iDock: a multifunctional intermediate instrument to improve efficiency of domestic delivery and storage system

Rui FUKUI, Masayuki SHODAI, Taketoshi MORI, Tomomasa SATO.

ABSTRACT

This paper describes development of "iDock", which is used for a container temporal stacker. iDock serves as if it is a mail-box in the post-service or a service station of the door-to-door delivery system to improve efficiency of domestic delivery and storage robot system. The instrument realizes stack of containers, recognition of contents in containers, and navigation of robots. To acquire information of contents in containers, RFID tags are attached to contents and scanned by movable RFID antenna of iDock. By experiments, it is confirmed that the movable RFID antenna is applicable to robust reading, and guide plates for human and robot can actualize smooth handing over task of containers between a user and a robot.

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, 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"[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.

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

This system consists of following five subsystems.

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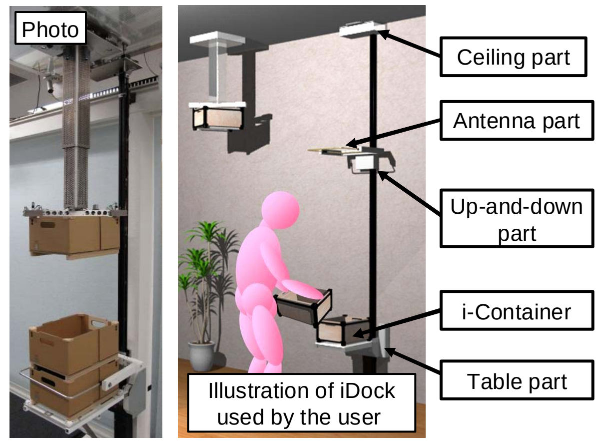


Fig. 2. Photo and illustration of iDock

1) intelligent Container(i-Container), which is a sophisticated storage box and plays a role of mediator between human and robots in the presented system[2].
2) Ceiling mobile robot, which carries i-Containers[3].
3) Automated container storage/retrieval system, a high space-efficient home-use warehouse which is composed of a rack system and a special designed stacking robot[4].
4) intelligent Dock (iDock), which helps users to access i-Containers from/to the ceiling mobile robot.

This paper discusses development of an intelligent dock "iDock"(Fig.2) to improve logistical efficiency in the presented system.

The framework or this paper is as follows; Firstly section II analyzes and discusses benefit of introducing the multifunctional intermediate instrument "iDock" into the home logistical support robot system and organizes required functions. In section III, design and implementation process to realize the required functions is explained. In section IV, basic ability of iDock is confirmed by experiments. Finally section V is conclusion.

II. MULTIFUCTIONAL INTERMEDIATE INSTRUMENT: IDOCK

A. iDock's role in the home logistical support robot system

When the home logistical support system is compared to existing logistic systems, iDock in home logistics plays a roll of intermediate facility almost same as a service station in the door-to-door delivery systems or a mailbox in the post-service. As Fig.3 shows, iDock will be installed in each room and each key point at home. When a user wants to have an i-Container transferred from living room to a child's room,

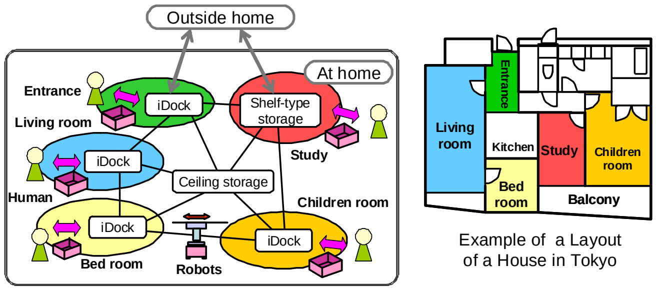


Fig. 3. Concept diagram of iDock

he or she has only to put the i-Container on an iDock in the living room and order the destination on a user interface of iDock. After user puts i-Container on iDock, the ceiling mobile robot will carry it to the destination, such as iDock in the destination room, or storage of the home logistical support robot system at appropriate timing. iDock will be expected to play a role as an access point of "Room to Room" delivery system.

