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Development of a manipulation component for a container transferring robot in living space
(Design and evaluation of a high compliant manipulation mechanism)

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Summary. This paper discusses significance of passive compliant mechanisms in home-use robots, and describes development of a manipulation component for transferring home-use containers. The component has two characteristic functions in mechanics. (1) Robust joint/release function by pin-connection method utilizing crank rotation shaft mechanism, (2) Misalignment tolerate function for horizontal and inclination positioning error by 2-axis sliders and revolution mechanism.

1 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, human cannot find a drastic solution for the problems of real object handling, consequently expect physical robot support to be an answer.

Accordingly our research project is developing "a logistical support robot system in living space" as Fig.1 shows. The system is an intelligent environment which supports our daily access to such objects as books, magazines, CDs, preservative foods, grocery stock and so on. In this system, an intelligent container (i-Container[1]) plays a role of mediator and cooperates with a ceiling mobile robot[2] and rack systems to realize a space efficient storage/retrieval system in a living space. This paper describes the development of a manipulation component which will be installed at the tip of expansion mechanism of ceiling mobile robot as shown in Fig.Fig.1(right). Through this development, the significance and design tips of mechanical compliance will be discussed.

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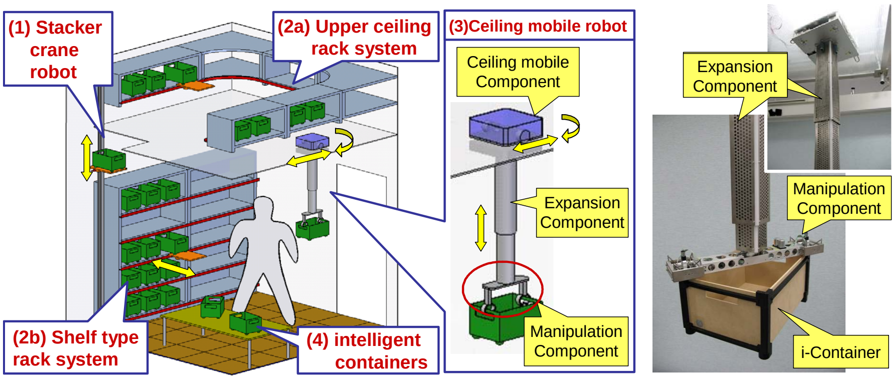

Fig. 1. Conceptual sketch of logistical support robot system in living space(left) and Overview of container transferring robot.(right, photo)

2 Manipulation mechanism for home-use container transferring

Firstly in this section, previous developed object transferring (logistical) robots are introduced and importance of compliance is explained. Secondly, several methods for actualizing mechanical compliance are explained and compared, and our design policy is selected. Finally, concrete required functions for our manipulation component will be stated.

2.1 Logistical robots and significance of compliance

In factories and logistical base, many automated facilities (FA) have developed to achieve efficient storage/retrieval of products. Cosma et al. developed a light weight logistical robot for factory use[3]. On another front, some office-use logistical robots are developed [4, 5], but these robots can not achieve stable motions compared to FA robots, hence there are few actual applications. There seems to be two significant unsolved problems for home robot application. The first problem is safety for human. It's more and more important for home-use robots to ensure the safety than industrial robots, because home-use robots have to operate nearby human. The other problem is difficulty for robots to realize robust motions under variable and volatile circumstances. To clear up these problems, robotic system should be implemented 2 different kinds of flexibility or compliance, i.e. strategic and mechanical compliance. As a strategic compliance in our project, the system need not deal with daily-use objects themselves but specialized i-Containers. For robots, this regulation can reduce difficulty of object handling. In general, the more strategic compliant the system is the less freely user can act. In other words, the main assignment of strategic compliance is to induce the user's specific action without stress. In our system, i-Containers can lead the users to fix commodities

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in themselves (i-Containers). The strategic compliance, however, has its limit, mechanical compliance must make up for the rest of variable circumstance problem. Therefore, mechanical compliance will be organized and discussed in the next section.

