

Development of a Home-use Automated Container Storage/Retrieval System

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ABSTRACT

This paper describes development of home-use automated container storage/retrieval system, a sub-system of a logistical support robot system in living space. The s/r system has 3 features. (1) Elevator type structure enables not only auto stocking motion, but also human access to containers as if the auto rack is a general shelf. (2) A separated motion layout enables us to utilize upper ceiling space as a stock space, and decreases possibility of accidental stuck by reducing the volume of robot's motion. (3) The collaboration of a container guide plate and sensing with RFID actualize to navigate people to place a container on a shelf with desired position and posture. By experiments, it is confirmed that the ACSRS can transfer a container and 5 [kg] load (total 8 [kg]). We summarize significant technical points to design a system of this type. The keywords for design are cantilever structure, overcoming bump and human navigation.

I. INTRODUCTION

A. Background and motivation

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 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" as Fig.1 shows. The system is an intelligent environment which supports our daily access to objects. As commodities, we suppose books,

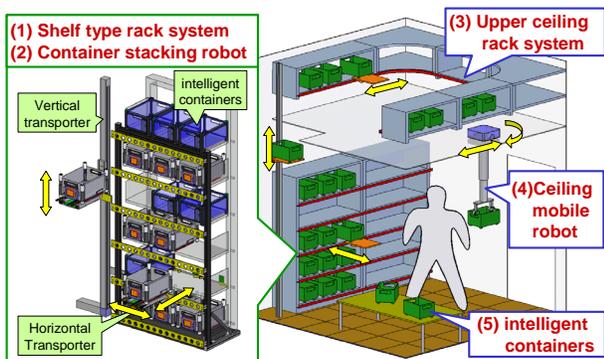


Fig. 1. Conceptual sketch of the logistical support robot system

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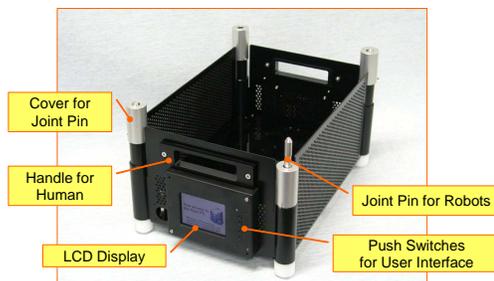


Fig. 2. Overview of intelligent container prototype

magazines, CDs, preservative foods, grocery stock and so on. In this system, an intelligent container (i-Container, Fig.2 [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 discusses development of a home-use automated container storage/retrieval system (ACSRS) which is realized by integrating rack systems and container stacking robot.

B. Related works and our mission.

In logistical and industrial use, many automated facilities have been developed and researched to achieve efficient storage, transferring and management. Products' management by automated warehouse is one of the most important task in modern manufacturing companies, hence there are many trials to achieve high efficiency[3],[4]. To summarize our mission in other words, our goal is to convert such sophisticated industrial techniques to some real applications in human living space.

1) *Mechanical technology aspects:* In mechanical technology aspects, stacked 3 dimensional warehouses are important to save space. Especially in full automated manufacturing system, all parts and tools should be managed in a concentrated method, therefore many different type automated warehouses have been developed[5][6]. On the other hand, home-use automated storage/retrieval systems may realize arrangement of daily objects with high space efficiency in living space, but because of reasons below there are few actual applications until now.

- Problem of install cost
- Problem of object variation
- Problem of safety and interference with human.

The problem of install cost is not fatal in some specific locations. Because cost to obtain a storage space in urban area is very high in advanced countries, the install cost is not so dominant in some applications. In general use of automated storage/retrieval(s/r) system, the system handle not objects themselves but containers or pallets. In our system the i-Container can be a such standard target, so

the problem of object variation is solved. The i-Container is helpful to reduce difficulty of task for automated facilities. On another front, industrial automated s/r system can not be used in living space, because of safety and space. i.e. the system need to balance between space occupation by the system and safety with low interference to human. To make a balanced solution is the main theme of our development.

2) *Information technology aspects:* In informative support, Supply Chain Management techniques in logistical application can achieve high efficient storing and transporting of products.[7] The intelligent container can acquire a log of commodities' use by utilizing RFID techniques, therefore we can obtain never lost memories of commodities' arrangement. Thanks to the feature, the system can actualize a object search procedure like WWW search engines (ex. Google).

In recent researches to sophisticate automated warehouse, optimization procedure is developed that can deal with seasonal products[8]. In general living space, almost all commodities are seasonal objects (ex. clothes, bedclothes etc..), therefore such techniques can be leveraged for home-use storage system. For example, the system can sort things whether frequently used ones or not by data-mining the log of commodities use. The system may arrange the frequently used tools at shelf type rack, and rare used objects at upper ceiling rack. To actualize this service application, it is essential to design an automated home-use r/s system, which can use upper ceiling space for storage, can obtain information of content's transition and can transfer i-Containers inside the s/r system. In addition, the handling over i-Containers between the r/s system and the ceiling mobile robot is significant optional function in a view of system integration.

