Non-Industrial Stacker Crane with Compatibility/Extensibility between Manual Operation and Electrical Driving

Rui Fukui, Shuhei Kousaka, Tomomasa Sato and Masamichi Shimosaka

Abstract— **The goal of this research is development of a novel non-industrial stacker crane that enables humans to utilize high place for storage. Our proposing instrument has two features for cost reduction and easy-installation. One is a novel storage style that does not use shelves but uses specially designed wall hangers with high tolerance to positioning errors. The other is a mechanism configuration to utilize human abilities as driving source with a T-shaped timing belt and torque diodes, and they realize compatibility between manual operation and electrical driving in the common framework. That means the configuration has expansive capability to conform to changing user's requirements and environments. In this paper, we develop a prototype of the non-industrial stacker crane, and execute experiments both in manual operation by a user and in automatic control by a motor. The experimental results confirm that the proposed stacker crane has enough compatibility between two operation modes, and demonstrate the validity of our novel storage style and mechanism configuration.**

I. Introduction

In general, humans prefer to an open-plan space with high ceiling for daily life. However, in conventional storage system with shelves, he or she has to go up by a ladder or a pedestal to access to a high storage space. Even if we install a tall storage instrument, we cannot utilize high place efficiently and safely. Fig. 1 shows an example of such condition. In industrial and logistical applications, on the other hand, stacker cranes become powerful tools to use space efficiently. Thus, we introduce "non-industrial" (i.e. for store, home, and so on) stacker crane to space for humans. We expect improvement of storage capacity and accessibility by the stacker crane, because it can access to high place securely and quickly. The goal of this research is development of a stacker crane with practicability of easy-installation, cost reduction, and low interference.

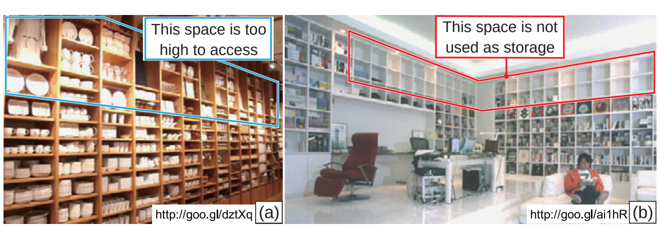

Fig. 1. High storage place cannot be used efficiently [(a) Shop interior of MUJI; a household goods store (b) Den of Ira Ishida; a novelist].

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In an industrial use, work space for robots is divided from the space for humans considering safety. But in a non-industrial use, such as living space, we have to consider a symbiosis between robots and residents. Consequently, full automatic robots must be installed with expensive sensors to detect collision and avoid runaway, and the cost prevents us from introducing robots easily.

First, our stacker crane realizes manual operations for storage and retrieval in its concise system configuration. Next, we expand the instrument to automatic/electrical drive by adding motors and sensors for the aged or the physically challenged, who is hard to operate manually. In addition, some users may prefer automatic background action.

Compared with frameworks where robots operate automatically, frameworks which allow humans to cooperate proactively with robot control seem to be more practical in current conditions. The cooperative framework compensates lack of robot intelligence. In current researches about robot configuration, humans tend to be ruled out for full-automatization. But, in the research about human error, "the Rotten Apple Theory" is out of date; which indicates imperfect humans are blame for all operational errors. On the other hand, in a modern theory[1], there is no perfect (robot) system and humans can be a good clue to improve the system performance. Based on such knowledge of ergonomics, robotic systems should involve humans actively.

There were some previous researches that incorporate humans into robot systems, where humans bring the best out of robots' performance or supplements robots' weakness. A master-slave manipulator is a typical example, which entrusts users to global decision and planning. Master-slave surgical robots[2], [3] and space robots [4] will be popular in immediate future. To reduce physical strain of users in nursing care or in transportation of heavy load, exoskeleton robots have been developed[5], [6], [7]. These robots are expected to realize practical use earlier than full automatic robots, because they entrust users to response to environmental variations. In manufacturing, the direct teaching method[8] is indispensable to realize easy motion planning of robots.

These system configurations utilize human abilities to support robots in "planning, recognition, and control" and they enable users to get desirable motion more easily and safely than full automatic robots.

We aim to develop an instrument easy to purchase by using human help not only for "planning, recognition, and control" but also as "driving source". There are a few related works. Peshkin et al. developed Cobot[9], which controls only its trajectory and users become energy sources for transportation. Regarding Tread-Walk (a walking support machine)[10], elderly users walk on the machine to input locomotion commands, and it aims to prevent these users from losing walking ability.

Our research focuses on not only functions but also the cost of installation. If we implement a manual operation machine and an electrical driving machine independently, it will cost much. Thus, if we implement these two modes in a common structure, it may realize drastic cost reduction. In addition, users who have the instrument in the manual mode may want to expand their instruments into the electrical driving mode easily just by attaching motors and sensors.

