Measurement and Control Scheme for a Container Transfer Robot in Living Space

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ABSTRACT

We aim to realize a home-use container logistical system, which transfers, stocks and manages daily objects in our living space. In previous researches, some key technologies for robust robot locomotion, accurate container position measurement and compliant container manipulation are developed. A purpose of this paper is to integrate the stated elemental technologies into measurement and control system and evaluate capabilities of the system. There are two characteristics in our measurement and control scheme. (1) Mechanical compliant elements can absorb measurement and control errors. (2) In an object handling phase, there is no obvious feedback control. By experiments, robustness of the presented scheme and effectiveness of compliant mechanisms were confirmed. Thorough the development and experiment, this paper revealed several technical key points to apply industrial know-how of mechanical compliance to home-use robots.

I. INTRODUCTION

Technical innovations provided us affluent lives, but such affluence makes our living space over-flown with a lot of daily-use objects and too much information. To solve the over-flown state in information, robotic search engines (ex. Google) were developed to summarize enormous electrical information. On the other hand, humans cannot find a drastic solution for the real object fixing problems, hence physical robot support is expected to be an answer. Accordingly our research project is developing ”a logistical support robot system in living space”[1] as Fig.1 shows. The system is an intelligent environment which supports our daily access to objects. As commodities, we suppose books, magazines, CDs, preservative foods, grocery stock and so on. The system is composed of following sub-systems.

1) intelligent container(i-Container) which plays a role of mediator between humans and robot system[2].
2) Ceiling mobile type container transfer robot.
3) home-use automated container store/retrieve system[3].
4) Container position recognition system[4].
5) iDock: Multi-functional dock for i-Container[5].

In previous researches, several elemental technologies for container transfer robot system were developed.

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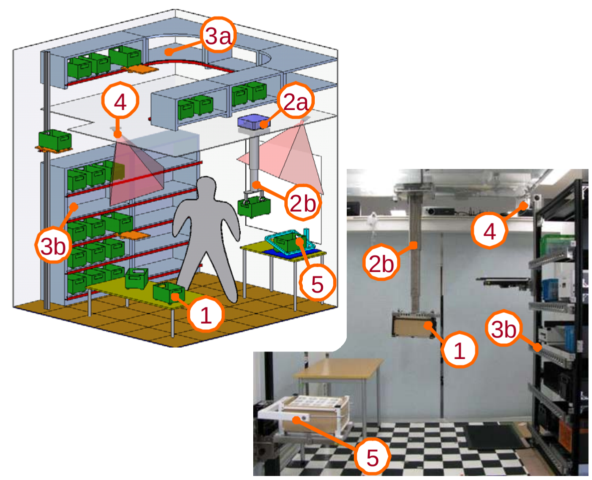


Fig. 1. Conceptual sketch and snapshot of logistical support robot system in living space

(A) A ceiling mobile robot platform which enables robots to move unlimitedly under a ceiling plate by utilizing permanent magnet force, and to measure their position very accurately by 2D code markers[6].
(B) An optical position measurement system for i-Container. The system can acquire abstract (global) position of i-Container by distributed multi-cameras in an environment and can measure accurate (local) position of i-Container by a camera installed on a robot. By the accurate position data, robot can manipulate the target i-Container[4].
(C) A container manipulation mechanism which can absorb measurement or positioning control error by compliant mechanisms[7].

This paper aims to integrate these elemental technologies, and realize a robust scheme for container transfer task.

A. Standpoint of this research

There were many researches to handle or manipulate objects until now. Object handling or manipulation needs some contacts with environment or target object, hence some trials for position/force hybrid control[8] or grasping[9] achieved many fundamental and important knowledge. On the other hand some soft or compliant mechanisms (ex. Remote center compliance[10], [11], Pneumatic cylinder) contribute to realize robust motions in industrial manipulation robots. In addition to the industrial applications, some researchers tried to demonstrate effects of mechanical compliance in robot control. For example, Yun et al. indicated importance of mechanical compliance in a learning phase of robot[12].

Therefore this research aspires to construct a "compliant scheme" that can actualize robust and flexible container handling without complex measurement and control procedure. Although in a general manipulating motion control, feedback control(Fig.2, Upper) was thought to be essential, in our scheme there is no apparent feedback control as Fig.2(Lower) shows, but mechanical compliant elements contribute to realize smooth contact with environment.

