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A Proposal of Super Long Reach Articulated Manipulator with Gravity Compensation using Thrusters

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Abstract— **This paper proposes a super long reach articulated manipulator with gravity compensation using thrusters. The proposed manipulator has (1) ground fixed base, (2) tethers for power and information transmission, (3) articulated links connected by joints, and (4) thruster(s) for weight compensation. Because of weight compensation by thruster(s), the proposed manipulator can be super long reach due to free from gravity. After an experiment using 1 D.O.F experimental setup for principle confirmation, and dynamics numerical simulation, an experimental prototype consisted of passive four-bar linkages, active yaw joints and paired counter-rotating propellers, was developed. We successfully demonstrated the proposed concept by three dimensional motions controlled by thrusters and yaw joints.**

I. INTRODUCTION

A long reach redundant manipulator is required for various tasks such as infrastructure inspection in high places, plant inspection in a confined environment, decommissioning work for Fukushima Daiichi Nuclear Power Plants, pesticide spraying for agricultural field and so on. Although many construction machines such as cranes and concrete pumping trucks exist, these machines are heavy, huge and sometimes difficult to be deployed. Thus, many robotics researchers and industries have attempted to develop a long reach redundant manipulator such as [1], [2], [3]. .

With regard to mechanical design, the longer cantilever manipulator is more difficult to develop than a conventional manipulator due to large gravity torque. In order to cope with the large gravity torque, [1] utilized weight compensation mechanism by parallel linkages and springs, [2] introduced multiple tendons (wires), and [3] structurally supported the gravity using serially connected yaw joints like SCARA robot.

In our previous work, we proposed a coupled tendon-driven 3D multi-joint manipulator "Mini 3D CT-Arm" using special tendon pulley arrangement [4]. The design was extended to incorporate a large actuator mainly supporting gravity torque, and small actuators controlling each joint angles [5]. In our design, we can develop 10 meters long articulated manipulator with 10 kg payload. However, it is very challenging to increase manipulator length while achieving the same payload.

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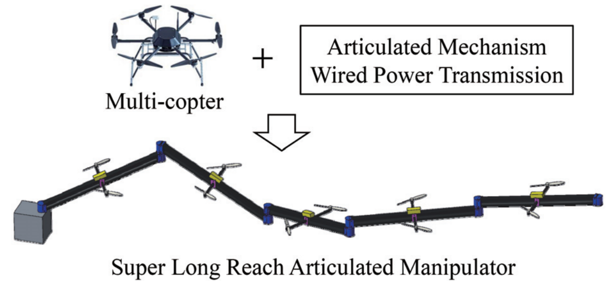

Fig. 1. Basic concept of proposed articulated manipulator.

With regard to length extension, we succeeded to develop a 20 meters long manipulator. The manipulator, named "Giacometti arm with balloon body", had inflatable cylindrical balloon bodies filled with helium gas, and body segments generate buoyancy[6][7]. We installed extremely light weight artificial muscles driven by pneumatic power for joint movements. We succeeded inspection task using micro camera attached at the end of manipulator. However, its payload was limited only 30 grams.

Currently, multi-copter aerial robots, commonly known as drones, are extremely active research topics, and above mentioned tasks can be done by drones. However, aerial robots are very sensitive to weather conditions and have possibility of crash, that leads to a fatal accident. Moreover their operation time are very limited. For example, conventional electric quad-copter requires frequent battery change every 20-30 minutes. A tethered drone is one of the option to solve the energy problem, however, safety issues still remain.

In this paper, our ultimate target is to develop 20-30 meters long light weight articulated manipulator with 10 kg payload, which has ease of deployment. In order to achieve this goal, we propose a brand new idea that combining drone technology with articulated manipulator shown in Fig.1. Thrusters (propellers in this case) are installed to compensate weight of the manipulator. To the best of our knowledge, there is no proposal utilizing thrusters for gravity compensation. The manipulator is free from gravity, and this concept permits us to develop a super long reach manipulator with sufficient payload.

