A Spatial Motion Control to Transfer an Object between a Pair of Air Jet

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Abstract: We propose a method in which multiple nozzles are arranged consecutively along a conveying line and an object can be relayed one after another. In this paper, as a most essential technology for such a conveyor, we focus on the transferring control of the object between a pair of air jet on a vertical plane. We propose a relaying control method based on some natural behaviours of an object in a fluid field where two air jet streams collide. Some successful experiment results are shown.

1 INTRODUCTION

Non-contact object manipulation technology using air jets has excellent features such as cleanness and no need for a transmission mechanism. It has been extensively studied for some years mainly aiming at an application to a conveying system for relatively smaller and lighter objects such as fruits or vegetable. In a three-dimensional space, the three translational DOF control method using a single air jet nozzle mounted on a pan-tilt actuator has been proposed (Becker, A. et al., 2009). In (Becker, A. et al., 2009), it is possible to freely control the translational 3-DOF within the range where the object can be held by the Coanda effect. However, since the range in which an object can be held against gravity is at most about 40 degrees, the driving range is inherently narrow. In order to solve this problem, in this paper we propose a method in which multiple nozzles are continuously arranged along a conveyance line, and an object is relayed one after another on each air jet stream. Especially we focus on a control method to transfer an object between a pair of air jet on a vertical plane, which is the most fundamental problem to realize such a transport system.

2 RELATED RESEARCH

2.1 On a 2D Plane

On a flat plane, the 3-DOF (two translational DOF + one rotational DOF) control method for a single object by changing the flow rate and angle of four air jet nozzles has been proposed (Matsushita et al., 2014) (Matsushita et al., 2016). In these technologies, wind force applied to an object is approximated as a linear lumped constant system without distance dependence. And because it is unilateral actuation, they prepared an air jet nozzle which is one or more than the object control degree of freedom, and solved this redundant DOF problem by linear programming. Eventually the feedback controllers were independently adopted for each DOF.

2.2 In a 3D Space

In three-dimensional space, a 3-DOF operation technique (Becker, A. et al., 2009) by a single air jet nozzle mounted on a pan tilt actuator has been proposed. The decisive difference from the above two-dimensional plane problem is to actively utilize the Coanda effect. The Coanda effect is a hydrodynamic property as represented a phenomena in which a smooth convex shaped object in a jet stream will stay in its stream. The object can be

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passively floated in the air because the wind force, gravity force and the restoring force by this Coanda effect are naturally balancing. Then, by moving the pan tilt actuator, two argument angles on a spatial polar coordinate system are actively controlled. On the other hand, regarding the jet stream direction, a position feedback control system is constructed in which the distance between the nozzle and the object is measured and the air jet flow rate is manipulated as a control input. In this way, total translational 3 degrees of freedom is actively controlled. However, with this method, since the object can be lifted only in a narrow range about 40 degrees where the vertical component of the Coanda force is larger than the gravity. This is a fatal problem as a conveying system. In this paper, to solve this problem, we propose a method in which multiple nozzles are continuously arranged along a conveyance line, and an object is relayed one after another on each air jet stream.

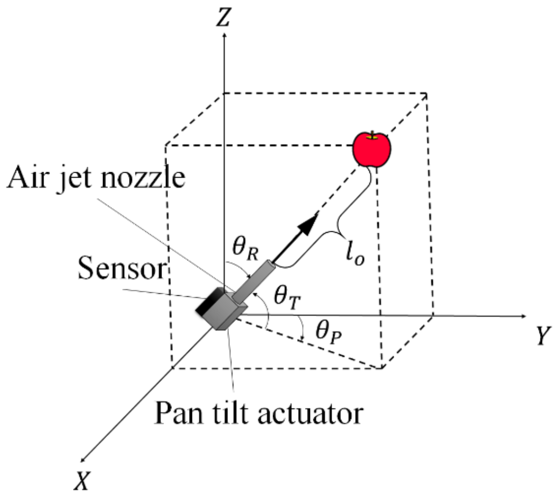

Figure 1: Configuration of "one nozzle control module".

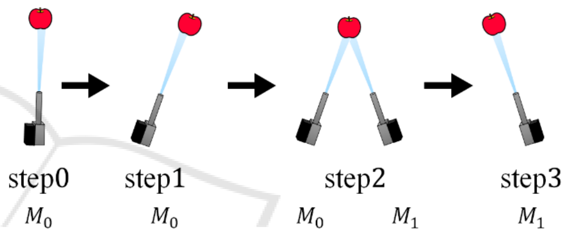

Figure 2: An image of object transportation.

