

# Construction of Ceiling Adsorbed Mobile Robots Platform Utilizing Permanent Magnet Inductive Traction Method

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## Abstract

*This paper presents a ceiling mobile robot platform that enables multiple robots to move with low possibility of interference with humans and obstacles in an intelligent environment. An advantage of this platform is the potential to reduce sharing space between humans and robots while maintaining the robots' access to humans when their supports are needed. To realize the platform, two key techniques are developed. The first one is permanent magnet inductive traction method for the robots hanging under the ceiling plate. The second one is multiple robots simultaneous position measurement method using matrix of two dimensional codes. Validity of permanent magnet inductive traction method is confirmed by an experiment using a mock-up ceiling plate. Repeatability of position estimation using matrix of two dimensional codes is demonstrated by evaluation experiment. Finally as a demonstration of human support by the platform, transportation task is successfully performed.*

## 1 Introduction

For a long time of researches on robotics in human living space, there has been an interference problem of robots with humans and obstacles. Previously a lot of methods were proposed as solutions such as obstacle recognition by sophisticated sensors and dynamic motion planning based on the probabilistic expectation of obstacle location. However those methods couldn't be an absolute answer to the interference problem, because those methods only consider space division between robots and obstacles based on time sharing. To solve the problem, this research applies an approach: "Reducing the sharing space of humans and robots primarily". This approach enables robots to occupy their own space in usual while maintaining the access to humans' space when humans need their support.

In addition to this, such approach is also tried in this paper as making fully use of robot "structure

and function" which humans cannot realize. Concretely speaking, by utilizing specified mechanisms robots should use the space that previously humans could not use. Consequently this research focuses on "Ceiling Plane" as previous unused space in human living environment. The purpose of this research is to construct a platform where robots can move on the ceiling plate with low possibility of interference with humans and obstacles.

There have been proposed several ceiling mobile machines such as nursing lift[1], cargo transfer trolley, RobotWorld[2] and walking support machine (Flora)[3]. From the standpoint of application in living space, those are not adequate ones because of construction method and motion area restriction of multiple robots. Therefore this research aims to devise a novel ceiling hanging mechanism for robots and construct a platform where multiple robots can move unrestrictedly at the ceiling of human living space.

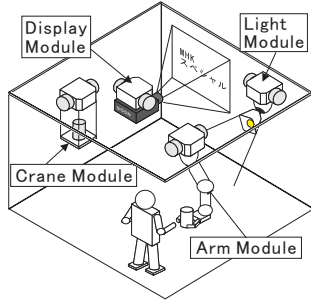
The structure of this paper is as follows. In chapter2, firstly a concept of the platform is proposed. Secondly key techniques that are essential to realize the concept is made clear. Finally the structure of the platform is presented. In chapter3, implementation of platform component units are described. In chapter4, experiments to evaluate basic specification of the platform are shown. Besides the basic experiments, an experiment to confirm the total performance of the platform is also described. Chapter5 is the conclusion. Finally the applications of ceiling mobile robot are presented in appendix.

## 2 Ceiling Adsorbed Mobile Robots Platform

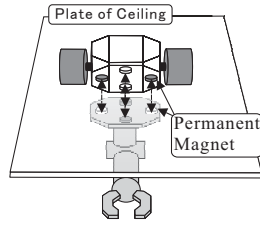
In the first part of this section, a concept of platform will be proposed that forms the goal of this research.

### 2.1 Concept of Platform

Figure1 is the concept sketch of the platform. In this concept various robots coexist and act around



**Figure 1:** Concept sketch of the platform



**Figure 2:** Permanent magnet inductive traction method

the ceiling. When a task to support human is requested, a robot extends its actuation part from the ceiling plate to human and executes the task. To realize the concept, two key techniques become essential. The first one is “ceiling hanging mechanism of robots”. The second one is the position measurement method of multiple robot simultaneously. The latter key technique is referred as “Multiple robots position simultaneous measurement method” hereafter in this paper. In the next two subsections the considerations to realize the key techniques are described.

