Contactless active force closure manipulation using multiple air jets

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***Abstract*—We propose a technology for manipulating the position and attitude 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 air jet directions and volumes, the object can be actively "force closured" and its position and attitude can be manipulated freely. As the first step of this research, in this paper, we discuss its potential future applications, and summarize the technological challenges for this technology. Next we provide a preliminary investigation with one degree-of-freedom planar experimental system. 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.**

Keywords-contactlsee object manipulation; air jet; force closure; control

I. INTRODUCTION

Contactless active force-closure manipulation is extremely advantageous because it does not entail friction, backlash, or the need for lubrication or a transmission mechanism. Related existing technologies can be generally categorized into methods that utilize either electromagnetism or air. Although 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. Methods air-based technologies are listed in Table 1, and again, there are currently no methods that enable multiple-degree-of-freedom manipulation with ranges of actuation exceeding several centimeters except only one challenge [2]. In our paper, we propose a technology for manipulating the position and attitude 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 (Figure 1). By regulating air jet directions and volumes, the

TABLE I. COMPARISON BETWEEN CONVENTIONAL AND OUR APPROACH

	Objective and use	*Degree of freedom*	*Driving range*
Magnetically syspended actuator [1]	Object manipulation	6	2 mm
Linear motor car	Guide	5	10 - 50 mm
Air bering	Guide	5	less than 1 mm
Force feedback interface [3]	Tactile display	1	0.2 m
Referrence [2] (University of Illinois)	Object manipulation	3	0.5 m
Our approach [4-7]	Object manipalation	6 (goal)	2 m (goal)

object can be actively force closured and made to float in midair in a stable manner, and its position and attitude can be manipulated freely. 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 more 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. 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 discuss potential future applications, and summarize the technological challenges for this technology in Section *III*. Based on knowledge of these challenges, a planar (flat surface) experimental system with one DOF, and a planar experimental system with two DOF are discussed in Sections *IV* and *V*, respectively. The conclusions of this research are presented in Section *VI*.

II. POTENTIAL FUTURE APPLICATIONS

Because this technology is based on typical air compression systems, it is clearly not suited for manipulating heavy objects. Therefore, promising areas of application include midair manipulation of relatively lightweight objects and the manipulation of objects on a flat surface or in zero-gravity conditions. Figure 2 shows a conceptual illustration of a video-oriented education or amusement system where four air ejectors are used to control the three-dimensional position of a light ball. Air creates no visual obstacles as it is clear, and air blowing against human skin typically poses no threat to personal safety.

Figure 3 shows a conceptual illustration of a transport system that uses an air table (air blown from underneath the table makes objects passively float) and four air ejectors for sorting lightweight objects on a flat surface. Using this technology, the lines of transport (A to B, A to C, etc) can be controlled in a flexible manner simply by controlling the four air ejectors. This method is advantageous over belt conveyors in terms of facility configuration, and is safer and more assuring than robots. Other potential applications are in the area of micro-manipulation technologies that utilize air's contactless and insulating nature, as well as its optical transparency. The technology can also potentially be used to control the shape, position or attitude of an object floating in a zero-gravity lab environment such as on a space shuttle.

As an extension of this technology, small amounts of volatile liquids can be added to the air jet to increase actuation force. As we have described, once completed, we can expect to see a broad range of applications for this technology having characteristics that are not possible with existing technology.

III. 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 exponentially as the number of DOF increase and the range of actuation expands. Specifically, the following problems arise.

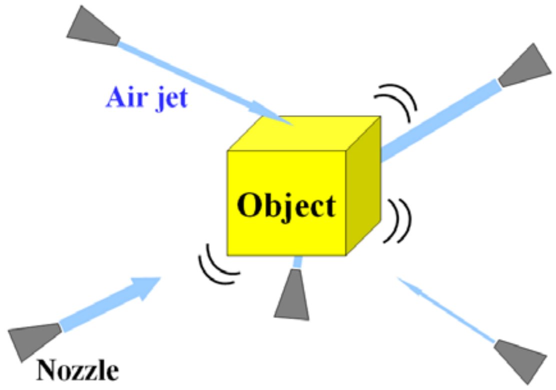

Figure 1. An image of contactless active force-closure manipulation using maltiple air jets

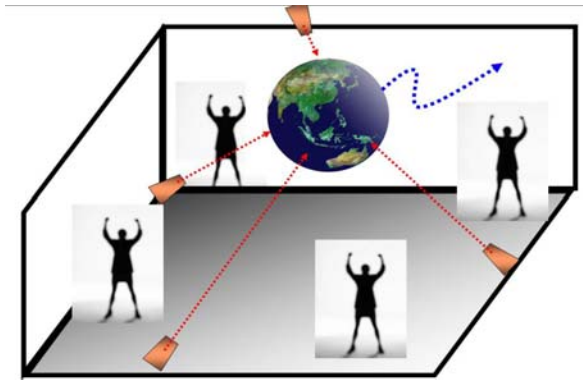

Figure 2. A conceptual illustration of a education or amusement system where four air ejectors are used to control the three-dimensional position of a light ball