The purpose of this paper is to propose our basic concept, and confirm its feasibility by hardware prototypes. Mathematical formulation and detailed control algorithm will be reported in the near future. The rest of paper is organized as follows. Section II proposes our novel concept and discusses its advantages. Section III confirms basic principle of gravity compensation using thrusters for 1 D.O.F system. Section IV describes numerical simulation for three unit prototype to investigate modularity. Section V addresses development of a three unit prototype, and Section VI reports experimental results. Finally, Section VII concludes this paper.

II. Proposal of a Super Long Reach Articulated Manipulator with Gravity Compensation using Thrusters

In this section, we propose a new super long reach articulated manipulator with gravity compensation using thrusters, and its examples and advantages are also discussed.

A. Definitions

We propose an articulated manipulator possessing the following items.

- The base is fixed on the ground.
- The manipulator is a tethered system.
- The multiple joints serially connect multiple links.
- The weight of the link is compensated by thruster(s).

First, we assume that the base is fixed to the ground during a manipulation task. The base can be a mobile robot keeping its position, which has sufficiently heavy in weight compared with the manipulator.

Secondly, we assume the energy for operation is externally supplied. The ground fixed structure allows the manipulator to be a tethered system. Control command signals and measured data from sensors can be transmitted via wired connections.

Thirdly, the proposed manipulator has serial articulated structures with multiple links and joints. The joints can be rotational and/or translational joints. The joint can be active joint, passive joint and passive joint with a brake. Of course, various combinations of joints are acceptable.

Fourth, thruster(s) are introduced to compensate gravity. Examples of thruster are a propeller, gas combustion turbine, high pressure air, high pressure water and so on. There is no restriction of number of installed thrusters and/or location of thrusters. Thrusters are installed mainly for gravity compensation, however the usages are not limited to. Thrusting force can be used to move the joints of manipulator.

B. Examples

We show three examples of the proposed manipulator shown in Fig.1-3. The lower figure depicted in Fig.1 has multiple four-bar linkages serially connected by active joints which rotate around yaw and pitch axes. Thanks to the parallel four-bar linkage, the thruster (propeller) axis is kept parallel to gravity. Therefore the mass of the link can be always compensated regardless of joint angle. Figure 2 shows horizontally extendable super long reach manipulator. All joints are passive, however end position of the manipulator can be controlled by a quad-copter attached. Propellers are attached at joints in order to make the manipulator structure simple. Figure 3 shows the proposed manipulator with prismatic joints driven by tendons. A propeller is installed at the end of manipulator to compensate the weight of end effector. The thrusting force can be adjusted depending on the object handled by the end effector.

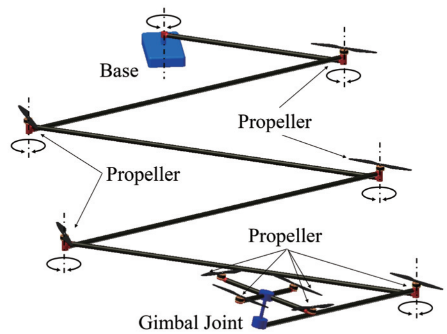

Fig. 2. Example of the proposed super long reach manipulator that moves in a horizontal plane.

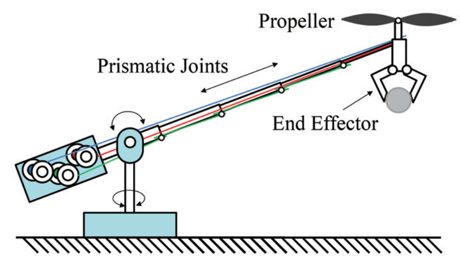

Fig. 3. Example of the manipulator with prismatic joints and a propeller.