In industrial application, almost all control schemes are open-loop and no-feedback, in this point of view our presented scheme is inspired by those industrial methods. But those industrial schemes cannot permit some error or disturbance which is well observed in home-use application. Hence our technical challenge is to apply or convert such industrial methods to home-use application.

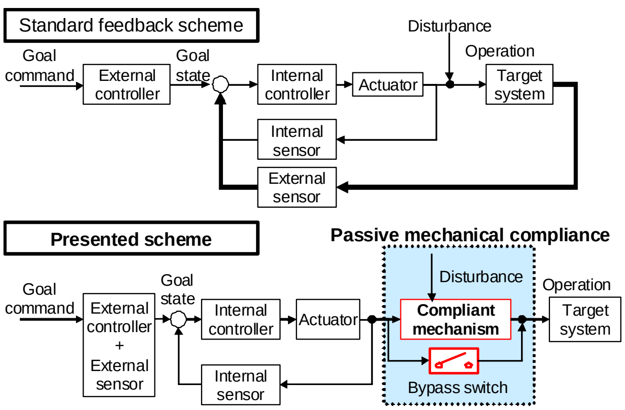


Fig. 2. Difference of measurement and control scheme

B. Framework of this paper

In section II, system configuration to realize container transfer task is described firstly, and overview of each subsystem is explained. In section III, design of task controller for container transfer task is discussed. In section IV, several experiments to confirm performance of the implemented measurement and control scheme is described. Section V is conclusion.

II. Container transfer by a robot

Firstly this section describes a system configuration which realizes container transfer task. In the next, overview and capabilities of each sub-system are organized.

A. System configuration of container transfer task

Fig.3 shows abstract of the system configuration. Firstly the transfer task controller acquires information about rough position of transfer target container from container position recognition system. Secondly based on the information, container transfer robot (Mobile component) moves to the position and rotates only horizontally to the posture of a target container. Finally container handling component of the transfer robot manipulates the target actually.

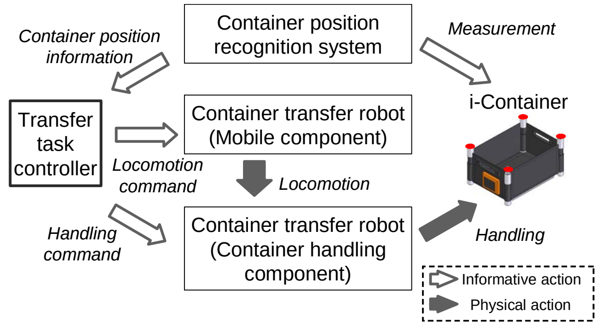


Fig. 3. System configuration for container transfer task

B. Overview and specification of container position recognition system

Fig.4 shows system architecture of container position recognition system. The system is composed of low-price IEEE1394 cameras which are distributed in living space, a wireless LAN camera installed on the container transfer robot and LED markers implemented on i-Containers. A global position measurement: container detection from a living environment and rough position measurement is realized by the distributed cameras, and a local position measurement: accurate position and posture measurement which are essential for container handling motion is actualized by the on-robot camera. As markers, 7.5[Hz] periodical blinking LEDs are utilized, hence the both measurements can be achieved in spite of environmental brightness change or any other noise. In global measurement, maximum measurement error of horizontal position is 67[mm]. On the other hand in local measurement, maximum measurement error of horizontal position is 7.3[mm]. As well, calibration procedure of local measurement is executed with special designed jig, therefore the container position data can be acquired in a coordinate system of the container transfer robot.