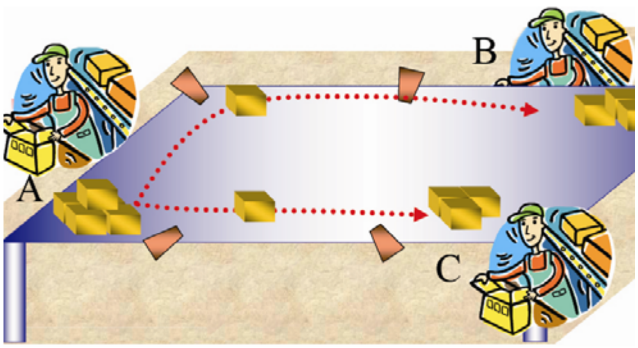

Figure 3. A conceptual illustration of a transport system for sorting lightweight objects on a flat surface

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, air movement 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 [8, 9]. 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, 8, 9].

B. Delay

The propagation 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 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 rectilinearity 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. As mentioned above, we can expect to achieve a degree of improvement with respect to this problem by including small amounts of a 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 non-interfering control methods provided that the object's position and attitude can be accurately measured.

As described above, this method entails difficult challenges that are not associated with conventional methods. Therefore, we plan to begin by first establishing the simplest model, namely, one that provides one linear DOF on a flat surface, and then increasing the DOF gradually to resolve the problems cited above in phases. Our plan is ultimately to establish a system that allows for control of all six DOF in midair. As the first step of development, this paper focuses on planar systems with one and two DOF.

IV. EXPERIMENTAL PLANAR SYSTEM WITH ONE DEGREE OF FREEDOM

A. experimental stetup

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 Figure 4, to control the rectilinear position of a hard cubical object. Here we 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) Electropneumatic regulator : This device includes a feedback mechanism in which the flow rate is controlled. The input signal to the electropneumatic 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 cotrol 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 acting 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 under conditions where the object's position and attitude are in constant flux, as in the system targeted in this study. Therefore, a preliminary experiment was conducted using a force-of-air measurement device to measure and evaluate these characteristics experimentally (Figure 5).

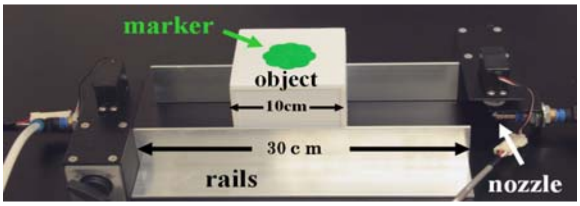

Figure 4. The system that control for an object on a flat surface with one DOF in a straight line

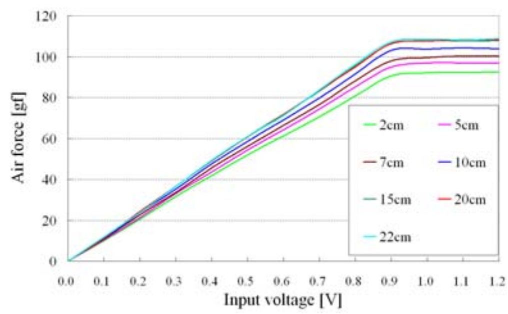

Figure 5. Experimental result for force-of-air

This graph shows the linearity, up to a distance of 22 cm, of the electropneumatic regulator input signals of 0–1 Voltage. Before the experiment, although the force of air was initially expected to decrease with distance, the experiment shows that, contrary to 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 relatively large 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 electropneumatic regulator, we expected that we could linearize the air jet dynamics with severe nonlinearity.

C. Experimental stetup

Based on the results of the preliminary experiment, a positional feedback control system (Proportional control) relative to the position of the object's center of gravity is established (Figure 6). In figure 6, x_r stands for target position, e for position error, K_p for proportional gain, m for object mass, u denotes control input (command to the electropneumatic 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 electropneumatic regulator is used : Preliminary experiments indicate that use of this device allows air dynamics, inherently an extremely complex matter, 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) Square response : An experiment was conducted in which a ±5 cm square wave was used as the target position. In cases where biased airflow was not applied (Figure 7), we observe large overshoots and oscillation phenomena. Meanwhile, as a result of applying biased airflow (Figure 7), a dramatic reduction in oscillation was observed. We understand this reason as fllows; since the bias air jet reduced the transit change of the air flow, it could decrease the air jet's nonlinearity and also increased theviscosity 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. 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 Section *IV*, positional feedback control could be achieved for an object relative to 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 and object. As for the air equipment used in this experimental system, the electropneumatic 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.