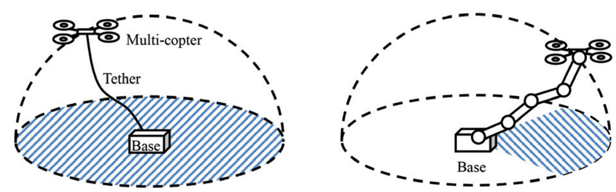

Fig. 4. Dangerous area in case of crash (left) tethered drone, (right) proposed manipulator.

C. Advantages

In this subsection, we discuss advantages of the proposed manipulator. In particular, we compare the proposed manipulator with aerial robots (drones).

The common characteristics of the proposed manipulator are as follows.

- Scalability
- Ease of control (higher robustness and safety)
- Unlimited operation time

The most interesting feature of this concept is scalability. Ideally speaking, thanks to the weight compensation by thrusters, the manipulator becomes free from gravity. Thus, we can construct a super long reach cantilever-type manipulator by increasing the number of connecting units. The control of the manipulator is easy and robust compared with aerial robots because the base is fixed to the ground. Moreover, we can explicitly limit the operational area of the proposed manipulator thanks to the constraint of the links, whereas a tethered drone can not (Fig.4). Finally, the manipulator can be operated unlimitedly because of external power supply, whereas conventional drone requires frequent battery changes. In addition, we can use thicker cables compared with the tethered drone because the proposed manipulator has rigid links. This characteristic makes inspection operation more efficient because we can use high speed data transfer using wired connection.

D. The model for initial verification

In order to verify our proposed concept, we consider the simplest model of the manipulator. Kinematics model of first prototype is shown in Fig.5. Multiple four-bar linkages with passive joints, are serially connected by active yaw joints. Propeller is used as a thruster. By controlling rotational velocity of the propeller, we can control thrust force so as to compensate weight of the manipulator as well as to control pitch joint angles.

Figure 6 shows basic principle of gravity compensation using thruster. The left figure shows inverted pendulum and its gravity torque is $\tau = mg\cos\theta$. A four-bar linkage and propeller are introduced as shown in the right figure. The four-bar linkage always keep the propeller axis parallel to gravity. If the lift force generated by propeller always equals to gravitational force on the end mass, gravity torque becomes $\tau = 0$ regardless of joint angle θ. (The other masses on the links can come down to the end mass.) Therefore change of the thrust force is only required in acceleration/deceleration phase, suggesting extremely simple control.

III. Principle Confirmation

In order to verify feasibility of gravity compensation using propeller(s), this section describes 1 D.O.F experiment for the principle confirmation.

Figure 7(a) shows the basic mechanism of 1 D.O.F. unit. There is a four-bar linkage to keep the propeller axis perpendicular to the ground regardless of link pitch angle θ_p. All revolute joint is passive, and thus θ_p should be controlled by thrust force generated by the propeller. Figure 7(b) shows 3DCAD model of the experimental setup. Two counter-rotating propellers are installed to generate the thrust force while cancelling reaction torque due to propeller rotations. The link length is 1.0 meter and pitch angle θ_p is measured by a potentiometer. Mass property data is acquired by 3DCAD model. The thruster unit is composed of a brushless DC actuator (Tarot: 4114), Electronic Speed Controller (ESC) (HOBBYWING: FLYFUN 40A V5) and a propeller made by CFRP (Tarot: TL2812). The nominal thrust force is 24.3N, where applied voltage is 25.2V and current is 15.6A. The ESC is controlled by PWM signal generated by a micro controller (MPU: Renesas Electronics: RX62T, board: Alpha Project: AP-RX62-T). The pulse width for ESC is associated with normalized value of control input. Thus, if control input equals 100%, then the output thrust force is 24.3N.

Before carrying out 1 D.O.F. experiment, we calibrated the relationship between normalized control input signal and output thrust force. A testing device to measure thrust force is developed as shown in Fig. 8(a). The propeller thruster unit is attached to the linear guide, and the linear guide pulls a rod that applies a bending moment to the load cell. We introduce the rod to avoid direct influence of the wind caused by the propeller. Figure 8(b) is step response where input command changed from 0.1 to 1.0[1]. It is required about 0.3 seconds to reach steady state.Figure 8(c) shows almost linear relationship between normalized input command and thrust force.