In this research, we implement two driving modes in a common framework, and propose mechanism configuration of the non-industrial stacker crane with compatibility between manual operation and electrical driving. Our proposing configuration is novel and progressive compared with previous robot configuration, because there have been no similar previous robots that have compatibility and extensibility.

This paper proceeds as follows. Section II mentions system design. Section III indicates the development of proposed stacker crane, mainly focusing on manual operation. Section IV explains implementation of expansive component required for electrical driving. Section V describes experiments to validate the compatibility and the extensibility of the developed prototype. Section VI concludes this paper.

II. System design of non-industrial stacker crane

In this section, first of all, we describe a handling target of the stacker crane, and then explain a novel storage style suitable for the non-industrial stacker crane. Finally, we discuss problems; how to implement both manual operation and electrical driving in the common framework.

A. Handling target

A stacker crane is designed to transfer standardized containers, and as our targets we use i-Container Class E (Fig. 2) developed in a previous work[11]. i-Container Class E is a card board box with wooden foot bars, and it can connect smoothly with container handling robots. The maximum size of stored object is A4 (297 [mm] $\times$ 210 [mm]), and the maximum payload is 8 [kg] including its own weight.

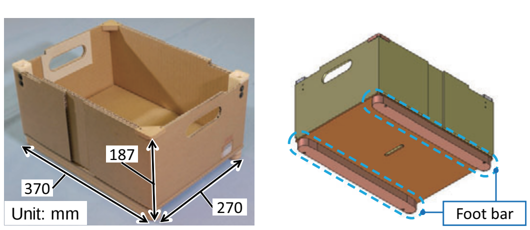

Fig. 2. Handling target; i-Container (Class E)

B. Novel storage style

When introducing a stacker crane into non-industrial space, the problem about storage shelf should be solved. In industrial space, multiple-layered and huge shelves are frequently used as special storage facilities. In living space, however, these huge shelves occupy too much space. In addition, the installation cost for those is significant.

Therefore, we propose a new method to utilize walls as storage facilities. In our method, metal wall hangers are fixed on a wall by bolts, and containers are placed on the wall hangers. While containers are not on these storage facilities, they do not compress our living space, in contrast, they afford sufficient storage ability when containers are on them.

For container operation by stacker cranes, guide structures to absorb positioning error are essential on the shelves. Nevertheless, the proposed wall hangers can play the role of guide structure, and contributes reduction of parts quantity.

C. How to implement both manual operation and electrical driving in a common framework

In manual operation, users should be on the ground, at the point of safety and usability, and this is the most severe constraint. As shown in Fig. 3(a), users cannot access to an instrument located at high space. In other words, a mechanism for manual operation has to transmit power from users on the ground, even if a component for container insertion is located at a high place. Utilizing chains or wires seem to be solutions to this problem, but the chain becomes an obstacle when this component locates at a low place.

We invented an integrated power-transmit system with a 2 DOF shared mechanism; vertical motion and insertion. The container lifting mechanism needs to have full stroke from top to bottom of the stacker crane. A user interface (i.e. handle) for manual operation is placed at the bottom of the lifting mechanism, therefore users can stay on the ground during manual operation.

In addition, as shown in Fig. 3(b), the system has to transmit two inputs selectively for realization of manual/electrical switchable framework. Because there occurs two problems if bidirectional torque transmission is possible.

1) When the motor drives, the handle spins automatically and may harm users.
2) When the user rotates the handle for manual operation, friction of the geared motor becomes large resistance.

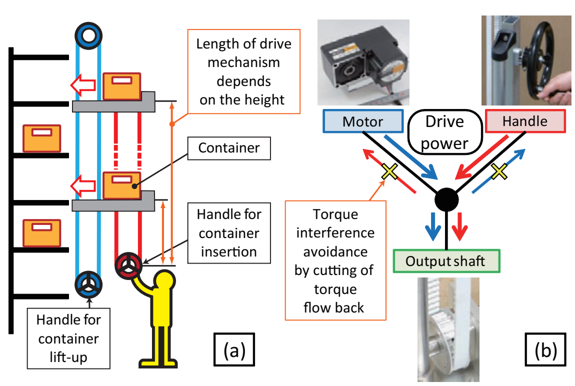

Fig. 3. (a) Restriction of drive mechanism for manual operation (b) Cutting off of torque flow back.

Consequently, a special mechanism is required, which cut off flow back from output to input and prevents the handle and the motor from interfering each other.

D. Summary of design concept

To summarize the above discussions, a conceptual sketch of non-industrial stacker crane is illustrated in Fig. 4.

