HangBot: a Ceiling Mobile Robot with Robust Locomotion under a Large Payload
(Key mechanisms integration and performance experiments)

Rui Fukui, Hiroshi Morishita, Taketoshi Mori, Tomomasa Sato.

ABSTRACT

This research aims to develop a ceiling mobile robot that can sustain a large payload and can locomote freely under a ceiling space. In our approach, a perforated metal, one of the recent popular architectural materials, is utilized as a ceiling plate and the robot hooks and hangs the sequential holes of the ceiling plate by mechanical constraint. To realize the robot, the authors developed three key mechanisms, (1) ceiling hanging mechanism for the perforated metal, (2) horizontal locomotion mechanism like an inchworm, and (3) pantograph mechanism for smoothing horizontal locomotion speed and for load balancing. A unit testing of the ceiling hanging mechanism and the integration horizontal locomotion experiments confirmed the good performance of each mechanisms and the feasibility of mechanically constrained ceiling mobile robot. However, it was revealed that higher power motors and a stiffer body structure should be installed to sustain an extremely large payload like a human.

I. INTRODUCTION

In the previous work, our research group discussed the locomotion method of a home-use service robot, and suggested that residents and robots should separate the generally using space for safety and efficiency[1]. Especially we focused on the ceiling space that is not generally used by human, and the robots use the ceiling space for locomotion or executing their internal tasks. If necessary, the robots access the floor space by expanding their manipulators, and can prevent from unintended interference with humans.

There were many kinds of hanging or adsorption mechanisms for a ceiling mobile robot or a wall climbing robot; rail type[2], vacuum suction type[3], [4], [5], electro-magnet type[6], [7], [8] and so on. However, we proposed a novel ceiling adsorption and mobile methodology designated as "Permanent Magnet Inductive Traction Method"[1]. In the method, permanent magnets connect the upper ceiling robot and the lower ceiling robot, consequently the locomotion of the upper mobile robot can induce the lower actuation robot.

On the other hand, when a ceiling mobile robot will be applied for walking support as shown in Fig. 1(a), the robot must sustain a very heavy weight, and the required maximum payload is quite different from the previous work. In such a large payload application, utilization of mechanical constraint like hook mechanism as depicted in Fig. 1(b), can be a potential candidate. Table I indicates a qualitative comparison of the permanent magnet method and the mechanical constraint method. As described in the table, the mechanical constraint method seems to have different features or advantages compared with the permanent magnet method. Therefore, this research aims to confirm the feasibility of mechanically constrained ceiling mobile robot that can sustain a large payload, and clarify the assignments and solutions to realize such kind of robot. Concretely speaking, this paper describes development of (1) ceiling hanging mechanisms and (2) horizontal locomotion mechanisms, and experiments of the each mechanisms and the integrated ceiling mobile robot.

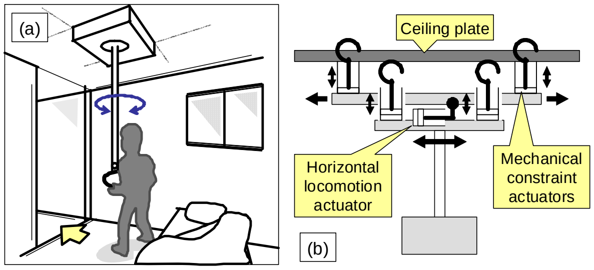

Fig. 1. (a) Conceptual image of walking support application, (b) conceptual image of mechanically constrained ceiling mobile robot.

TABLE I

QUALITATIVE COMPARISON OF HANGING METHODS.

Method	Permanent magnet	Mechanical constraint
Constraint of horizontal locomotion	No constraint	
Energy for sustaining	Unnecessary	
Horizontal locomotion smoothness	Very smooth	Smooth but noisy because of mechanical contacts
Payload limitation factor	Magnet absorption force	Mechanism strength
Anti-drop mechanism	Essential	Optional
Ceiling material	Any kinds	Materials with mechanical workability

The framework of this paper is as follows. Section II arranges the previous works, discusses our approach and summarizes the specification of the target ceiling mobile robot. Section III explains the development of the robot; two key mechanisms and the integration of the key mechanisms. Section IV indicates the unit testing of the developed key mechanism and experiments of the integrated robot. Section V describes conclusion.

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II. PREVIOUS WORKS AND OUR APPROACH

First, previous works of mechanically constrained ceiling mobile robots are arranged and the assignment of our research is defined. Next, our approach to solve the assignment is discussed. Finally the specifications of the target robot is summarized and it leads to the next design section.