3) *Framework of this paper:* In section II, required functions for home-use ACSRS is analyzed and discussed. In section III, overview of design and implementation is explained. In section IV and V, the design and implementation of home-use ACSRS is described. In section VI, the basic ability of the system is confirmed by experiments. Finally, section VII is the conclusion.

II. SPECIFICATION OF HOME-USE ACSRS

In this section, major roles of the home-use automated container storage/retrieval system are defined and required functions for each roles are listed.

- (A) **Stocking** : the s/r system stocks and fetches smoothly i-Containers at shelf or upper ceiling.
- (B) **Transferring** : the s/r system transfers i-Containers in cooperation with the ceiling mobile robot.
- (C) **Information management**: the s/r system saves history of i-Container's storage and retrieval.

Next sub-sections discuss required functions for each roles.

A. Required functions for stocking.

Next three functions are required to realize stocking role.

- [A1] Human life symbiotic storage function
The s/r system must adapt not only robotic auto stacking but also human traditional arrangement.

- [A2] Upper ceiling utilization function
The s/r system should utilize upper ceiling space for storing. This realizes high space efficiency in our home.
- [A3] Human placing navigation function
The s/r system needs to navigate human to place an i-Container at desired position and direction on the shelf for making robot task easier.

B. Required functions for transferring.

The maximum load of i-Container is designed to 5 [kg]. Because the i-Container's weight is set to 3 [kg] at maximum, the s/r system should be able to transfer 8 [kg] load. Three functions below are required to realize the transferring role.

- [B1] Low interference locomotion function
The s/r system should not invade human activity, so needs to move in low interference with human life space.
- [B2] Position error adaptive function
The i-Container's position which is placed by human is not always ideal for robot actuation, hence the robot must be equipped with adaptive mechanism or controller to the position error of the containers.
- [B3] Container position validity displaying function
When human places an i-Container on a shelf, the rack should inform whether the container is set at desired place for robot. This function should collaborate with the former "human placing navigation function".

C. Required functions for information management.

Next two functions are essential to actualize sophisticated information management role.

- [C1] Container property recognition function
The system should obtain i-Container's property (ex. container ID, contents' info) on the rack.
- [C2] Storage/Retrieval history recording function
The system should save log about the i-Container's storage and retrieval.

III. OVERVIEW OF DESIGN AND IMPLEMENTATION

Before explanations of design detail, this section indicates overview and design procedure of the home-use ACSRS.

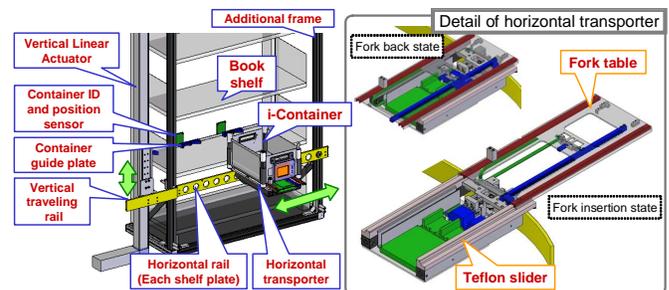


Fig. 3. Abstract of home-use ACSRS.

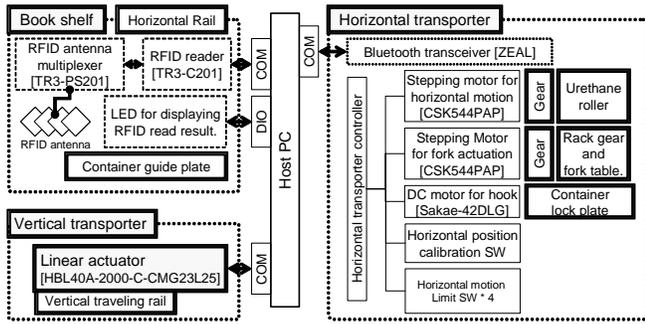


Fig. 4. System block diagram of home-use ACSRS.

A. Abstract of home-use automated container storage and retrieval system

At first, Fig.3 shows an abstract of developed home-use ACSRS, and Fig.4 expresses a system block diagram. The s/r system is mainly composed of a book shelf with some devices, a vertical transporter and a horizontal transporter which also executes picking and placing motion of i-Containers.

B. Design flow of home-use ACSRS

Fig.5 shows the design flow of home-use ACSRS. The symbol and number corresponds to later section numbers. In basic design, primary structure and method will be selected based on the required specifications in section II. After that, detailed design and implementation, concrete mechanisms and devices are discussed.