## 2.2 Ceiling Hanging Mechanism of Robots

First of all, essential conditions of hanging mechanism for the robots moving under the ceiling plate in living space are enumerated.

1. Sufficient hanging sustain force is needed for robots locomote safely without accidental drop from the ceiling.
2. Each robot should be able to move two dimensional area unstrictedly on the ceiling plate.
3. The ceiling material shouldn't be special and the construction of the ceiling plate should be easy.
4. Active energy supply should not be required, i.e. the robot should hang on the ceiling without constant power supply such as electricity.

Taking account of the above four conditions, several hanging mechanism candidates are listed together with each advantages and disadvantages.

1. Rail type This mechanism is used for nursing lift[1], cargo transfer trolley. Locomotion unit is hanging on rails.
2. Lane (X-Y Lane) type This mechanism needs ceiling plate with horizontal and vertical lanes. The robots hang on those lanes and they can locomote under the ceiling where lanes are equipped.

3. Bridge type This mechanism is used by factory cranes. The human support actuator moves with its sustaining crossbeam. The crossbeam is locomoted by the bridge piers movement.
4. Plane adsorption type This mechanism let the robots adsorb to the ceiling plane by some adhesion force. Robot World[2] and Flora[3] adopt this type.

Rail, lane and bridge type have advantage in motion stability. But because rails and lanes restrict the robots locomotion area, robots can move only limited area of the ceiling plate. Hence the bridge type have to move large bridge piers, the mechanism has disadvantage in overweighting feelings to human in the motion space. In addition to such disadvantage, this mechanism prevents multiple robot simultaneous motion. On the other hand, plane adsorption type has advantage in potential that enable multiple robots move two dimension freely on the ceiling plate. From such reason the plane adsorption type is adopted in this platform and the possible candidates of power source for adsorption are enumerated. The list of candidates is shown below.

1. Permanent magnet method This method requires the ceiling plate of magnetic material (ex. iron) and the robots loaded permanent magnets.
2. Electromagnet method This method use electromagnet instead of permanent one.
3. Air compression method This method needs to set up suckers at robot and robots hang on ceiling by compressing the air between suckers and ceiling plate.
4. Capacitor method This method regards the ceiling plate as a pole plate of capacitor and setup the other side plate to robot. The attraction force between pole plates enable robot to adsorb the ceiling.

As for material of ceiling plate, the magnetic method restricts the ceiling material to magnetic one (ex. iron). Magnetic material is not popular as a ceiling material, so it's difficult to apply this method in general living space. As for energy supply, electro magnet, air compression and capacitor method require constant energy (electric power) supply, so if there is power failure these method cannot sustain hanging state. This factor is very fatal for safety. In addition to these factors, it is revealed in calculation that the capacitor method needs vast size pole plate which is impossible to implement. Even though the plane adsorption type has potential of robot's unrestricted motion, this type still has some unsolved problems

in terms of ceiling material and power supply. To solve those problems, “permanent magnet inductive traction method” is devised as a robot ceiling hanging mechanism. Figure2 illustrates this method. The method utilizes several pairs of permanent magnet. One of the magnet pair exists upper side of the ceiling plate and the other attaches the lower side. When a mobile robot transfer the upper side magnets, the lower side magnets and actuation robot hanging the magnet is induced and trailed by the upper magnet locomotion.

### 2.3 Multiple Robots Position Simultaneous Measurement Method

There are two major approaches in simultaneous measurement method of multiple robots position. The approaches are explained below.

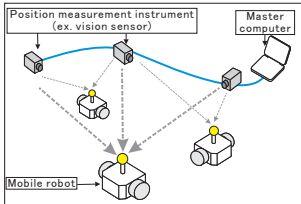


Figure 3: Integrated system approach

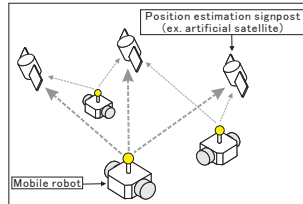


Figure 4: Individual robot measurement approach

#### Integrated system approach!

As shown in figure3, a master computer collects the data of several measurement equipments and calculates all robots’ position in the sensing area by integrating the data. (ex. optical motion capture.) Hence the approach concentrates the process of measurement to master computer, it becomes easy and inexpensive to implement each robot.