3 OUTLINE AND PROBLEM SETTING OF PROPOSED METHOD

3.1 Basic Idea and Conveyance Image

Here a system equipped with an active air jet nozzle and a distance sensor mounted on a pan-tilt actuator is called "one nozzle control module" (Fig.1). Prepare N "modules" and connect them from module 1 to module N along a given object transport path. Fig.2 shows an image of such a system where an object is relayed (M denotes a module).

In order to realize such a transportation system, it is essential to create a relay control method between a pair of air jet nozzle in a vertical plane. In the following, we formulate this problem.

3.2 Problem Setting

Fig.3 is a diagram showing the experimental coordinate system of this time taking the state of step 2 (Fig.2) as an example. In a vertical YZ plane as shown in Fig.3, let's consider that a spherical object is moved horizontally from the start point $\boldsymbol{P_s}$ to the goal point $\boldsymbol{P_g}$ by using two air jet nozzles separated by a distance l [mm]. Our problem here is to determine the air jet nozzle angles θ_L, θ_R and the air jet flow rates f_L, f_R (proportional solenoid valve supply voltage).

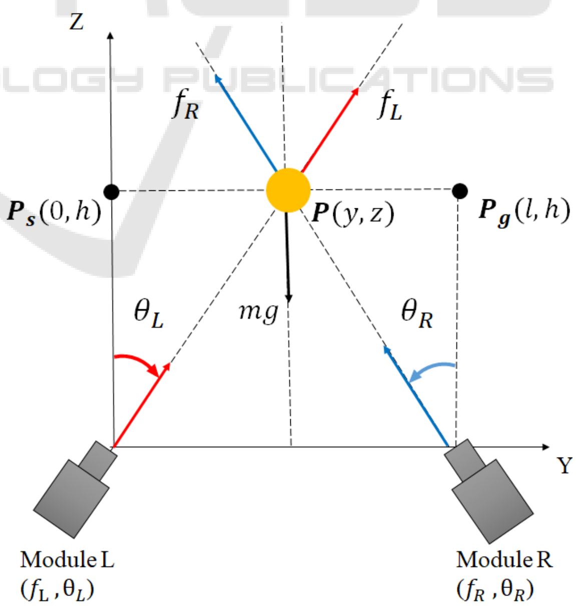

Figure3: Configuration of the experiment system (The angle is positive for clockwise rotation).

4 PRELIMINARY EXPERIMENT

4.1 Purpose

In addressing the above problem, the most difficult challenge would be a collision between two air jet streams, which probably generates turbulence. Regarding a motion of an object in a single air jet stream, hydrodynamic analysis is possible to some extent, and there is a model-based control approach (Becker, A. et al., 2009). However, neither theory nor experiments have been reported on a behaviour of an object in a turbulent field where two air jets collide, therefore there have been absolutely no idea how to address it. Thus, in order to get a hint for the problem, we first decided to observe natural phenomena as it is. Namely, as a preliminary experiment, we tried to investigate the behaviour of the object in the confluence area between the two air jets under a condition that the two air jet flow rates are constant.

4.2 Preliminary Experiment Content

4.2.1 2 Observation of Object Behaviour at the Confluence Area

Experiments were conducted to measure the object levitation steady position in the state of collision between the two air jet flow rates (f_L, f_R) and the angles (θ_L, θ_R) as parameters. An example is shown below. Fig. 4 shows the results when the input voltage $f_L = f_R = 5.5$[V] and the injection angle $\theta_L = \theta_R =$ 60[deg]. From this result, it is possible to float by the Coanda effect even in a fluid field where two jet streams merge. And also, it was confirmed that the resultant force applied to the object from the two air jets can be roughly handled as a vector in a linear lumped constant system.

4.2.2 An Experiment of the Object Relay by a Passive and Heuristic Method

According to the above primary experiment, it was confirmed that it is possible to hold an object at the confluence area of two air jets, so next experiments are performed to change these nozzle angles. As shown in Fig.2, under the condition that the two air jet flow rates are constant or zero, we conducted a simple and heuristic experiment as follows;

(1) The left nozzle passively holds the object vertically.

(2) Its angle slowly tilts toward the right nozzle while the right nozzle is waiting for the object in the intermediate point with the same air jet flow rate.

(3) When the left air jet reaches the intermediate point, then its air jet turns off and simultaneously the right nozzle starts to clockwisely rotate.