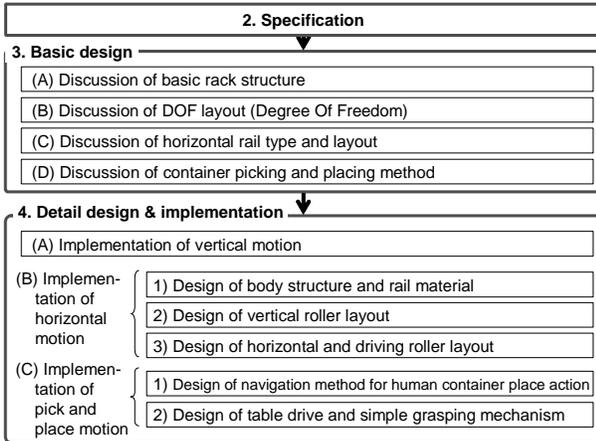


Fig. 5. Design and implementation flow.

IV. BASIC DESIGN OF CONTAINER STOCKING ROBOT.

To realize the required functions in section II, this section discusses basic rack structure, layout of DOF (Degree Of Freedom), rail type/layout and pick/place method.

A. Discussion of basic rack structure

There are two fundamental strategies as ACSRS. The first is elevator type and the other is circulation type as Fig.6 shows. Abstract and features of each types are shown below.

• Elevator type

In this type, the automated s/r system is composed of shelves and a stacker crane, and picking and placing

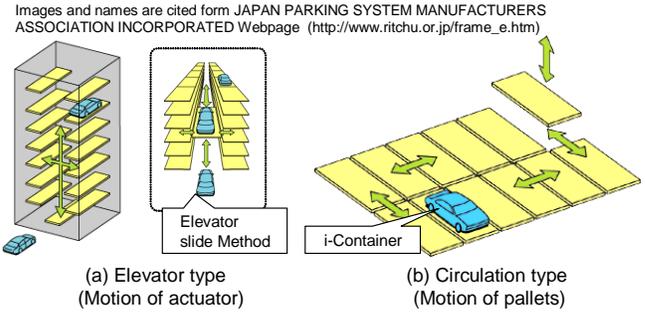


Fig. 6. Basic structure types of auto rack.

motion is executed at each shelf plates. The type of a shelf is the same as traditional home-use shelf, so human can arrange and fix objects at a shelf without special care. Because only the stacker crane actuates, it is not necessary to equip a large power source.

• Circulation type

In this type, whole structure is actuated circularly, and picking and placing motion is performed at a specific gate. This type can utilize whole rack space for stocking, hence the space efficiency is considerably high.

Because the elevator type does not require a special change to human living style, we adopt this type. As a shelf structure, a book shelf on the market is utilized in our research.

B. Discussion of DOF layout (Degree Of Freedom)

To realize elevator type ACSRS, vertical and horizontal motions are essential. There are two candidates of layout as Fig.7 shows.

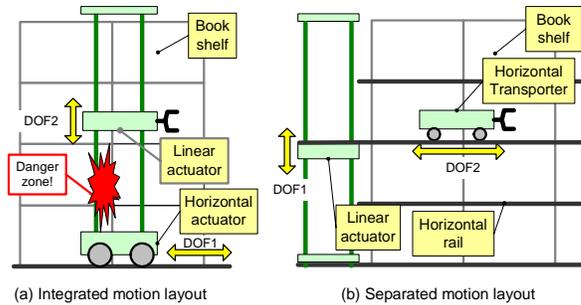


Fig. 7. Comparison of DOF layout.

Abstract and features of each layouts are below.

• Integrated motion layout

This layout is used for factory stacker cranes. Vertical and horizontal actuators are installed at the same body. This layout enables vertical and horizontal simultaneous motion and realizes high speed transferring.

• Separated motion layout

This layout is sometimes used for automated library[9]. The layout is composed of a vertical linear actuator and a horizontal transporter. This layout can make motion volume small and realize high safety in living space.

We adopt the separated motion layout, because in living space it is important to keep high level safety than in factories, i.e. most users are not engineering professionals in living space. In addition, the separated motion layout has an advantage that can utilize upper ceiling space for storage by extending only the length of a linear actuator.

C. Discussion of horizontal rail type and layout

In factories, under ceiling transferring systems adopt mono rail structure to actualize horizontal motion as Fig.8 shows. Because this structure can support large mass and route of



Fig. 8. An example of mono rail type transporter

robot can be designed with high flexibility. This research plans to settle mono rail structures upper the ceiling as shown in Fig.1 (Red lines). To utilize whole space of upper ceiling, straight rails and bended rails should be equipped. As well as upper ceiling, some mono rails are installed at each shelf plates which make it possible for the horizontal transporter to access the containers on the shelf rack.