B. Advantages of iDock's introduction and required functions for iDock

The main role of iDock is helping users to pass i-Containers to the ceiling mobile robot, and vice versa. Of course users can handover i-Containers to the ceiling mobile robot directly, but smoother logistic system would be realized by introducing relay points, as is the case in existing logistic systems. In existing logistic systems, advantages of relay points introduction can be summarized below.

- Secure handover of cargoes
- Temporal storage of cargoes
- Information management of carried items

By extrapolating these advantages in the existing system to the home logistical support robot system, we defined three + one required functions as follows.

1) **To ensure handing over between humans and robots:** It's difficult for human to pass an i-Container to the robot by hand (Fig.4(A)), while it's also difficult to designate a specific place where the robot should release an i-Container. And if robots are expected to release i-Containers steadily, some sensors should be installed to ensure vacancy of the spot (Fig.4(B)). To solve these problems, a specialized

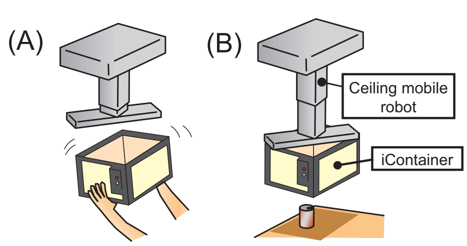


Fig. 4. Difficult examples of i-Container handover task between human and robot

stack yard for i-Containers should be prepared. In this case, it will be able to make a container transfer robot move directly to a previously-defined point. It means simple position adjustment tool can be installed (ex. guide plate, shock absorber), and fast and robust i-Container handing over task would be possible.

2) **To stack i-Containers temporarily:** If iDock accept not only a single i-Container but also multiple stacked i-Containers, it will be able to reduce substantial waiting time of humans or robots. In case iDock cannot stack i-Containers and cannot buffer them, a user must wait for the ceiling mobile robot to carry away first i-Container, to put second i-Container on the iDock. If iDock has a function to stack multiple i-Containers, a user has simply to stack the second i-Container on the first one.

3) **To recognize items in i-Containers:** In the home logistical support robot system, items are identified and managed with RFID tags on themselves. If iDock can read the RFID tags, the system can update information of items at every transfer point. This information makes it possible to track and search items in i-Containers easily as if they are files in folders of personal computers file system.

4) **To be small-footprint not to make living space narrow:** If introducing iDock makes life space narrow, it may be against main policy and benefit of the presented system, so this guideline is added to the required functions.

C. Difficulty level of realizing each required functions

In this subsection difficulty level of realizing each required functions is described.

1) **Required functions for ensuring handing over between humans and robots:** To realize this required function, the ceiling mobile robot should be guided to the right position, and absorb positioning errors, and several solutions would realize this function. Therefore details of the solutions will be discussed in the next section.

2) **Required functions for stacking multiple i-Containers:** This function is important and there seems to be no big difficult problems technically. iDock has simply to prepare a structure for stacking multiple i-Containers. However the structure needs to be as compact as possible, not to invade our living space.

3) **Required functions for recognizing items in i-Containers:** Recognizing items in i-Containers with RFID tags is the most difficult to realize among the required functions. There were many studies which utilize RFID tags to identify items in living space[5][6]. Near field UHF tags are drawing attentions these days[7], but HF tags are widely spread for item-level-tagging, so HF tags are adopted in the home logistical support robot system. However, HF tags are orientation-sensitive[8], and a reader antenna must be large to cover the volume of i-Container.

However, when iDock is installed in living space, it's undesirable to use huge antenna. To identify each item with reasonable size antenna, we have studied several methods for reading multiple RFID tags in i-Containers In the next section, design process of RFID antenna will be described in detail.

III. Design and implementation of iDock

Fig.5 shows an abstract of developed iDock and Fig.6 expresses a system block diagram. As Fig.2 shows, iDock is mainly composed of four parts: table part, up-and-down part, antenna part and ceiling part. or three principle components: guide plate for ceiling robot, movable RFID antenna and fold-down table for i-Containers. In the following subsections, design details of iDock are discussed.