2.2 Mechanical compliance

To considerate mutual interaction between robot and objects, or between robots and environment, mechanical compliance was thought to be essential in robotics researches. Especially in peg-in-hole insertion task, there were many discussions about methodology.

Firstly this section summarizes those discussions. There are 3 different major methodologies to realize mechanical compliance.

1. **Passive compliance :**
   RCC (Remote Center Compliance) device is the most representative passive compliance mechanism. In this method, mechanical elements such as springs, damper and slide guide are installed at tip of actuator to tolerate positioning misalignment. There found to be many applications in factory, and these capabilities are trusted. D.E.Whitney et. al. analyzed in details the motion of RCC[6, 7]. As an extended version of RCC, VRCC(Variable Remote Center Compliance)[8] were presented, which can be tuned the stiffness of supporting elastomers.
2. **Concentrated active compliance :**
   In this method active actuation module is settled at the tip of manipulator, preferable compliance characteristics can be realized by the actuators' motion. This hardware architecture is called Macro/Micro Manipulator or Coarse-Fine Manipulator, and tried by many researchers during 1980∼90[9, 10, 11, 12]. Because in 1980's, resolution and accuracy of encoder to measure arm angle are not sufficient, this method was popular to cover the sensor specification. But these days specification of encoders are drastically advanced, so this type hardware architecture are used mainly in semiconductor process. Layout and major application of this compliance type is not different from the passive type. But no friction compliant characteristics realized by magnetically levitation is desirable[10, 11, 12].
3. **Distributed active compliance :**
   In this method, all actuators of a manipulator are utilized to realize virtual compliance at the tip of end effector. The method is frequently used for positioning a part by pressing to a guide plate. In 1980's, after M. H. Raibert and J. J. Craig [13] presented position/force hybrid control method, the simultaneous position/force control problem was one of the hot robotic research topics. Recently, this type compliance is applied to a human symbiotic robot arm[14, 15, 16].

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Among these 3 different compliance types, we focus on the "passive compliance", because the mechanical elements can operate robustly and fail-safe security can be realized easily without complex controller.

2.3 Extraction of required functions

In the container transferring motion, vertical (lift-up and down) motion is actualized by another expansion component. Accordingly essential potentials of manipulation component are (1) to set up a good condition for grasping motion in spite of variant circumstances, and (2) to grasp/release the i-Container robustly. The former potential is mechanical compliance and supports the latter target motion. It is also important the method to realize the latter ability should not disturb the compliance motion. That means the combination of compliance motion and target motion is essential to realize a sophisticated actuation. To actualize the two capabilities, functions below are required.

(1) Horizontal and inclination positioning misalignment tolerate function (Compliance function)
In general, living space is not ideal circumstance for accurate container position measurement and handling. Therefore manipulation component must absorb the measurement and control error. We assume this error 10[mm] horizontally. In addition to the position error, i-Container sometimes is put on a inclined surface. We configure the maximum pitch or roll inclination angle to 10[deg] .

(2a) i-Container grasp/release function
The manipulation component should be able to change grasp/release state easily, and recognize the state robustly.

(2b) i-Container no energy sustaining function
In our system design, the component is expected to be able to sustain 8[kg] load (i-Container itself and expected contents weight). In addition, the component should sustain the load with no power source for safety, i.e. the component needs to hold i-Container even if power source is cut.

3 Design and implementation of manipulation component

This section explains the details of design and implementation. Fig.2(upper) shows an overview of developed manipulation component and Fig.2(lower) expresses a block diagram. Hereafter, firstly design of grasp/release mechanism which does not disturb the compliant motion is discussed, next compliant mechanism design and layout design is discussed.

