Contactless Manipulation of an Object on a Plane Surface using Multiple Air Jets

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Abstract— **We propose a technology for manipulating the position and orientation of an object in a contactless manner over an extended range. This technology involves multiple ejectors that stream jets of compressed air onto an object from various directions. By regulating the air jet directions and flow rates, the object can be actively "force closured" and its position and orientation can be manipulated freely. As the first step of this research, in this paper, we discuss technological challenges for this method. Next we provide a preliminary investigation with one degree-of-freedom planar experimental system using a continuous and a PWM air jet ejection method. Based on this investigation, we examine problems relating to the use of three air nozzles to control the position of a cylindrical object in two degrees of planar freedom.**

I. INTRODUCTION

CONTACTLESS manipulation of an object is extremely advantageous because it does not entail mechanical friction, backlash, or the need for lubrication or a bulky transmission mechanism. Related existing technologies can be generally categorized into methods that utilize either electromagnetism or air. Although the technologies based on electromagnetism, for example, active magnetic levitation using either attractive or repulsive electromagnetic force [1], passive levitation using superconductive magnets, and levitation technologies based on the Lorentz force, are widely known and have been commercialized, their range of actuation is limited to between several millimeters and up to several centimeters at most. As for methods air-based technologies, there are currently no methods that enable multiple degree-of-freedom manipulation with ranges of actuation exceeding several centimeters. In this paper, we propose a contactless object manipulation technology by regulating multiple air jet directions and flow rates. We are not aware of existing research on such methods of multiple degree-of-freedom manipulation.

We should note that systems that use air ejected vertically by fan or other methods to levitate small balls in midair can be found in facilities such as amusement parks. These systems passively manipulate objects with only one DOF in the direction of gravity, however, and are inherently different from the proposed system which actively controls multiple degree-of-freedom. One novel and pioneering related work has been reported recently [2]. This interesting paper presents a mechanism and a control strategy that enables automated non-contact manipulation of spherical objects in three dimensions using a single air jet. The biggest difference between [2] and ours would be number of air jets and degree of freedom and how to control. In this paper, inspired by our own past work [3], we try to manipulate an object by using multiple air jets by which the object can be actively force closured.

In Section *II* of this paper, we summarize the technological challenges for our method. Next, based on knowledge of these challenges, some planar (flat surface) experimental systems with one and two DOF are discussed, including proposal of a continuous and a PWM air jet ejection method. The conclusions of this research are presented as well as some future perspective in the last Section.

II. SUMMARY OF TECHNOLOGICAL CHALLENGES

Unlike flows of water, flows of air have only the weakest tendency to move in a straight line within a space. Therefore, technological difficulties increase dramatically as the number of DOF increase and the range of actuation expands. Specifically, the following problems arise.

A. Unilateral actuation

The most important characteristic of this technology is the unilateral (one-directional) nature of its actuation. Just as electromagnets have only attractive force but no repelling force for iron, air flow can exert only pushing force but no pulling force. When using unilateral actuators such as these, the geometric arrangement of the actuators is crucial for stability. In other words, unlike bi-directional actuators, the full rank condition of the allocation matrix is just a necessary condition for force closure, not always a sufficient condition [6, 7]. In this study, we determine the number of required nozzles and their geometric positioning, making full use of the technology and information presented in reference [1, 6, 7].

B. Delay

The travelling velocity of air jets is determined primarily by the pressure of the compressed air and the shape of the nozzle. The time required for air molecules being ejected at the nozzle to reach the object increases with the distance to the object. This is an extremely difficult issue to address in any feedback control theory. Because no fundamental solution to this problem appears imminent, practical constraints are likely

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to remain in terms of the manipulation speed and transportable weight.