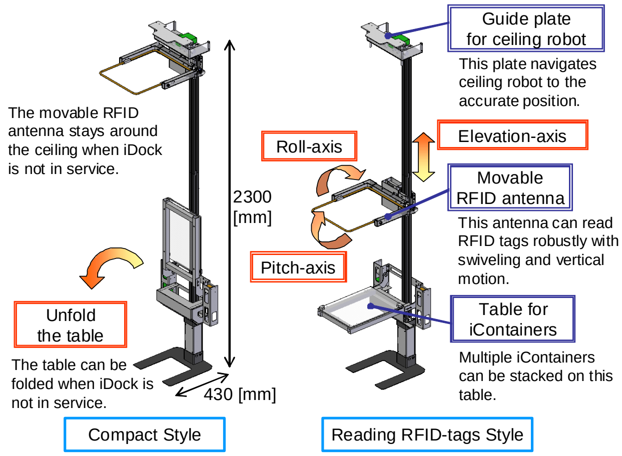


Fig. 5. Abstract of iDock implementation

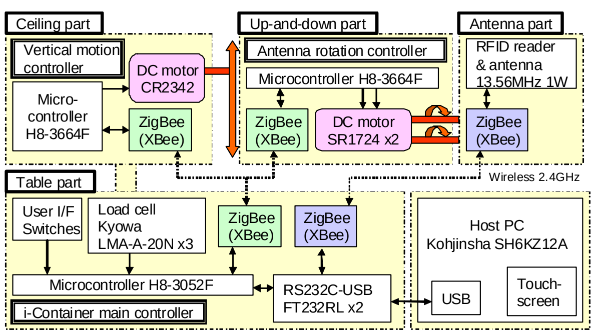


Fig. 6. System block diagram of iDock

A. Recognition method for i-Container contents

RFID systems can be classified with their frequency. and have different characteristics with the frequency. In addition, usage of near field or far field also affects RFID tags' characteristic. In the home logistical support robot system, HF (13.56[MHz]) tags are used. It's because HF tags are widely used in Japan, and also they have few serious defects in item-level tagging.

HF RFID systems utilize inductive coupling between a reader and a tag antenna through magnetic field. In general[7], power P_{chip} recieved by an RFID tag chip can be expressed as equation (1).

$$P_{chip} = P_{reader}\rho C\tau \quad (1)$$

where P_{reader} is output power of a reader, ρ is impedance matching coefficient between reader and its antenna, C is coupling coefficient between the two arbitrarily oriented reader and tag antennas, and τ is impedance matching coefficient between tag chip and its antenna.

Among these parameters, P_{reader} is regulated by law of each country, ρ and τ are supposed to be optimized, and so we focused on C. When we discuss RFID tags which is located in the near field of the reader antenna, they affect each other, and so their performance parameters can no longer be specified independently.

If a tag antenna is small, C can be expressed as

$$C \propto f^2 N^2 B^2 S^2 \alpha \quad (2)$$

where f is frequency, N is number of turns in tag antenna coil, S is cross-section area of the coil, B is magnetic field at the location created by the reader antenna, and α is coil misalignment loss[7]. Equation (2) indicates that increasing B and S enhance coupling coefficient, so relative position and orientation of the RFID tag to the reader antenna is significant.

In general, read rate of RFID tags becomes low progressively by distance, and also RFID tags are orientation-sensitive. When a tag antenna and reader antenna is coaxially-arranged and when tag and reader antennas are orthogonal each other, communication can't be established. Therefore, we have tried some methods to solve the problem of relative position and orientation between tags and a antenna. It's difficult to read RFID tags oriented in various directions with single static loop antenna. To solve this problem, three different methods (Fig.7) are considered and examined their performance by simple experiment .

In the experiment, we use a special test piece which has 98 RFID tags in 3 directions (Fig.8), and examine how many tags can be read by each method. Table I shows an experimental result.