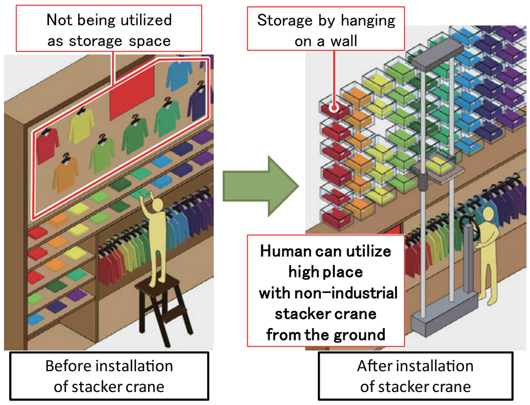

Fig. 4. Conceptual sketch of the non-industrial stacker crane.

III. Implementation of non-industrial stacker crane

This section describes the implementation of the proposed stacker crane. The framework of this section is as follows. An overview of the proposed stacker crane and the way how to use this crane is described in sub section A. Sub section B explains the novel storage style with wall hangers. Sub section C describes the configuration of the 2 DOF sharing mechanism for manual operation. Sub section D shows implementation of sensors for internal state recognition for both manual operation and electrical driving. Sub section E represents user interface for manual operation.

A. Overview of non-industrial stacker crane

Fig. 5 represents an overview of the proposed non-industrial stacker crane. This instrument is composed of three components. First component is a container holder to mount a container and to store/retrieve to/from wall hangers, second is rollers and rails structure for right-left slide, and last is sliders and post pipes structure for vertical motion. A handle is installed at the side of main structure for manual operation.

Fig. 6 shows how to use our stacker crane. The container storage motion comprises following processes.
1) Right-left slide of the whole instrument.
2) Adjustment of the right-left position.
3) Unlocking of the vertical brake and lifting up.
4) Adjustment of the vertical position.
5) Unlocking of the insertion brake and insertion.
6) Unlocking of the vertical brake and lifting down.
This sequence is almost same in both manual operation and electrical driving. In the manual operation, first, a user adjusts the position roughly by direct eyesight. Next, the user adjusts the position by watching a user interface on the handle, and the user interface indicates where the instrument is.

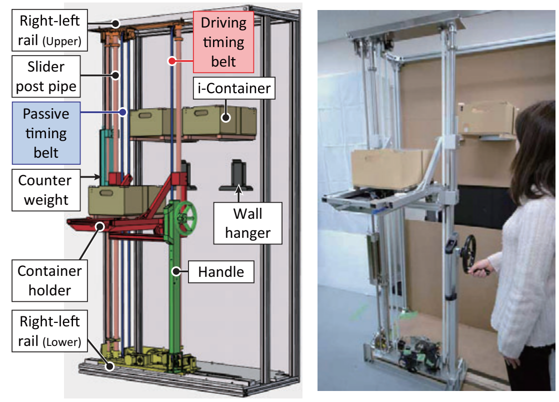

Fig. 5. Overview and snapshot of non-industrial stacker crane.

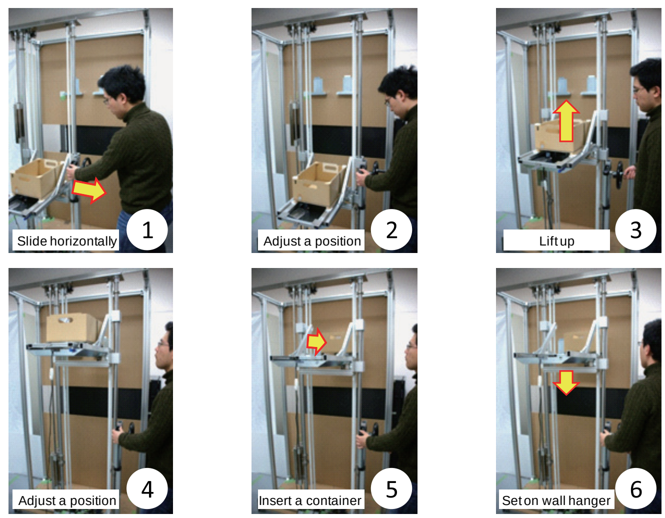

Fig. 6. Sequential snapshots of container storage motion.

B. Novel storage style; storage of container without shelves

To utilize a wall as storage space directly, Fig. 7 shows the developed wall hanger to store a container. As a method to fix a container, we employed a caging approach to fix geometrically, in the same way of our previous work[12]. The lower part of the hanger holds container foot bars, and the top hook holds a handgrip of the container. Thus, this hanger can constrain a container at horizontal 2 DOF. In addition, the hanger has guide tapers to absorb positioning errors. The container is navigated to a stable position by slipping on these tapers.

To measure the acceptable error range of the wall hanger, a preliminary experiment about container position adjustment was executed. The container was displaced from a center position, and with an off-centered load. Fig. 8 shows the measured acceptable error range. The acceptable error range was ± 10 [mm] in vertical and right-left direction, and $\pm$ 5 [mm] in insertion direction.