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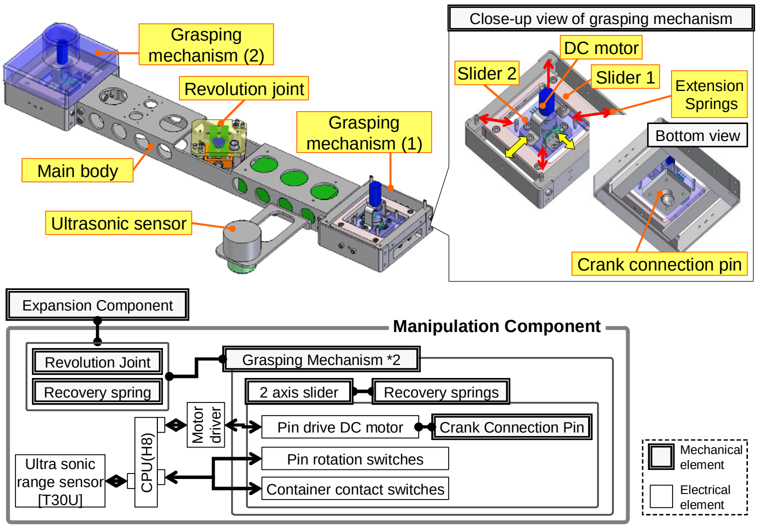

Fig. 2. Overview and block diagram of manipulation component

3.1 Realization of i-Container grasp/release function and no energy sustaining function

This section discusses following design studies, (1)grasping method, (2)number of grasping points, (3)grasping structure, (4)dimension of structure.

Discussion of grasping method

Fig.3 explains general methods for logistical object handling. This research elected the pin-connection method because of connection robustness and easiness of connection recognition. In the pin-connection method, there are two selections for pin and hole installation, i.e. whether pin structure is installed at i-Container or the manipulation mechanism. This research selected installing pin structure to manipulator and hole structure to i-Containers, because pin

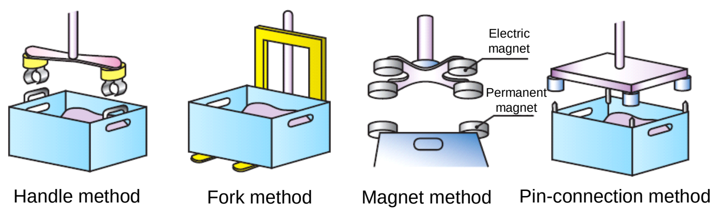

Fig. 3. Candidates of grasping method

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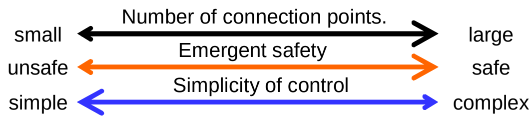

Fig. 4. Number of grasping points and each abilities

structure needs outer cover for safety and the cost for implementation of covers to each containers must be considerable.

Discussion of grasping points number

For pin-connection method, more than two joint point is essential to restrict i-Container rotation freedom. Because of the i-Container box structure, grasping points can be laid at corners only. Consequently number of grasping points must be selected from 2 to 4. Fig.4 shows the relation ship between the grasping points number and each abilities. At the more points the manipulation component grasps i-Container, the more robust and secure the handling state may be, but the more complex control of manipulation might be, and consequently the robot frequently cannot achieve grasping task. To avoid such complexity, we selected the minimum 2 connection points. Because a secure grasping structure must be able to ensure safety.

Discussion of grasping structure

As shown in Fig.5 there are 3 candidates for the grasping structure. Abstract and characteristics of each structures are below.

- Clip method : scissor plates clip a chase of a pin. This method can be implemented in simple structures, however the scissor plates have possible to open unintentionally when excessive load is applied.
- Slide method : a key hole of a slide plate can lock a chase of a pin. This method can sustain a load at safer state, because direction of force applied and direction of the slide lock plate motion is orthogonal.