A. Previous works

As for general ceiling mobile machines, hanging rail and gate shape structure are popular. However these methods can not be a candidate because of (1) limitation of the locomotion area, (2) number limitation of simultaneous operative robots, and (3) impossibility of cross or overtake motion for multiple robots.

As a solution of the above limitations, Inoue et al. developed a multi-legs mobile robot (ASTERISK) hanging under a wire mesh with hook[9]. Lu et al. developed a monkey like multi-joints robot (Gorilla III) that can hangs and locomote under a overhead ladder. These multi-joints robot can realize a flexible motion, but the many actuators make it difficult to produce and maintain the robot, that means they are over actuated to realize planar two DOF translational and one DOF rotational locomotion. Smith et al. developed ACROBOTER that hangs under anchor bolts installed on the ceiling plate and locomotes like pivot turning[10]. To realize precisely aligned sequential anchor bolts, ACROBOTER uses specially designed ceiling structure and the transfer control with pivot turning seems to be too complex.

These previous works show the effectiveness of the ceiling architecture with sequential patterning structure for realizing the mechanically constrained ceiling mobile robot. Consequently the assignments of this research are summarized as below.

1) The actuator number should be as small as possible to realize planar two DOF translational and one DOF rotational locomotion.
2) The locomotion method should be simple, and does not require a complex control.
3) The ceiling architecture should be simple.

B. Approach of this research

This research focuses on the perforated metal (Fig. 2), which is becoming popular as architectural material. A perforated metal has sequential patterning structures, and joint portion can be easily formed to connect with the neighbor ceiling plates. A robot inserts mechanisms into the holes of the perforated metal and hangs under the plate. In this research, we will realize the translational motion and the rotational motion in different frameworks. That means that the two DOF translational motion will be realized by continuous grasping and releasing motion (inchworm-like motion) of the perforated metal as shown in Fig. 3. In contrast, the rotational motion will be realized by a rotary actuator equipped at the bottom of the ceiling mobile robot. This rotational motion can be realized easily by commercial products, therefore it is out of this paper range.

Fig. 2. Application examples of perforated metal for architecture.

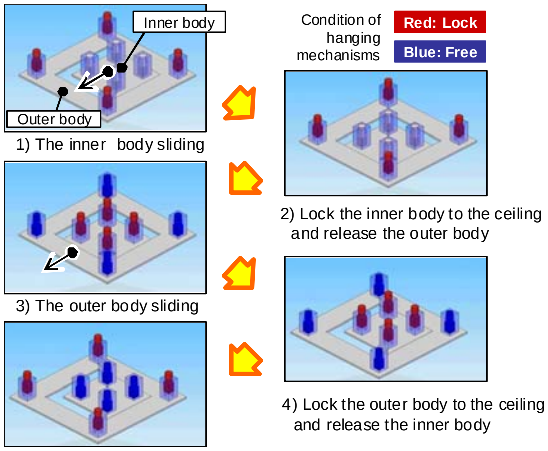


Fig. 3. Sequential images of horizontal inchworm-like locomotion.

C. Target specification of the ceiling mobile robot

Table II summarizes the target specifications of the mechanically constrained ceiling mobile robot. As basic necessary specifications, the locomotion area should be extendable, and multiple robots can be in the simultaneous operation; they should come and go freely. The ceiling mobile robot aspires to execute not only object transferring tasks but also human walking support tasks. So the maximum payload is configured for sustaining a human body weight, and the maximum horizontal locomotion speed can be the slow walking speed.

TABLE II

CONFIGURED SPECIFICATION OF A CELING MOBILE ROBOT.

Locomotion area : **Scalable**	Ceiling height : **Preference**
Robot number in the simultaneous operation : **Multiple**	Overtaking or crossing locomotion between robots : **Possible**
Ceiling material : **Perforated metal made of stainless steel**	Locomotion direction: **Two directions (X and Y)**
Maximum payload : **100 [kg]**	Maximum horizontal locomotion speed : **100 [mm/s]**

III. DESIGN OF CEILING MOBILE ROBOT

This section describes the details of robot design to satisfy the above specifications. Firstly, as the most major key components, a ceiling hanging mechanism and a horizontal locomotion mechanism will be explained. Next, the integration of the major components will be described.

A. *Design of the ceiling hanging mechanism*

To hang under the perforated metal plate, two elemental motions of (1) mechanism insert motion and (2) lock motion are essential as Fig. 4 shows.

