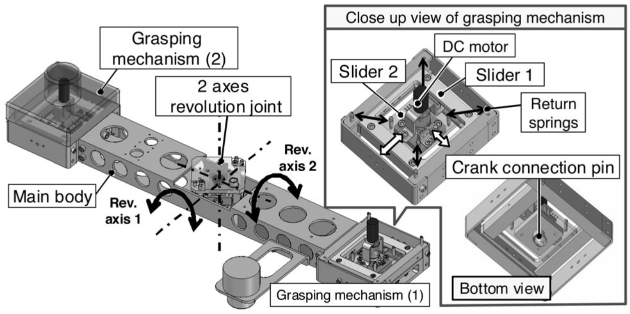


Fig. 8. Overview of the manipulation component.

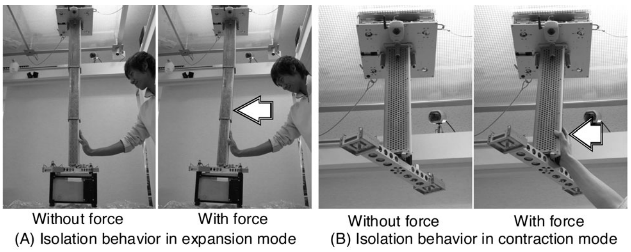


Fig. 9. External force isolation behavior.

Table 4. Specification of the container handling unit.

Size	340 * 320 * 610 [mm] (Contraction state)		
Pay load	8 [kg] (Including container weight 3 [kg])		
Grasping mechanism	Jamming free crank connection pin x2		
Compliant capability	Horizontal: 10 [mm], Roll/Pitch: 10 [deg]		
Mechanisms for external force isolation	Torque limiter, constant load spring and permanent magnet for decoupling		
Safe working load	10 [kg]	Lift stroke	610 - 1,835[mm]
Lift-up speed	100 [mm/s]	Lifting mech.	Steel belt winch

employed. The container handling unit (**Fig. 7**) consists of the manipulation component, the ceiling hanging component, the crane winding component and the expansion and contraction component.

The manipulation component in **Fig. 8** has the following features:

(A1) Short and small crank connection pins are used in the connecting and releasing mechanism for i-containers enabling the container-grasping function to be jam-free and robust. The crank connecting pins address the problem of grasping containers by transforming it into the "problem of inserting two pins simultaneously into objects with 3-DOF (x, y, yaw) horizontally and 2-DOF (pitch, roll) in inclination."

(A2) Passive mechanical compliance element is provided to absorb errors in horizontal and inclination positioning of containers to be grasped.

(A3) In the horizontal compliance element, the element slides smoothly, contacting low frictional materials in the unloaded condition, while it stops sliding when the slider contacts high frictional materials in the loaded condition. If containers are not well balanced in weight of contents, inclination of the containers is restricted by means of the limiter mechanism which only works in the loaded condition. But the mechanism cannot properly respond to extreme imbalance in weight of container contents, which leaves some room for improvements in the future.

The expansion and contraction component and the crane winding component have the following features:

(B1) Use of bamboo-like expansion and contraction mechanism allows robots to gain access to the living space from the ceiling surface with comparatively small twists and vibrations.

(B2) By applying plastic rails and holding covers used in the translation/rotation fixing mechanism, undesired displacements are restricted during operation, and passive mechanical compliance elements are incorporated reducing contact forces by flexibly deforming when they contact humans or objects as shown in **Fig. 9**.

(B3) The steel-belt winding mechanism ensures that no loads greater than the weights of the manipulation component plus the container should be applied even if the robots contact unexpected objects.

Specifications of the container-transfer robot (container handling unit) are given in **Table 4**.

3.3. Home-Use Automated Container Warehouse

Unlike industrial-use automated container warehouse for use in factories or logistics bases where high operational speeds are required, requirements for the robot systems for use in the living space are to ensure high levels of symbiosis with humans. Home-use automated container warehouse (**Fig. 10**) therefore possesses the following three features:

(1) Use of elevator type storage allows for both ordinary storage actions by humans and automated storage operation by robots.

