Multiple DOF Platform with Multiple Air Jets

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Abstract: We have been studying noncontact object manipulation technology in which a single ball-shaped object is floated and controlled for its 3D position with multiple air jets driven by a pan-tilt actuator. In this paper, we try to control position and orientation of an arbitrary shaped object. Here an arbitrary object is connected with a triangle platform which is composed of three spheres linked with thin wires. Each sphere is spatially controlled by an air jet unit which consists of an air jet on a pan-tilt actuator. Kinematics of the air jet platform as a parallel link mechanism is calculated and a control method for the air jet platform is proposed.

1 INTRODUCTION

Non-contact object manipulation technology has excellent features such as frictionlessness, transparency, cleanliness, etc. because it does not require a transmission mechanism, and various studies have been advanced in recent years. Until now, non-contact object manipulation technology using air jet has been reported object manipulation technology (Matsushita et al., 2014) (Matsushita et al., 2016) (T. Yamamoto et al., 2009) on a plane as manipulation technology to control position and posture in two dimensions. Further, in the operation technique in a three-dimensional space, there is a single nozzle operation method (Becker, A. et al., 2009) using a pan and tilt actuator. As a transfer technique using a plurality of nozzles, a relay transfer method (Yoshinaga et al, 2018), a pitching catch method (Abe et al, 2018) and the like have been reported. However, in these methods, the shape of the object that can be manipulated is limited to a specific shape such as a cylinder, square pole, or sphere. In essence, it is impossible to manipulate three translational DOF + three rotational DOF in a three-dimensional space of an arbitrarily shaped object. Therefore, in this research, we change the viewpoint and give up the complete non-contact operation of the object itself. Instead, we try the non-contact 6-DOF control of the platform which is the base to attach the arbitrarily shaped object. Specifically, a structure (called Air jet platform) in which a plurality of spheres are connected by a high rigidity wire is configured, and the three-dimensional position of each sphere is controlled by a dedicated air jet mounted on a pan and tilt actuator. We propose a method to control the position and attitude of the air jet platform with 6-DOF. In this paper, we clarify the mechanism, kinematics and control method when using the minimum three spheres, and confirm the effectiveness of these by experiments.

2 RELATED RESEARCH AS FOR AIR JET MANIPULATION

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.

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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. In order to expand the motion space of the object, (Becker, A. et al., 2009) has been drastically modified with multiple air jet units, such as relay transport method (Yoshinaga et al, 2018) and pitching catching method (Abe et al, 2018).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 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 DOF is actively controlled. However, with these methods, only position control of an object in space is possible, and attitude control is impossible. Moreover, available shape of the object is limited to smooth convex shape.

Here, 6-DOF can be controlled by a drive mechanism called Stewart platform (Stewart, D. 1965–1966) that can control the position and attitude of an arbitrary object placed on the platform. The platform and the six translational actuators are mechanically coupled at a universal joint. Also, there is a drawback that it is difficult to take a large drive range of the table because it is necessary to avoid collisions between the actuators. Compared with this, our air jet platform has a much lower payload, but it does not require a thick rod, so it can take a wider range of motion. And it has the advantage that there is nothing to block the view between the stator and the rotor.

3 PROPOSAL OF STRUCTURE AND KINEMATICS

3.1 Coordinate System and Geometric Analysis

Fig. 1 and Fig. 2 shows a proposed structure of the air jet platform and its coordinate system respectively. $\Sigma_{P_f}$is a platform coordinate system fixed to the center of gravityP_f of the equilateral triangular platform of sidel_{P_f}. Σ_B is a base coordinate system fixed to the center of gravity B of an equilateral triangle with three air jet nozzles of side l_{P_f}. Σ_{B_i} is fixed to the i-th nozzle. The x-axis of all coordinate systems is parallel to the base of each triangle. In the following, i assumes the values 1, 2, and 3. A position vector representing each vertex P_i of the platform in the coordinate system Σ_{P_f} is represented as ${}^{P_f}\boldsymbol{p}_{P_i}$. In addition, position vectors when the center of gravity of the platform, each vertex P_i of the platform, and the vertex B_i of the base are viewed from the coordinate system Σ_B are denoted as ${}^B\boldsymbol{p}_{P_f}$, ${}^B\boldsymbol{p}_{P_i}$, and ${}^B\boldsymbol{p}_{B_i}$, respectively. Assuming that the attitude of the platform coordinate system is ${}^B\boldsymbol{R}_{P_f}$, the geometrical relationship with ${}^B\boldsymbol{p}_{P_i}$ is obtained, when the homogeneous transformation matrix ${}^B\boldsymbol{T}_{P_f}$ from the coordinate system Σ_B to the coordinate system Σ_{P_f} is given. First, since the origin P_f of Σ_{P_f} is the barycentric position of P_1, P_2 and P_3, the following is obtained.