C. *Diffusivity*

The moment it leaves the nozzle, the air jet begins to expand in a radiating fashion, and the angle of expansion is empirically known to be approximately 14º. The force acting on the object decreases with distance, and takes on distributed constant characteristics. While airflow's linearity can be achieved to some degree by narrowing the nozzle orifice and tuning the shape of the nozzle, such measures also reduce the number of air molecules that are released in a unit time, consequently reducing the force that acts on the object. We can expect to achieve a degree of improvement with respect to this problem by including small amounts of volatile liquid in the air jet.

D. *Interference*

One aspect of interference related to diffusivity is that when multiple air jets are directed towards an object, interference occurs between these different streams of air; consequently, it is extremely difficult to estimate and control the total force acting on the object. This same problem exists for magnetic levitation-based multiple-degree-of-freedom positioning systems; this problem can potentially be resolved to some degree through the use of decoupling feedback control methods provided that the object's position and orientation can be accurately measured.

As described above, since the proposed manipulation method includes not a few challenging problems, we first start to investigate the simplest example with one DOF.

III. EXPERIMENTAL PLANAR SYSTEM WITH ONE DEGREE OF FREEDOM

A. *Experimental setup*

Here, we consider the actuation and control of an object on a flat surface with one DOF, that is, movement in a straight line. As force closure conditions dictate the need for two actuators, we examine problems relating to the use of two opposing air nozzles as shown in fig. 1 to control the rectilinear position of a hard cubical object. Here we tentatively set our goal for the position control precision to that the position error should be less than 10% of the driving range. The devices used in the system are described below.

1) Electro pneumatic regulator: This device includes a feedback mechanism in which the flow rate is controlled. The input signal to the electro pneumatic regulator (target air jet flow rate) is roughly proportional to the flow rate of the air jet. The input signal to this device is the control input u_L , u_R of the flow rate to be controlled.

2) Camera: The camera acquires binary image data on the color of the designated marker. By calculating the object's center of gravity using this data, the position of the object (*X*, *Y* coordinates) can be obtained at the camera's frame rate.

B. *Preliminary experiments*

The characteristics of the force of air exerting on the object are critical for designing the control system. It would be extremely difficult to apply fluid dynamics-based theory to force-of-air characteristics because the object's position and orientation aren't constant in this study. Therefore, to experimentally investigate the characteristics, a preliminary experiment was conducted using a force-of-air measurement device.

Fig. 2 shows linearity with respect to the force versus the electro pneumatic regulator input signals of 0–1 Voltage, up to a distance of 22 cm. Before the experiment, although the force of air was expected to decrease with distance, the experiment shows that, contrary to the expectations, the force of air remains roughly constant up to a distance of 22 cm. This finding is likely attributable to the fact that the surface area of the object is large enough and the majority of air molecules aimed at the object actually hit it. On the basis of these results, we conducted the first stage of experiments, considering the range in which it was assumed that the forces acting on the object can be manipulated in a roughly linear manner. For this reason, with the electro pneumatic regulator, we expected that we could linearize the air jet dynamics with severe nonlinearity.

C. *Experimental setup*

Based on the results of the preliminary experiment, a positional feedback control system (P-control) for the position of the object's center of gravity was constructed (fig.

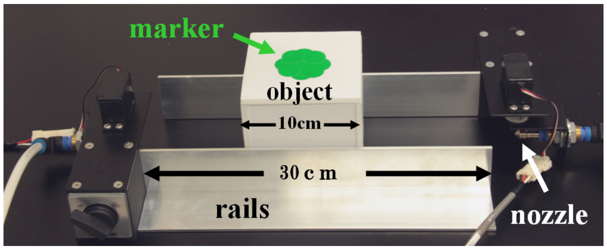

Fig. 1. One DOF experimental system with two air jet nozzles

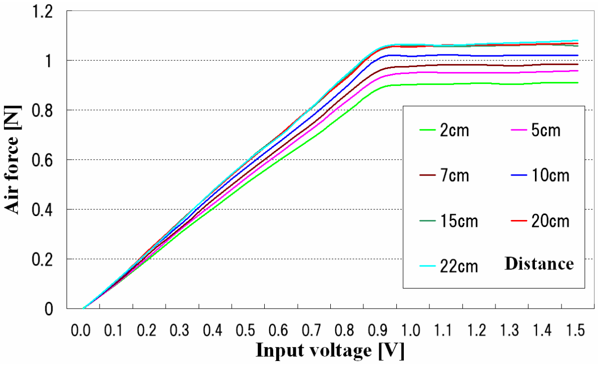

Fig. 2. Force versus input signal to an electrical pneumatic regulator for some distances to an object