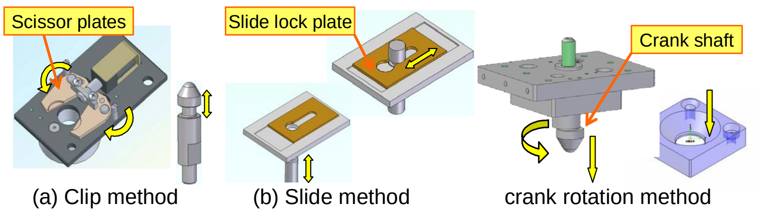

Fig. 5. Candidates of pin and hole connection structure

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- Crank rotation method : an end part of crank shaft sticks out by rotating the shaft and supports a load. This is almost the same method as the logistical containers' one. This method can be installed at small space, and can sustain a load at the same safe state as the slide method.

We selected the crank rotation method, because the pins must be set at grasping mechanisms (i.e. not at i-Containers) and the method can be realized in very simple and small structure.

Discussion of structural dimension for connection pins.

There are two significant items to consider in the design of connection pin dimension.

1. Avoidance of jamming : jamming state may occur when the friction force and the insertion force are balanced unfortunately.
2. Robust recognition of grasping state : outputs of sensors for recognizing grasping state should be unique to the state of lock or free.

• **Avoidance of jamming :** To avoid the pin and hole jamming problem Whitney presented a simple conclusion[6]. A jamming state happens when there are two contact points between pin and hole, therefore it is possible to prevent from jamming by escaping two points' contact. In general industrial use, length of peg and depth of hole are decided by total design, so the parameters cannot be changed. Thus RCC(Remote Center Compliance) is utilized to shorten virtually the length between the tip of peg and center of rotation. In our application, the parameters of pin and hole can be selected for our convenience, hence the length of pin insertion (L_2) was designed to be as short as possible like Fig.6.
• **Robust recognition of grasping state :** Two different sensors are essential to recognize grasping state. The first sensor must detect whether the pin is inserting in the hole sufficiently. The other sensor must measure the position of the crank shaft for detecting lock or free state. Fig.7(left) shows the designed pin and hole structure, accordingly complete of pin insertion equals to definite contact of surface(A) and (B). So we install a contact switch at the surface(A) to detect touching of surfaces. Next a position sensor needs

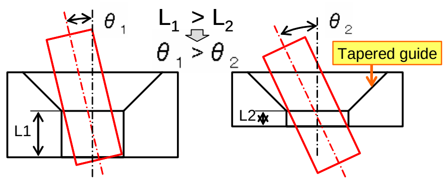

Fig. 6. Pin and hole dimension that can avoid jamming.

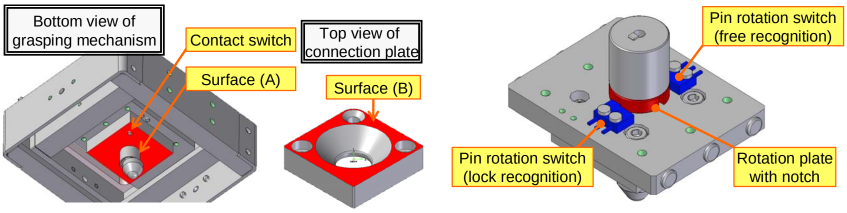

Fig. 7. Structure of pin and hole(left), Switches for lock state recognition(right)

to distinguish whether the crank shaft is at lock position or free position. As shown in Fig.7(right), a round plate with notches is settled around the crank shaft and two independent contact switches are places to detect the notch position.

3.2 Implementation of horizontal and inclination positioning misalignment tolerate function (Compliance function)

In this section, firstly composition and layout of compliant elements are discussed and secondly realization of each compliant elements are explained.

Discussion of compliant elements' composition

As described former sections, the manipulation component grasps an i-Container at two corners by crank rotation method. Namely, the mission of this function is interpreted as a problem to insert simultaneously two pins at two holes of a target under a circumstance the target can take different postures in horizontal 3 DOF (X,Y,Yaw) and inclination 2 DOF (Pitch,Roll).