$$ {}^B\boldsymbol{p}_{P_f} = \frac{{}^B\boldsymbol{p}_{P_1} + {}^B\boldsymbol{p}_{P_2} + {}^b\boldsymbol{p}_{P_3}}{3} \tag{1} $$

The attitude matrix ${}^B\boldsymbol{R}_{P_f}$ of the platform is expressed as follows from Fig. 2.

$$ {}^B\boldsymbol{R}_{P_f} = ({}^B\boldsymbol{x}_{P_f} \vdots {}^B\boldsymbol{y}_{P_f} \vdots {}^B\boldsymbol{z}_{P_f}) \in \boldsymbol{R}^{3\times 3} $$

Here, ${}^B\boldsymbol{x}_{P_f}$ is in the same direction as ${}^B\boldsymbol{p}_{P_3} - {}^B\boldsymbol{p}_{P_2}$ of size l_{P_f}, and ${}^B\boldsymbol{y}_{P_f}$ is in the same direction as the composite vector of ${}^B\boldsymbol{p}_{P_3} - {}^B\boldsymbol{p}_{P_1}$ and ${}^B\boldsymbol{p}_{P_2} - {}^B\boldsymbol{p}_{P_1}$. The magnitude of the composite vector is $\sqrt{3}l_{P_f}$ according to the Pythagorean proposition. Also, since Σ_{P_f} is a right-handed orthogonal coordinate system, ${}^B\boldsymbol{z}_{P_f}$ can be represented by the outer product of ${}^B\boldsymbol{x}_{P_f}$ and ${}^B\boldsymbol{y}_{P_f}$.

$$ \begin{cases} {}^B\boldsymbol{x}_{P_f} = \dfrac{{}^B\boldsymbol{p}_{P_3} - {}^B\boldsymbol{p}_{P_2}}{l_{P_f}} & (2) \\ {}^B\boldsymbol{y}_{P_f} = \dfrac{2{}^B\boldsymbol{p}_{P_1} - {}^B\boldsymbol{p}_{P_2} - {}^B\boldsymbol{p}_{P_3}}{\sqrt{3}l_{P_f}} & (3) \\ {}^B\boldsymbol{z}_{P_f} = {}^B\boldsymbol{x}_{P_f} \times {}^B\boldsymbol{y}_{P_f} & (4) \end{cases} $$

Since the coordinate systemΣ_{B_i} is translated from coordinate system Σ_B by ${}^B\boldsymbol{p}_{B_i}$ in parallel, each vertex P_i of the platform viewed from the coordinate system Σ_{B_i} is expressed as follows.

$$^{B_i}\boldsymbol{p}_{P_i} = {}^{B}\boldsymbol{p}_{P_i} - {}^{B}\boldsymbol{p}_{B_i} \tag{5}$$

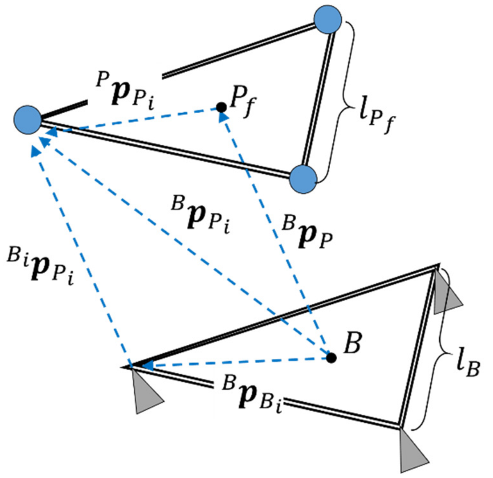

Figure 1: Structure of the base and the platform.