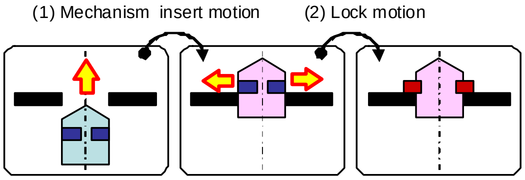


Fig. 4. Ceiling hanging motion comprises insert motion and lock motion.

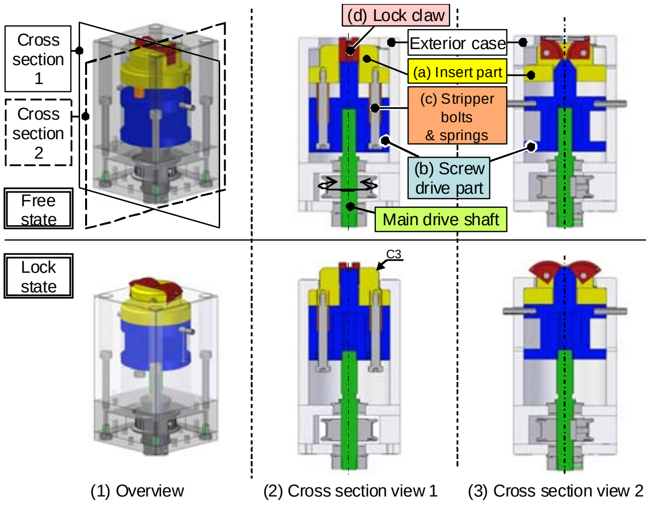
To realize these two motions without artifice, two actuators are necessary. However we need to minimize the actuator number, so only one actuator can be used for these motions.

There may be some gap between the hanging mechanism and the ceiling plate in an actual condition, so the hanging mechanism needs to lift up the body while lock motion. In our approach the robot body consists of two parts to generate inchworm-like motion. While one body is locked to the ceiling plate, the other body is free and must sustain the self weight and the payload. With these loads, the free body may bend downward. So the hanging mechanisms on the free body should lift up to compensate the bent displacement of the body. We assumed the displacement 5 [mm] and the maximum lift up stroke was configured to the same length.

To summarize the above discussions, the hanging mechanism must solve the following two assignments.

- The mechanism insert motion and the lock motion should be realized by only one actuator.
- The hanging mechanism should lift up the body even if there is a 5 [mm] gap between the ceiling plate and the hanging mechanism.

To solve the assignments, this research developed a hanging mechanism as shown in Fig. 5. The hanging mechanism is driven by the rotation of the screw drive shaft, and the insert part (a) is supported by the springs (c) on the screw drive part (b). When drive shaft rotates, the insert part and screw drive part uprise together and the insert part can go through the ceiling hole, and as the drive shaft continues rotating, the springs between the insert part and the screw drive part contract and the screw drive part pushes the lock claws (d) and they rotate for constraining the ceiling hole. So the drive shaft rotation realizes both the mechanism insert motion and the lock motion .



(1) Overview (2) Cross section view 1 (3) Cross section view 2

Fig. 5. Overview and cross section view of the hanging mechanism.

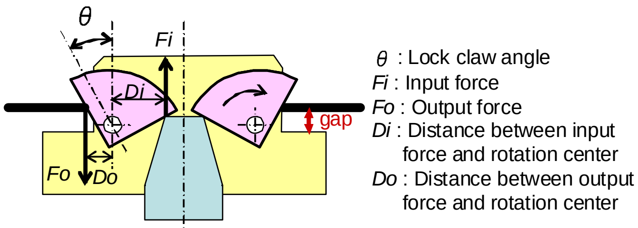


Fig. 6. Detailed view of the lock plate.

In the prototype design, the hole diameter was configured 30 [mm] which was suitable for an universal punching die. The top of insert part is chamfered 3 [mm] to absorb the misalignment of the hanging mechanism and the ceiling hole.

The lock claw can lift up the body even if there is a gap against the ceiling plate, because the lock claw is expanded in a rotational motion as shown in Fig. 6. The force relation between the input force to the drive shaft (F_i) and the output force to the lock claw (F_o) is described in eq. (1).

$$F_o = F_i \times (D_i/D_o) \tag{1}$$

In the equation, D_i and D_o are static parameters, so the in-out force relation is constant. This characteristic have an advantage of making the design calculation simple and easy. In the prototype, D_i is comparable to D_i, so the output force is equivalent to the input force. Section IV-A will explains the unit testing of the hanging mechanism.