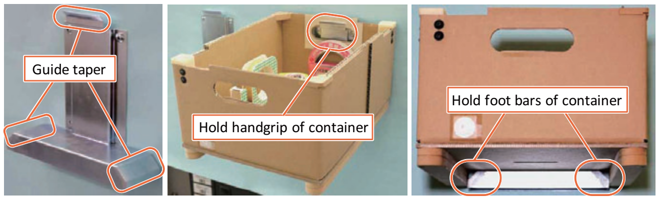

Fig. 7. Snapshot of wall hanger for i-Container.

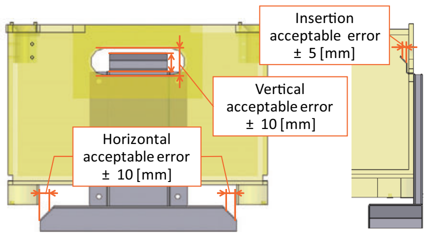

Fig. 8. Error tolerance capability of wall hanger.

From this result, acceptable positioning error of the stacker crane is less than ±10 [mm] in both vertical and right-left control. On the other hand, acceptable range of insertion was smaller than the other 2 DOF. However, the insertion mechanism needs to stop at only two places; the home position and the inserted position. Accordingly, position control of insertion is easy, because mechanical stoppers can realize accurate insertion without sensors.

C. Design of 2 DOF sharing mechanism

Fig. 9 shows a sketch diagram of the 2 DOF sharing mechanism. This mechanism realizes 2 DOF driving; lifting and insertion, by switching two brakes on the T-shaped timing belt. Fig. 10 shows the implemented 2 DOF sharing mechanism. Compared with the image model described in Fig. 9, it can reduce length of a timing belt, thanks to a rack-and-pinion mechanism.

For container lifting, a counter weight is essential to cancel the weight of the container holder. However, if this is attached to the T-shaped timing belt directly, this weight interferes while container inserting. Therefore, we divided the timing belt into two. One is the driving timing belt to transmit torque from the handle or the motor. The other is the passive timing belt with the counter weight, a brake for vertical motion and vertical location sensors. Container insertion is realized by locking the passive timing belt with an electro-magnetic brake, and container vertical motion is realized by locking the rack-and-pinion with a latch mechanism.

Two timing belts should be placed at both ends of the container holder. This configuration enlarges the moment of the container holder during lifting motion, because the driving timing belt must support an end of the container holder. Liner bushes are used to make the friction small between the container holder and post pipes.

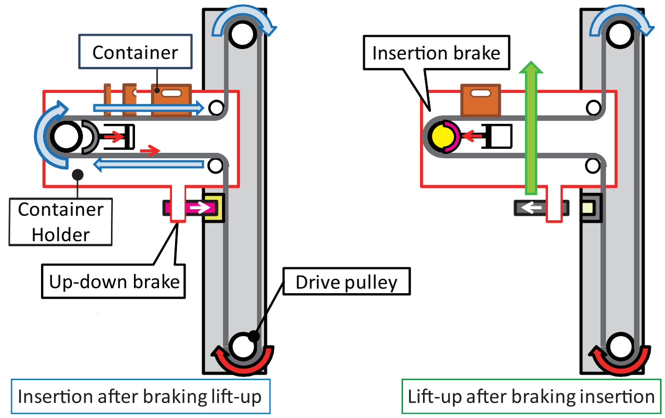

Fig. 9. Sketch diagram of the 2 DOF sharing mechanism.

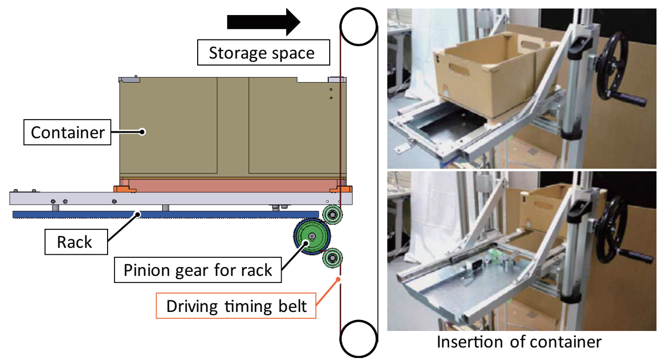

Fig. 10. Snapshot of the implemented 2 DOF sharing mechanism.

D. Sensors for internal state recognition

To implement the proposed stacker crane, sensors for internal state recognition should be inexpensive for cost reduction. For right-left localization, photo reflectors were attached under the stacker crane to read markers on the lower rail. These markers are placed where the wall hangers exist. This recognition method is a kind of absolute binary positioning system. Therefore, the more the horizontal number of wall hangers increases, the more photo reflectors are needed.

An absolute rotary encoder and a multi-turn potentiometer were combined to recognize vertical location. This method can measure an absolute vertical location without initialization. When the container falls by gravity, the vertical velocity should be monitored for safety, and these sensors can realize the monitoring.

In container insertion, the latch stopper realizes physical positioning. Therefore, simple binary positioning sensors can satisfy the requirement.