D. Discussion of container picking and placing method

In this section, a method for picking up i-Containers from the rack and setting containers to the rack is discussed. As

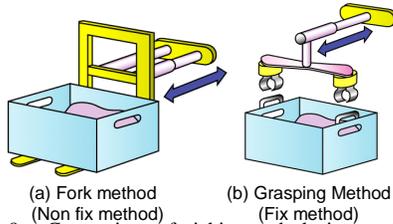


Fig. 9. Comparison of picking and placing method.

transferring method, fork method and grasping method are well known as Fig.9 shows. Abstract and characteristics of each methods are explained below.

- Fork method (Non fix method)
This method is usually used for transferring pallets in factory. Like forklift, this method insert fork structure under a target. Accurate positioning is not necessary for this insertion action. On the other hand, this method needs high power and short stroke actuator for lifting up a target from a shelf plate.
- Grasping method (Fix method)
In this method, robot hands grasp or connection pins lock a target. This method can hold the target rigidly, so sliding failure does not occur. In addition, lifting up motion is needless if friction is properly small between bottom of i-Container and a shelf plate.

This research adopt a hybrid method 'Fork and simple grasping method' that takes advantages of both the fork method and the grasping method. Fig.10 explains an example of container picking motion by the hybrid method. In the picking motion of this method, fork table is just inserted under a target and lock actuator enables container pulling motion without jacking up the target.

V. DETAIL DESIGN AND IMPLEMENTATION

This section explains detail design and implementation to actualize the selected structure and methods. Firstly the

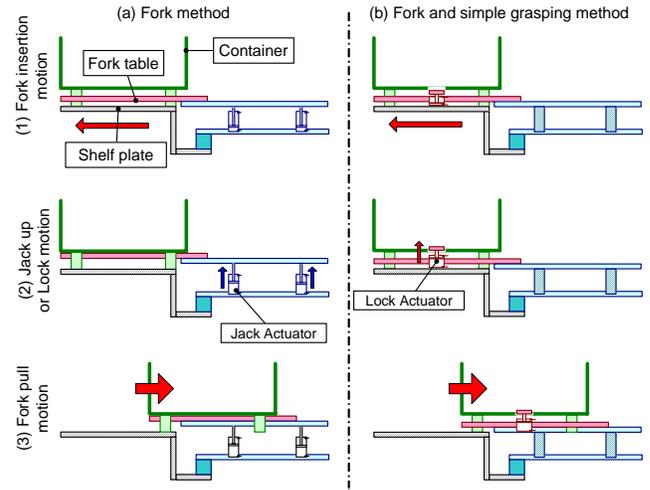


Fig. 10. Comparison of container picking motion.

implementation of vertical motion is discussed, and secondly the implementation of horizontal motion is considered, finally the implementation of pick and place motion for i-Container is explained.

A. Implementation of vertical motion

To realize a vertical motion, a long stroke linear actuator is convenient. This research adopt a timing belt driven linear actuator 'HBL40A-2000-C-CMG23L25' which is produced by Mecha Industry co. Ltd. This actuator contains the controller in its body, so it can save space.

B. Implementation of horizontal motion

First of all, main body structure and material for horizontal rails are discussed briefly. Nextly design of support rollers that sustain the load of horizontal transporter is discussed. In the roller layout design, two kinds of consideration are essential. The first is the design of vertical layout of rollers that has relation with vertical force and moment, and the other is the design of horizontal layout of rollers which has effect to navigation ability along to bended rails in upper ceiling. And design of a driving roller is explained in the horizontal layout design.

1) *Design of body structure and rail material:* As described in the former section, rails at each shelf plates may invade the human living space. To avoid interference, it is essential to align the rails and shelf with small gap as shown in Fig.11. As a result, the horizontal transporter must overhang the rail with cantilever state and the body needs to be stiff enough to support load. To build a high stiff and light weight main body, two aluminum square pipes are aligned parallel. In addition to robot body design, stiffness of mono rail is significant to support large moment. Hence "SUS304HL" is selected as a rigid material for mono rail.

2) *Design of vertical roller layout:* As described in the former section, the horizontal transporter must sustain large moment because of the cantilever situation. Fig.12 (left) shows a layout model of vertical rollers. The meanings of the symbols in Fig.12 are explained below.

m : load (containing weight of body), L : distance between rail and

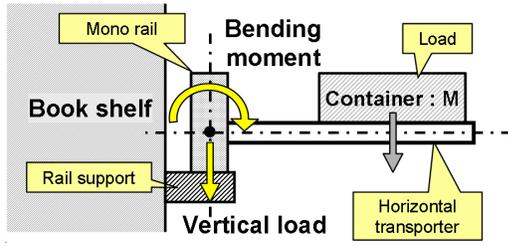


Fig. 11. Simple rail and load model of horizontal transporter.

load center, t : thickness of rail, w : horizontal distance between upper roller and lower roller. h : vertical distance between upper roller and lower roller. f : sustaining force of rollers. θ : inclining angle of body.