As shown in Fig. 5, immediately after the confluence of the two air jets, Z has shown severe vibrations with a maximum amplitude of about 180 mm. And after that, the vibration amplitude gradually decreased passively due to air friction and finally the success of the relay motion was confirmed. And we can see that Y almost perfectly synchronized with the movement of θ_L, θ_R. In this passive and heuristic experiment, the relay operation success rate was 7 out of 10 times (70%).

5 PROPOSED CONTROL METHOD

5.1 Approach to Problem Solving

The above preliminary experiments are based on simple natural phenomena where there is no artificial control for the air jet. Here, we aim to realize more stable relay operation by adding active feedback control. Based on the preliminary experiment results, we expected that regarding the horizontal direction, the object can be passively stabilized by the Coanda effect. Simultaneously regarding the vertical direction, we expected that the feedback control can work to stabilize the position utilizing the two air jet resultant force. Specifically, we propose the following three policies based on the assumption of the lumped constant system.

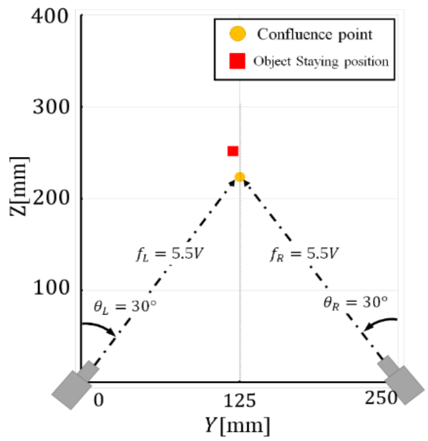

Figure 4: Position of the levitated object and confluence point of the two air jets.

(Policy 1) The two air jet nozzle angles are manipulated assuming that the object will stay near the confluent point thanks to the Coanda effect.
(Policy 2) The flow rate of each air jet nozzle is controlled so that the horizontal component of the resultant force of the wind forces at the confluence point is always balanced to zero.
(Policy 3) Regarding the vertical direction, the flow rate of each air jet nozzle is feedback controlled so that the vertical component of the resultant force and the gravity are balanced.

5.2 Proposed Algorithm

Based on the above policy, we created our relay control algorithm as follows.

(*i*) Determination of θ_L, θ_R

From the policy 1, the angle of each nozzle is calculated from the object position target value $\boldsymbol{P_r}(r_y, r_z)$ and the module-to-module distance, as shown in the following expression and Fig. 3.

$$\theta_L = tan^{-1}\left(\frac{r_y}{r_z}\right), \theta_R = tan^{-1}\left(\frac{l - r_y}{r_z}\right) \quad (1)$$

Where $r_z = h$ and $r_y = v_y\, t$ when the object should be horizontally moved with a constant speed v_y.

(*ii*) Determination of f_L, f_R

From the policy 2, each air jet flow rate is set so that the Y direction resultant force is constantly cancelled as follows;

$$f_L \sin \theta_L + f_R sin\theta_R = 0 \quad (2)$$

Further, from the policy 3, the resultant force in the Z direction f_z is determined using a PID controller as follows;

$$f_z = PID(r_z - z) + f_{min} \quad (3)$$

where PID denotes the function of the PID compensator and $f_{min} = mg$ is a bias force to cancel the gravity force (*m* is a mass of the object).

$$f_z = f_L \cos \theta_L + f_R cos\theta_R \quad (4)$$

Accordingly, by simultaneously solving the equations (3) and (4), f_L and f_R are calculated as follows;

$$f_L = -\frac{f_z sin\theta_R}{sin(\theta_L - \theta_R)} \quad (5)$$

$$f_R = \frac{f_z sin\theta_L}{sin(\theta_L - \theta_R)} \quad (6)$$

This is our proposed relay control algorithm.

6 DEMONSTRATION EXPERIMENT

6.1 Outline of Experiment

In order to demonstrate the validity of the proposed algorithm, an experimental system was constructed (Fig. 6, Fig. 7). In this experiment, a ball with a diameter of 100 [mm] and a weight of 10.24 [g] was chosen and the module-to-module distance l was 250 [mm]. In addition, we set the height h = 230. We tried 10 times and recorded the movement trajectory of the object with a camera senor.

6.2 Experimental Results and Discussion

The experiment results are shown in Fig 8. When comparing with the results of 4.4.2 in Fig 5, we can confirm that in the passive control experiment, the maximum vibration amplitude in the Z direction is about 180 [mm], and in the proposed method, it is reduced to about 100 [mm]. And also we can confirm that height of the object Z accurately follows its target value h = 230mm. And as a result, the success rate of the relay operation also are improved from 70 [%] to 80 [%].