3). In fig. 3, x_r stands for target position, e for position error, k_p for proportional gain, m for object mass, u for control input (command to the electro pneumatic regulator), f for resultant force, and x for object's position. In this figure, the friction block expresses viscous term in proportion to speed, whereas the other nonlinear friction's characters such as static friction are included in the air dynamics block. The characteristics of this control system are described below.

1) An electro pneumatic regulator is used: Preliminary experiments indicate that use of this device allows air dynamics, inherently an extremely complex behavior, to be treated as a simple linear system. For this reason, we challenged to control the object by using just a proportional control law (Proportional control).

2) Biased airflow is applied: The air flow rates from each of the ejectors are provided with a certain degree of bias as $u = u_0 + \Delta u$ (u_0 is the constant flow rate). Similar methods are frequently used in magnetic levitation systems, and this approach is expected to contribute to the reduction of transitory air dynamical behavior. Accordingly, the control method of this study can be described as follows.

D. Results of experiments and simulations

1) Step response: An experiment was conducted in which a ±5 cm step wave was used as the target position. In cases where biased airflow was not applied (fig. 4), we observe large overshoots and oscillation phenomena. Meanwhile, as a result of applying biased airflow, a dramatic reduction in oscillation was observed. We understand this reason as follows; since the bias air jet reduced the transit change of the air flow, it could decrease the air jet's nonlinearity and also increased the viscosity of the air jet.

2) Disturbance response: An experiment was conducted in which the object was placed in a state of equilibrium at its target position and then subjected to external forces by hand. Without biased airflow, a nonlinear phenomenon was observed where the overshoot increased with the objects distance from its target position, making it difficult to return the object to its target position. With biased airflow, we were able to verify that the object returns smoothly to its target position even if it has been moved far from the target position.

3) *Discussion:* By using the control method proposed in previous section, acceptable positional feedback control could be achieved for an object with an arbitrary target position. We also found that the use of biased airflow contributed considerably to the reduction of oscillation. Additionally, we believe that the currently observed deviation from the steady state of ±1 cm was caused by friction between the experiment table's surface and the object. As for the air equipment used in this experimental system, the electro pneumatic regulator was used at approximately 60% of its rated power (0.6 V/1.0 V) and at approximately 30% of its compressed air pressure rating (0.2 MPa/0.6 MPa) to achieve an actuation range of approximately 20 cm. Going forward, by making full use of the capacity of these devices, we expect to be able to further extend the range of actuation.

IV. AIR JET EJECTION METHOD BASED ON PULSE WIDTH MODULATION

A. Proposed idea

In the field of the micro-displacement manipulation of an object on a frictional surface, the impact control method has been conventionally employed to overcome the effect of the static friction [14]. On the other hand, in the field of electrical power control, Pulse Width Modulation (PWM) has been in practical use widely to improve the energy efficiency. Considering the both technologies, in this section, we aim to improve the control performance by making a discontinuous impact of the air jet to an object to reduce the static friction effect. To rapidly valve the air flow, an air solenoid valve is employed instead of an electro pneumatic regulator, generally much slower than a solenoid valve in the response. The solenoid valve is provided with the PWM signal of which duty cycle is determined by control law.

B. Preliminary experiment

The factors of the PWM air jet force include PWM period, duty cycle, distance from a nozzle to object and pressure of compressed air. At first, we conducted some force measurement experiments for the factors.