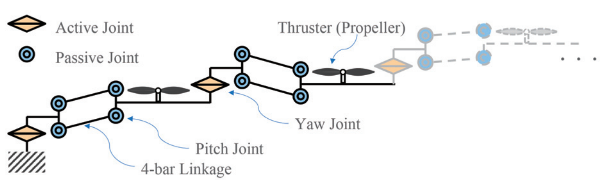

Fig. 5. Kinematics model of prototype in this paper for first verification of the concept.

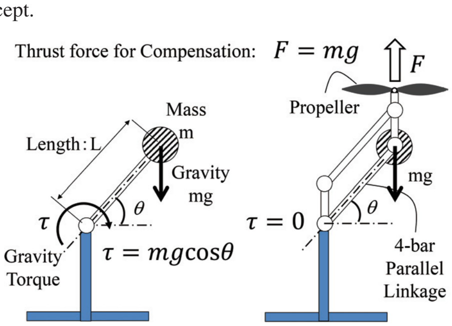

Fig. 6. Basic principle of gravity compensation with thruster.

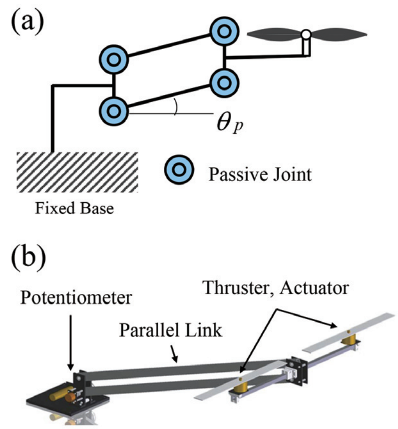

Fig. 7. 1 D.O.F. principle confirmation model: (a) kinematic configuration and (b) 3DCAD model.

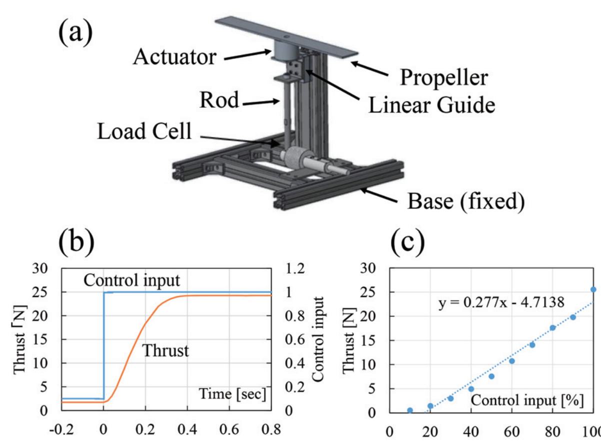

Fig. 8. Thrust force measurement: (a)experimental setup, (b)step response, and (c)relationship between control input and output thrust.

[1]During this experiment, we noticed that there was huge time delay when the actuator started from zero angular velocity. Maybe this was due to ESC control algorithm. Thus, we measured step input from 0.1 to 1.0

In terms of a control algorithm, a simple PID control is applied shown in Fig. 9. Gravity force is cancelled based on the feedforward term, and desired joint angle θ_{p_d} is achieved by PID controller.

1 D.O.F. control experiment was conducted where θ_{p_d} was periodically changed from -10 to +10 deg with 3 sec intervals. The joint angle θ_p was successfully controlled as shown in Fig. 10. Figure 11 shows trajectories of desired/measured joint angle and thrust force command for F_d. The joint angle exhibited over shoot, but reached desired joint angle within 1.5 seconds. The thrust force was basically constant, and changed only when the desired joint angle changed. To increase (decrease) joint angle, it is required to increase (decrease) thrust force to accelerate (decelerate) the mass of the system. These results agree with the discussion described in Section II. Therefore basic principle of weight compensation, and feasibility of joint control by thrusters were experimentally confirmed.