#### Individual robot measurement approach :

As shown in figure4, each robot has its own measurement sensors and obtains signpost information by itself (ex. Global Positioning System). In this approach it’s needless to prepare a sophisticated master computer because each robot gets its position independently. This factor becomes significant merit in expanding locomotion area.

The individual robot measurement approach was adopted, because this research regards expansion of motion area and each robot !G independence as important. In addition to this approach, an idea of intelligent environment is utilized. In an intelligent environment, the system also supports the motion of robots. This time, many two dimensional codes with coordinate data are scattered in the motion area for the sake of robot position measurement support.

### 2.4 Whole Structure of Platform

Figure5 shows the whole structure of the platform. The platform consists of the following six units de-

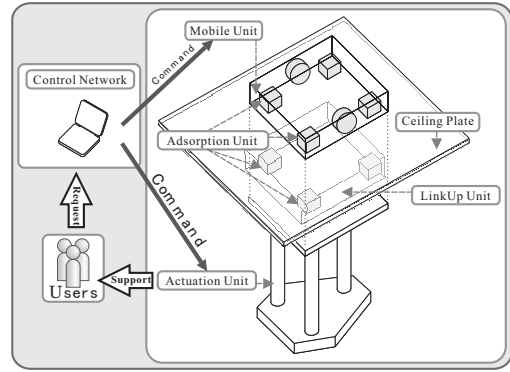


Figure 5: Platform whole structure

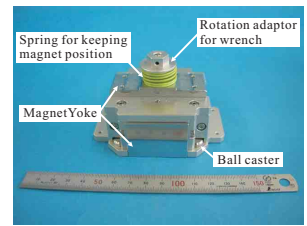
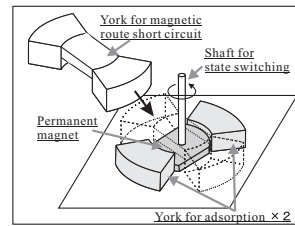


Figure 6: Basic structure Figure 7: Implemented of magnet module Magnet module ver.2

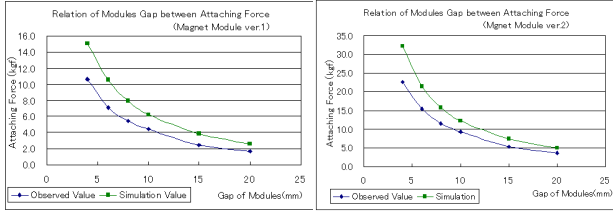
scribed below. (1) “Adsorption Unit” attaches both side of ceiling plate by magnetic attraction force and enables robots to hang under a ceiling plate. (2) ” Mobile Unit” moves upper side of ceiling and transfers adsorption unit, (3) “Ceiling for Robot Motion” (4) “Link-up Unit” hangs on the lower adsorption unit and sustains the actuation unit by mechanical connection. (5) “Actuation Unit” supports humans under the ceiling. (6) “Control Network” integrates the information and controls those units totally.

## 3 Implementation of Platform

In this section required functions of each unit and implementation of those functions is explained.

### 3.1 Adsorption Unit Implementation

Adsorption unit consists of several “magnet module” pairs. The magnet module is composed of one permanent magnet and yokes. There were two implementation phases. In the 1st phase, magnet module ver.1 is produced for confirmation of basic mechanism and accuracy in magnetic circuit simulation. In the following 2nd phase, magnet module ver.2 that aims to be installed on the mobile unit and link-up unit is implemented. Figure6 shows the basic structure of a magnet module. Neodymium-iron-boron magnet was adopted as permanent magnet. The magnet module can control the ON-OFF of adsorption state by switching magnetic route loop. The switching of magnetic route loop is done by rotating the magnet against the yokes as general mag-