Figure 9 shows a comparison between the results of a simulation that incorporates a numerical model of the force-of-air characteristics found in our preliminary experiments and the actual results of experiments. In this simulation, the friction parameters including viscosity friction, static and dynamic friction were simulated based on the experimental results so that the both corresponded with each other. Figure 9 shows that the rise time, the incline as the object approaches the target value, the steady-state deviation, and delay time are reproduced sufficiently well. Therefore, the force-of-air characteristics found in the preliminary experiment carried over to this experiment. From this study of an experimental planar system with one DOF, we were able to verify basic items such as force-of-air characteristics, as well as the effects of the electropneumatic regulator, biased airflow, and friction. And

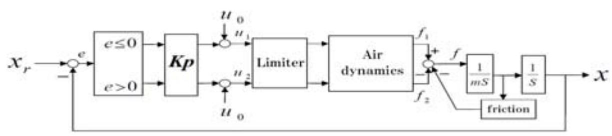

Figure 6. Block diagram of the one DOF control system

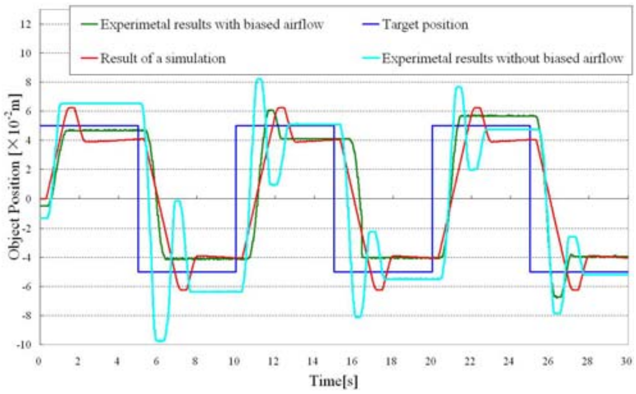

Figure 7. A comparison between the results of a simulation and our preliminary experiments

also we could achieve our goal about the position error (less than 10% of driving range). As presented in the following section, the degree of actuation freedom was increased on the basis of these findings.

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 air jet volumes and the angles of three nozzles installed on a flat surface (Figure 10). As shown in Figure 11, the three nozzles were placed at 120° intervals around the circumference of a circle having a 30 cm radius, taking into account force closure conditions. In Figure 11, O_w denotes the center of the object, and ($\theta_1, \theta_2, \theta_3$) denotes the differences in nozzle angles relative to when they are pointed towards coordinate (*0, 0*).

B. Proposed control method

1) Basic strategy : In this system, based on the experimental results reported in Section *IV*, 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 potentially possible for ejection angle, ejection method, and biased airflow.

a) Ejection anagle :

a-1) The three nozzles are controlled such that they are always pointed towards the center of the object. In this strategy, a simpler decomposition algorithm can be used to calculate the control inputs. In this strategy, it should be noted that the controlled object's center point must be always inside the equilateral triangle with vertices of the nozzle 1-3 in figure 8.

a-2) 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-1.

b) Ejiection method:

b-1) The force of air is adjusted by continuously varying the airflow by means of an electropneumatic regulator.

b-2) The force of air is adjusted by opening and closing proportional solenoid valves to discretely eject airflow having a constant air pressure as in pulse width modulation(PWM). This method has potential advantages over method b-1 in terms of conserving air volume and reducing noise.

c) Biased airflow:

c-1) Constant biased airflows are applied regardless of the position of the object. Although this method involves a simpler control law, the farther away the object is from the three nozzles, the more distorted the total force of the three biased airflows becomes.

c-2) This method attempts to achieve a theoretical net force of 0 by adjusting the biased airflows on each nozzle depending on the position of the object.

In this study, we employed the simplest strategies listed above, namely, a-1, b-1, and c-1.

2) Decomposing the manipulation amount : The volume of air ejected from the three nozzles must be determined based on position errors in the X and Y directions. In other words, this system constitutes a redundant system in which three actuators are used to achieve two DOF for the object. Therefore, there are an infinite number of combinations of forces produced by each of the three actuators to produce total manipulation forces that achieve two DOF, that is, motion in the X and Y directions. Here, we adopt a pseudo inverse matrix $\mathbf{K}_w^+$ (1) as the solution with the smallest square sum of each of the outputs using the nozzle allocation matrix (2) shown in (3).