In discussion of inclination error compliance composition, the two connection points are inclined together, so only 1 compliant element with 2 DOF compliance are necessary. On the other hand in discussion of horizontal error compliance composition, there are 3 essential discussion topics.

1. How many elements are needed to absorb sufficiently the 3 DOF horizontal misalignment?
2. Do production errors of i-Containers induce jamming?
3. Is there possibility of new jamming state because of cooperative motion of two pins?

Firstly item 1 is considered. There are two candidates for composition of horizontal compliant elements, (1) Concentrated compliance type (One horizontal compliance and 1 yaw axis revolution compliance), (2) Distributed compliance type (Two horizontal compliance). Fig.8(left) shows skeleton sketches of both types. As shown in Fig.9(a, lower), if there is initial position misalignment in yaw axis, it generates large horizontal position error at the position of connection pin, hence it is practically difficult to use yaw axis compliance. In addition

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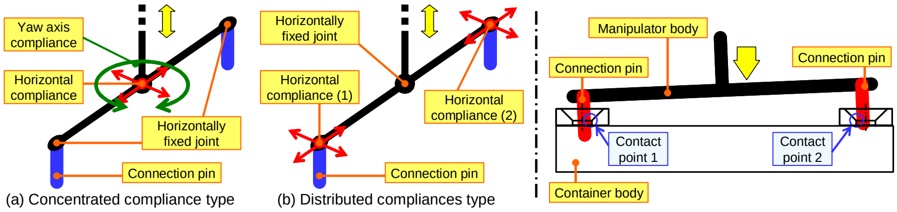

Fig. 8. Layout candidates of compliant elements(left), Jamming state caused by two contact points(right)

to the yaw axis design, production error can be minimized by utilizing precise jig, however cost of jig and labor hour are problems. Furthermore cooperative inserting motion of two pins sometimes cause a new jamming state as shown in Fig.8(right). In Fig.8(right), there occur two contact points (One contact point at each pin and hole) if the distance of connection pin is invariable. For all of these reasons, the distributed compliance type is more consistent.

Discussion of detail layout for compliant elements

This section describes detail layout design of compliant elements at horizontal view and vertical view. In the horizontal layout design, there is no need for artifice, because laying horizontal compliance at each ends of the body and inclination compliance at the center of the body (as shown in Fig.9(a, upper)) is sufficiently reasonable in a view of weight balance. On the other hand in the vertical layout design, distance between the pin tip and the revolution center of inclination compliance should be as short as possible like Fig.9(b, upper). Because if the distance (Lg in Fig.9(b, lower)) is unnecessarily long,

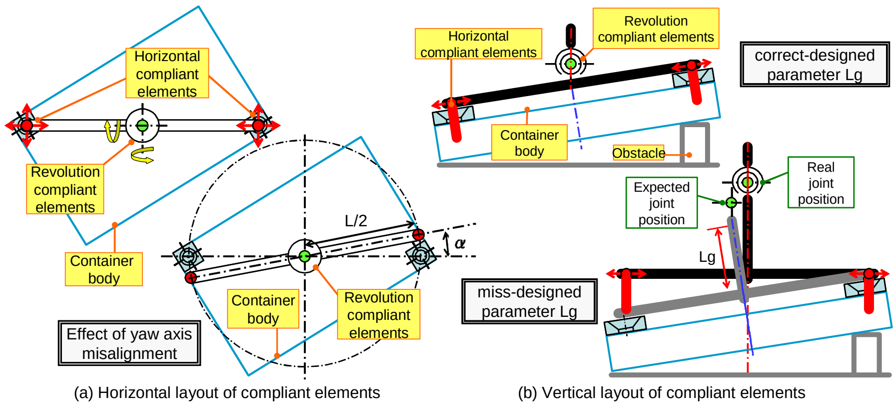

Fig. 9. Designed layout of compliant elements.