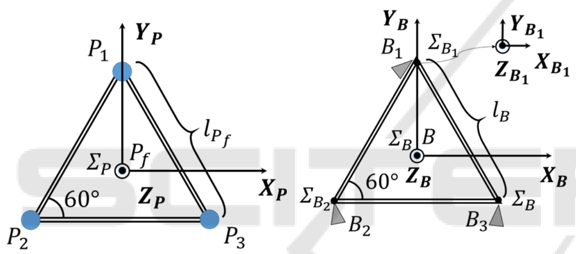

Figure 2: Coordinate system of the base and the platform.

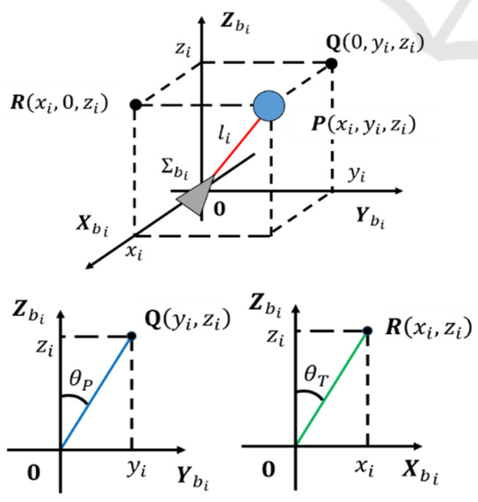

Figure 3: Pan-tilt actuator and coordinates.

3.2 Forward Kinematics Solution

The proposed mechanism can be considered as a kind of parallel link mechanism. That is, the three air jet streams are considered to be links with adjustable and flexible length and pan tilt angle respectively. Here we consider a forward kinematics problem with the position and attitude of the platform as output, with the position of each sphere as input. Each sphere position $^{B}\boldsymbol{p}_{P_i}$ of the platform is at the vertex of an equilateral triangle of one side l_{P_f}, the following constraints are satisfied.

$$\|^{B}\boldsymbol{p}_{P_1} - {}^{B}\boldsymbol{p}_{P_2}\| = \|^{B}\boldsymbol{p}_{P_2} - {}^{B}\boldsymbol{p}_{P_3}\| = \|^{B}\boldsymbol{p}_{P_3} - {}^{B}\boldsymbol{p}_{P_1}\| = l_{P_f} \tag{6}$$

The position and orientation of the platform can be expressed as (7) if $^{B}\boldsymbol{p}_{P_i}$ is arbitrarily determined within the range of this constraint. However, each element of Eq. (7) is given by (1) (2) (3) (4).

$$^{B}\boldsymbol{T}_{P_f} = \begin{pmatrix} ^{B}\boldsymbol{R}_{P_f} & ^{B}\boldsymbol{p}_{P_f} \\ 0 & 1 \end{pmatrix} \tag{7}$$

In practice, it is difficult to extract an independent variable from the constraints in (6), so it is difficult to find a solution of forward kinematics easily. Fortunately, from the viewpoint of mechanism control, the following inverse kinematics is more important than this forward kinematics, and its solution is simpler.

3.3 Inverse Kinematics Solution

Kinematics is the problem of finding the pan-tilt angle of each nozzle and the air jet stream distance hereinafter referred to as the nozzle variable $(\theta_i, \phi_i, l_i)^T$ when $^{B}T_{P_f}$ is given. In order to do that, we first calculate $^{B}\boldsymbol{p}_{P_1}$, $^{B}\boldsymbol{p}_{P_2}$, and $^{B}\boldsymbol{p}_{P_3}$. The following is obtained from the linear simultaneous equations of (1), (2), and (3).

$$^{B}\boldsymbol{p}_{P_1} = {}^{B}\boldsymbol{p}_{\mathrm{P_f}} + \frac{l_{P_f}}{\sqrt{3}} {}^{B}\boldsymbol{y}_{P_f} \tag{8}$$

$$^{B}\boldsymbol{p}_{P_2} = {}^{B}\boldsymbol{p}_{\mathrm{P_f}} - \frac{l_{P_f}}{2} {}^{B}\boldsymbol{x}_{P_f} - \frac{l_{P_f}}{2\sqrt{3}} {}^{B}\boldsymbol{y}_{P_f} \tag{9}$$

$$^{B}\boldsymbol{p}_{P_3} = {}^{B}\boldsymbol{p}_{\mathrm{P_f}} - \frac{l_{P_f}}{2} {}^{B}\boldsymbol{x}_{P_f} + \frac{l_{P_f}}{2\sqrt{3}} {}^{B}\boldsymbol{y}_{P_f} \tag{10}$$