Fig. 5 shows graphs of force for duty cycle with 0.1～0.6s PWM period while the nozzle-object distance is 1cm and the air pressure is 0.2 M Pa. This graph indicates that the force is approximately linear to the duty cycle between 20% and 80% in any PWM period.

Fig. 6 shows graphs of the force for the nozzle-object distance while the duty cycle is 0.2 sec, the PWM period is 50% and the air pressure is 0.2 M Pa. The force is

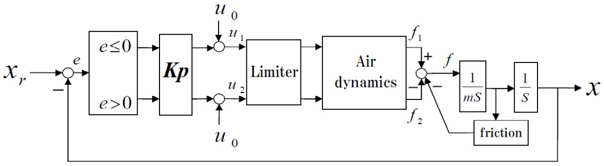

Fig. 3. Block diagram of one DOF control system

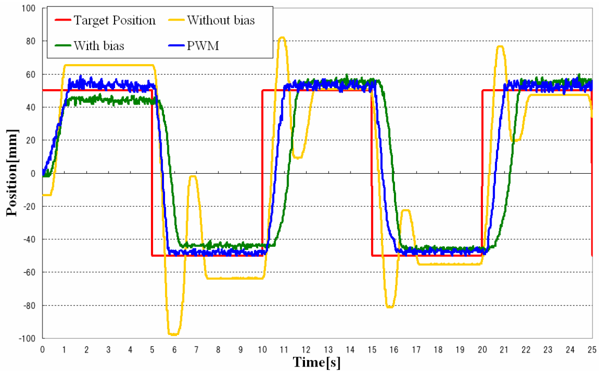

Fig. 4. Step responses of one DOF control system for some cases

approximately constant for the distance up to about 30cm and linearly decreasing over 30cm. We believe that amount of the air molecule acting onto the object is linearly decreased with the longer distance.

To evaluate the proposed PWM method, we conducted some comparison experiments with the conventional one (the continuous ejection with an electrical pneumatic regulator). Fig. 4 shows step responses including this PWM case, based on the same P-controller illustrated in fig. 3. From these graphs, in the PWM case, we confirm that the steady state error and the rising time are improved even without bias air flow.

V. EXPERIMENTAL PLANAR SYSTEM WITH TWO DEGREE OF FREEDOM

A. *Experimental setup*

This experiment addresses control of a cylindrical object using three nozzles. This experimental system was created for controlling the position of a cylindrical object (radius: 15 cm; height: 6 cm; weight: 15 g) in two degrees of planar freedom (X, Y coordinates) by controlling the flow rates and the angles of three nozzles installed on a flat surface (fig. 7). As shown in fig. 8, the three nozzles were placed at 120º intervals around the circumference of a circle having a 30 cm radius, taking into account force closure conditions. This condition is met as long as the center of the cylindrical object is always inside of the equilateral triangle that consists of the three nozzle's rotation center. In fig. 8, O_w denotes the center of the object, and $\boldsymbol{\theta} = \left[\theta_1, \theta_2, \theta_3\right]^T$ denotes three air nozzle angles from each initial orientation.

B. *Proposed control method*

1) Basic strategy:

In this system, based on the experimental results reported in the previous section, we aim to control the object by means of feedback on the position of the cylinder's center coordinate. In this case, the following strategies are available for ejection angles.

a) In order to avoid the Coanda effect [13], the three nozzles are controlled such that they are always pointed towards the center of the object. In this strategy, a simpler force distribution algorithm can be used to calculate the control inputs. It should be noted that, based on the force closure condition, the controlled object's center must be always inside the equilateral triangle with vertices of the three nozzles in fig. 8.

b) The object is controlled by pointing airflow towards not only the center of the object, but also the off-center surfaces. This strategy can potentially enable more stable and more rapid control over a wider range compared to strategy (a).