(2) Use of guide plates and RFIDs for sensing navigates users in putting containers in ideal positions or postures that will facilitate their handling by automated equipment.

(3) Use of stacker cranes with distinct horizontal and vertical DOFs offers both the shelves and ceiling space as potentially available storage space. It also serves to reduce occupied space, which in turn reduces the number of mechanisms where humans could be caught.

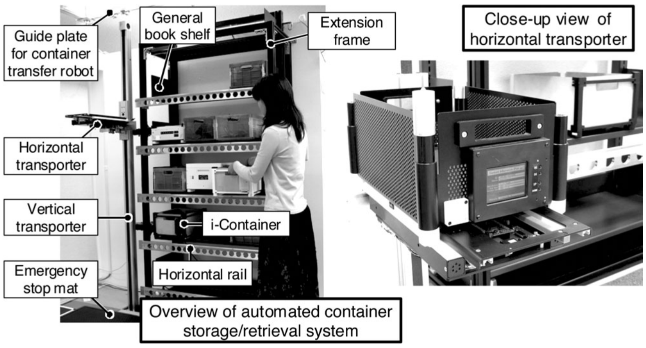


Fig. 10. Snapshot of the home-use automated warehouse.

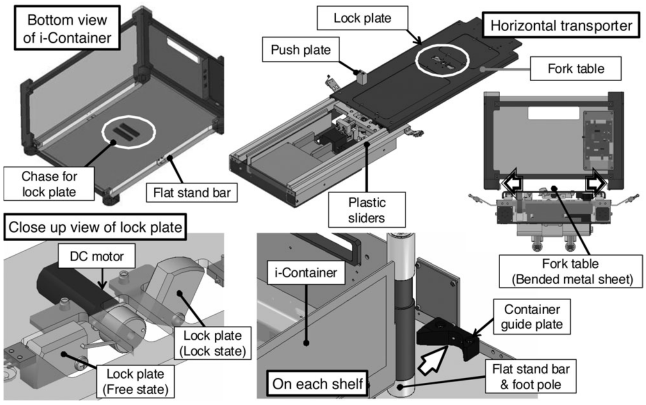


Fig. 11. Structural parts that contribute to GOC.

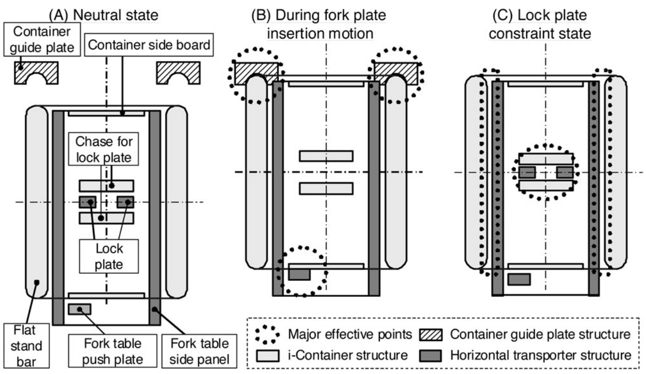


Fig. 12. GOC state realized in horizontal transporter.

The above-mentioned feature (2), which corresponds to the strategic compliance for navigation, provides a critical function in the home-use automated container warehouse system which is designed for both humans and robots to handle identical objects (containers).

There is one more feature to mention, that is, robust handling of containers using GOC in the horizontal container-transfer mechanism. Intelligent containers and automated warehouse are of such construction as shown in **Fig. 11** to create GOC conditions. **Fig. 12** shows the positional relations among the mechanical structures for different transfer states. What is characteristic of this figure is that not only container constraint state **(C)** but also the fork plate insertion motion **(B)** represent the caging states; these two stages of caging ensure smooth and robust constraint.