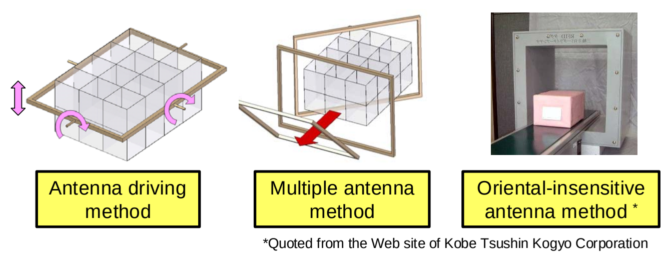


Fig. 7. Candidates of orientation-insensitive RFID reading method

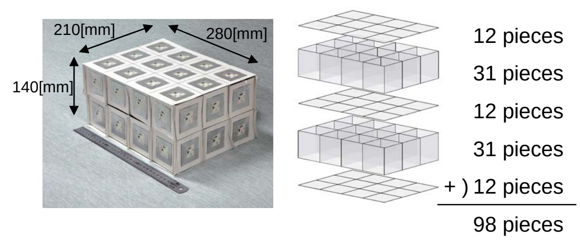


Fig. 8. RFID tag test piece

TABLE I
RESULT OF BASIC ANTENNA PERFORMANCE EXPERIMENT

	The number of unreadable RFID tags
1. Antenna driving method	0 / 98
2. Multiple antenna method	0 / 98
3. Oriental-insensitive antenna method	5 / 98

Firstly "Oriental-insensitive antenna method" couldn't actualize high performance in the experiment, hence another method is desirable. Secondly the performance test result of "Multiple antenna method" is good, and its scheme is effective in belt conveyer application, however it requires a broad space, so it's not suitable for home environment.

"Antenna driving method" can realize high recognition performance by rotating reader antenna on 2-axes and translating vertically on 1-axis (movable RFID antenna) as shown in Fig.9. In addition to the good performance, the method can put its antenna away by the vertical translating action and can reduce the occupied space when the antenna is not necessary. Therefore the antenna driving method is a leading candidate.

To examine mutual negative effect between the RFID reader antenna and actuator or electrical device for automation such as motors or wires, we made an RFID tag reader prototype (Fig.10) equipped with a movable RFID antenna[9]. It is confirmed that this prototype can read RFID tags in high recognition rate without negative effect of motors or wires, so we decided to adopt antenna driving method.

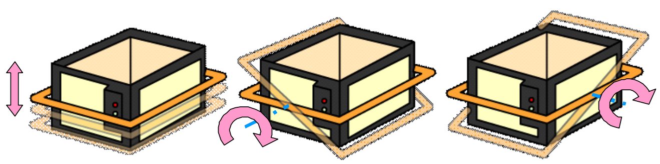


Fig. 9. 3 antenna motions of antenna driving method

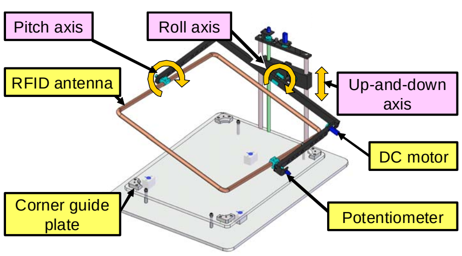


Fig. 10. RFID tag reader prototype with antenna driving method

B. Vertical motion and guide structure

This subsection discusses following 2 items.

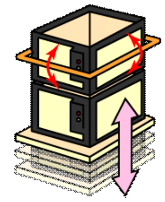
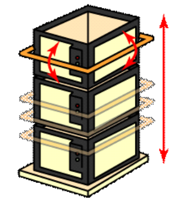
- how to stack multiple i-Containers and recognize tags in the i-Containers
- how to realize reliable (fail-proof) in handing over process between user and robot

1) how to stack multiple i-Containers and recognize tags in the i-Containers: In this research "antenna driving method" has been adopted, but vertical position of RFID tags to the reader antenna is relative, so we have two candidates as shown in Table II to stack multiple i-Containers and recognize RFID tags in these containers.

This research adopted "static i-Container table method & up-and-down RFID antenna method", because weight of moving part in this method is smaller than the other method, and it will be safe and won't need high power actuators. At the same time when iDock is not in service, small foot-print of is realized by evacuating the reader antenna from living space to neighbor of ceiling and preparing fold-away table.

TABLE II

COMPARISON TABLE OF VERTICAL MOTION

Method	Static RFID antenna & up-and-down i-Container table	Static i-Container table & up-and-down RFID antenna
Pictures		
Advantages	The height of the i-Container table is adjustable, so it's easy for us to put another i-Container on the stacked i-Containers.	iDock has to elevate only RFID antenna, and it's much lighter than i-Containers themselves.
Dis-advantages	iDock must elevate heavy i-Containers.	The height of i-Container table is not adjustable.