Considering the balance of moment, rollers must support force in equation (1).

$$f = m \times L/h \quad (1)$$

If the roller force (f) is too large, the life time of bearings that supports a roller shaft may become shorter than usual. In addition to the problem of life time, too large force invokes the deformation of urethane and shafts. These deformations makes the gap large between horizontal roller distance (w) and rail thick (t), as a result the body of horizontal transporter inclines as shown Fig.12 (right). In this situation, the inclining angle of body can be calculated as equation (2). The equation shows that the longer vertical roller distance (h) the smaller the body inclining angle (θ).

$$\theta = \arctan\left(\frac{w-t}{h}\right) \quad (2)$$

Therefore it is significant to set the roller force (f) to adequate range, and it is necessary to design the vertical roller (h) as long as possible. On the other hand, the vertical roller distance corresponds to the rail height, so too long vertical roller distance interferes the front side of the shelf. The height of the i-Container is ruled to 170[mm] and the height of each book shelf is designed to about 300[mm]. Additionally people need at least 50[mm] gap to take out an i-Container from a rack, so the maximum length of vertical rollers are calculated as $300 - (170 + 50) = 80$ [mm]. On another front, the longer the rail height is, the stronger twisting force becomes. Consequently, thick rail is required that can hold the horizontal transporter flat. To summarize former

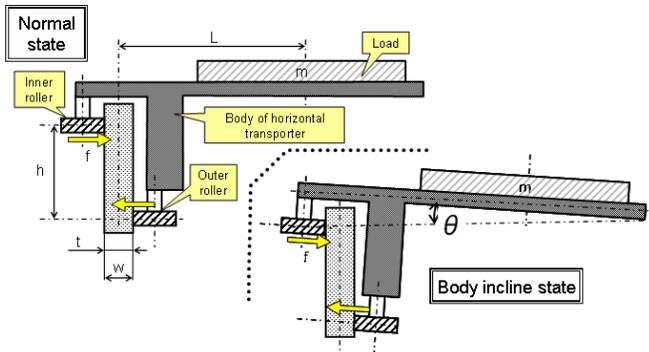


Fig. 12. Layout model of vertical roller layout.

discussion, three conditions below should be discussed in the design of roller layout.

- The distance of vertical rollers should be long enough to support the large moment.
- The height of rails must be short enough for people to pick up i-Containers from the rack.
- The rail should be thick enough to sustain the twisting force by the rollers.

The vertical distance of rollers is designed to be 55[mm] (Rail height 65[mm]) because of industrial standard for SUS304HL material, and the thickness of the rail is decided to 9[mm] by FEM analysis.

3) Design of horizontal and driving roller layout: In the design of horizontal roller layout, we must take into accounts turning motion of horizontal transporter along a bended rail. For this purpose turning guide roller is essential. In another topic, there are two types of driving roller as shown in Fig.13. The first is (a)integrated roller type and the other is (b)Separated roller type. If we adopt (a)Integrated roller type in our prototype, the main center roller seems to support large moment, hence the motor must have large power. To save energy consumption, we select (b)Separated roller type in spite of the increasing number of parts. The inner rollers which are installed at the rack side of rail, have position adjustable structure that can change the roller sustaining force. This structure can change the gradient of body. (The loading space should be flat generally.) But too much sustaining force caused loss of driving power, the position should be adjusted carefully.

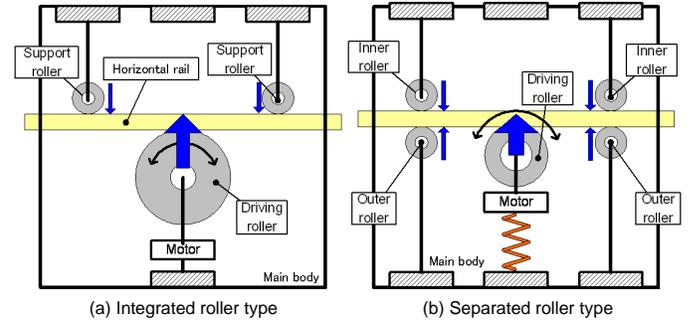


Fig. 13. Candidates of horizontal roller layout

C. Implementation of pick and place motion

Firstly, the method for navigating people to place an i-Container at desired position and posture is described. Secondly, mechanism design for driving fork table and locking i-Container is explained.