Assuming that the solution of the equations (8), (9) and (10) is $^{B_i}\boldsymbol{p}_{P_i} = (x_i, y_i, z_i)^T$ for simplification, the nozzle variable B is as follows from Fig 4.

$$\begin{pmatrix} \theta_i \\ \phi_i \\ l_i \end{pmatrix} = \begin{pmatrix} -tan^{-1}\dfrac{y_i}{z_i} \\ tan^{-1}\dfrac{x_i}{z_i} \\ \sqrt{x_i^2 + y_i^2 + z_i^2} \end{pmatrix} \tag{11}$$

The above is the solution of inverse kinematics.

4 PROPOSAL OF CONTROL METHOD

Based on the solution of inverse kinematics obtained above, the feedback control law independent of each nozzle is determined.

4.1 Air Jet Flow Rates u_i

Each air jet flow rate u_i is calculated by the following PID control operation. Where l_{act_i} is the current distance of the air jet stream and l_i is the target distance.

$$u_i = PID(l_i - l_{act_i}) \tag{12}$$

4.2 Nozzle Angle $(\theta_i, \ \phi_i)$

Set the angle target value of the pan and tilt actuator as follows.

$$(\theta_i, \ \phi_i)^T = \left(-tan^{-1}\left(\frac{y_i}{z_i}\right), \ \ tan^{-1}\left(\frac{x_i}{z_i}\right)\right)^T \tag{13}$$

5 DEMONSTRATION EXPERIMENT

5.1 Outline of Experiment

In order to verify the validity of the proposed method, we constructed an experimental system (Figs. 4). In this experiment, we confirmed the operation of translation and rotation of the air jet platform. At this time, the movement locus was confirmed from the distance sensor and the pan and tilt actuator. The outline of the experimental setup is as follows.

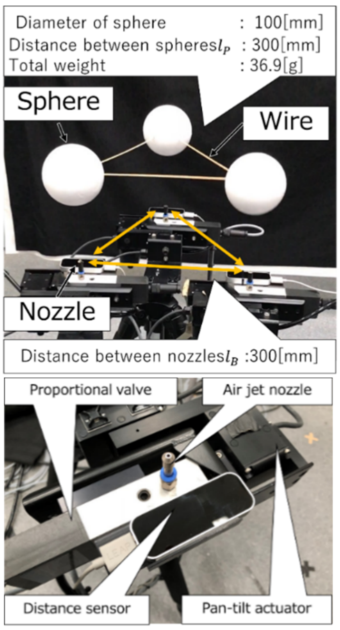

Figure 4: Overviews of the experiment system.

5.2 Experimental Result and Consideration

Fig. 5 show the position of the center of gravity of the platform and the trajectories of each sphere when translated 100 mm in the x-axis direction. At this time, the motion on the actuator side performs feedback control so that the air jet rotates at a constant z coordinate while rotating the pan tilt so that the nozzle tilts in the positive direction of the x-axis. The graphs in Figs. 6 and 7 show the trajectories in the x-axis and z-axis directions, and it is clear that they converge to the target position (red line).

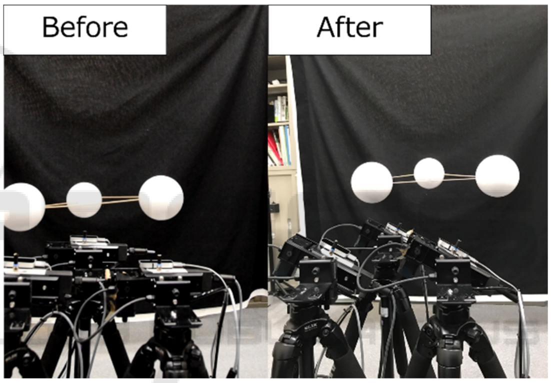

Figure 5: The platform translated +100 [mm] parallel in the X-axis direction.