2) how to realize reliable handing over between user and robot: The ceiling mobile robot in the home logistical support robot system grasps two corners of i-Container. When the robot grasps i-Container, it tolerates 10[mm] position error, so relative position between i-Container and the robot should be restricted within the range.

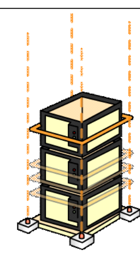
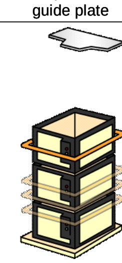
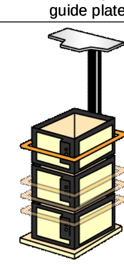
To guide ceiling mobile robot with 10[mm] accuracy, following three methods can be candidates.

- Optical marker method
- Separated guide plate method
- Mechanically-linked guide plate method

These three methods are shown in Table III. This research adopted "Mechanically-linked guide plate method", because this method is expected to realize more accurate and faster positioning, and it can also reduce complex installation procedure.

TABLE III

COMPARISON TABLE OF THE GUIDE STRUCTURE

Methods	Optical marker	Separated guide plate	Mechanically-linked guide plate
Pictures			
Advantages	-Structure is smaller. -It's easy to install iDock in a room.	-Structure is smaller. -Alignment is speedy.	-Robot can execute positioning quickly. -iDock can be installed in a room with no care.
Dis-advantages	-In case makers are covered by something, system cannot work. -Positioning is slow.	-When iDock is installed in a room, careful positioning calibration is essential.	-Structure is large.

C. Movable RFID antenna implementation

In this subsection, detail design and implementation of movable RFID antenna is described. Following 3 items should to be considered when the movable RFID antenna is designed.

- **RFID tags with various orientation can be read**: To realize robust orientation-insensitive reading of RFID tags, adequate antenna motion area is required.
- **Frames and mechanical parts should reduce negative effect to the antenna**: HF RFID system is affected by metal material as well as other RFID systems, so support structure, such as antenna support arm, should be constructed with non-metal material as possible. In this research acrylic plastic is selected for the material of the antenna support arm.
- **i-Containers can be stacked easily**: iDock should have structure that enables users to stack i-Containers easily.

1) Design of antenna size and range of motion : If the distance between tag and reader antenna can be estimated previously, reader antenna size can be determined by the size of tag antenna via technical calculations[10].

However, to read RFID tags in i-Container from outside, communication distance will be 200[mm], and the antenna size must be over 300[mm]. It means smaller antenna arrays can't read RFID tags in this application, because communication range or the antenna is not sufficient. Besides antenna must be able to rotate around i-Container. Foot-print of i-Container is regulated as 380[mm] x 270[mm], and height of i-Container as 188[mm]. The center of antenna rotation is settled to the center of i-Container. As Fig.11 shows, the antenna can rotate 35[deg] on the roll axis (in the front view), and 26[deg] on the pitch axis (in the side view). These angles are optimal for reading orthogonal oriented tags when antenna is horizontally supported. Based on these descriptions above, antenna size is determined as 450[mm] x 350[mm].

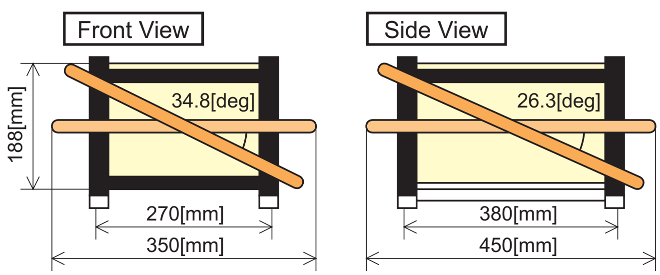


Fig. 11. Design of the antenna size

2) Layout design of the movable RFID antenna: To adopt "antenna driving method", iDock needs two-axis rotation mechanism and one-axis translation mechanism. Not to interfere with users' accessibility and not to make users' living space narrow, the framework for up-and-down of the movable RFID antenna and that for structure support is unified, and cantilever structure is selected. Fig.12 shows the mechanical parts. The motor for the pitch axis is arranged near the roll axis, to diminish inertia moment. To ensure user's safety in case the user hits his or her body against the movable antenna, torque limiters are implemented in all drive axes.