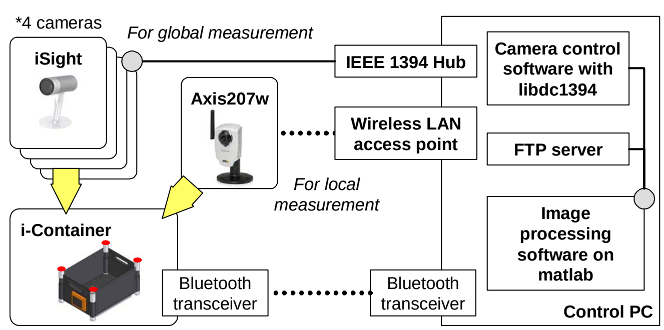


Fig. 4. Abstract of container position recognition system

C. Overview and specification of container transfer robot (mobile component)

Fig.5 shows snapshot of container transfer robot (mobile component). In the mobile component, permanent magnet inductive traction method[6] is utilized as shown Fig.5 (Left, Lower). The method utilizes several pairs of permanent magnet. One of the magnet pairs exists upper side of the ceiling plate and the other attaches the lower side. When a mobile robot transfer the upper side magnets, the lower side magnets and an actuation robot hanging the magnet is induced and trailed by the upper magnet locomotion. Maximum driving speed is 125[mm/s], but general driving speed is about 50[mm/s]. As Fig.5(Right, Lower) shows, 2D codes (QR code) are arranged in matrix layout on a surface of the ceiling plate. Each robot has 2D code reader as Fig.5 (Right, Upper), so the "2D code matrix" enables robots to estimate their position and direction by reading the 2D code data. It was confirmed that induction error of the "permanent magnet inductive traction method" is less than 1[mm] in dynamic motion, therefore static induction error is expected to be sub-millimeter order. In addition, standard deviation[1] of position estimation by 2D code matrix is under 0.33[mm] in position and 0.30[deg] in direction.

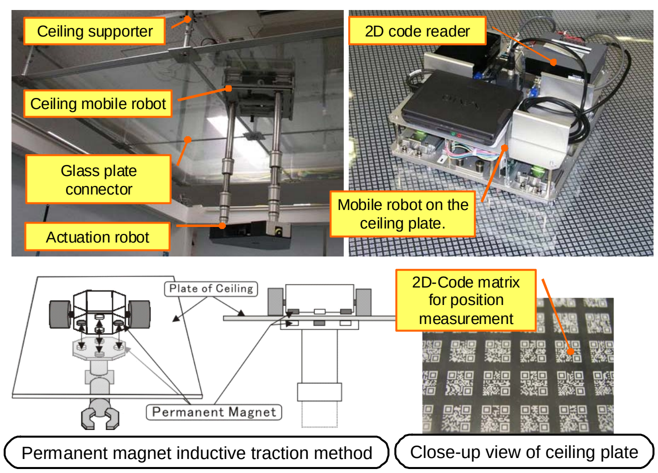


Fig. 5. Abstract of ceiling mobile component

D. Overview and specification of container transfer robot (container handling component)

Fig.6 expresses a snapshot of container transfer robot (container handling component), and Fig.7 indicates detailed

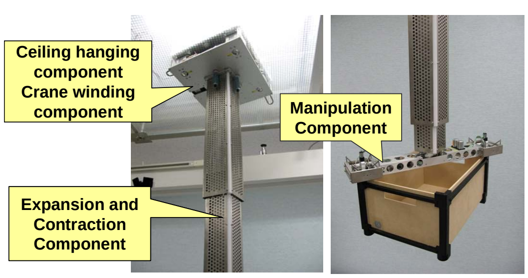


Fig. 6. Abstract of container handling component

architecture of manipulation component. Characteristics of the manipulation component are as follows. (1) Crank connection pin can realize a robust container handling motion only by inserting the connection pin into holes on i-Containers. (2) The manipulation component is installed

[1]This method is very precise so absolute accuracy is difficult to measure.

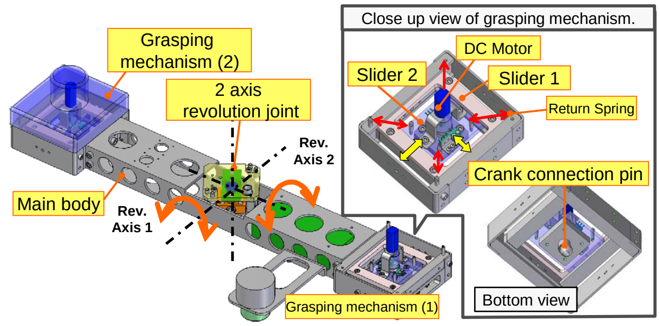


Fig. 7. Detailed architecture of manipulation component

with two horizontal compliant elements, and each element is composed of 2-axes linear sliders and tension springs. (3) A 2-axes inclination compliant element is settled at the center of body, so it can absorb slope of a target container. (4) When grasping a container with certain load, each compliant elements' functions become low or invalid. Therefore stable transport can be feasible.

Above features of the manipulation component actualize robust container handling motion even if there are 10[mm] position misalignment or 10[deg] inclination mismatch. Expansion and contraction component utilizes bamboo like slide mechanism as shown in Fig.8. In this mechanism, open steel belt actualized up/down lifting motion, and sliders made of plastic rail and bended metal plate can prevent unintended rotating and twisting motion of the steel belt. When no load is applied, the sliders can restrict unintended deformation of component, but if some external force (ex. human contact) is applied to the component, these can deform and reduce the contact force. The steel belt is driven by pulleys which is actuated by DC motor and reduction gear box. Maximum weight capacity is 8[kg][2] and maximum winching speed is 100[mm/s].