B. *Design of horizontal locomotion mechanism*

As described in Fig. 3, the robot body is separated in the inner body and the outer body. In this framework, if the lower components (e.g. walking support handles) are installed at the inner body or the outer body, the locomotion speed of the lower component is intermittent as expressed in Fig. 7(b) or (c). The motion of home-use service robot should be intuitive for the residents, but the intermittent locomotion is undesirable because the robot looks to stop even if the robot is in the locomotion state.

To solve the problem, locomotion speed averaging mechanisms were introduced between the inner and outer bodies as shown Fig. 8, and the lower body, a base body for the walking support handles or the actuation robot, hangs under the averaging mechanisms. Consequently the locomotion speed becomes continuous except while the hanging mechanisms are actuated as shown in Fig. 7(d).

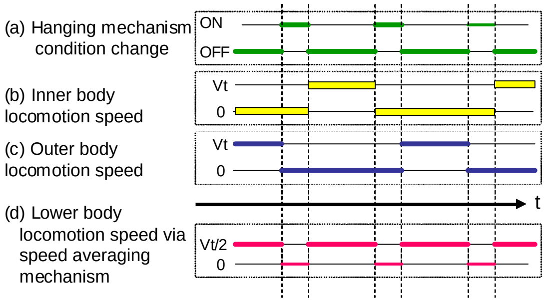


Fig. 7. Sequential actuation pattern for horizontal locomotion.

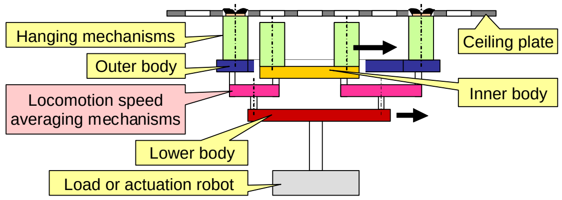
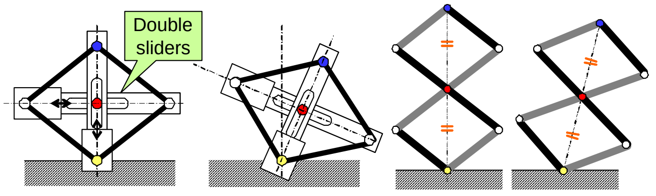
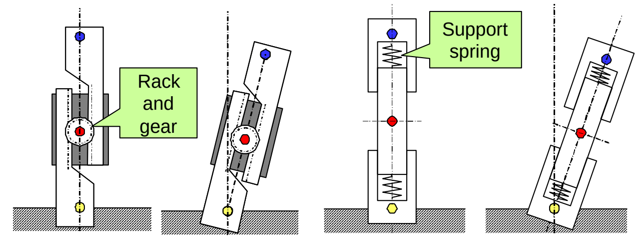


Fig. 8. Body framework with locomotion speed averaging mechanisms.

Fig. 9 shows the candidates of the locomotion speed averaging mechanism. Fig. 9(a) shows a diamond mechanism and the cross point of the diagonal lines is the connector to the lower body. This mechanism can be compact, but it needs various kinds of parts to realize translational sliders and rotary links. Fig. 9(b) shows a pantograph mechanism, and the lower body hangs at the middle joint. The pantograph mechanism is larger than other candidates, but has advantage that the mechanism comprises a few kind parts. Fig. 9(c) shows a mechanism that uses two racks and a gear wheel, and the lower body hangs at the gear wheel. This mechanism has quite simple frameworks, but the each part must have gear structure and translational slider mechanism, so it can be a little complex shape. Fig. 9(d) is a spring supported mechanism, it uses springs to sustain the lower body at the middle of the inner and the outer body, but discrepancy of the springs' characteristic and the frictional condition difference causes the misalignment of the intermediate point. In addition to the above feature, the lower body must sustain 100 [kg] load, and the mechanism should be a stiff structure.

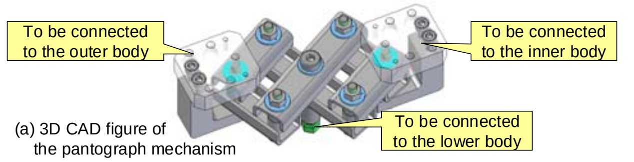


(a) Diamond shape mechanism (b) Pantograph mechanism

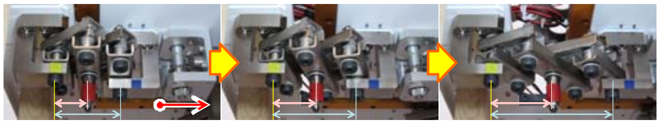


(c) Rack & gear centered mechanism (d) Spring supported mechanism

Fig. 9. Mechanisms for locomotion speed averaging.