IV. Experiments

This section explains 2 basic experiments: (1) Performance experiment of RFID tag reading and (2) Container hand over experiment between the ceiling mobile robot and iDock.

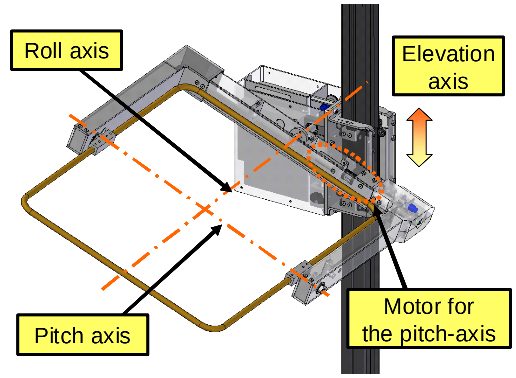


Fig. 12. Design of the antenna rotating and elevating mechanism

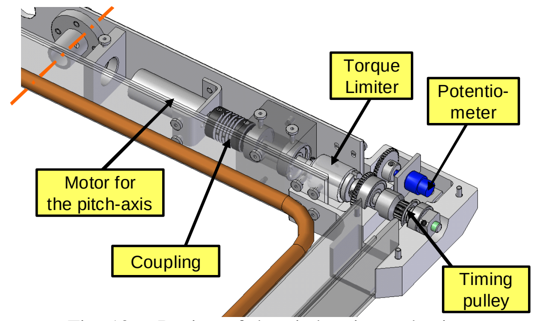


Fig. 13. Design of the pitch-axis mechanism

A. Performance experiment of RFID tag reading

We examined performance of iDock's reading RFID tags. Fig.8 shows the experimental test piece. 98 tags, which are 45-mm-square, are attached to each plane, not only to the surface but also to the inside. We put this test piece in an i-Container and examined read rate.

1) Sequence of antenna movement: the sequence of antenna movement is as follows, and Fig.14 shows a snapshot of the sequence. It takes about ?? [s] to execute 1 reading sequence.

1) The antenna starts from the lowest position.
2) iDock lifts up its antenna to half the height of the target i-Container.
3) iDock rotates the antenna ±25 [deg] on the roll axis.
4) iDock rotates the antenna ±25 [deg] on the pitch axis.
5) iDock lifts up the antenna to the top height of i-Container.

iDock can stack i-Containers as high as roof, but we assumed that more than three i-Containers wouldn't be stacked in everyday use. Therefore, we set the test piece in each i-Container from the first stacked one to the third one, and examined the reading performance. In the experiment, all RFID tags in all i-Containers could be read successfully regardless of tags' orientation.

2) Improvement of reading performance by rotating the RFID antenna: To ensure the improvement of reading performance by rotating the RFID antenna, we examined which tags are read in each state as follows: horizontal, rolled 25[deg] on the roll axis, rolled 25[deg] on the pitch axis. The height of the antenna is fixed to the half height of the

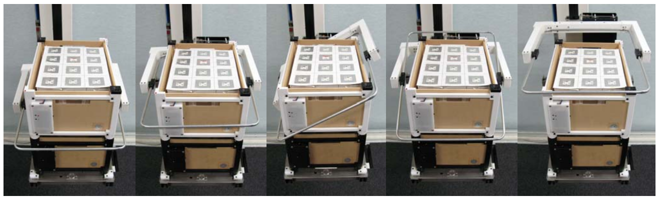


Fig. 14. Photos of an antenna motion sequence

target i-Container. Fig.15 shows an example of this result. Red pieces are tags which couldn't be read.