E. User interface

In manual operation, temporal user interface (Fig. 11) was installed on the top of the handle, and users can select the driving direction through it. The interface has switches/LEDs for brakes' control and an LCD displaying internal state.

In container insertion, a solenoid on the latch mechanism needs to be controlled even in manual operation. However, it is difficult to connect the container holder and the user interface with a wire. Accordingly, a battery and a solenoid controller are installed on the container holder, and a ZigBee device is equipped to transfer the user commands.

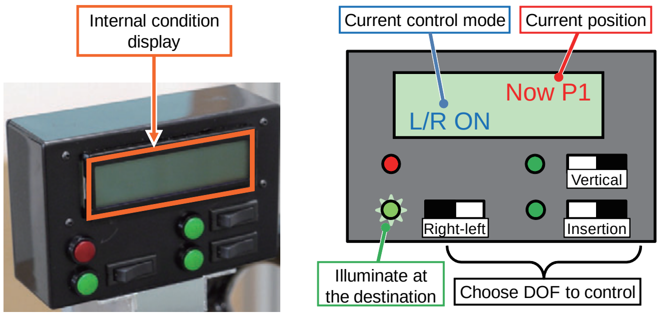

Fig. 11. Snapshot of temporal user interface.

IV. Expansive components for electrical driving

In this section, we discuss implementation of expansive components for electrical driving. Fig. 12 illustrates a block diagram of whole electrical system. In electrical driving, micro computers transmit control commands to each component by ZigBee communication.

A. Electrical driving sources

Two brushless DC motors were used for both motions; vertical motion and right-left motion. As shown in Fig. 13, these motors were placed on the bottom plate of the stacker crane. The control circuit was attached to the same place.

Lifting up of the container holder was realized by the vertical motor. On the other hand, lifting down motion by the motor interferes the motor drive circuit without a regenerative resistance. Thus, we designed that the container holder comes down automatically by gravity. When the container is empty, the motor must rotate slowly because large friction stops automatic falling motion. The torque diode can be an absorber of speed mismatch between falling motion and motor rotation. When the container is filled with objects, it is dangerous to fall down without restriction. Therefore, the brake regulates the maximum speed to 200 [mm/s].

In right-left motion, as illustrated in Fig. 13, a motor drives a pinion gear at the center of the bottom plate. This pinion gear creates liner motion by a rack gear parallel to the rail.

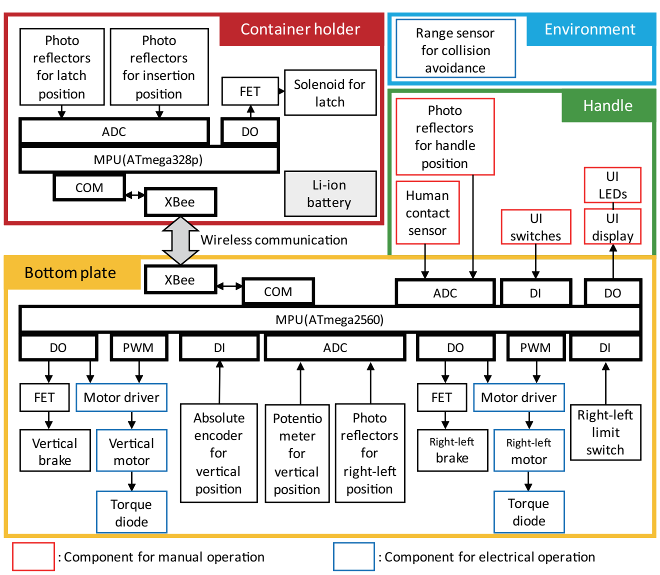

Fig. 12. Block diagram of expansive components for electrical driving.

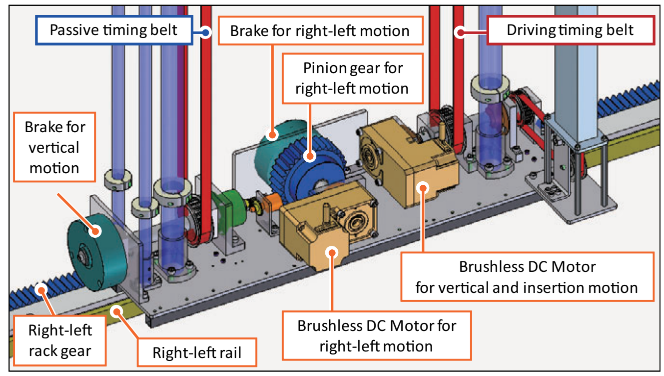

Fig. 13. Brushless DC motors and rack-and-pinion at the bottom plate.

B. Selection of input torque

To limit torque transmission in one direction, torque diodes is attached on both input shafts of the handle and the motor. Adopted torque diodes are ”TDF18” produced by NTN Corporation. Fig. 14(left) shows a snapshot of the torque diode. As shown in Fig. 14(right), while no torque is applied to input shaft, the connection between the input shaft and the output shaft is cut off, and the output shaft idles away. In contrast, while the input shaft rotates, the input shaft connects to the output shaft. These torque diode functions make it possible to realize the common framework with two independent power sources.