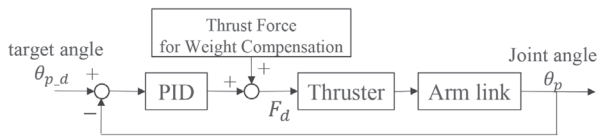

Fig. 9. Block diagram for 1 D.O.F. weight compensation experiment.

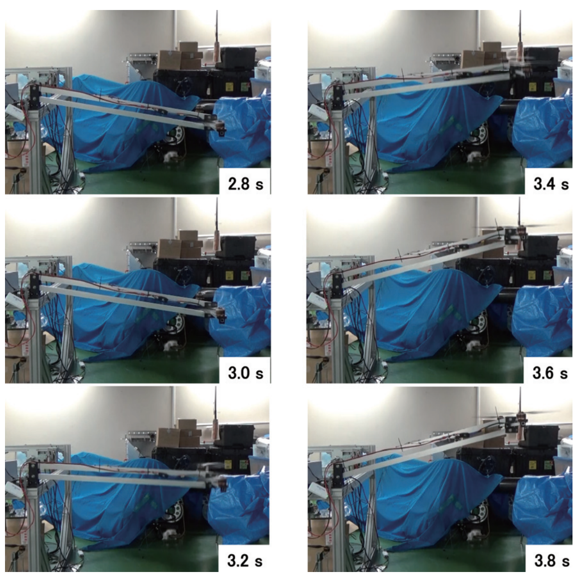

Fig. 10. 1 D.O.F. weight compensation experiment where $\theta_{d_p} = \pm 10$deg.

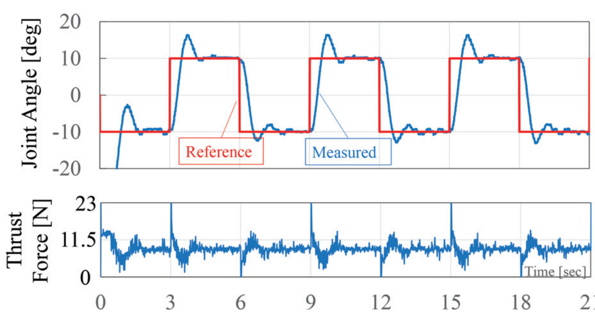

Fig. 11. Trajectories of desired joint angle, measured joint angle and thrust force command.

IV. Numerical Simulation for Three Unit Prototype

In this section, we numerically verify if we can increase the number of units to construct an articulated structure. Ideally speaking, the arm structures are scalable because the weight of each unit is individually compensated by each thruster, and each pitch joint is completely passive so that there is no torque propagation through each pitch joint. Only interaction between each unit is translational forces due to dynamic effect of the connecting unit.

To verify this effect, we constructed a numerical simulator on MatLab as shown in Fig. 12. Three identical four-bar linkage structures are serially connected. The length of the unit is 1.0 m, and mass of the unit is 2.1 kg. All mass property data is derived by 3DCAD model of the three unit prototype, which will be mentioned in the next section. All the pitch joints are independently controlled by PID described in the previous section, and there is no interaction between controllers. PID gains are manually tuned through trial and error. Each compensation force by the thruster F_i is applied on the distal joint of the unit.

Figure 13 shows a typical result of numerical simulation. Initial configuration of the manipulator is $\theta_{pi} = 0$. A step angular velocity input of 20 deg/s on θ_{p2} is applied from 10 to 13 sec, while θ_{p1}=$\theta_{p3} = 0$.