2) Control law:

In this study, as an air jet shooting method, we employed the simpler strategy (a). Based on the condition (a), as shown

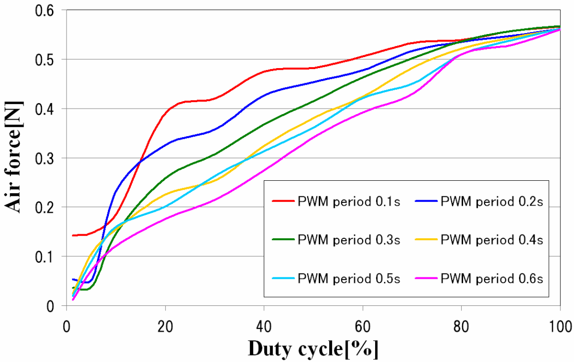

Fig. 5. Force versus duty cycle for some PWM period

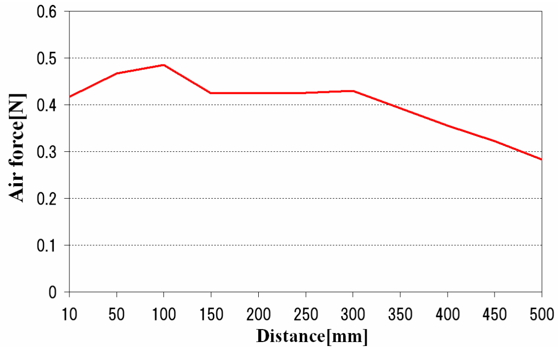

Fig. 6. Force versus distance to an object

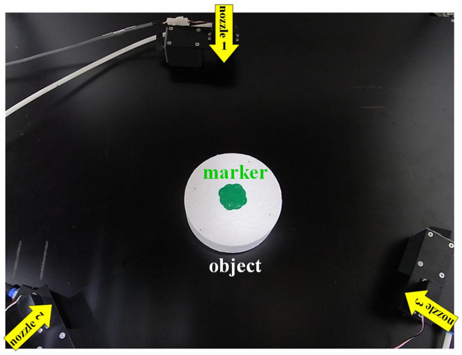

Fig. 7. Experimental system to manipulate the position of a cylindrical object in two degrees of planar freedom

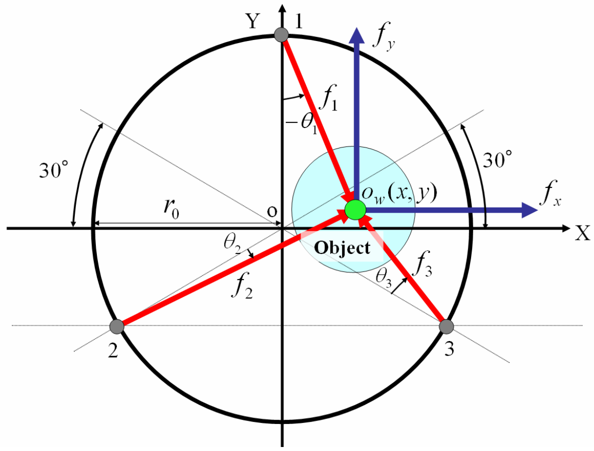

Fig. 8. The coordinate system of two DOF control system

in fig. 8, three air jets are always ejected toward the center of the object. Then we have:

$$\boldsymbol{f}_p = \boldsymbol{K}_w \boldsymbol{f}_w \tag{1}$$

$$\boldsymbol{K}_w(\boldsymbol{\theta}) = \begin{bmatrix} -\sin\theta_1 & \cos\left(\frac{\pi}{6}-\theta_2\right) & -\cos\left(\frac{\pi}{6}+\theta_3\right) \\ -\cos\theta_1 & \sin\left(\frac{\pi}{6}-\theta_2\right) & \sin\left(\frac{\pi}{6}+\theta_3\right) \end{bmatrix} \tag{2}$$