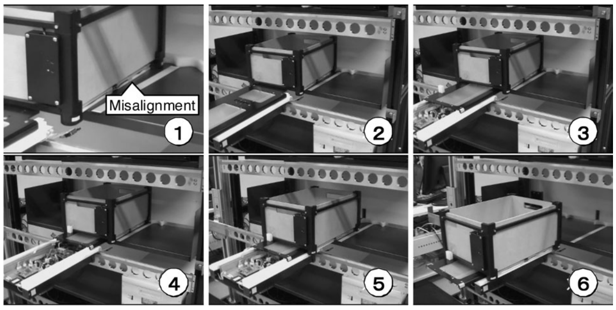


Fig. 13. Sequential images of a container retrieval motion under an artificial misalignment condition.

Table 5. Specification of the home-use automated warehouse.

Basic structure	Elevator type
Size	W1,500 * H2,300 * D450 [mm]
Motion layout	Separated motion layout (Linear actuator and horizontal transporter)
Rail type	Mono rail. Cantilever state.
Pick / Place method	Fork and simple lock method
Maximum payload	8 [kg] (Including container weight 3 [kg])
Transport speed	Slow for safety (horizontal: 0.2 [m/s])
Container recognition	RFID tag and antenna
Space occupation	Small (Escape mode is available)
Human pick/place	Available
Compliance to errors	High compliant
Obstacle recognition	Infra-red sensor and contact switches

We have confirmed through the experiments as shown in **Fig. 13** that even if there are some errors in positioning of containers when stored by humans, the proposed robot system can retrieve such containers without any problem. This is made possible by the plate insertion motions which prompt the containers to transition into a caging state (**Fig. 12(B)**), an advantage gained from use of caging (GOC).

Specifications of the home-use automated warehouse are given in **Table 5**.

3.4. Summary of System Architecture

Figure 14 is a diagram to illustrate where technologies for the strategic compliance, passive mechanical compliance and geometric object closure are used in the home-use logistical support robot system.

4. Experiments to Evaluate Coordinated Operation of the System

In this section, we describe the experiments to evaluate the system performance in the container grasp, transfer task, and the container delivery task which are accomplished through coordinated operations among the subsystems.

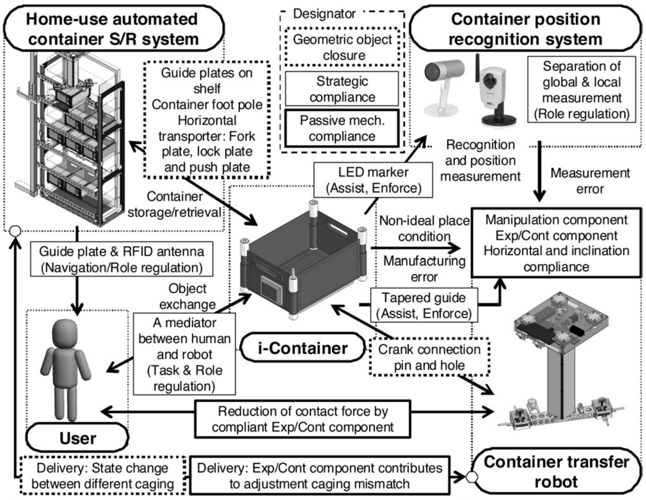


Fig. 14. Three major technologies in the presented system.