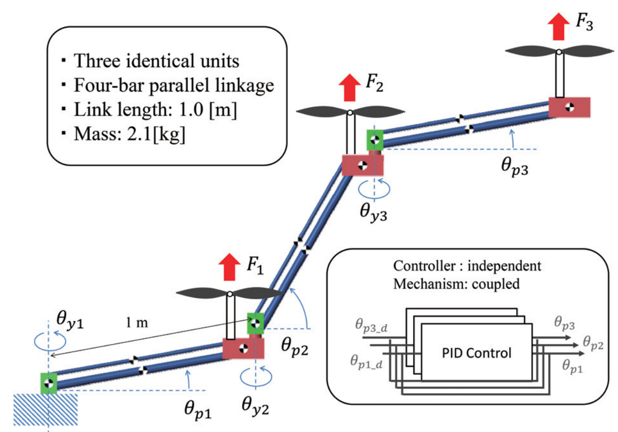

Fig. 12. Three unit model for numerical simulation.

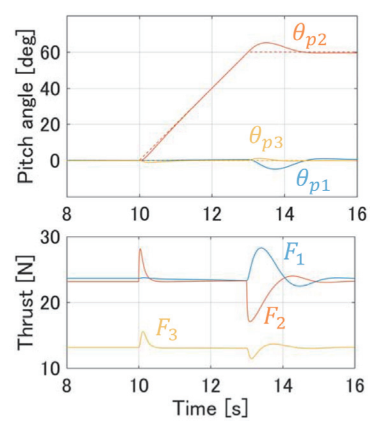

Fig. 13. Numerical simulation result: all joint angle is zero except θ_{p2}. Step input of 20 deg/s was applied to θ_{p3} from 10 to 13 sec.

As we expected, thrust forces F_2 and F_3 increased when these two unit started to move because they required accelerations. Then, the thrust forces remained the same values while θ_{p2} moved at the constant velocity. When θ_{p2} made stopping motion, then thrust forces F_2 and F_3 decreased to decelerate the distal two units, while F_1 increased to compensate counter force for stopping movement. Although there existed physical interactions when the manipulator generated dynamic movements, individual PID controllers with appropriate gain parameters could cope with force interactions as disturbances to some extent.

V. Development of Three Unit Prototype

In order to prove our overall concept, we developed a prototype model that consisted of three identical units. The purpose of this prototyping is to confirm (1) multiple link weight compensation by thrusters, (2) multiple pitch joint control by thrusters, and (3) three dimensional movement using yaw joints and pitch joints.

Figure 14 shows three units prototype model "Hiryu-I (Frying Dragon-I)", and its specifications are described in Table I. The prototype model consisted of three identical units, where one unit has four-bar linkage using two CFRP pipes and aluminium parts, two counter-rotating propellers, and a yaw actuator. The specification of thruster is the same described in Section III. The yaw actuators should be located in the base in order to reduce total weight of the robot. However, we installed the yaw actuators in each unit due to the ease of implementation for initial verification of the concept. We used DC servo actuator (ROBOTIS: MX-106R) with additional reduction mechanism using timing belt and pulley. The actuator output power was approximately 30 W, and maximum stall torque was about 15 Nm. The yaw joint angles were directly controlled by micro controller via RS485, whereas pitch joint angles were controlled by thrust forces. We could attach a small video camera (SONY: HDR-AS100V) at the end of manipulator because it had sufficient payload of 2 kg. The total weight of the manipulator was only 11 kg, suggesting easy deployment.

TABLE I

Specifications of Hiryu-I

Length (Horizontally extended)	3000 mm
Width	1000 mm
Mass	11 kg (Arm: 6.5 kg, Base: 4.5 kg)
Payload (at Arm End)	2 kg
Power Consumption (at static posture, payload 0.5 kg)	750 W
Range of Motion	θ_{yi}: -180 deg $\sim$ 180 deg, θ_{pi}: -30 deg $\sim$ 60 deg

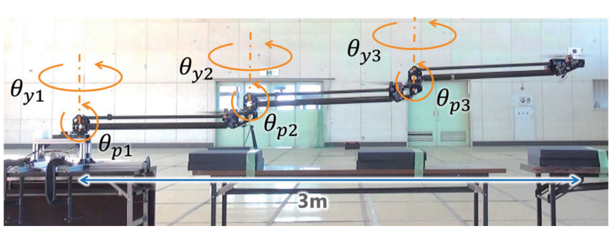

Fig. 14. Three units prototype model "Hiryu-I".