7 CONCLUSION

Aiming at a long distance and non-contact conveyor system, we have proposed an air jet manipulation system in which multiple nozzles are continuously arranged along a conveyance line, and an object is relayed one after another on each air jet stream. Especially, we focused on a control method to transfer an object between a pair of air jet on a vertical plane. Our experimental results are never satisfactory so far, nevertheless we can confirm the qualitative validity of our proposed method. In the future, we will improve the method by decreasing the influence of the turbulence generated by the air jet collision.

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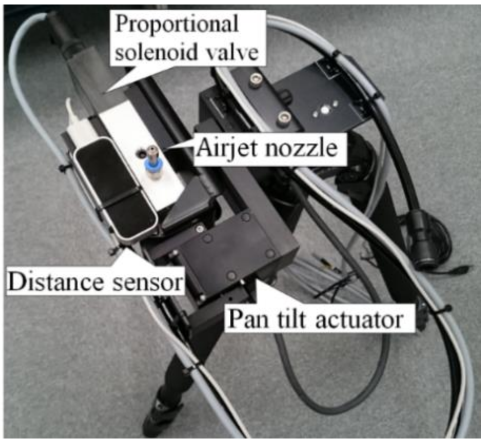

Figure 6: An overview of "one nozzle control module".

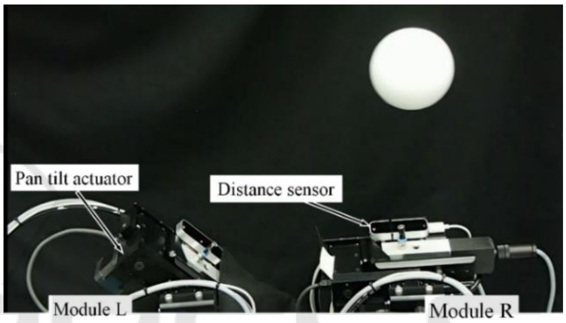

Figure 7: The object and the relaying system.

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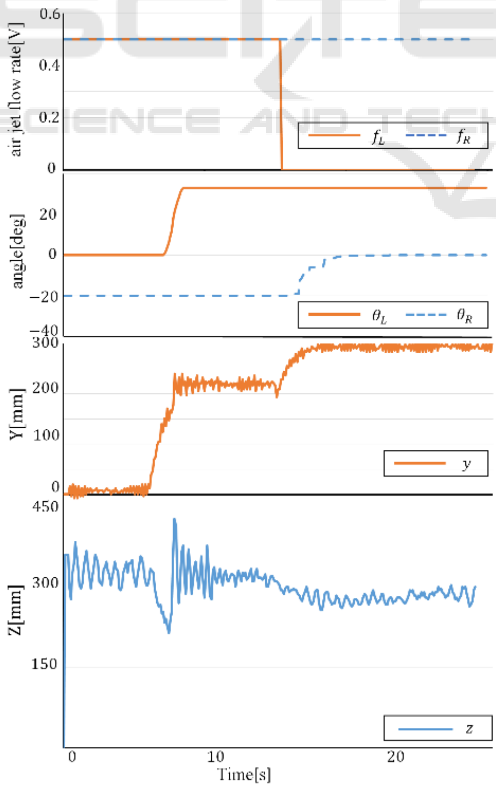

Figure 5: Experiment results with the passive and heuristic method.

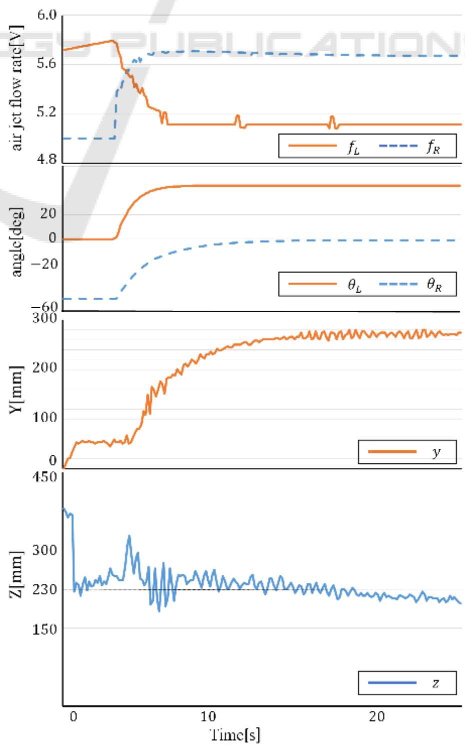

Figure 8: Experiment results with the proposed method.