1) Design of navigation method for human container place action: Unlike in the case of industrial ACSRS, in the home-use ACSRS users can put i-Containers by their hands. Hence positions of placed i-Containers are non-constant. It thought to be difficult to realize robust handling control that can deal with i-Containers which are placed by human arbitrarily, even if an accurate position measurement method is realized. Therefore a scheme for navigating human to place i-Containers at desired position and posture is required. To actualize this purpose, there are two methodologies, one is structural method and the other is information display

method utilizing a simple sensor. As Fig.14 shows, the guide plate navigates the container to specific position by leading foot parts of container to holes of guide plates. By this scheme, even if a user put an i-Container roughly,

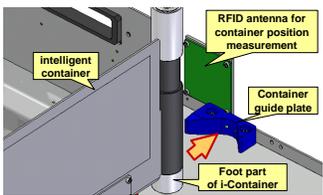


Fig. 14. Guide plate and foot part of container.

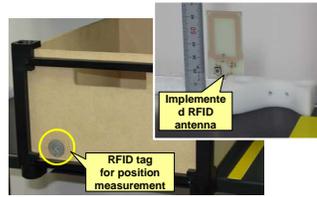


Fig. 15. RFID tag for container identification and antenna for measurement

the table insertion motion can modify the position. On the other hand in information display method, RFID tag for i-Container ID recognition (Fig.15 left) is utilized for abstract position measurement. A RFID antenna (Fig.14 right) can detect an i-Container only when the i-Container is placed in the neighborhood of the desired position. When a new i-Container is placed, a information device inform the user about the result. The method for displaying information will be selected based on experimental results in section VI.

2) *Design of table drive and simple grasping mechanism:* The container guide plate provides the horizontal transporter high compliance ability. Thereby the fork table driving and container lock motion can be realized by very simple mechanisms. The power source for actuating table is stepping motor and rack gear. The rack gear works out linear motion of the fork table. As simple grasping mechanism, lock plate mechanism are adopted as Fig.16 (left) shows. For locking an i-Container, the lock plate chucks a chase under i-Container as shown in Fig.16 (right).

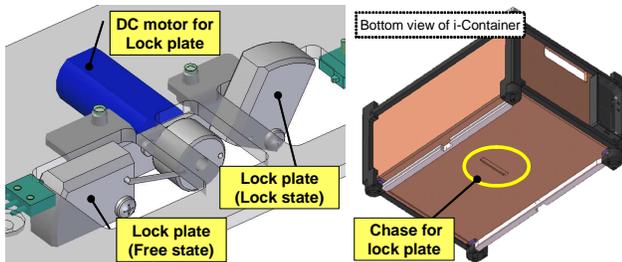


Fig. 16. Lock plate for simple grasping mechanism and a chase of i-Container.

VI. EXPERIMENTS

As experiments, firstly experiment to examine the ability of human container placing navigation function is executed, and in the next step transporting experiment is done to confirm the performance of the s/r system.

A. Human container placing navigation experiment

A purpose of this experiment is to confirm the ability of navigation function and examine an effect of user interface difference.

1) *Experimental setting:* The settings of the experiment are below.

- Subjects: 5 persons. (2 women, 3 men)
- Navigation scheme: 4 patterns.
SET 1 : Only guide plate.
SET 2 : Guide plate and border lines.
SET 3 : SET2 + LED displays RFID recognition.
SET 4 : SET2 + Beep sound indicates RFID recognition.
- Repeat count : 5 times at each scheme.
- Measurement item 1 : Time for stocking motion.
- Measurement item 2 : Position of placed i-Container. (Measured by ultraviolet LED measurement system. Accuracy : RMS 0.1[mm])
- Questionnaire item : Usability of each schemes.

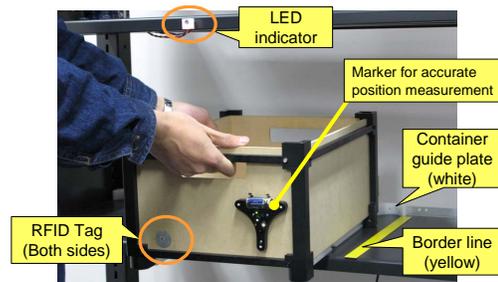


Fig. 17. Snapshot of container placing position navigation experiment

2) *Experimental result:* Fig.18 shows result. Fig.18(left) describes the average stocking motion time. About all subjects, time for SET2(Guide plate + border line) is longer than SET1(Only guide plate). This result might indicate that the border line can make the subjects' motion more careful. In most subjects, the RFID recognition information by LED or sound can make the work time shorter. Secondly, Fig.18(center) shows the distance between the desired i-Container position and placed one. The average error of SET1 is less than 2[mm], it is very good result. This result shows that only guide plate can navigate users sufficiently. Finally, Fig.18(right) shows the questionnaire result by the subjects. The RFID recognition displaying (SET 3 or 4) is highly evaluated because it becomes easy for user to know the condition of i-Container. But the displaying methods themselves are pointed out to be questionable. Here is summarization of experimental results.