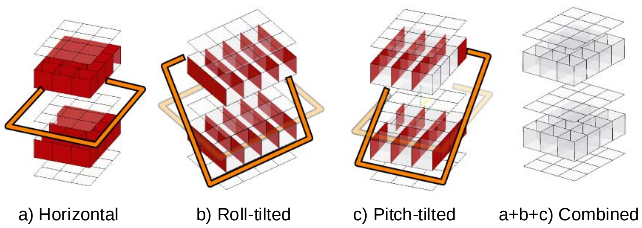


Fig. 15. The positions of unreadable RFID tags

It's confirmed that orthogonal tags to the antenna couldn't be read. However, when antenna is rotated it could read RFID tags which couldn't be read when antenna posture is horizontal. This experimental result clearly indicates that the influence of tags' orientation is improved by antenna driving method.

3) Influence of metal structure: The arm part which supports RFID antenna is made of plastic material, but the other parts of iDock, including a table frame, are made of metal material to ensure stiffness. So there is a possibility that the metal structure of a table frame affects tag reading performance, when reading RFID tags in the first stacked i-Container. To confirm this prediction, we examined tag reading performance of each stacked i-Container without rotating its antenna. Fig.16 shows the result. As figure shows, when the antenna is at the lowest position, reading performance is rapidly declining. Hence, the influence of metal structure cannot be neglected. However, total reading performance of the first stacked i-Container was verified good, so it doesn't become a serious problem in daily use.

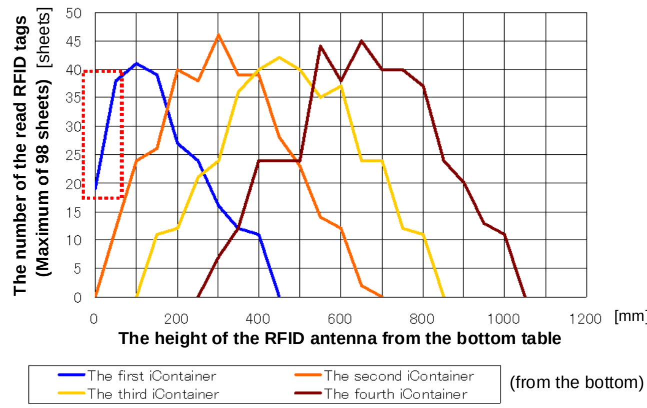


Fig. 16. Influence of metal material

B. Container hand over experiment between the ceiling mobile robot and iDock

To evaluate the guide plate performance, we examined whether the robot can hand over i-Containers to iDock, and vice versa. First we tested to confirm that all three i-Containers on i-Dock can be grasped and carried by the ceiling mobile robot. Then, we checked that the ceiling mobile robot can stack three i-Containers on the iDock table.

1) Bringing out i-Containers from iDock: As Fig.17 shows, it is confirmed that grasping and transferring i-Containers are realized.

However, it's also confirmed that certain degree of calibration is required to fit positions of the lower table part and the upper ceiling part. The ceiling mobile robot can absorb 10[mm] position error between its manipulation and i-Container, so the distance between the upper part and the lower part should be within 10[mm]. The ceiling mobile robot accesses i-Container on iDock from ceiling. The length between the table and the ceiling is more than 1800[mm]. Therefore if iDock is not exactly placed horizontally and vertically, the position error will increase and will induce bringing task failure. To solve this problem, the table of iDock should be designed so that inclination of the table could be adjustable, and stiffness and vertical accuracy of the pole which connects the lower part and the upper part

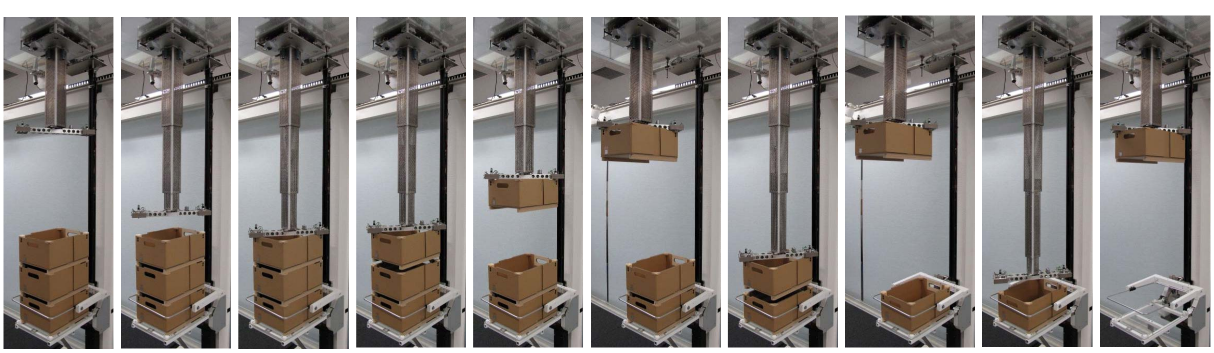


Fig. 17. Bringing out sequence of i-Containers from iDock to other spot

should be designed carefully.