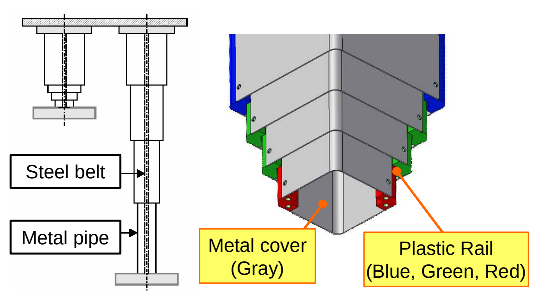


Fig. 8. Abstract of expansion and contraction component

III. Design of Container Transfer Task Controller

Firstly in this section, task flow of container transfer is presented and design items to configure the task controller are listed. Secondly detailed discussions of each design items are described.

A. Task flow of container transfer

There are 2 kinds of container transfer operation, one is retrieval transfer operation "from" a warehouse and the other

[2]This value includes weight of i-Container itself.

is storing transfer operation "to" a warehouse. Generally speaking, retrieval transfer operation is not difficult, because destination state of the operation isn't usually restricted one state. For example, when the container transfer robot executes retrieval transfer of i-Container, destination may be on desk, table or any other furniture, therefore precise positioning motion is unnecessary and rough place motion is sufficient. On the other hand, in storing transfer operation the robot needs to pick up i-Container in a specific state (position and posture), hence higher accurate motion is required in the storing operation. Consequently this section concentrates discussion points to storing transfer operation, in which the container transfer robot have to grasp i-Container at a particular point and transport it.

Fig.9 shows the task flow of container transfer task. As the figure indicates, feature of this control flow is "measurement" procedure of container position and "control" procedure of container handling are absolutely separated. It means that there is no feedback control while executing container grasping operation except component internal control (ex. height control, crank connection pin rotation control). In this task flow, three items below should be discussed.

- Relative position between the robot and i-Container during local measurement.
- Allowable positioning error of the robot preparing for grasping motion.
- Positioning routine of the robot before grasping motion.

The 3 technical items will be discussed hereafter.

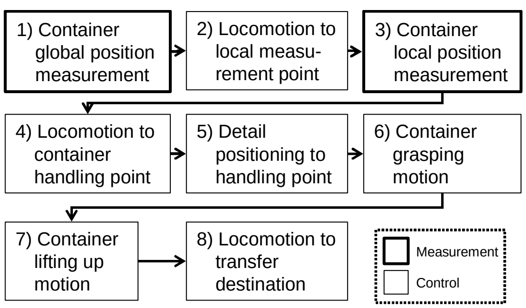


Fig. 9. Container transferring task flow

B. Discussion of relative position between the robot and i-Container during local measurement

As described before, the local measurement of container position is performed by the wireless LAN camera installed on the container transfer robot. Fig.10 shows a sample image shot by the camera. As you can see Fig.10, the manipulation component is in the field of camera view, so it is impossible to lay i-Container at the center of image. Consequently the shooting point of i-Container needs some offset from the center of image. To decide the offset following items should be taken into account.

- Even if data of global measurement has some error, LED markers should not be hidden by the manipulation component body, accordingly sufficient offset is required.

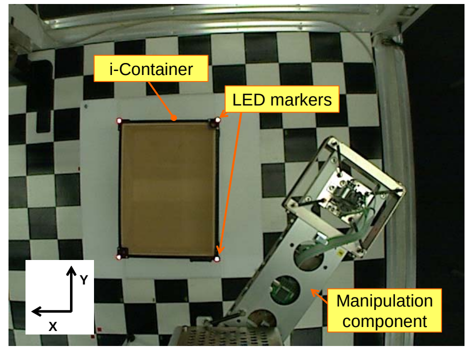


Fig. 10. Camera image for local measurement

- Too large offset makes distance large between shooting point and grasping point, and causes large error of local measurement[3].

As an example of the 2nd discussion item, if the offset is designed to 500[mm] and the direction estimation error of the robot are 0.30[deg], these conditions result in 2.6[mm] ($\simeq$500*0.30*(π/180)) underlying measurement error of i-Container. Because worst error in local measurement itself is 7.3[mm], so sum of these errors equal 9.9[mm]. This 9.9[mm] error is almost the same value as limit of compliance capability of the container transfer robot, and this design is not desirable. In response to the above assumption, X offset are designed to 175[mm] and Y offset to 200[mm]. Even if the global measurement has worst error (67[mm]) in this condition, target i-Container will not be hidden by the body of container transfer robot.