(a) 3D CAD figure of the pantograph mechanism



(b) Sequential snapshots of the pantograph mechanism motion

Fig. 10. The pantograph mechanism.

Consequently, the authors adopted the pantograph mechanisms. Although this mechanism needs a number of parts, those parts have almost the same structure, and it is rather easy to make the whole structure stiff. Unlike the rest three candidates, the pantograph mechanism comprises only revolution joints, so the manufacture process is quite simple and easy to manage the precision.

Fig. 10(a) shows the 3D CAD figure of the developed pantograph and Fig. 10(b) depicts the motion of the pantograph mechanism prototype. By seeing the snapshots, the red point (connector to the lower body) is displaced at the half distance of the blue point. The detail experiment of the pantograph mechanism will be explained in section IV-B.

C. Mechanisms integration to the ceiling mobile robot

This section explains about the integration design of the former key mechanisms. Fig. 11 shows the overview of the ceiling mobile robot and Fig. 12 indicates the functional block diagram. The inner or outer body has four hanging mechanisms at each, and the both bodies are connected via two translational sliders and four pantograph mechanisms. A dummy lower body plate is installed at the bottom of the pantograph mechanisms. The lower body is constrained by

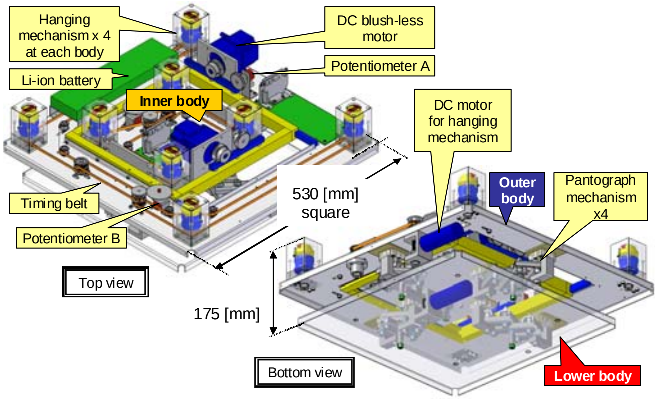


Fig. 11. Overview of the ceiling mobile robot.

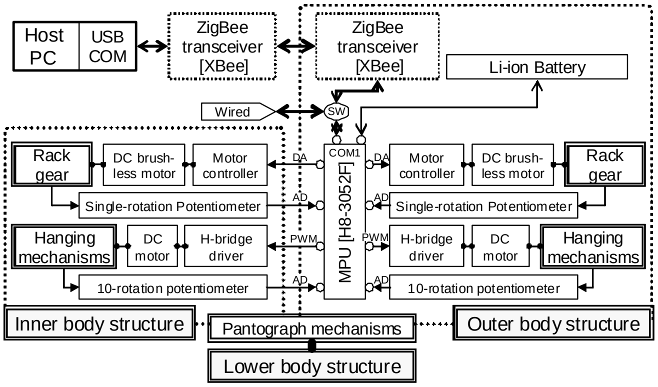


Fig. 12. Functional block diagram of the ceiling mobile robot.

the four pantograph mechanisms, so the connection between the pantograph mechanisms and the lower body have a little horizontal and vertical margin to avoid the over-constrained condition. The minimum number of the hanging mechanism is two for constraining the robot body, but in the current temporal configuration, four mechanisms are installed at each body, but in a future work the optimized number must be considered taking account of the strength of each part.

To minimize the number of actuator for the hanging mechanisms, four hanging mechanisms at each body are connected via timing belts, and one DC motor drives the four mechanisms. The condition of the hanging mechanisms are monitored by a multiple rotational potentiometer. On the other hand, DC brushless motor is used for the horizontal locomotion and a single rotational potentiometer is used for the position recognition. In the hanging mechanism, the insert motion and the lock motion switches automatically by the rotation of drive shaft. That means the required torque is quite different at the motion phases. The DC brushless motor is suitable for velocity control, so if the output torque changes drastically the target speed of the DC brushless motor should be tuned adequately. On the other hand, the rotary speed of a DC motor varies corresponding to the output torque, so if the required output torque is small (i.e. mechanism insert motion) the rotary speed is high, in contrast the output torque is large (i.e. lock motion) the rotary speed decreases automatically. The automatic speed adjustment is the reason of the DC motor adoption.

The traveling distance of one horizontal motion is configured to 50 [mm], consequently the stroke of the translational slide mechanisms and the hole pitch of the perforated ceiling plate are also defined to 50 [mm].