**Figure 8:** Magnet module ver.1 attractive force. **Figure 9:** Magnet module ver.2 attractive force.

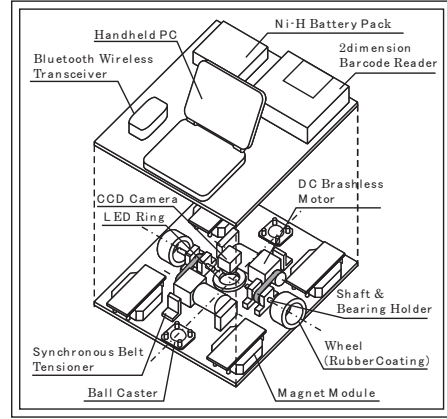
net chuck. Figure 8 is the measurement experiment result of attractive force between magnet module pair. From the experiment, it is revealed that magnet modules ver.1 can attract each other at 4.2(kgf) in the condition of 10(mm) modules' gap. Besides the simulation error was found to be about 30(%). With reference of this result, magnet module ver.2 is designed and produced. Adsorption force and basic functional specification are determined as follows. (1)Attraction force should surpass 7.5(kgf) at the 10(mm) modules' gap, (2)Three adsorption states should be realized: "Adsorb - Sustain - Release", (3)The distance to ceiling plate should be kept constant and the friction against the ceiling plate should be low.

The attractive force is decided on the assumption that 4 magnet module pairs should sustain 30(kgf) load. From the data of magnet module ver.1, simulated attraction force is assumed to be 30(%) more than the real force in the design of this version. Figure 7 is the overview of implemented magnet module 2nd version. Figure 9 is the result of attraction force measurement.

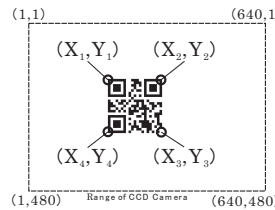
By the experiment, the difference between actual and simulation value in the magnet module ver.2 is confirmed to be 30(%). This module attraction force satisfies the required one. The switching of adsorption ON-OFF is realized by a 3 steps' rotation mechanism mostly same as magnet module ver.1. Four ball casters are equipped at the bottom of the magnet module. Those casters realize the function of keeping the distance to ceiling plate constant and reducing the friction against the ceiling plate.

### 3.2 Mobile Unit Implementation

Figure 10 is the perspective sketch of mobile unit. The mobile unit requires driving function and self position recognition function. The former one is implemented by 2 driving wheels and 2 casters mechanism. The second one is actualized by "two dimensional code matrix" sheets spread on the motion area and code reader loaded on the mobile unit body. For the purpose of robot position measurement, 2D code reader on the market place was remodeled. By this remodeling the reader can output the code position (4 corners' coordinates) in the CCD image as fig-



**Figure 10:** Mobile unit perspective sketch

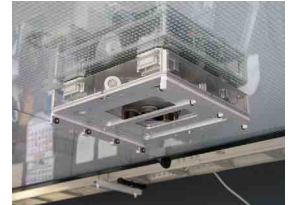
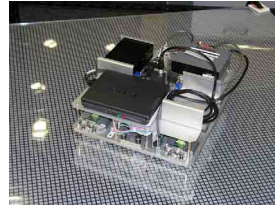


**Figure 11:** 2D Code Reader CCD Image

**Figure 12:** QR Code Spec. for 2D Code Matrix

Code Model	Model 2
Err Level	"M"
Version	1
Cell Size	8(Pixels)
Code Size	7.11(sq-mm)

ure 11 shows. This remodeling enables high accuracy position and orientation estimation. Figure 12 is the basic code specification for 2D code matrix. Figure 13 is the overview of implemented mobile unit. The size of mobile unit is 340 × 320 × 150 (mm), weight is 10 (kgf) and the max driving speed is 125(mm/sec).



**Figure 13:** Mobile unit **Figure 14:** Link-up unit

### 3.3 Ceiling for Robot Motion Implementation

The ceiling for robot motion is composed of three material layers. (A) tempered glass, (B) clear sheet printed 2D code matrix, (C) polycarbonate sheet for protection of 2D code matrix sheet. By arranging this three layers plates, 2×2(m) motion area was produced. Figure 15 shows the implemented ceiling and the plate of the ceiling.