C. Discussion of allowable positioning error of the robot before grasping motion

Here allowable positioning error means a maximum misalignment which can be permit, between locomotion target position of the container transfer robot and estimated position by the 2D code method. Following two items should be considered to design the allowable error.

- Positioning error should be small enough to tolerate the local measurement error of i-Container position.
- Allowable error should not be configured too small because the position estimation by 2D code has some deviation and positioning capability of the container transfer robot has limit.

If allowable error is configured too small, convergence of the positioning routine becomes slow and time to execute the positioning mission becomes longer[4].

First, allowable direction error will be designed. As described before, the worst position estimation deviation of the container transfer robot is 0.33[mm] in distance, 0.3[deg] in

[3]In local measurement, direction of the container transfer robot is used in calculation, so large offset makes extensive an effect of the direction estimation error.

[4]In some case, the robot may be stuck because of infinite positioning routine.

direction, therefore the allowable direction error is designed to 0.20[deg] with a small margin.

On the other hand, allowable distance error is calculated from equation (2).

$$Allow = D_{hor} - (\sqrt{(X_{offset}^2 + Y_{offset}^2)} \times (Err_{2D-direct}/180) * \pi + Err_{Local}) \quad (1)$$
$$= 10 - (\sqrt{(175^2 + 200^2)} \times (0.3/180) * \pi + 7.3) = 1.3[mm] \quad (2)$$

where $Allow$ is allowable distance error, D_{hor} is maximum capability of horizontal compliant element, X_{offset}, Y_{offset} are offset between i-Container and the container transfer robot while local position measurement, $Err_{2D-direct}$ is standard deviation of direction estimation by 2D code, Err_{Local} is maximum horizontal position error of global measurement.

In the calculation some values are worst capability, therefore some safety margin can be expected. In actual implementation, we configured the allowable distance error to 1.5[mm] with our experimental margin.

D. Discussion of positioning routine of the robot preparing grasping motion

The allowable positioning error (1.5[mm] in distance, 0.20[deg] in direction) discussed in the former section are not easy configuration for the container transfer robot, because the mobile component is two wheel driven robot which is in non-holonomic constraint. Besides when the mobile component executes pivot turn motion, center position of the robot will change in real application and the change cannot be estimated easily because of complex frictional condition. Therefore we adopted a following detailed positioning routine to make rotation angle of pivot turn as small as possible. Fig.11 shows motion diagram of the positioning routine.

- STEP1: Go backward until rotation angle(θ) becomes under 15[deg].
- STEP2: Execute pivot turn and makes direction error to goal direction within 1.0[deg].
- STEP3: Go forward slowly. If position error is over 1.5[mm] go STEP1.
- STEP4: Execute pivot turn and makes direction error between the goal and estimated posture within 0.2[deg]. If the positioning error is less than 1.5[mm], then the routine is finished, else go STEP1.

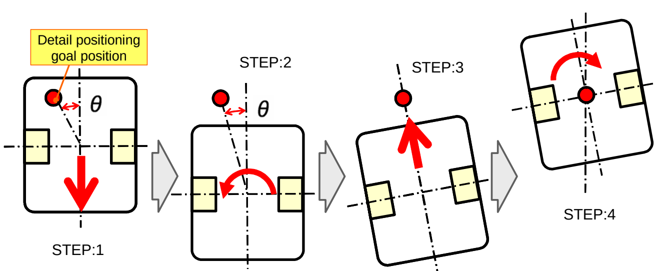


Fig. 11. Locomotion routine for detail positioning

IV. Experiment

Following 3 experiments were carried out to examine the performance of container transfer capability.

- Container handling experiment (1. i-Container on flat plate)
- Container handling experiment (2. Inclined i-Container)
- Compliance effect evaluation experiment

Details of each experiment will be described below.

A. Container handling experiment (1. i-Container on flat plate)

1) Objective of the experiment: As explained before, container place motion is easier than pick-up motion, so in this experiment performance of pick-up motion is confirmed. To confirm robustness of the motion, firstly different error conditions of global measurement for i-Container position are virtually duplicated, secondly local measurement is executed to acquire detailed position of i-Container, finally grasping motion (Pin insertion motion) is performed. By this experiment, robustness of the integrated container transfer system will be confirmed.