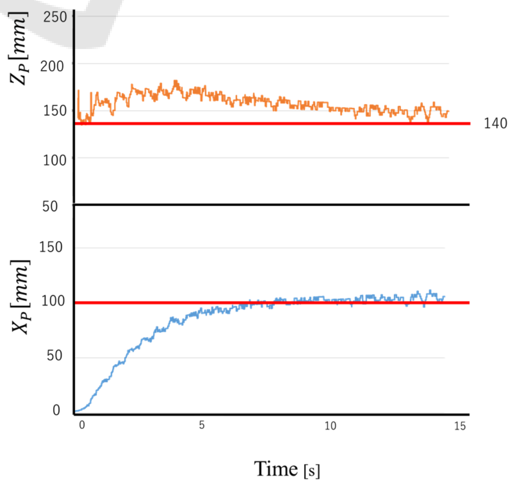

Figure 6: Time responses of the platform COG with respect to X and Z axis.

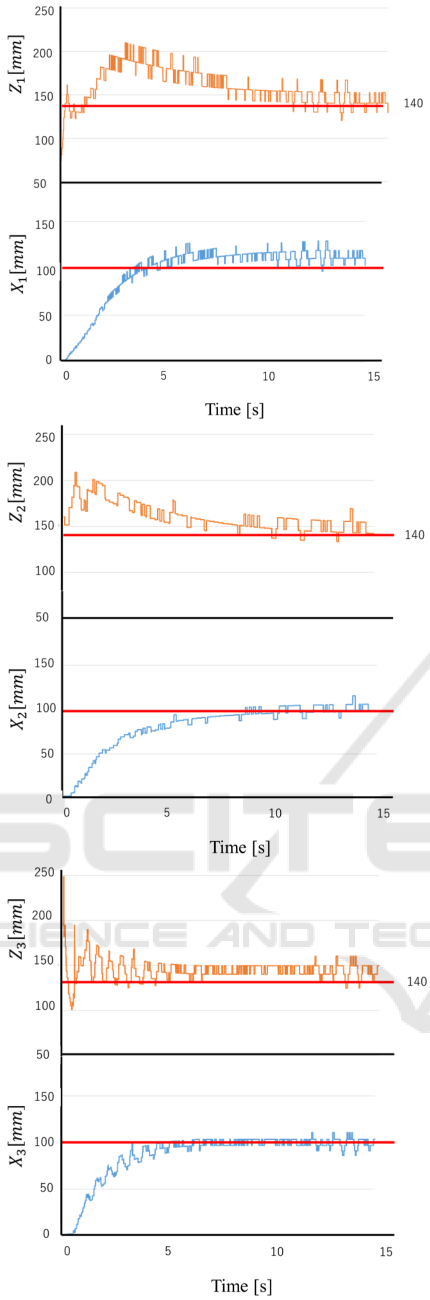

Figure 7: Time responses of each sphere with respect to X and Z axis (sphere 1, 2 and 3 from above).

Fig. 8 show the trajectory of each sphere and the rotation angle when rotating 30 degrees around the z-axis. At this time, on the actuator side, the air jet performs feedback control so that the z coordinate becomes constant while rotating the pan and tilt so that the nozzle tilts in the z-axis positive direction. The graphs in Fig. 9 and 10 shows the z-axis rotation and the trajectory in the z-axis direction, and it can be seen that the target angle and target position (red line) converge to some extent.

As a result, both parallel movement and rotational movement were confirmed to be successful.

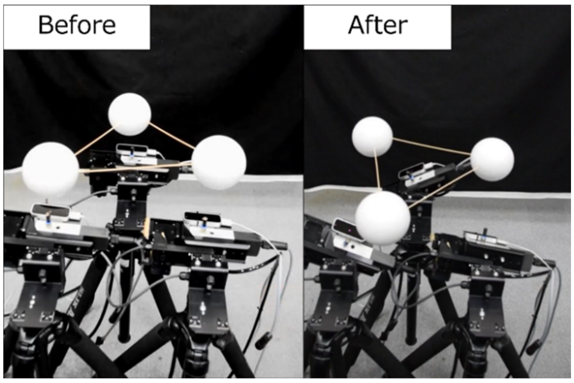

Figure 8: The platform rotated +30 [degrees] around the Z-axis.