D. *Design of perforated metal ceiling*

This section describes the design of the perforated metal ceiling for the mobile robot. Fig. 13 shows the abstract of the special designed perforated metal ceiling. Each module is 500 [mm] × 500 [mm] rectangle, and the anchor box hanging under an anchor bolt supports four modules. The neighbor ceiling plates are fastened each other at the bended ribs, and this can prevent from remarkable independent deflection of a single module. Although there are some reinforcing ribs at the upper side of the ceiling plate, the bottom side is completely flat, so a robot need not turn away the anchor bolts. Currently, four modules are connected and the locomotion area size is 1 [m]×1 [m].

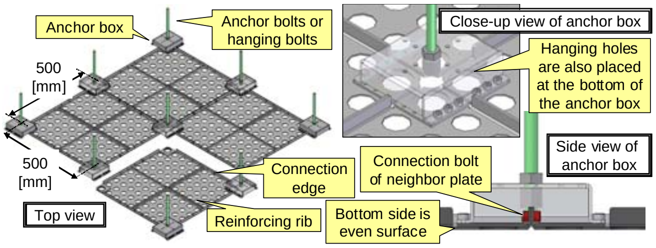


Fig. 13. Overview of the special designed ceiling for robot locomotion.

IV. EXPERIMENT

Firstly, this section describes an unit testing of the hanging mechanism, secondly explains the integration tests of locomotion speed averaging function and load transferring performance.

A. *Unit testing of the hanging mechanism*

This experiment was executed with the special designed test bench as shown in Fig. 14. The DC motor was directly connected to the power supply via the motor direction switch box, that means there is no feedback control. A limit switch is installed at the stroke end of lock side on the hanging mechanism, so the power supply is disconnected when the hanging mechanism completely becomes the lock state.

The experimental configurations are as follows.

- Distance between the hanging mechanism and the ceiling plate: 3 variations (1, 3, 5 [mm])
- Weight: 3 variations (10, 20, 25 [kg])
- Trial numbers: 3 times

The measurement items are as follows.

- Vertical displacement of the hanging mechanism: measured with two wire type potentiometers, “MTA-3E-5KW-MB” made by Celesco Transducer Products, Inc.
- Motor drive current: measured with a current sensor, ”HPS-15-AS” made by U.R.D. Co., LTD.

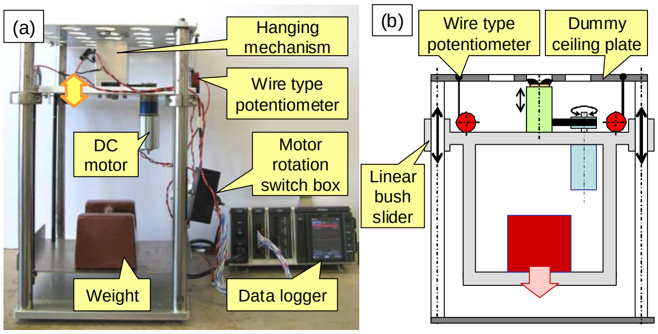


Fig. 14. (a) Hanging mechanism test bench, (b) schematic diagram.

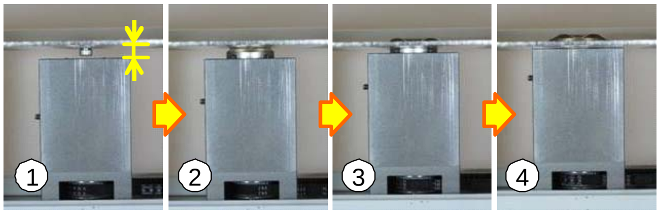


Fig. 15. Close-up side view of the hanging mechanism motion.

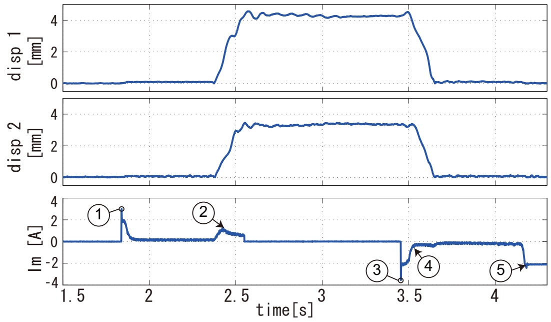


Fig. 16. Measured data example of hanging mechanism unit test (gap: 5 [mm], weight: 10 [kg]).