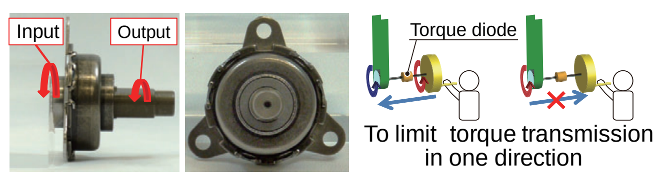

Fig. 14. Snapshot and function sketch of torque diode.

C. Positioning control

Based on the examined acceptable error range in both DOF, vertical and right-left positioning margin are configured to ± 5 [mm] (the measured acceptable ranges were $\pm$ 10 [mm]). The stacker crane can control the position in that range with a simple hysteresis control. Although the control system can get its location numerically in vertical direction, it cannot recognize right-left location continuously because the markers for photo reflectors are discrete. To avoid unintended overrun, it is necessary to control position based on the locomotion speed and time.

V. Performance evaluation experiments

A. Purpose of experiments

This section describes experiments to validate the compatibility and the extensibility of the developed prototype. In particular, the feasibility of utilizing human ability as machine driving source has to be verified. Therefore, we conducted experiments about performance of electrical driving and operability in manual operation.

These experiments confirms the performance in vertical motion to lift up and down the container holder and right-left motion to carry the whole instrument, but not in container insertion, because container insertion is simple motion to make contact with physical stoppers.

B. General experimental condition

Fig. 15 describes an experimental set-up. A wire-type encoder was attached to measure right-left position continuously. Subjects or the control system moved the instrument from a start point to a destination. The travel distance was 600 [mm] in vertical motion and 200 [mm] in right-left motion. The elapsed time and the trajectory were measured. The load configuration was 0 [kg] or 5 [kg].

C. Electrical driving experiment

In this experiment, acceleration was configured as 6.0×10^2 [mm/s^2] or 1.2 [mm/s^2].

In lifting up motion, the velocity conditions were 180 [mm/s], 120 [mm/s], and 60 [mm/s]. Fig. 16 illustrates measured data examples of lifting up motion in electrical driving. TABLE I describes a summary of lifting up motion. In each cell, the upper is an average, and the lower is [maximum, minimum].

In the lifting up experiment, the electrical system can control the vertical position very accurately; at the nearly same position, in the nearly same time, without overshoot, if acceleration and velocity are same. The load variations have small effect in vertical electrical driving.

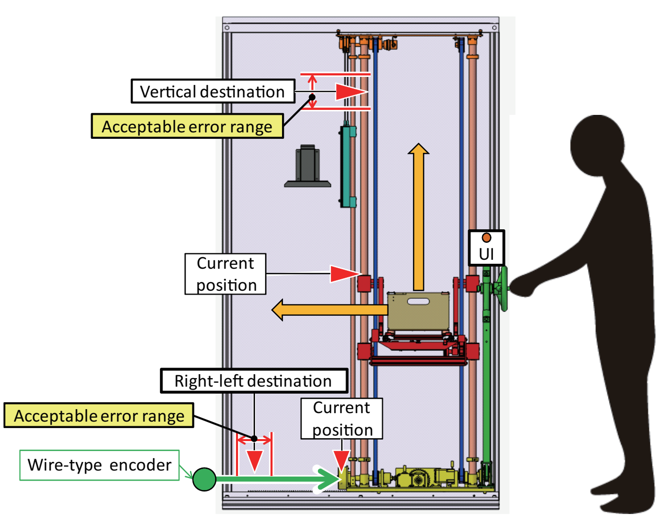

Fig. 15. Experimental set-up.

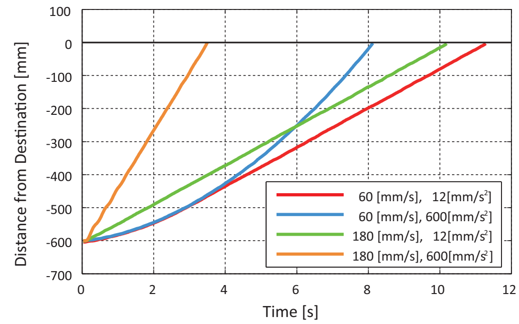

Fig. 16. Measured data examples of lifting up motion in electrical driving.

TABLE I

Summary of lifting up motion in electrical driving.