2) Experimental setting: An experimental table and i-Container(Fig.12) are used in the experiment.

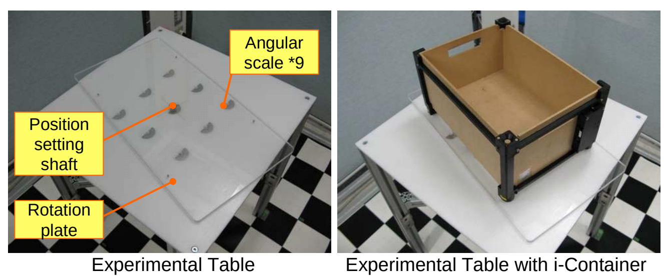


Fig. 12. Experimental table and i-Container

Experimental items are listed below.

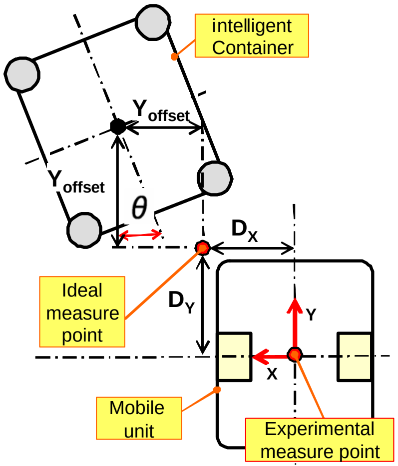
- Position configuration: 9 variations in Fig.13.
- Direction configuration: 3 variations (-15, 0, 15[deg]).
- Trial number: 3 times at each configuration.

Experiments are executed in the next procedure.

1) The mobile component moves to an experimental measurement point in rough positioning mode.
2) Execute local measurement of container position.
3) The mobile component moves to grasping point in detailed positioning mode.
4) The container handling component executes grasping motion (until pin insertion).

To execute the procedure, it takes 3∼4 minutes, but this procedure can be done in background of human activity. Therefore the time itself is not significant.

3) Experimental result: Fig.14 show snapshot of experiment and Table I indicates the experimental results. As a whole, it is confirmed that the presented system has excellent container handling capability, and that the longer of distance between i-Container and the robot becomes the



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. 13. Position setup for experiment

lower grasping success rate drops. This result indicates that the distance should be designed appropriately as described in the controller design section. If the distance found to be too long, once more locomotion and measurement process is essential before handling phase, and this can easily prevent from mission failure.

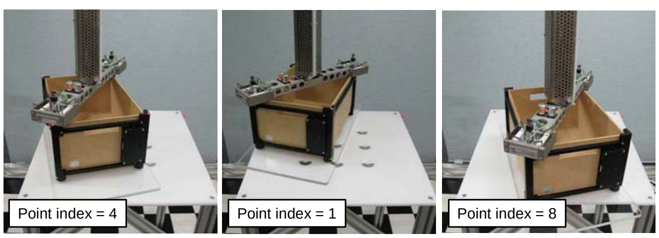


Fig. 14. Snapshot of grasping experiment

TABLE I
RESULT OF GRASPING EXPERIMENT

Point index	Theta					
	-15 [deg]		0 [deg]		15 [deg]	
	state	rate	state	rate	state	rate
1	NA	2/3	OK	2/3	NA	2/3
2	OK	3/3	OK	3/3	OK	3/3
3	OK	3/3	OK	3/3	OK	2/3
4	OK	3/3	OK	3/3	OK	3/3
5	OK	3/3	OK	3/3	OK	3/3
6	OK	3/3	OK	3/3	OK	3/3
7	OK	3/3	OK	3/3	OK	3/3
8	OK	3/3	OK	3/3	OK	3/3
9	OK	3/3	-	-	-	-

OK: Mission completed.
NA: Mission completed but not in all trials.
- : Not tested because 1 LED marker is not in image.

B. Container handling experiment (2. Inclined i-Container)

1) Objective and setting of the experiment: To confirm robustness against interference of other objects, i-Container is place on a obstacle (45[mm] thick) and grasping motion is executed. The thickness of obstacle(45[mm]) is supposed 3 stacked books, and maximum inclination angle of i-Container on this obstacle is 10.3[deg] in roll or 7.4[deg] in pitch.

2) Experimental result: Fig.15 and Fig.16 shows sequential images of inclined container grasping motion. By the experiment, it is ascertained that the system can manipulate robustly i-Container on a 45[mm] thick obstacle.