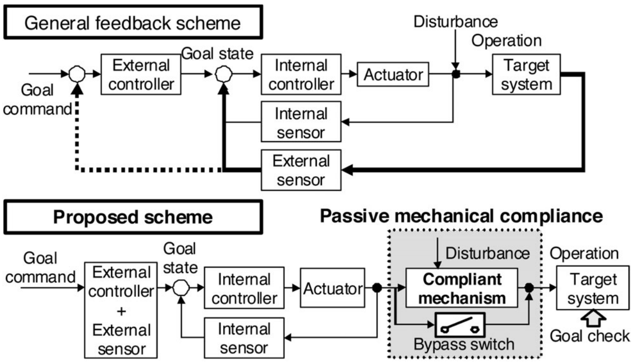
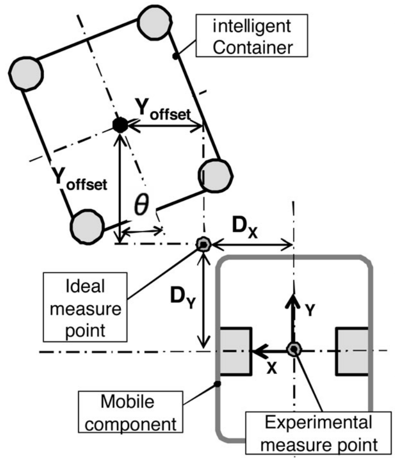


Fig. 15. Difference of measurement and control schemes.



Point index	D_X	D_Y
1	100	100
2	0	100
3	−100	100
4	100	0
5	0	0
6	−100	0
7	100	−100
8	0	−100
9	−100	−100

unit [mm]

θ	−15	0	+15

unit [deg]

Fig. 16. Experimental position setup.

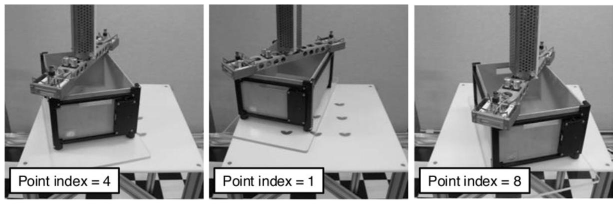


Fig. 17. Snapshot of grasping experiment.

4.1. Experiments for the Container Grasp and Transfer Task

The experiments are conducted in the quasi-living environments where containers are first recognized and measured for positions by the container position recognition system, and then are grasped and transferred by the container-transfer robot. Although feedback controls with force sensors are generally employed in the entire process of grasp as shown in **Fig. 15** (top), we have completely separated measuring processes and grasping processes without the explicit use of feedback controls in this task as shown in **Fig. 15** (bottom). We intend to confirm through these experiments that use of the passive mechanical compliance could reduce reliance on feedback controls.

4.1.1. Experiments on Robustness in Container Grasping Motions (with Errors in Horizontal Positioning)

The purpose of this experiment is to evaluate effects of errors in global position measurements and to confirm the performance in local position measurements as well as the container-transfer robot's error-tolerance capability. In the experiment, we have configured relative positions and angles between container and transfer-robot as follows: (1) a total of nine relative positions: -100 mm, 0 mm and 100 mm from the reference position in two orthogonal directions; (2) a total of three relative angles: $-15°$, $0°$ and $15°$ from the reference position. Container-grasping task has been executed in the above-mentioned 27 different conditions as shown in **Fig. 16**. We have confirmed through the experiments shown in **Fig. 17** that the container-transfer robot can grasp containers without difficulties except in the case where the container-transfer robot must move horizontally for significantly large distances (conditions corresponding to point indices 1 and 3 in **Fig. 16**), where one of the three attempts has failed. This failure in grasping containers may be due to the fact that when the horizontal moving distance gets longer, it will cause larger errors in predicting the directions of the ceiling mobile unit to calculate relative positions to the containers.

4.1.2. Experiments on Robustness in Container Grasping Motions (with Errors in Inclinational Positioning)

The purpose of this experiment is to confirm whether or not the container-transfer robot can grasp containers with robustness even if they are placed somewhat inclined. In the container-grasping experiment, we have placed some obstacles at the bottom of containers to incline them at the maximum pitch of 10.3° and the maximum roll of 7.4°. The experimental results have confirmed robust performance of the inclination compliance component in grasping containers in either case of inclinations. **Fig. 18** are some snapshots of grasping inclined containers.