### 3.4 Link-up Unit Implementation

Figure 16 indicates the perspective drawing of link-up unit. The link-up unit needs "connection function" to actuation unit and "overload prevention function"

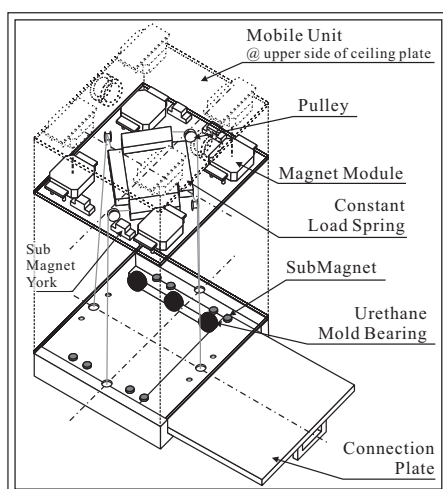


**Figure 15:** Implemented ceiling for robot motion and its ceiling plate.

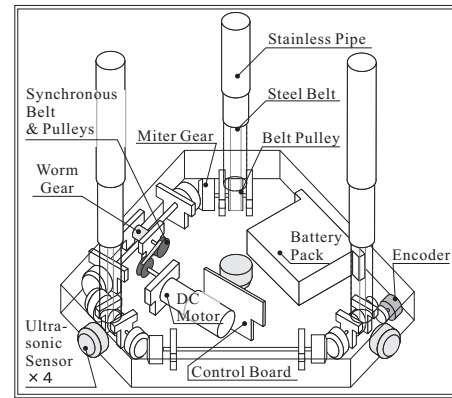
for adsorption unit. The connection function is realized by a slide mechanism. The mechanism regulates the connection plate size. The connection is done by inserting the plate to sliders and fix by plungers. Four “Constant Load Springs” actualize the “overload prevention function”. When any overload is applied to the link-up unit, the constant springs expand those stroke and let the body goes down. This action makes it possible to prevent over load to adsorption unit. Figure14 is the implemented link-up unit.

### 3.5 Actuation Unit Implementation

In this research, a simple crane unit that can execute only vertical motion is realized. The unit consists of “expansion and contraction function” for robot to access humans and “environment monitoring function” for detection of obstacles. Expansion and contraction function was realized by bamboo shoot mechanism, i.e. thin steel pipes cover the winding parts (steel belt and pulley). Environment monitoring function was actualized by ultrasonic sensors. The crane unit uses three sets of the bamboo shoot mechanism for lifting up the carrier. Figure18,19 are the overview of implemented crane unit at expansion and contraction states. Figure20 shows the connecting action between the link-up unit and the crane unit.



**Figure 16:** Perspective sketch of link-up unit



**Figure 17:** Crane unit perspective sketch



**Figure 18:** Crane Unit (Expansion)



**Figure 19:** Crane Unit (Contraction)



**Figure 20:** Slide insertion mechanism

### 3.6 Control Network Implimentation

Figure21 shows the framework of control network. The network requires following three functions.

1. The network should receive commands from users and interpret those contexts.
2. In consequence of the user commands' interpretation, each unit's motion should be determined. The target motions are transferred to the units.
3. According to the transferred command each unit should actuate and report the result.

**Structuring of Transfer Command Layers.** To realize the above network functions, data transferred in the network should be categorized in terms of its transmission area. The command and command transfer layer are categorized into three layers.

1. User Command Layer  
This layer receives the system task command.

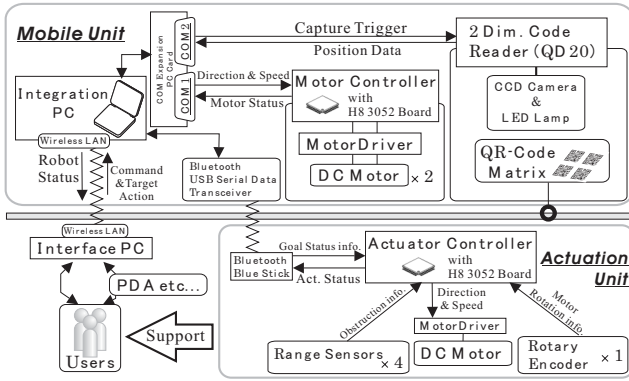


Figure 21: Framework of control network

The context of user command is very abstract. (ex. "Bring the thing to my position!")