- Only container guide plate has sufficient position navigation ability.
- Border lines can make users more careful and strict in stocking motion.
- RFID recognition displaying by LED or sound can let users feel relief and make work time shorter. But sound tone and position of LED should be modified for real application.

B. Container transporting experiment.

To confirm basic transporting potential, three different experiments are performed. Fig.19 shows a snapshot of experiment.

- Horizontal transporting experiment

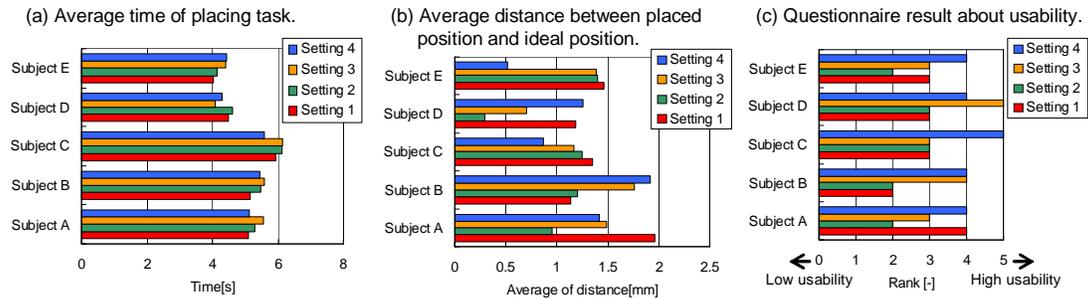


Fig. 18. Result of container placing position navigation experiment

- Going over rails motion experiment
- Container pick and place motion experiment

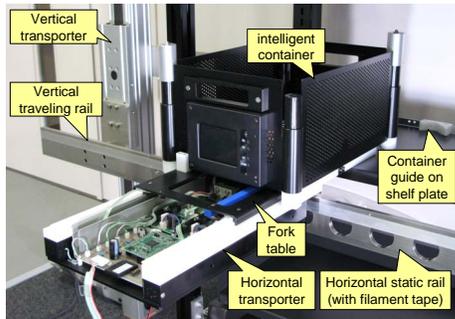


Fig. 19. Snapshot of container transporting experiment

1) *Horizontal transporting experiment*: Before the experiment, the driving roller was slipped because friction between urethane of roller and stainless rail was not enough. Therefore filament tape was attached to the stainless rail. Thanks to this treatment, the horizontal transporter can transfer an i-Container with 5 [kg] load (total 8 [kg]). In the mono rail structure, the body and load weight does not affect to the friction force between roller and rail, so it found to be important to manage friction coefficient of the metal rail.

2) *Going over rails motion experiment*: It was estimated that driving force might be maximum when going over rails. Therefore in this experiment, the driving roller is removed from the horizontal transporter and force to transfer the body is measured. In Appendix. A, by comparing the measured data with calculated data, calculation method is evaluated. Measurement settings are shown below.

- Force source : hand power (Manual).
- Sensor : Load Cell (KYOWA:”LM10KA”)
- Sampling Rate : 1k [Hz]
- Locomotion : Vertical. From static rail to movable rail.
- Roller setting : 2 variations.
- Load : 0, 3, 5.5, 8 [kg] (4 variations.)

Fig.20 indicates samples of measured force data. This figure shows that there are two peaks when each support roller overcomes a bump at the connection point of movable rail and static rail. Fig.21 shows summarization of results reordered by load. As shown in the experiment setting, two positions of inner roller are tried. In the setting A, the inner roller is 1[mm] closer to the rail than setting B.

The result shows that the position of inner roller has a lot effect to the driving force. Because the more inner roller

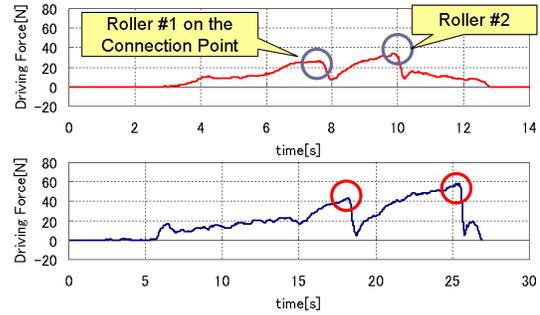


Fig. 20. Example data of driving force.
Upper : Load 0 [kg], Lower : Load 8 [kg]

is pushed to the rail, the larger sustaining force becomes, hence the driving force to overcome a bump might become larger. After driving force measurement, the inner roller is tuned to setting B. The horizontal transporter can go over rails supporting 8[kg] load with no trouble.

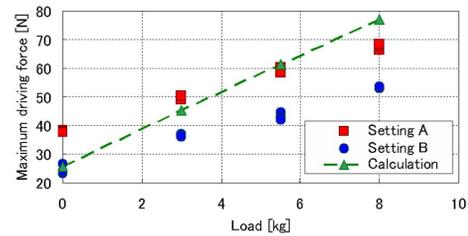


Fig. 21. Summarization of maximum driving force experiment.