where $\boldsymbol{f}_p = [f_x, f_y]^T$ is the resultant force onto the object's center in the X, Y direction and $\boldsymbol{f}_w = [f_1, f_2, f_3]^T$ is the exerting force onto the object's surface from each nozzle. The flow rates of the three nozzles must be determined based on position errors in the X and Y directions. In other words, this system inherently exhibits a redundant system in which three actuators must be used to control two DOF of the object. When given $\boldsymbol{f}_p$, there is infinite number of $\boldsymbol{f}_w$ satisfying (1). Here, we adopt a pseudo inverse matrix solution:

$$\boldsymbol{f}_w = \boldsymbol{K}_w^+ \boldsymbol{f}_p \tag{3}$$

$$\boldsymbol{K}_w^+ = \boldsymbol{K}_w^T \left(\boldsymbol{K}_w \boldsymbol{K}_w^T\right)^{-1}, \tag{4}$$

to minimize the square sum of each output. The use of (3), however, can result in situations where some elements of $\boldsymbol{f}_w$ take negative values. In such cases, since the force of the air jet acts unilaterally and only in the positive direction, appropriate bias air jets are required to get $\boldsymbol{f}_w > 0$ (This means all elements of vector $\boldsymbol{f}_w$ are positive). Here we offset (3) as follows. At first we must find i such that

$$f_i = \min\left(f_1, f_2, f_3\right) < 0. \tag{5}$$

For simplicity, here we will explain a case of $i = 1$ only, but for the other case, the similar argument is possible. Here we introduce a bias air jet $\varepsilon(\varepsilon > 0)$ for f_1, namely by setting $f_1^+ = |f_1| + \varepsilon$, then we propose a solution for (1) as follows:

$$\boldsymbol{f}_w = \boldsymbol{K}_w^+ \boldsymbol{f}_p + f_1^+ \begin{pmatrix} 1 \\ -\boldsymbol{K}_{23}^{-1} \boldsymbol{K}_1 \end{pmatrix} \tag{6}$$

where $\boldsymbol{K}_w = \left(\boldsymbol{K}_1 \vdots \boldsymbol{K}_{23}\right), \boldsymbol{K}_1 \in R^{2\times 1}, \boldsymbol{K}_{23} \in R^{2\times 2}$. To confirm that (6) is a solution for (1), we can calculate

$$\boldsymbol{K}_w f_1^+ \begin{pmatrix} 1 \\ -\boldsymbol{K}_{23}^{-1} \boldsymbol{K}_1 \end{pmatrix} = f_1^+ \left(\boldsymbol{K}_1 - \boldsymbol{K}_{23} \boldsymbol{K}_{23}^{-1} \boldsymbol{K}_1\right) = \boldsymbol{0}.$$

It should be noted that in (6) the 1st element of $\boldsymbol{f}_w$ is ε and $\boldsymbol{f}_w > 0$ under the condition of the force closure. Based on the investigation of the bias air force in the previous section, appropriate ε is determined. The final control law and block diagram are shown fig. 9.

C. *Experiment*

In the interest of time, (6) has not yet implemented. Instead of that here, the following simpler control law is tentatively adopted for our experiment:

$$\boldsymbol{f}_w = \boldsymbol{K}_w^+ \boldsymbol{f}_p + \begin{pmatrix} f_0 & f_0 & f_0 \end{pmatrix}^T, \tag{7}$$

where f_0 is an appropriate bias input. In this case, (1) is met only when the object is located near the center of the XY coordinate. We expected that experimentally (7) can work to some extent because air jet force becomes weaker for the longer distance. In this experiment, at first just a P-control was adopted only to find failure; a large position error with a small P-gain or instability with a large P-gain. Therefore, finally PI-control law was used. Fig. 10 shows that the