2) Stacking iContainers by the ceiling mobile robot: As Fig.18 shows, the ceiling mobile robot could stack i-Containers on the table, but it couldn't place i-Containers exactly to match corners to the guide plate for humans. This failure is caused by the tilt of i-Container which is translated by the ceiling mobile robot. To solve this problem, shape of the guide plate should be revised.

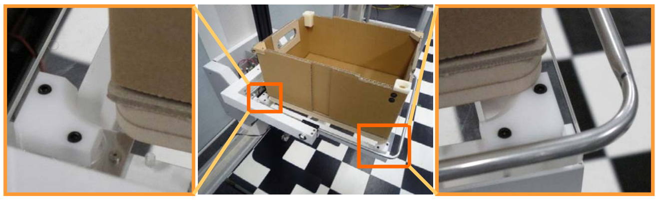


Fig. 18. Failure of stacking i-Container

V. CONCLUSION

This paper described development of a multifunctional intermediate instrument "iDock" to improve efficiency of the home logistical support robot system. To actualize the instrument, following three functions are required.

- Ensuring handing over between humans and robots
- Stacking multiple i-Containers
- Recognizing items in i-Containers

These functions were implemented without invading our living space. Through the development of iDock, there found to be two technical key points to design and implement this type of system.

- The method of RFID antenna rotating on two axes and translating vertically on one axis is very powerful solution to realize robust recognition in terms of insensitivity of RFID tag orientation.
- Simple container guide plate and robot guide plate can accurately navigate both position of i-Containers and the ceiling mobile robot, therefore fail-proof handing over between user and robot can be realized.

In order to use iDock as a multifunctional intermediate instrument in the system, more sophisticated user interface and software will be essential. By implementing user interface and software, we will be able to store and analyze users' log of item-access, such as when and where he or she uses and needs each item.

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APPENDEIX. THE CEILING MOBILE ROBOT

The ceiling mobile robot is a robot which transfer i-Containers in the home logistical support robot system. Fig.19 shows an abstract of the ceiling mobile robot. Ceiling hanging component adopts permanent magnet inductive traction method[11]. This method is realized by permanent magnet pairs which binds upper and lower sides of the ceiling. When a mobile robot on the ceiling transfers the upper side magnets, the actuation robot, hanging under the ceiling with the lower side magnets, is trailed by the upper magnet locomotion. Hence this method enables the ceiling mobile robot to transfer freely on the ceiling surface.

The actuation robot is composed of expansion component and manipulation component. Characteristics of the manipulation component are as follows,

1) To grasp an i-Container, crank connection pins are utilized. Manipulation component handles i-Containers by inserting its crank connection pins into the connection holes of the i-Container, and rotating them.
2) Manipulation component has mechanical compliance which can absorb horizontal position error and inclination error.

These compliant functions are turned off by the load of i-Container, which realizes adaptable grasp and stable transfer.

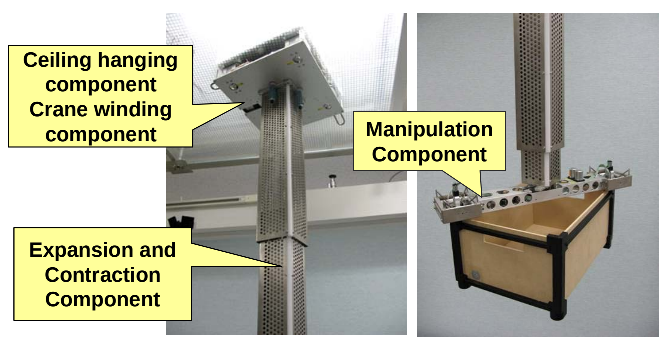

Fig. 19. Snapshot of the ceiling mobile robot