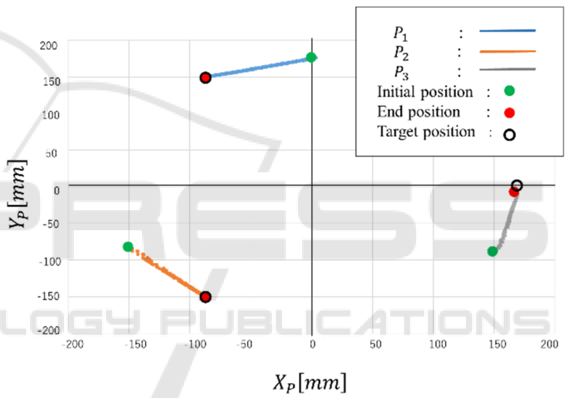

Figure 9: Trajectories of each sphere in XY plane.

Table 1: Outline of experimental equipment.

	Product name and remarks
Control computer	Microsoft Windows10 Home 64bit CPU：Intel® Core™ i7-7700 @ 3.60GHz
Proportional solenoid valve	MPYE-5-1/8-HF-010-B(FESTO)
Distance sensor	Leap Motion
Pan-tilt actuator	PTU-D46-70
Air nozzle	KN-Q06-20 （SMC） Nozzle diameter:2.0mm
Air compressor	PO-0.75PGS6 (Hitachi Industrial Equipment Systems Co,Ltd.) Out put：0.75kW Max pressure:0.93MPa
Air jet platform	Total weight : 36.9g Sphere diameter : 7.5mm Sphere weight: 10.2g

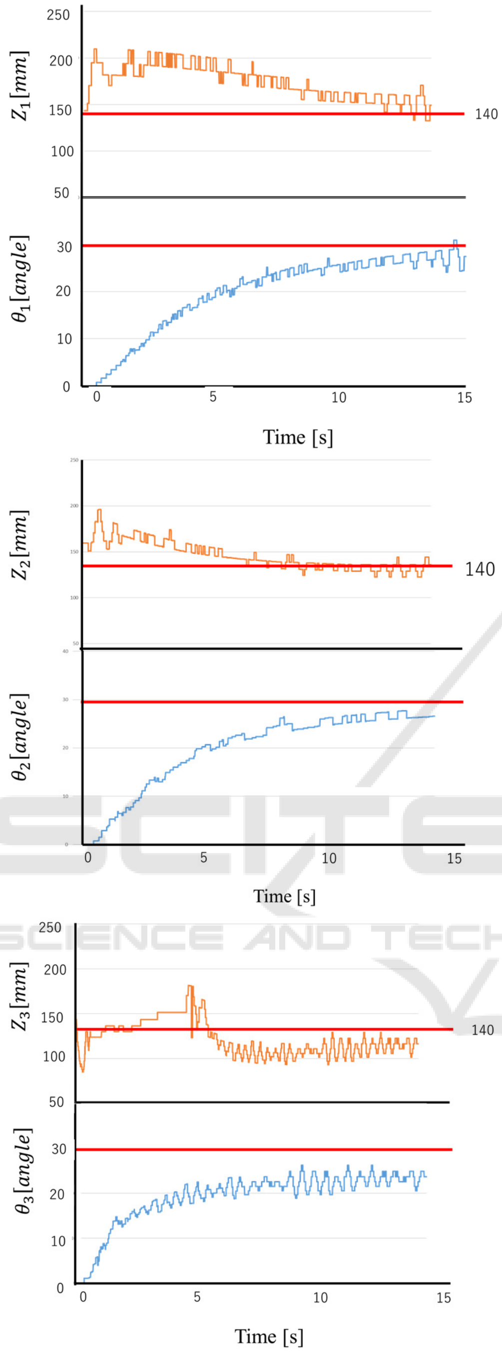

Figure 10: Time responses of each sphere with respect to translation and rotation of Z axis (sphere 1, 2 and 3 from above).

6 CONCLUSION

A platform was constructed by connecting multiple spheres with high rigidity wire, and a method to manipulate 6-DOF of the platform was proposed by controlling the three-dimensional position of each sphere with a dedicated air jet mounted on a pan-tilt actuator. For the case of three spheres as an example, we clarified forward kinematics, inverse kinematics, and control methods, and confirmed the validity of the proposed method by experiments.

In the future, we will improve the control performance of this system and challenge the drive system that enables endless rotation in various directions by increasing the number of spheres. This allows a 360-degree rotatable 3D digitizer. And, we will consider applications such as video content creation device that floats an arbitrary shaped object in the air.

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