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unintended problems that posture of the manipulation component cannot fit to posture of the i-Container may happen. To solve this problem, precise measurement and control might be an answer if possible, but to shorten the distance(Lg) is the most simple and practical solution.

Discussion of horizontal compliance structure

For horizontal compliance structure, it is necessary to sustain vertical load rigidly and to transform horizontally smoothly. In industrial usages RCC is very popular, but RCC cannot realize large displacement because it uses deformation of elastomer shear pad. Therefore we developed a novel slide mechanism called "Hybrid friction slide mechanism"

This method is composed of an orthogonal pair of sliders as Fig.10(left). The center plate can move in 2 DOF(X, Y) motion. Fig.10(center) shows a cross section of the sliders. Upper side and lower side of the slider is made of different friction material. When a load is applied to the pin and plate, the plate touches to the lower high friction material and the plate is fixed. On the other hand when no load is applied, the plate touches to the upper low friction material and can slide smoothly. The slider is supported by tension springs to recover initial position.

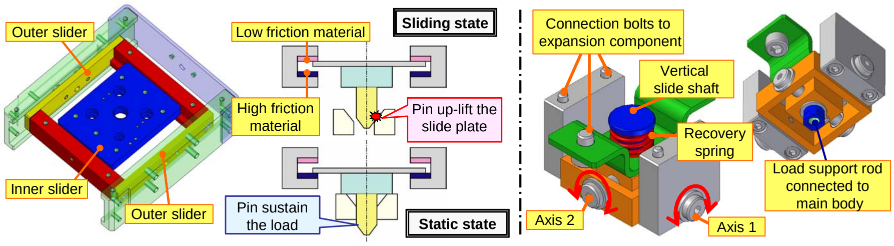

Fig. 10. Horizontal compliant mechanism(left). Inclination compliant mechanism(right)

Discussion of inclination compliance structure

The inclination compliance should realize two revolution DOF (Pitch and Roll). To realize 2 DOF revolution motion, there are two implementation methods. Abstract and characteristics of each methods are below.

- Orthogonal two axes method : this method utilizes 2 rotation shafts and lays the shafts orthogonally. It needs many support parts and the size cannot be small, but is easy to control because there is no extra revolution DOF.

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- Spherical joint method : this method utilizes 1 spherical joint (3 DOF) and fixs an extra axis by a supporting structure. It can be realized by very simple parts but is difficult to fix the extra axis motion.

In our application, the extra axis motion might be fatal positioning error. Because length of the body is not small as shown in Fig.9(a, lower), therefore only small extra axis motion conduces large positioning error($\epsilon = \alpha \times (L/2)$). On that count orthogonal two axes method was adopted. Fig.10(right) shows the designed inclination compliant element. 4 elastomer poles are installed around the element to recover the initial position and prevent vibration motion. (An elastomer pole can be a simple damper.) Additionally when a load is applied, the vertical slide shaft inserts in the hole of bracket(Fig.10(right), green) and the revolution motion is restricted.

Summary

Based on the former discussions, the manipulation component was designed as shown in Fig.2. Fig.1(rightmost) presents i-Container transferring motion by the ceiling robot which is equipped with a developed manipulation component.

4 Experiments

In this section, horizontal and inclination compliant capabilities are examined.

4.1 Experiment for horizontal error toleration

In the experiment, a specialized test bench (Fig.11) was used to confirm possibility of connection pins insertion. The test bench can imitate a vertical motion which is performed by a expansion component of the ceiling mobile robot. Fig.12(a) indicates the coordinate systems of the test bench and the manipulation component. In experiments, i-Container imitation plate is settled at 13 points as Fig.12(b) shows, and examined whether pin insertion motion is achieved with no trouble. Each test was executed at 3 times. Fig.13(left) shows horizontal displacement of both connection pins and combined force applied at the imitation plate. Next Table 1 explains summarization of experiment results. It is examined that the manipulation component can complete the pin inserting motion smoothly at 13 different position with horizontal positioning misalignment. These results indicate that the component has enough compliant capability.