## 2. Control Command Layer

The context of control command is task of each unit (ex. The mobile unit should move to certain position, the crane unit should lift up, etc...). This layer interprets the commands and decides the motions of each unit's part. The integration PC on the mobile unit belongs to this layer.

## 3. Internal Command Layer

From the control command layer, this layer receives command about motion of each part. According to the command, each circuit controls the mechanical parts. The motor controllers, the 2D code reader on the mobile unit and the crane unit controller belong to this layer.

# 4 Platform Evaluation Experiments

This section describes five experiments to evaluate basic specification of the implemented platform.

## 4.1 Adsorption Unit and Link-up Unit Evaluation Experiment

The purpose of this experiment is to ascertain the maximum load that the adsorption unit can sustain and whether the "overload prevention function" can perform as desired. To examine the sustainable load of the adsorption unit, heavier and heavier load is applied to the link-up unit. Figure 22 is the result of the experiment. By the graph, it is found that the adsorption unit can sustain as heavy load as 34.2(kgf). This value is 10(%) smaller than the sum of each magnet modules attracting force (36(kgf)), but satisfies the supposed weight (30(kgf)). As figure 23 indicates, the "overload prevention function" performs successfully. This performance can prevent accidental drop of the robot.

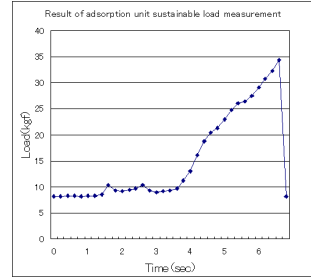


Figure 22: Result of adsorption unit sustainable load measurement



## 4.2 Evaluation Experiment of Magnet Inductive Traction Error

In this ceiling hanging mechanism, there found no static inductive position error between the mobile unit and the link-up unit. On the other hand, small dynamic inductive position error was detected while mobile unit was driving. The experiment purpose is to measure this dynamic inductive position error. The driving speed is set to be 15, 30(mm/sec). Figure 24 shows the result at 30(mm/sec). By this experiment, the range of this dynamic inductive position error is confirmed to be less than 1(mm). This small dynamic error doesn't matter for robot motion in living space.

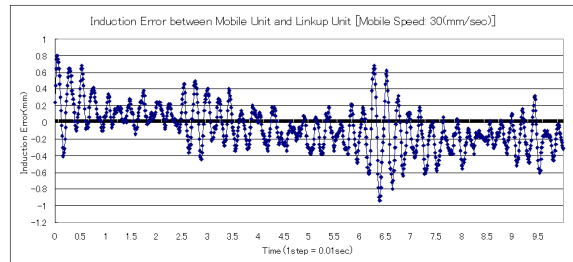


Figure 24: Dynamic inductive position error between mobile and link-up units. Speed: 30mm/sec

## 4.3 Repeatability Evaluation Experiment of Position Measurement Utilizing 2D Code Matrix

To analyze the repeatability of position measurement with 2D code matrix, the mobile unit was rotated 30(degree) step. At each direction the standard deviation of 20 data about position and direction were calculated. Table 1 is result of the experiment. The maximum of position SD is 0.57(mm), and direction's max is 0.67(degree). These value shows that the method has enough repeatability for robot position measurement in human living space.