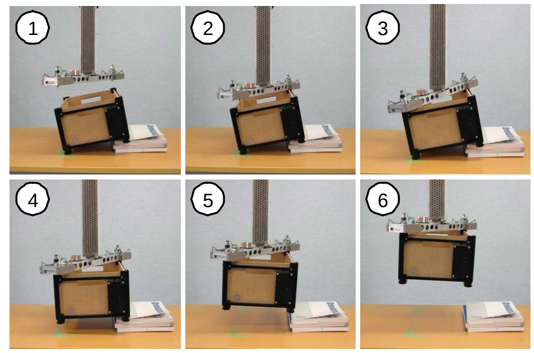


Fig. 15. Snapshot of roll inclined container grasping

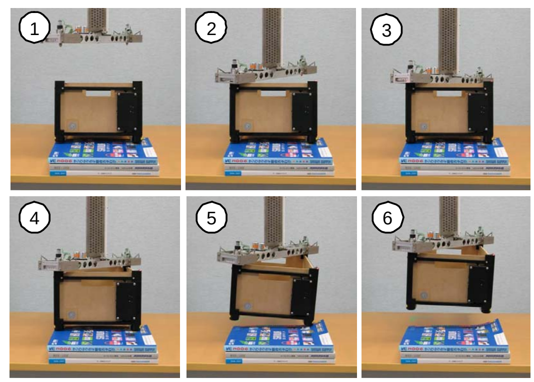


Fig. 16. Snapshot of pitch inclined container grasping

C. Compliance effect evaluation experiment

1) Objective and setting of the experiment: The container transfer robot is installed with two horizontal compliant mechanisms and one inclination compliant mechanism. In addition to these mechanisms, the expansion and contraction component has compliant capability to avoid danger of hard contact with humans. This experiment aims to examine the integration possibility of multiple compliant mechanisms by monitoring each mechanisms' contribution. Fig.17 shows setup of the experiment. In the experiment i-Container is placed on a flat table with 10[mm] misalignment and grasping motion is performed.

2) Experimental result: Fig.18 describes sequential data of each sensor while performing grasping motion. This graph indicates that initially horizontal compliant mechanisms absorb certain position misalignments(DispA,B-x,y), but finally almost all 10[mm] misalignments are absorbed by the expansion and contraction component. This result implies that it is not necessary to realize all compliant capability by stand-alone performance of horizontal mechanism, but is possible to collaborate multiple mechanisms to actualize required compliant capability. Besides it indicates that downsizing of each mechanism is feasible.

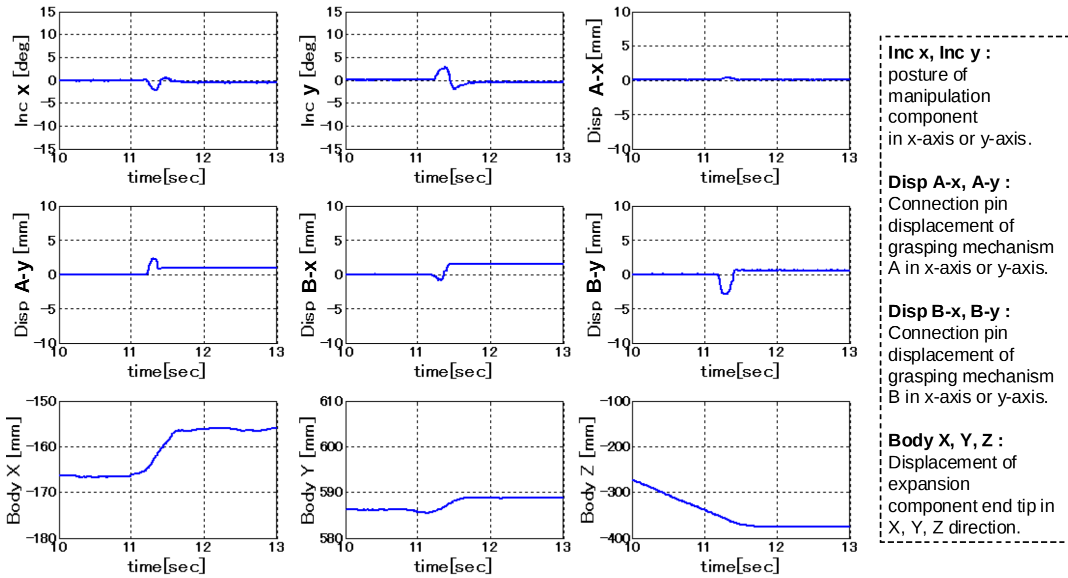
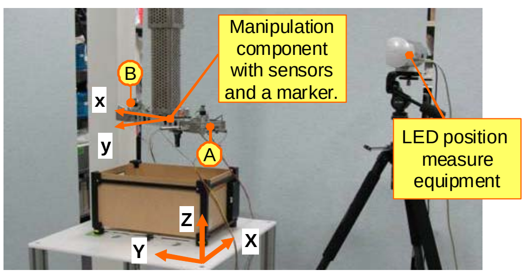