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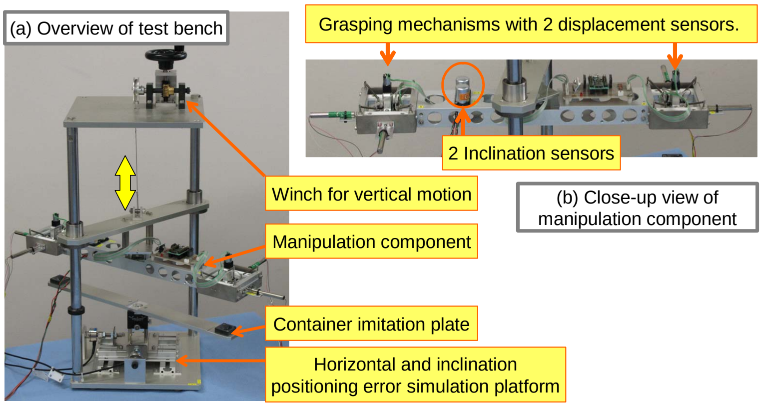
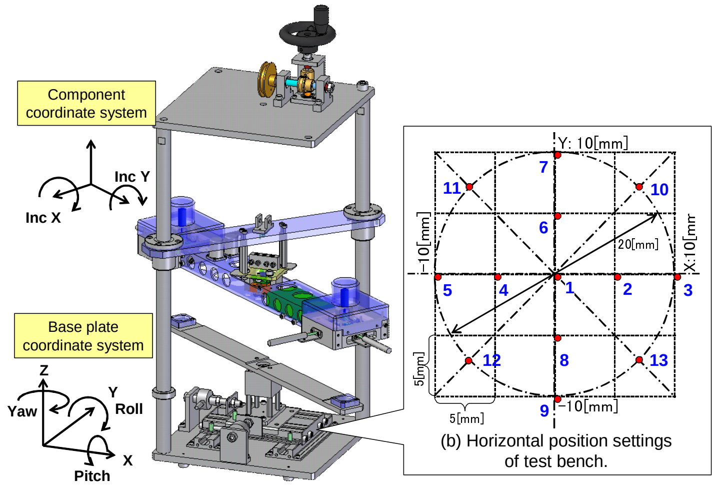


Fig. 11. Test bench for manipulating



(a) Coordinate systems of test bench and component.

Fig. 12. The coordinate systems of test bench and horizontal position settings

4.2 Experiment for inclination error toleration

As well as the former experiment, the test bench was used. In this experiment, container imitation plate is inclined pitch +/-10[deg] or roll +/-10[deg] at 3 different points (Point 1,4,8 in Fig.12). These configures are decided by geometric limitations, i.e. At initial state, connection pins must be allocated on the upper side of taper guide holes. Fig.13(right) shows inclinations of the manipulation component body, horizontal displacement of both connection pins and combined force applied at the imitation plate. This time series graph explains a flow of grasping motion of the mechanism, (1) one connection pin is navigated to a hole by the horizontal compliance, (2) the body is inclining

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Table 1. Maximum force generated by insertion motion with only horizontal error

Measurement point	Position Error		Yaw angle					
			0 [deg]		2 [deg] *1		-2 [deg] *1	
	X	Y	state	force	state	force	state	force
1	0	0	○	2.1	○	5.1	○	3.2
2	5	0	○	3.1	○	2.7	○	5.0
3	10	0	△	5.0	-	-	-	-
4	-5	0	○	2.5	○	2.6	○	2.5
5	-10	0	○	5.5	-	-	-	-
6	0	5	○	1.7	○	2.6	△	3.1
7	0	10	○	4.8	-	-	-	-
8	0	-5	○	3.3	○	3.4	○	2.9
9	0	-10	○	3.2	-	-	-	-
10	7.1	7.1	△	5.4	-	-	-	-
11	-7.1	7.1	○	3.0	-	-	-	-
12	-7.1	-7.1	○	2.7	-	-	-	-
13	7.1	-7.1	○	2.8	-	-	-	-

Unit of force : [N]
○ : Insert motion is completed.
△ : Insert motion is completed with initial position adjustment.
- : Not tested.