## 4.4 Operation Check of Crane Unit

The purpose of this experiment is to check whether the crane unit can actuate as designed. For

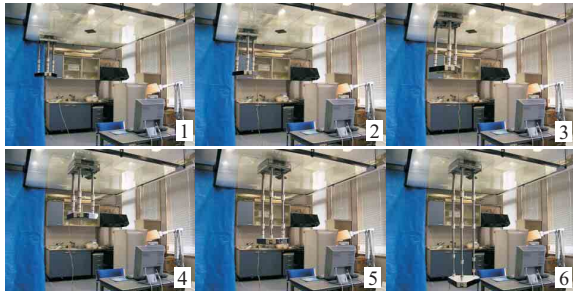
**Table 1:** Standard deviation of mobile unit position and direction measurement by 2D code matrix

Unit Angle	X_Coord SD	Y_Coord SD	Angle SD
180	0.18	0.14	0.67
150	0.17	0.22	0.27
120	0.017	0.017	0.15
90	0.12	0.028	0.11
60	0.57	0.038	0.23
30	0.014	0.010	0.12
0	0.012	0.0092	0.092
-30	0.14	0.32	0.17
-60	0.22	0.024	0.20
-90	0.15	0.027	0.30
-120	0.024	0.045	0.36
-150	0.032	0.045	0.21

2,000(mm) stroke motion, it takes 21~22(sec) at lifting up and 16~17(sec) at lifting down. The total time of crane unit expansion and contraction is less than 40(sec). It was confirmed that the crane unit satisfies the required lifting speed (100(mm/sec)). The height tolerance is examined to be less than 1(mm).

#### 4.5 Transport Demonstration Experiment

This experiment aims to examine the total performance of the platform. It was confirmed that the combination of each unit's motion makes it possible to transport things at the crane unit carrier to the ordered position and height.



**Figure 25:** Platform performance in transport demonstration experiment

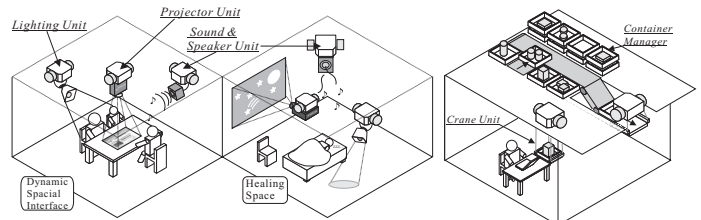
## 5 Conclusion

This paper purposed to realize a concept of “robot noninterference to human” in the human living space. To actualize the purpose, ceiling space is focused on as one of the spaces that humans usually don't exist and use. In this approach, robots can locomote the ceiling plate unrestrictedly. But when humans need the support, robots go down from ceiling space and access human to complete the tasks. For the actualization of this approach, “Ceiling Adsorbed Mobile Robots Platform” was presented and constructed. As a robot ceiling hanging mechanism “Permanent Magnet Inductive Traction Method” was devised and implemented. As a

multiple robots position simultaneous measurement method, “2D Code Matrix” was presented and implemented. By experiments, “Permanent Magnet Inductive Traction Method” enables robots to move smoothly in the condition of less than 1(mm) stick slips. “2D Code Matrix” was confirmed to have high repeatability in position measurement, i.e. max position SD is 0.57(mm), max direction SD is 0.64(degree). Finally units of the platform were integrated and the transport demonstrational task was completed by combination of the units.

## Appendix: Suggestion of Ceiling Mobile Robot Application

This appendix presents two applications of the ceiling mobile robot platform.



**Figure 26:** Dynamic Space

**Figure 27:** Ceiling Container System

### A1. Dynamic Space Representation System

Figure26 is the concept of this system. The system is composed of projector unit for image output, lighting unit for control of room brightness and sound-speaker unit for audio output. The collaboration of those units enables space representation that users expect. There thought to be some examples of contents, a dynamic interface space for informative media and a healing space and so on.

### A2. Robotic Ceiling Container System

Figure27 shows the overview of this system. The system consists of “Container Management Robot” for the organization of containers on the upper side of ceiling and “Crane Unit” for container transport. The realization of this system enables much higher efficient space usage than at present.

## References

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- [2] Victor Scheinman, “ROBOTWORLD: A Multiple Robot Vision Guided Assembly System”, *Proceedings of the 4th Int'l Symposium on Robotics Research*,pp.23-27,1987.
- [3] (Only in Japanese) FATEC Corporation,”Flora”, <http://www.fa-tec.co.jp/products/flora.htm>