Fig. 15 shows sequential snapshots of the lock motion. Fig. 16 shows an example of the measured data. This graph shows the transition of the measured data from free state via lock state to free state again. the "disp 1" and "disp 2" show the displacement data of the wire type potentiometers and the "Im" expresses the motor current. The positive motor current means the motor is activated for the lock motion.

The graph explicitly shows the transition.① Inrush current activates the motor by making the switch box to the lock side. ② The lock claws start pulling the ceiling hole and the lifts up the mechanism and the load.③ The motor starts opposite rotation by changing the switch box to the release side. ④ The lock claws release the ceiling hole.⑤ The screw drive part comes to the stroke end and stops.

In the graph, configured displacement was 5 [mm] but the maximum displacement of the potentiometer was less than 5 [mm]. Because the test bench structure was bent with the heavy weight, so the displacement of the plate edge was different from the center's.

The hanging mechanism could execute the lock and release transition in $3 \times 3 = 9$ various conditions. Table III shows the maximum current and the elapsed time for the lock motion. The elapsed time is measured from① to the motor current zero crossing time after② in Fig. 16. And the each value is the average of three trials. This result indicates that the heavier the load is or the longer the distance is the more current is required for the DC motor. The heavier load needs more motor torque, so it requires more current. On the other hand, the long distance make the lock motion slow and makes the required maximum torque large. This phenomenon can be observed in the elapsed time data (b), where the elapsed time becomes longer depending on the gap distance.

TABLE III

RESULT OF HANGING MECHANISM UNIT TEST.

(a) Maximum DC motor current

gap [mm]	Weight [kg]		
	10	20	25
1	**0.40**	**0.48**	**0.54**
3	**0.76**	**0.92**	**1.0**
5	**1.2**	**1.6**	**1.7**

unit [A]

(b) Elapsed time for lock motion

gap [mm]	Weight [kg]		
	10	20	25
1	**0.69**	**0.69**	**0.69**
3	**0.70**	**0.70**	**0.71**
5	**0.71**	**0.74**	**0.75**

unit [s]

B. *Horizontal locomotion performance experiment*

This experiment aims to confirm the performance of the locomotion speed averaging function by the pantograph mechanisms and the total load transferring performance. As shown in Fig. 17, a pole is placed at the rear side of the temporal ceiling plate, and three wire type linear encoders measured the length between the three bodies (outer, inner, and lower) and the pole. The encoders are "MLS-30-4500-1000" made by Microtech Laboratoy Inc., and the resolution is 0.02 [mm]. In addition, linear potentiometers ("LP-10FB", MIDORI PRECISIONS CO., LTD.) are installed at the hanging mechanisms as Fig. 18 shows.

Fig. 19 shows the sequential snapshot of the experiment. Fig. 20 indicates the experimental results. The Fig. 20(a) reveals that the locomotion speed of the inner and outer bodies are averaged to the lower body locomotion, and the lower body locomotes while the inner or outer body is transferring. In the experiment, the robot motion is controlled manually so the hanging mechanism switching time is longer than the automatic motion. It takes about 1.5 [s] for the hanging mechanism to execute the automatic switching from the inner body lock state to the outer body lock state.

Fig. 20(b)∼(d) reveals that while the inner body is transferring, the distance between the hanging mechanisms on the inner body and the ceiling plate becomes larger, and

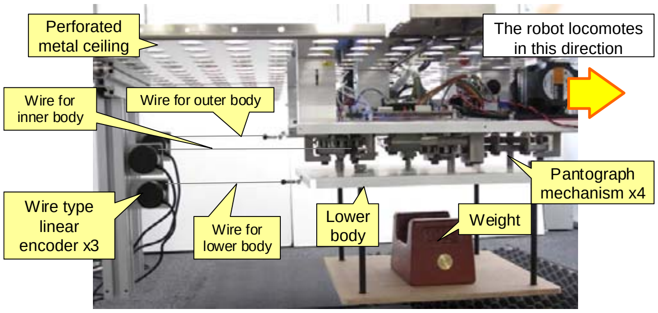


Fig. 17. Experimental setup for locomotion speed averaging experiment.

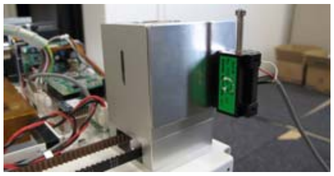


Fig. 18. Linear potentiometer equipped on the hanging mechanism.