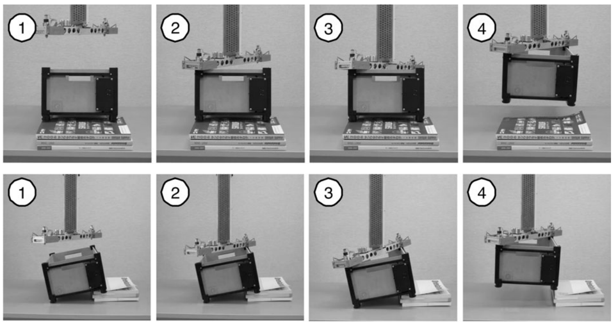


Fig. 18. Snapshot of roll or pitch inclined container grasping.

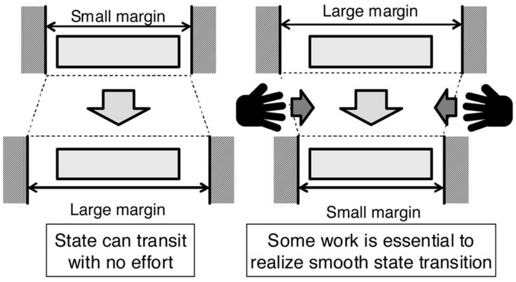


Fig. 19. Mismatch problem of allowable displacement between two caging conditions.

4.1.3. Consideration

The experiment on robustness in container-grasping motions has demonstrated that the proposed system involving no precise feedback controls in container-grasping operations can provide robust grasping motions by means of the passive mechanical compliance.

4.2. Experiments for the Container Delivery Task

We have conducted experiments on the container-transfer robot's performance in delivering and receiving containers between the robot and the automated warehouse. The container-delivering/receiving task may alternatively be called transition work between different caging states. In general, there exists a particular capture region margin for each casing state and some work may be necessary to correct any capture region mismatch as shown in **Fig. 19**. In the proposed system, where capture region margins of caging in the automated warehouse are set smaller, we need to confirm whether the container-transfer robot can correct such capture region mismatches.

4.2.1. Experiment on Container Delivery from Automated Warehouse

Delivery of containers from the automated warehouse to the transfer robot, which involves no capture region mismatches, has smoothly been executed as shown in **Fig. 20**.

4.2.2. Experiment on Container Storage into Automated Warehouse

Delivery of containers from the transfer robot to the automated warehouse, which involves capture region mismatches, corresponds to what is called caging state transition. The container storage task has been attempted by grasping containers with a horizontal positioning error of 10 mm. As shown in **Fig. 21**, the experimental results have confirmed smooth execution of the container storage task with the delivered containers positioned close to the ideal center position on the horizontal transfer mechanism.

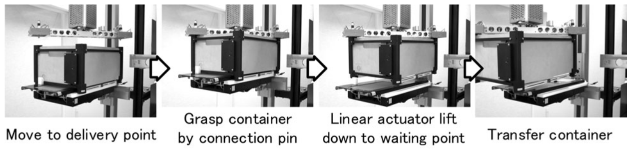


Fig. 20. Sequential images of container retrieve delivery.

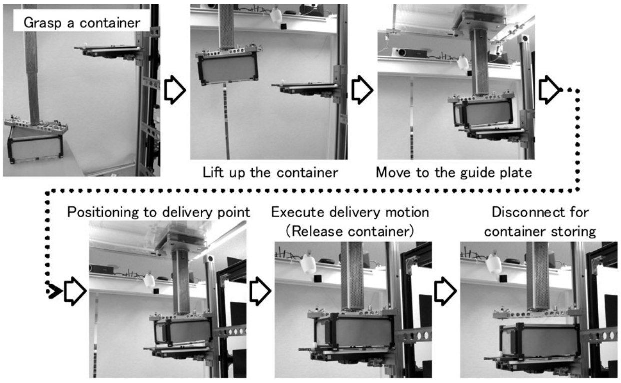


Fig. 21. Sequential images of container store delivery.