(a) Controlled position [mm]

Acceleration		600 [mm/s^2]		12 [mm/s^2]	
Load		0 [kg]	5 [kg]	0 [kg]	5 [kg]
Velocity [mm/s]	60	-3.15 [-3.15 — -3.15]	-3.15 [-3.15 — -3.15]	-2.86 [-3.15 — -2.40]	-3.15 [-3.15 — -3.15]
	120	-2.00 [-2.00 — -2.00]	-2.40 [-2.40 — -2.40]	-1.9 [-1.65 — -2.00]	-2.00 [-2.00 — -2.00]
	180	0.33 [0.60 — -0.15]	0.05 [0.25 — -0.15]	-1.5 [-1.25 — -2.00]	-1.83 [-1.65 — -2.00]

(b) Elapsed time [s]

Acceleration		600[mm/s^2]		12 [mm/s^2]	
Load		0 [kg]	5 [kg]	0 [kg]	5 [kg]
Velocity [mm/s]	60	10.17 [10.19 — 10.16]	10.29 [10.31 — 10.25]	11.33 [11.38 — 11.28]	11.42 [11.44 — 11.41]
	120	5.27 [5.28 — 5.25]	5.23 [5.25 — 5.22]	8.18 [8.19 — 8.16]	8.23 [8.25 — 8.19]
	180	3.47 [3.50 — 3.44]	3.48 [3.50 — 3.47]	8.15 [8.19 — 8.13]	8.19 [8.19 — 8.19]

Next, the lifting down experiment was conducted. The container holder with a 5 [kg] load fell down by gravity, and the travel distance was 500 [mm] or 300 [mm]. The control system stopped the container holder when the holder got into the target range. Fig. 17 shows trajectories and sequential velocities of the container holder. Though the velocity varied rapidly, totally the container holder falls down at about 150 [mm/s]. The positioning errors are both 4.9 [mm], and this result indicates that the control system has enough ability, and the torque diode contributes to smooth lifting down motion without interference against the motor.

In the final experiment of electrical driving, the right-left motion experiment was conducted. The velocity were configured to 120 [mm/s] and 60 [mm/s]. Fig. 18 shows measured data example of this experiment. Compared with vertical motion, it takes a long control period for stabilizing. This is because instrument inertia is substantially large and the right-left brake has a little backlash. TABLE II summarizes the results. The difference between the maximum and the minimum of the controlled position is larger than that in lifting up motion.

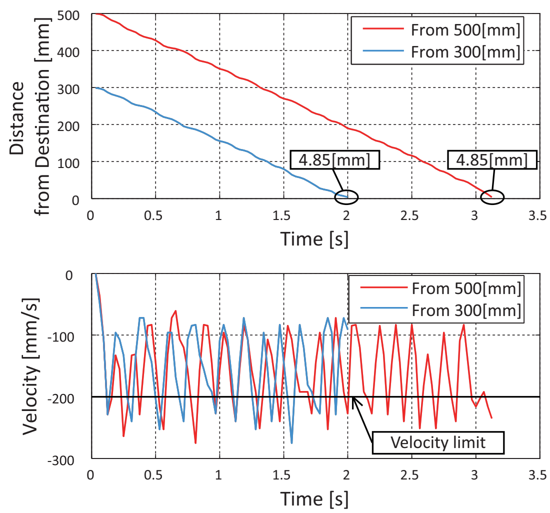

Fig. 17. Result examples of lifting down motion by the brake control.

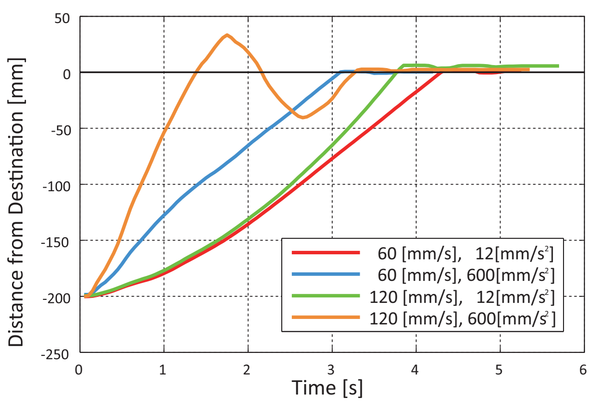

Fig. 18. Measured data examples of right-left motion in electrical driving.

TABLE II

SUMMARY OF RIGHT-LEFT MOTION IN ELECTRICAL DRIVING.

(a) Controlled position [mm]

Acceleration		600[mm/s²]		12 [mm/s²]	
Load		0 [kg]	5 [kg]	0 [kg]	5 [kg]
Velocity [mm/s]	60	1.23 [1.90 — 0.43]	1.68 [2.42 — 0.90]	1.48 [1.90 — 0.92]	1.41 [1.82 — 0.46]
	120	0.20 [2.39 — -4.92]	3.08 [4.35 — 2.39]	5.44 [6.05 — 4.75]	4.83 [5.20 — 4.33]

(b) Elapsed time [s]

Acceleration		600[mm/s²]		12 [mm/s²]	
Load		0 [kg]	5 [kg]	0 [kg]	5 [kg]
Velocity [mm/s]	60	4.84 [6.20 — 4.20]	4.51 [4.75 — 4.30]	5.34 [5.50 — 5.20]	5.70 [5.90 — 5.45]
	120	4.84 [5.35 — 4.10]	4.9 [5.00 —4.75]	5.54 [5.70 — 5.25]	5.30 [5.65 — 5.15]

D. Manual operation experiment

Four subjects; a 40's male, two 20's males, and a 20's female, operated the instrument. In manual operation, a user adjusts the position watching the temporal user interface.