Fig. 18. Result of compliance effect evaluation experiment



#	Measurement Item	Variation	Tools
1	Manipulation component posture	x, y axis	Hole IC type inclination sensor
2	Connection pin displacement	x, y 2 systems	Linear potentiometer
3	Displacement of expansion component end tip.	X, Y, Z	LED position measure equipment *1

*1: accuTrack, Precision RMS 0.3[mm]

Fig. 17. Setup of compliance effect evaluation experiment

V. Conclusion

In previous researches, some elemental technologies such as an accurate container position recognition system, a stable locomotion robot platform and compliant container handling mechanisms are developed. As a next step, in this paper we integrated these technologies into measurement and control system for home-use container transfer task and evaluated capability of the system. There are two characteristics in our measurement and control scheme. (1) Mechanical compliant elements can absorb measurement and control errors. (2) In an object handling phase, there is no feedback control. By experiments, it was confirmed that implemented measurement and control system with the presented scheme can actualize robust container handling motion. By another compliance effect evaluation experiment, an advantage of multiple compliant mechanisms' integration was demonstrated and this result implies possibility of downsizing or reduction of capability of each compliant mechanism.

Thorough the development and experiment, this paper revealed validity of presented open-loop measurement and control scheme and collaborative effectivity of multiple mechanical compliance to overcome error or disturbance which is impossible to pass over in home-use robot application.

References

[1] Rui Fukui et al. Demo movie for home-use logistical support robot system. `http://jp.youtube.com/watch?v=QxILo-Z2eJU`.

[2] Rui Fukui et al. Development of an intelligent container prototype for a logistical support robot system in living space. In *Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 3397–3402, 2007.

[3] Rui Fukui et al. Development of a home-use automated container storage/retrieval system. In *Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 2875–2882, Nice France, September 2008.

[4] Rui Fukui et al. Development of optical measurement system for acquiring position of container cases in living space. In *Proceedings of SICE SI2007*, pp. 1294–1295, Hiroshima Japan, December 2007.

[5] Rui Fukui et al. Development of a movable RFID antenna for recognizing contents of containers in living space (a prototype of the movable antenna realizing robust RFID tag reading regardless of container contents' postures). In *Proceedings of 13th Robotics Symposia*, pp. 39–44, Kagawa Japan, March 2008.

[6] Tomomasa Sato and Rui Fukui et al. Construction of ceiling adsorbed mobile robots platform utilizing permanent magnet inductive traction method. In *Proceedings of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 552–558, Sendai Japan, September 2004.

[7] Rui Fukui et al. Development of a manipulation component for a container transferring robot in living space (design and evaluation of a high compliant manipulation mechanism). In *Proceedings of 11th Int. Symposium on Experimental Robotics*, Athens, Greece, July 2008.

[8] J. J. Craig M. H. Raibert. Hybrid position/force control of manipulators. *ASME J. of Dynamic Systems, Measurement and Control*, Vol. 103, No. 2, pp. 126–133, 1981.

[9] K.B. Shimoga. Robot grasp synthesis algorithms: A survey. *Int. Journal of Robotics Research*, Vol. 15, No. 3, pp. 230–266, 1996.

[10] D.E.Whitney. Quasi-static assembly of compliantly supported rigid parts. *ASME Journal of Dynamic Systems, Measurement and Control*, Vol. 104, pp. 65–77, 1982.

[11] Sangcheol Lee. Development of a new variable remote center compliance (VRCC) with modified elastomer shear pad (esp) for robot assembly. *IEEE Transactions on Automation Science and Engineering*, Vol. 2, No. 2, pp. 193–197, April 2005.

[12] Seung kook Yun. Compliant manipulation for peg-in-hole: Is passive compliance a key to learn contact motion? In *Proceedings of IEEE Int. Conf. on Robotics and Automation*, pp. 1647–1652, 2008.