4.2.3. Consideration

We have confirmed smooth transition motions between different caging states in both delivery and storage tasks. In particular, success in the storage task may be owed to the container lifting motions which simultaneously correct any capture region margins. We have found that use of the passive mechanical compliance components like the expansion and contraction mechanism in the proposed robot system, where capture region margin can be changed according to the situation, can realize cooperative state transition work between robots without any actuators to do explicit tasks in particular.

5. Container-Case-Shaped Support System for the Elderly

According to References [31, 32], caring time for the elderly becomes longer as the levels of required nursing care service become higher, while it is highly recommended from the independent living points of view of the elderly that they should maintain their usual daily lifestyles as much as possible. We therefore aim to develop new applications of the above-mentioned home-use logistical support robot system to provide some "little support services" which the elderly would hesitate to ask for, so that the developed robot system could help encour-

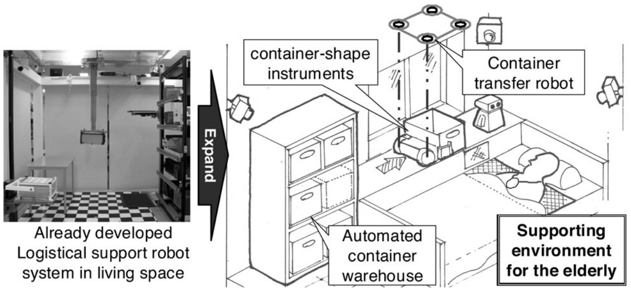


Fig. 22. Conceptual sketch of the elderly people support system.

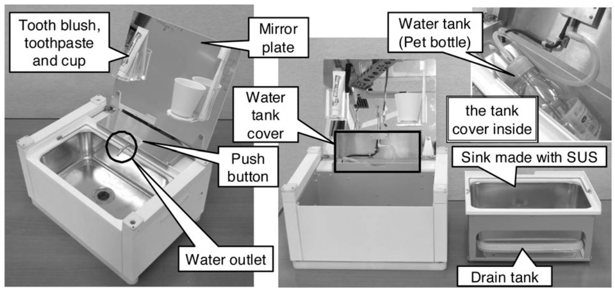


Fig. 23. Overview of lavatory container.

age the elderly to undertake self-independent activities in their daily life. Among plenty of contents in such "little support services," we discuss in this paper support services in lavatory and provision of drinks.

In providing such little support services, care supporters (the developed robot system) do not provide necessary goods item by item to the cared but provide environmental support packages in the form of containers as shown in **Fig. 22**. This is a typical application of ambient intelligence in that instead of items, environments containing them are moved to provide care support services; this approach has a big advantage that even if kinds of support contents are increased in future, the robot system can respond to such requirements by packaging necessary goods in the form of containers.

The system specification requirements have been determined based on the author's actual experience in nursing care, because we failed to obtain sufficient materials to quantitatively establish the system requirements for the above-mentioned two services.

Although current i-containers may not be of completely optimum standardized size for application to care support equipment, we have retained the standardized size of containers, placing greater emphasis on the advantage that the proposed system can be extended in application from the basic application for storage to nursing care support.

5.1. Lavatory Environmental Containers (Support for Acts in Lavatory)

Support is provided to the following three acts in lavatory: hand-washing, face-washing and tooth-brushing. The system is to be equipped with the following four functions: supply of fresh water, exchange of fresh water, collection of drains, and storage of toiletries.

Figure 23 shows the overview of lavatory environmental container. In the function to supply fresh water, an air pump is built in the container to pump fresh water out of the fresh water tank; hydraulic pumps like geared pumps with some water possibly remaining in the piping are not sanitarily preferable. In the function to exchange fresh water, we use pet bottles as a water tank to reduce the trouble of cleaning the tank. In the function to collect drains, a drain tank is built in the sink at the bottom, so that it can be removed as part of the sink out of the container for disposal of drains and cleaning of the tank as well. In the function to store toiletries, a holder for toothbrushes and tooth paste and a magnetic cup holder are provided.