Fig. 19 shows measured data examples of vertical motion and right-left motion by one subject (20's male).

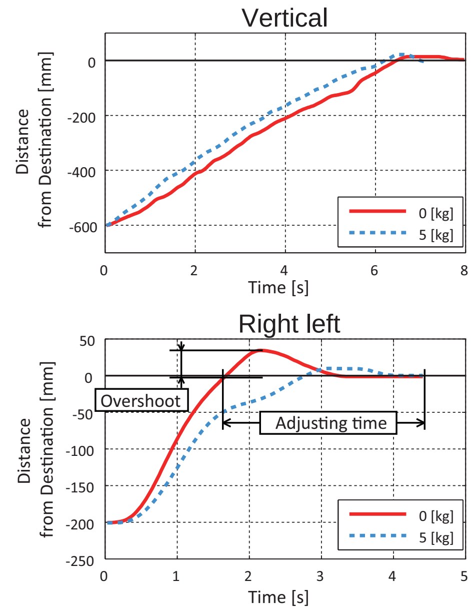

Fig. 19. Measured data examples of the vertical and right-left motion in manual operation.

For this experiment, we select two evaluation indicators. One is "overshoot"; a maximum overrunning distance and the other is "adjusting time"; a elapsed time from arrival at the target range to finish positioning.

Fig. 20 shows the summary of the overshoot and the adjusting time in each conditions. Each dot means a raw datum of each trial. In right-left motion, the average overshoot is 20.7 [mm] larger than one in vertical motion, and the average adjusting time is 3.04 [s] longer. This result shows that the right-left positioning of the developed stacker crane seems to be harder than the vertical one.

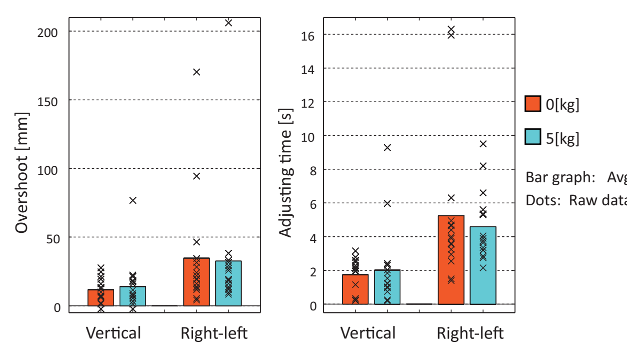

Fig. 20. Averages and distributions of the overshoot and the adjusting time in manual operation.

This is because the large control force makes it hard to control. The weight of right-left motion cannot be canceled by a counter weight. Therefore, we should reduce the whole weight of the stacker crane. In particular, weight saving of the container holder is important, because that can save the weight of the counter weight simultaneously.

One more reason is a human factor. When a subject misses a destination, it takes long time to recover. This can be solved by user interface improvement; for example, an LED blinks when the instrument is near to a final destination.

E. Discussion

Proposed mechanism has enough operability in manual operation as well as electrical driving. This result indicates that this mechanical configuration can utilize human natural abilities efficiently as driving source. Following three features are design key points to realize such superior configuration.

- The storage system with wall hangers can absorb misalignment widely, and it contributes to enlarge acceptable positioning error. Consequently, it supports human smooth storage motion without special attention.
- The mechanism with timing belts transmits driving force of a user/motor in the instrument overall. Therefore, human interface can be placed at suitable position for users. It realizes human natural operation without troublesome posture changes.
- Installation of torque diodes limits force transmission in one direction, and can avoid gear friction of motors while manual operation. It realizes compatibility between manual operation and electrical driving in a common framework.

VI. Conclusion

In this research, we proposed a non-industrial stacker crane as an assistant tool for storage in daily life. We focused on practicability of easy-installation, cost reduction, and low interference. The proposed non-industrial stacker crane has compatibility/expandability between manual operation and electrical driving.

The prototype could draw on human abilities as driving source effectively. The novel storage style with wall hangers to utilize a wall as storage space, and the hangers absorb misalignment caused by the instrument. The mechanism configuration with a T-shaped timing belt and torque diodes realizes smooth control in manual operation and compatibility between manual operation and electrical driving.

In this paper, we proposed a novel robot configuration with extensibility from manual to automation in a common framework. This framework has a big advantage at the point of initial cost and encourages introduction of service robot. Machine weight reduction and user interface improvement might increase the operability of the proposed stacker crane. In the future, we will apply this configuration not only to storage/retrieval instruments but also to various robotic systems that support humans in daily life.

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