3) *Container pick and place motion experiment*: To confirm the container picking motion, an i-Container is place at 7 different positions and postures as shown Fig.22. In all settings, the picking motion is executed with no problem, and the high compliant capability was confirmed. On the other hand, in the container placing motion the guide plate and fork plate can settle an i-Container at desired position.

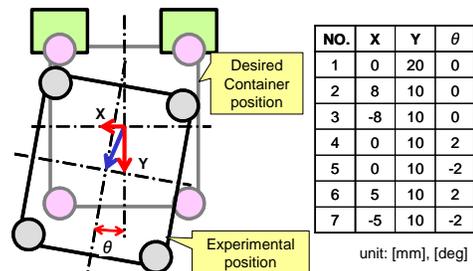


Fig. 22. Experimental setting for picking motion.



Fig. 23. Snapshot of developed home-use ACSRS

VII. CONCLUSION

This paper described development of home-use automated container storage/retrieval system (Fig.23) and confirmed the basic performance of prototype by experiment. Table I shows the summarization of presented home-use ACSRS features, comparing industrial ACSRS.

Through the development of the prototype, there found to be three significant key points in the design and implementation of this type system.

(a) In design of mono rail structure, height of rail (vertical distance between rollers) should be long enough to sustain large moment.

(b) In design of separated motion layout, driving force becomes maximum when rollers overcome bump between a movable rail and a static rail. Therefore the height of bumps should be small enough and the size of roller should be as large as possible. The details is described in Appendix A.

(c) Simple container guide plate can accurately navigate position of i-Container placed by human, in addition border lines and RFID recognition displaying method can promote users' psychological changes (ex. carefulness or relief).

There are some future tasks for us. The transporting performance on a bended rail should be performed to confirm the ability to use the upper ceiling space widely. Exception process with safety sensors should be developed to realize fail safe in living space.

TABLE I

CHARACTERISTICS COMPARISON OF THE ACSRS

| | Presented Home-use ACSRS | Industrial ACSRS |
|---------------------------------------|--|---|
| Basic structure | Elevator type | Elevator type / Circulation type |
| Degree of freedom layout | Separated motion layout (Linear actuator and horizontal transporter) | Mostly integrated motion layout (Stacker crane) |
| Rail type | Mono rail, Cantilever state. | --- |
| Pick / Place method | Fork and simple grasping method | Fork method / Grasping method |
| Container position recognition | RFID tag and antenna | Camera and marker |
| Space occupation | Low (Escape mode is available) | Very high (specially reserved space is necessary) |
| Human pick/place | Available | Impossible (Available for only a stacker crane) |
| Tolerance to disturbance | High compliant | Generally not supposed |
| Max locomotion speed | Slow for safety Horizontal : 0.2 [m/s] | Fast for efficiency (1~2 [m/s]) |

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APPENDIX A. COMPARISON OF MEASURED DRIVING FORCE AND CALCULATION.

The Fig.24 shows a simple model of roller when overcoming bump. In this model, R: radius of roller, h: height of bump, F_s : body sustaining force, F_d : required driving force. If η is defined as $\eta = h/R$, F_d is

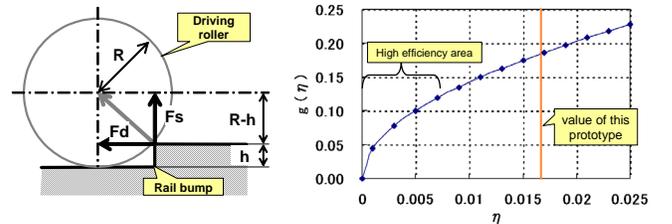


Fig. 24. Simple model of roller overcoming bump.

Fig. 25. Inclination of $g(\eta)$ calculated as next equation.

$$\begin{aligned}
 F_d &= F_s \times \frac{\sqrt{2Rh - h^2}}{R - h} \\
 &= F_s \times \frac{\sqrt{2\eta - \eta^2}}{1 - \eta} = F_s \times g(\eta) \quad (3)
 \end{aligned}$$

In this prototype R is 24[mm], h is measured to 0.2[mm], and the F_s is f in equation (1) which varies depending on the load. Dotted line in Fig.21 is the calculated values of required driving force. As described in the experiment result, the driving force is strongly associated with the inner roller position. However it is possible to set the inner roller in a situation where real driving force is almost same as or smaller than the calculated value. This calculation can be used for design practically. For reference, the relation of $g(\eta)$ and η is described in Fig.25. To actualize sophisticated design, we should use small η area. That means that it is significant to make the height of bumps (h) as small as possible and the roller size (R) as large as possible.