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

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

$$\mathbf{f}_p = \mathbf{K}_w \mathbf{f}_w \qquad (\mathbf{f}_p = [f_x, f_y]^T, \mathbf{f}_w = [f_1, f_2, f_3]^T) \tag{3}$$

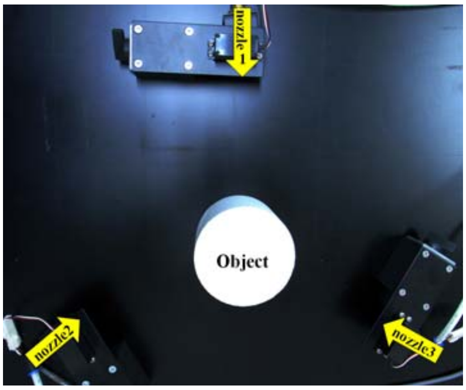

Figure 8. Experimental system that is created for controlling the position of a cylindrical object in two degrees of planar freedom (X, Y coordinates)

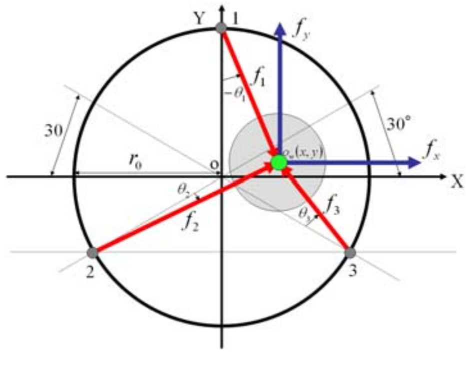

Figure 9. The model of two DOF experimental system

The use of (2) may result in situations where $\mathbf{f}_w$ takes a negative value. However, since the force of the air jet acts unilaterally and only in the positive direction, the biased control inputs (*ul, ur*) are incorporated such that all outputs are positive. The final control law and block diagram are shown Figure 12. Figure 12, K_v denotes voltage gain. 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 (Proportional - Integral)-control law was used.

C. Experimant results

Figure 13 shows that the cylindrical object follows the triangle-shaped target trajectory and therefore the positional feedback control can be achieved by using the control method proposed in sections *V-B*. And also 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 experimental table, long delay time, air dynamics. We expect that this distortion will be solved by adjusting the biased airflows on each nozzle depending on the position of the object so that the resultant force of the three air jets can be zero at the object's center (center of gravity).

VI. CONCLUSION

We proposed a technology for manipulating the position and attitude of an object in a contactless manner over an extended range. By regulating air jet directions and volumes, the object can be actively "force closured" and its position and attitude can be manipulated freely. We considered the actuation and control of an object on a flat surface with one DOF, that is, movement in a straight line. From this study of an experimental planar system with one DOF, we were able to verify basic items such as force-of-air characteristics, as well as the effects of the electropneumatic regulator, biased airflow, and friction. And also, we addressed control of a cylindrical object using three nozzles in two degrees of planar freedom (X, Y coordinates). This experimental results show that the cylindrical object follows the triangle-shaped target trajectory and therefore the positional feedback control can be achieved by using the control method proposed in sections *V-B*.

As our future work, we have already prepared an experiment system for three dimensional space; 3 DOF positions and 3DOF orientations. We will soon start this experiment.

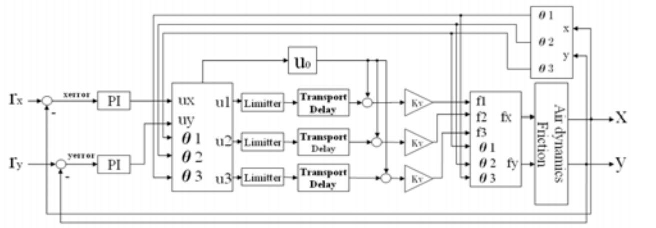

Figure 10. Block diagram of the two DOF control system

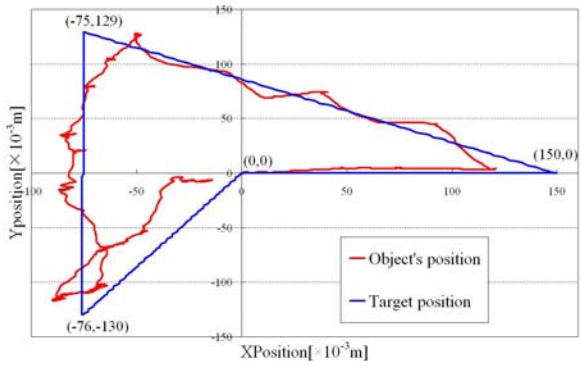

Figure 11. An experimental result of the cylindrical object's trajectory

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