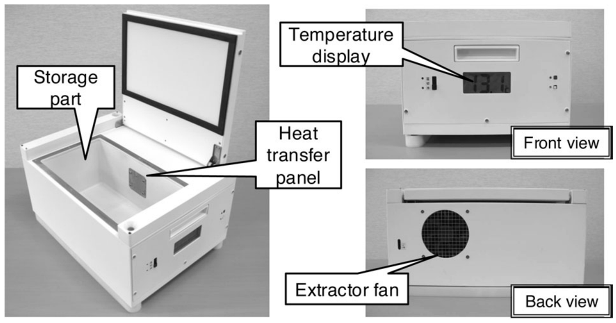


Fig. 24. Overview of refrigerator container.

As a common design, all containers are provided with magnetic suction inlets for AC power supply, in order to secure stable power supply as well as to ascertain that containers should in no way be affected by accidental pulling of power wire.

5.2. Refrigerator Containers (Support in Provision of Drinks)

While refrigerator containers are refilled with drinks by care takers, they are so designed as to allow keeping refilled drinks at appropriate temperatures and deliver them as requested by care receivers. Refrigerator containers are therefore required to have the functions to hold drinks and regulate and display the temperatures of the drinks. **Fig. 24** shows the overview of refrigerator containers. For the function to hold drinks, a case of heat-insulated structure has been provided to hold eight cans of 350-mℓ juice. For the function to regulate and display the temperatures of drinks, a heat exchanger using Peltier elements has been provided, as well as an extractor fan for air convection into the external atmosphere. The refrigerator container has a temperature display panel on the front panel so that the temperatures can be monitored even when the containers are stored on the shelves.

6. Conclusion

In this research, we aimed to realize a robot system to transfer and store commodities, making the best use of the features specific to robots such as unique construction and permanent memories, in order to solve the problems in the living environments which are flooded with too many commodities and too much information. We have noticed that the strategic compliance, the passive mechanical compliance and the geometric object closure constitute three fundamental technologies to realize such robot systems. Then, we have constructed a home-use logistical support robot system incorporating these fundamental technologies and have conducted experiments to evaluate the performance of the developed system.

The proposals and findings of this research may be summarized as follows:

(1) Introduction of the strategy to clearly define the tasks for the robots will make it possible for the robot system to handle commodities in a stable manner in the living environments which was previously considered too difficult to realize.

(2) Use of the caging constraint states as realized by the geometric designs makes it possible for engineers to study the drawings to ensure the stable manipulation of commodities by robots.

(3) The passive mechanical compliance has been proven to be effective for improvements not only in direct handling of objects but also in transition of caging states in the task to deliver commodities.

In an attempt to extend applications of the home-use logistical support robot system to nursing care support services for the elderly, we have proposed a new approach to move the whole environmental support packages, as well as the designs for a prototype support equipment to realize such applications.

The home-use logistical support robot system we have constructed is nothing but a prototype, leaving a number of problems yet to be solved. Specifically, such problems include methods to recover the system in case of errors in task execution, methods to navigate users to assist recovery of the system, and methods to monitor users and environments and reflect the observations into the robot's motion plans to prevent occurrence of errors.

Nevertheless, the approach we have taken in developing the proposed home-use logistical support robot system is universally applicable to robots which operate in the living environments and will ensure effective and robust robot systems in actual operations.

We hope that the developed home-use logistical support robot system will be introduced into our living environments to create societies which will be free from floods of unwanted (or excess) commodities and information. Ultimate target of this research is to seek a new type of architectural structures in which residences, offices, shops and various support infrastructures including storage of commodities are all assembled compact in the same buildings as shown in **Fig. 25**.