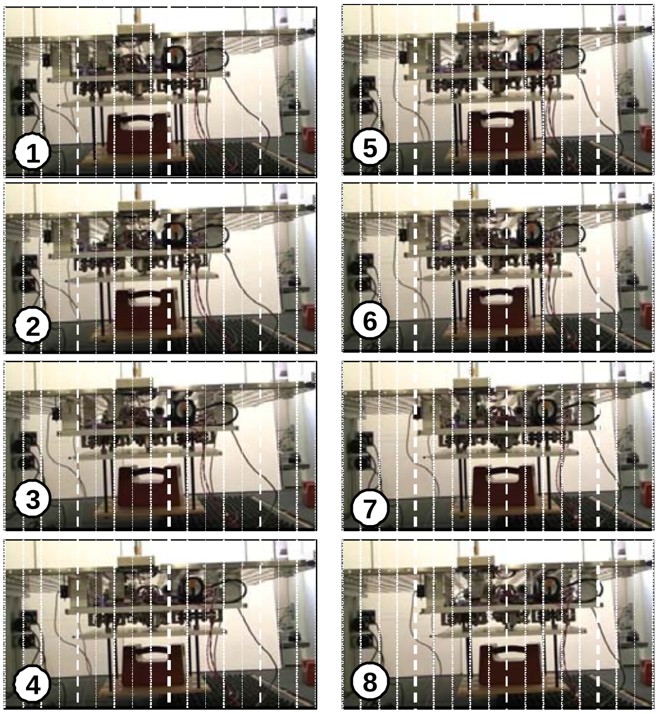


Fig. 19. Sequential images of horizontal locomotion with 20 [kg] weight.

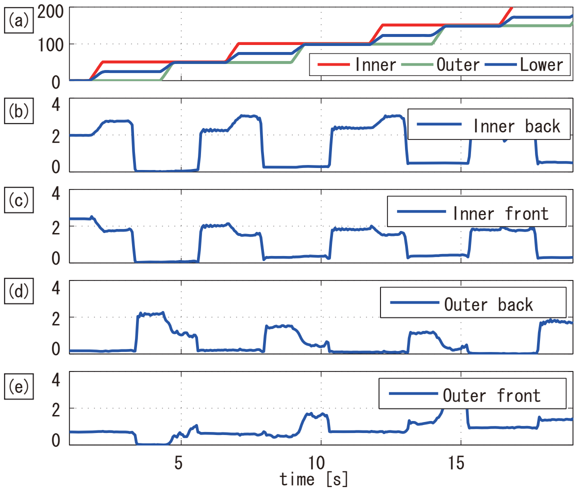


Fig. 20. Sensor outputs of horizontal locomotion experiment; (a) three bodies driven distance measured by the linear encoders, (b)$\sim$(d) displacement of the hanging mechanisms.

vice versa while outer body is transferring. This phenomenon happens because the load pulls both inner and outer bodies via the pantograph mechanisms, so the distance between the unlocked body and the ceiling plate becomes larger. But each body has four hanging mechanisms and it is over-constraint condition, so some hanging mechanisms always have small margin to the ceiling plate as shown in Fig. 20(e). The unlocked body is the transferring body, so this feature have good effect in the ceiling contactless locomotion in the inchworm-like locomotion. Surely if the load is suspended under the inner or outer body, this feature is not observed, hence this is an additional effect of the locomotion speed averaging mechanism.

But in this experiment, the maximum payload was 35 [kg], because the power supply for the driving motor was not sufficient, and the body stiffness is not sufficient. To realize the locomotion under a 100 [kg] payload (our target specification), we must revise the detailed design of the ceiling mobile robot body and the actuators.

V. CONCLUSION

This research aims to develop a ceiling mobile robot under a large payload. Our research group focused on the perforated metal as a ceiling material and proposed a mechanically constrained ceiling mobile robot that hangs under the holes of the perforated metal plate. To realize the robot, we developed three key mechanisms, (1) ceiling hanging mechanism for the perforated metal, (2) horizontal locomotion mechanism like an inchworm, and (3) pantograph mechanism for smoothing horizontal locomotion speed.

In the unit testing of the hanging mechanism, it was confirmed that the mechanism could execute lock and release motion under a 25 [kg] payload. After the integration of the key mechanisms into the ceiling mobile robot, it was confirmed by the integration experiments that the pantograph mechanism is effective to average the locomotion speed of the two separated bodies and has an additional load balancing effect that is preferable for a smooth inchworm-like locomotion.

The maximum payload was 35 [kg] in this paper, so to realize a locomotion with 100 [kg] load, detailed design must be revised in the next work. However, the basic feasibility of the mechanically constrained ceiling mobile robot was presented in this research.

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