VI. Experiment

First, we carried out independent pitch joint angle control by thrusters as shown in Fig. 15. Time course of pitch joint angles are depicted in Fig. 16(a), where solid lines are measured trajectories and dashed lines are desired trajectories. Figure 16(b) shows joint angle errors in degree. At the beginning of the experiment, all links were supported by external structures so as to set all pitch joints equaled to zero. After thrust force feedback control activated, the operator manually set desired pitch joint angles as $\theta_{id} = 10$ deg, and the manipulator successfully lifted its body and kept specified posture. Therefore we could confirm that multiple link weight compensation was achieved by thrusters. In this case, the total electric power consumption was about 750W. Then θ_{p1}, θ_{p2} and θ_{p3} were independently increased to 40 deg, and all pitch joints were increased to 50 deg. The manipulator successfully followed specified posture. Next, only θ_{p2} was decreased while θ_{p1} and θ_{p3} kept the same joint angle. Even in this case, we could change θ_{p2}. As we expected, we observed small pitch oscillations when pitch joints started/stopped its movements. However, independent PID controllers successfully handled these disturbances. In most of the cases, joint angle errors were less than ± 1 deg as shown in Fig. 16(b), suggesting sufficient control accuracy.

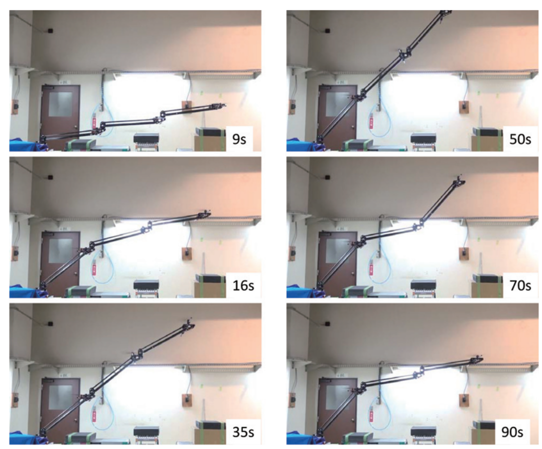

Fig. 15. Independent pitch joint angle control by thrusters.

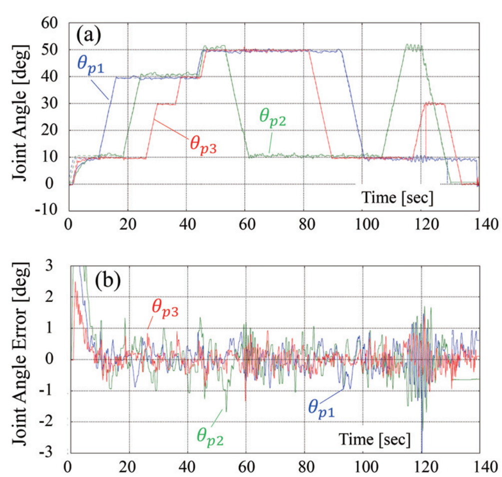

Fig. 16. Time course of joint trajectories: (a) desired joint angle (dashed) and measured joint angle (solid), (b) joint angle error.

Secondly, we demonstrated three dimensional manipulation combining yaw joint control and pitch joint control by thrusters. Figure 17 shows three dimensional movement and we verified that we could localize the end position of manipulator in order to observe target environment by the camera mounted at the tip of manipulator. Although the manipulator movements sometimes exhibited oscillation, the camera images captured were very stable by using built-in anti-shake algorithm.