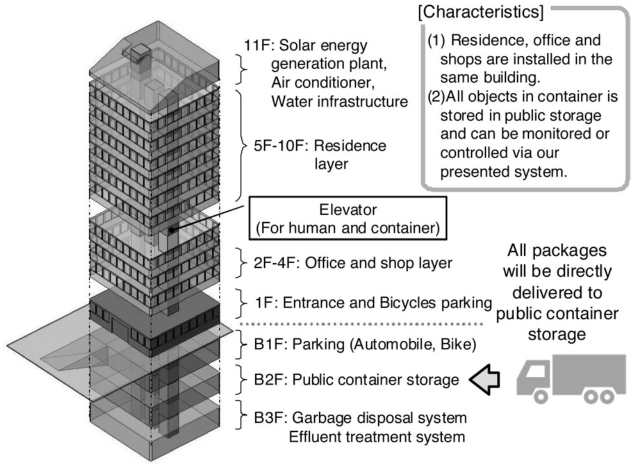


Fig. 25. Conceptual sketch of a future residence installed with our presented system.

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Name:
Rui Fukui

Affiliation:
Assistant Professor, Department of Mechano Informatics, Graduate School of Information Science and Technology, The University of Tokyo

Address:
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

Brief Biographical History:
2004-2006 Engineer, Mitsubishi Heavy Industries, Ltd.
2009 Received Ph.D. from Department of Mechano-Informatics, The University of Tokyo
2009-2011 Project Assistant Professor, Department of Mechano-Informatics, The University of Tokyo

Main Works:
- "HangBot: a Ceiling Mobile Robot with Robust Locomotion under a Large Payload (Key mechanisms integration and performance experiments)," Proc. of Int. Conf. on Robotics and Automation, pp. 4601-4607, 2011.
- "Application of Caging Manipulation and Compliant Mechanism for a Container Case Hand-over Task," Proc. of IEEE Int. Conf. on Robotics and Automation, pp. 4511-4518, 2010.

Membership in Academic Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Robotics Society of Japan (RSJ)
- The Institute of Electrical and Electronics Engineers (IEEE) Robotics and Automation Society

Name:
Taketoshi Mori

Affiliation:
Project Associate Professor, Department of Life Support Technology (Molten), Graduate School of Medicine, The University of Tokyo

Address:
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

Brief Biographical History:
1995- Research Associate, The University of Tokyo
1998- Lecturer, The University of Tokyo
2001- Visiting Scientist, Massachusetts Institute of Technology
2002- Associate Professor, Graduate School of Information Science and Technology, The University of Tokyo
2010- Project Associate Professor, Graduate School of Medicine, The University of Tokyo

Main Works:
- "Object Usual Places Extraction in Smart Space: Robotic Room," Robotics Research: Springer Tracts in Advanced Robotics, Vol.66, pp. 111-122, 2011.

Membership in Academic Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Robotics Society of Japan (RSJ)
- The Society of Instrument and Control Engineers (SICE)
- Japan Society for Medical and Biological Engineering (JSMBE)
- The Institute of Electronics, Information and Communication Engineers (IEICE)
- The Institute of Electrical and Electronics Engineers (IEEE)
- Association for Computing Machinery (ACM)

Name:
Tomomasa Sato

Affiliation:
Professor, Department of Mechano Informatics, Graduate School of Information Science and Technology, The University of Tokyo

Address:
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

Brief Biographical History:
1876- Researcher, the Electrotechnical Laboratory (ETL), The Ministry of Industrial Science and Technology
1991- Professor, the Research Center for Advanced Science and Technology (RCAST), The University of Tokyo
1998- Professor, the Department of Mechano-Informatics, The University of Tokyo

Main Works:
- "Development of a tiny orientation estimation device to operate under motion and magnetic disturbance," The International Journal of Robotics Research, Vol.26, No.6, pp. 547-559, June 2007.
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Membership in Academic Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Robotics Society of Japan (RSJ)
- The Society of Instrument and Control Engineers (SICE)
- The Japanese Society for Artificial Intelligence (JSAI)
- The Institute of Electrical and Electronics Engineers (IEEE) Robotics and Automation Society