*1: 3 or -3 [deg] at measurement point 1.

gradually, (3) the other connection pin inserts in another hole, (4) Finally posture of the mechanism body fits to the container imitation plate. By this experiment, it is ascertained that the manipulation component can absorb simultaneously +/-10[deg] inclination error and 5[mm] horizontal positioning error, under a circumstance where the connection pins are allocated on the upper side of the taper guide holes.

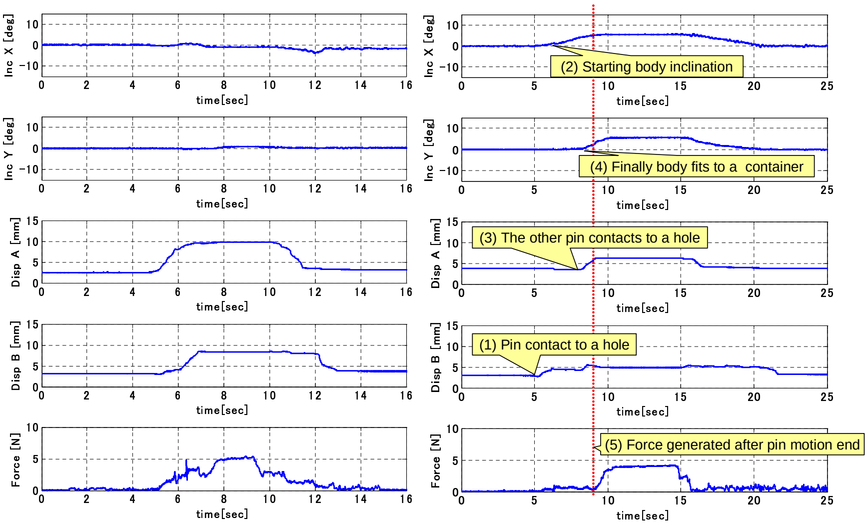

Fig. 13. Displacement and force graph of insertion motion (Left) with only horizontal error, (right)with horizontal and inclination error

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5 Conclusion

This research developed a manipulation component for transferring home-use specialized containers (i-Containers) by utilizing the ceiling mobile robot. Through the development, we discussed design of compliance mechanisms.

The component has two mechanical characteristic functions. (1) Robust joint/release function by pin-connection method utilizing crank rotation shaft mechanism, (2) Horizontal and inclination positioning misalignment tolerate function by 2-axis sliders and a revolution mechanism.

By the first characteristic function, the manipulation mission can be converted as a problem to insert simultaneously two pins at two holes of a target, under a circumstance the target can take different postures in horizontal 3 DOF (X, Y, Yaw) and inclination 2 DOF (Pitch, Roll). To solve insertion problems, key points for compliant mechanism design are organized. According to the technical key points, a manipulation component prototype is constructed and evaluated by experiments with a purpose-built test bench. It is confirmed that by utilizing its high compliant capability the component can achieve a grasping motion with no jamming failure under a condition with horizontal 10[mm] position error or 10[deg] inclination error at max.

In compliance mechanism design, there found to be 2 significant points.

1. It is significant to implement a proper scheme for restoring initial state, because it affects much to the compliant capability.
2. It is necessary to design a compliant mechanism which can stop or reduce the compliant ability, when some load is applied.

For robots in human living space, not small measurement or control errors are always observed between a robotic end effector and target objects, therefore a robot should be implemented a compliant function like the presented manipulation component. This approach will accelerate actual applications of service robots in human living space.

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