Finally, we conducted an experiment using longer links to show scalability of this system. We extended proximal two links from 1.0 meter to 2.0 meters. Thus, total length of the manipulator became five meters. Even in this case, the manipulator successfully lifted its pitch joints. This result suggested the feasibility of much longer manipulator. However, we could not control θ_{y1} because miss alignment of thruster axes and structural deformation of joint parts generated large torque that exceeded output torque of yaw joint actuator. Symmetrically slanted thruster axes and velocity control of each thrusters may solve this problem.

VII. CONCLUSIONS

In this paper, we have proposed a new super long reach articulated manipulator with gravity compensation using thrusters. The proposed manipulator is a base-fixed manipulator that equips with thruster(s) to compensate gravity. The advantages of the proposed manipulators are: (1) long operation duration thanks to wired power transmission, (2) ease of control and higher robustness compared with conventional multi-copter, (3) explicit determination of workspace that leads to safer operation. After 1 D.O.F. gravity compensation experiment for principle confirmation, we showed that a simple PID controller could be applicable to three units model by numerical simulation. Finally, overall concept was embodied by three units prototype model "Hien-I", and demonstrated three dimensional large workspace movements. Scalability of the proposed concept was also suggested by changing the link lengths. In this paper, we only verified one of the proposed concept. We need to explore various types of the proposed concept. For example, yaw joint control can be also done by thrusters shown in Fig. 19. Investigation and formulation of control algorithm to increase robustness against disturbance in an outdoor environment is quite important topic to apply this manipulator to practical tasks. Scalability, energy efficiency and comparison between other solutions, such as balloon-type manipulator, tendon-driven coupled manipulator, tethered drone and conventional drone, are also important issues to be discussed in the near future.

ACKNOWLEDGMENT

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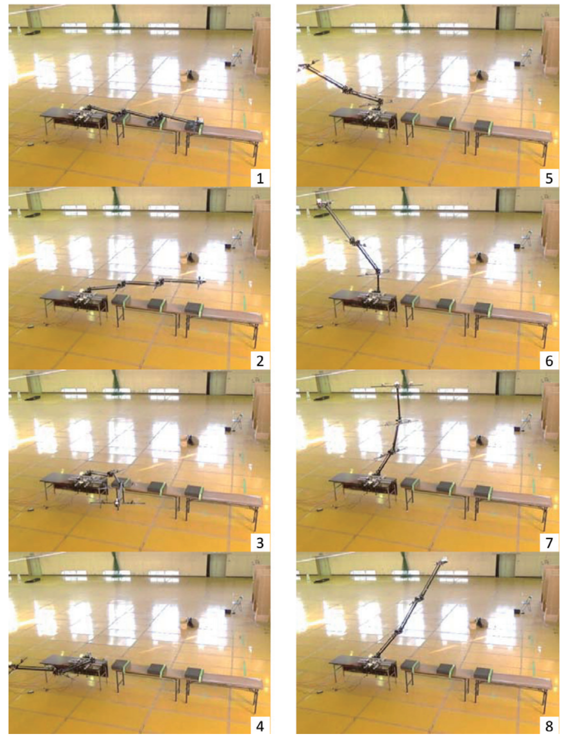

Fig. 17. Three dimensional movement using active yaw joints and thruster driven pitch joints.

Fig. 18. Experiment with 5 meters model (lengths of the first and second proximal links are 2.0 m).

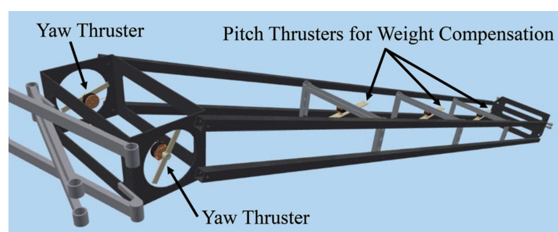

Fig. 19. Yaw joint control by thrusters.

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