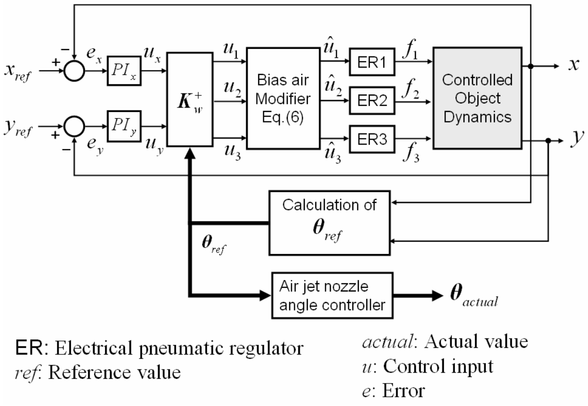

Fig. 9. Block diagram of two DOF control system

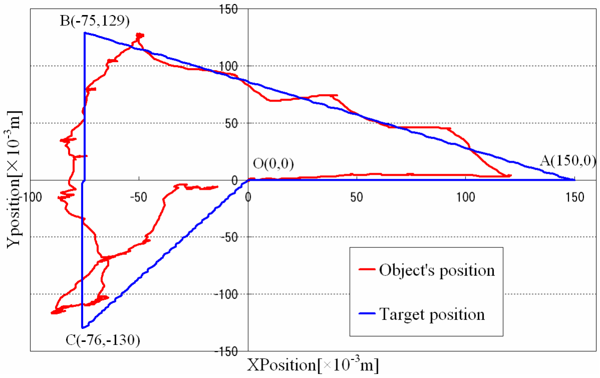

Fig. 10. Experimental results (trajectory)

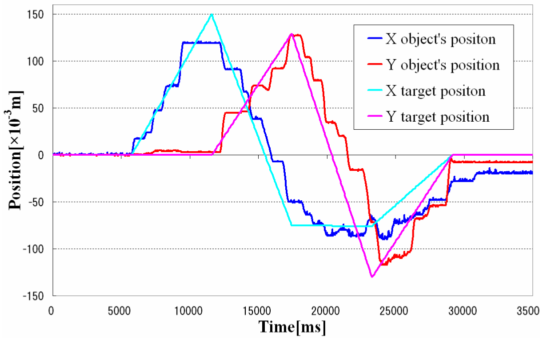

Fig. 11. Experimental results (time response)

cylindrical object follows the triangle-shaped target trajectory and therefore the positional feedback control can be achieved. Fig. 11 shows time response for some target waves. From these figures, we could achieve our goal of the position error (less than 10 % of driving range) in almost all of the driving range. And also, we understand that the trajectory of the object is complexly distorted possibly due to the nonlinearity such as friction between the object and the experiment table's surface, long delay time and the bias input in (7). We expect that this distortion will be solved by precisely adjusting the biased airflows on each nozzle depending on the distance and the angle to the object's surface so that the resultant bias force of the three air jets can be precisely zero at the object's center (center of gravity).

VI. CONCLUSION

We proposed a contactless object manipulation technology by regulating multiple air jet directions and flow rates. In this paper, we treated just simple cylindrical object to be manipulated. Although the expansion to arbitrary shape is not so easy, we have a strategy only for arbitrary shape that can be approximated to regular polygon. We expect that we can control the object's center position by manipulating only the flow of each air jet ejected toward the center. On the other hand, its torque can be controlled by slightly changing the shooting angle of all air jets from the center position in the same direction angle.

With respect to the precise manipulation range on an air float transportation system, from the point of practical view, we don't believe the range more than about 1 meter will be needed. Accurate manipulation will be needed only when the object must be rightly arranged in a shipping corner. Namely, when the object is far away from the corner, active manipulation won't be needed but rather just a uniform linear motion is acceptable. When the object approaches the corner, multiple air jets should trap it to manipulate.

As for the size of the object, in this paper, we roughly assumed that the size is big enough such that air jet stream can be treated as a thin line for the object surface. Outside of this assumption, for the smaller object, we expect that the object will be surrounded by multiple air jets and passively stabilized due to the Coanda effect attracting the object into the center of the vortex. If so, at least only the position can be manipulated.

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