Realizing Large Shape Deformations of a Flying Continuum Robot With a Passive Rotating Nozzle Unit That Enlarges Jet Directions in Three-Dimensional Space

YU YAMAUCHI1, (Graduate Student Member, IEEE), YUICHI AMBE2, (Member, IEEE), MASASHI KONYO1, (Member, IEEE), KENJIRO TADAKUMA2, (Member, IEEE), AND SATOSHI TADOKORO1, (Fellow, IEEE)

1Graduate School of Information Sciences, Tohoku University, Sendai 9808579, Japan
2Tough Cyberphysical AI Research Center, Tohoku University, Sendai 9808579, Japan

Corresponding author: Yu Yamauchi (yamauchi.yu@rm.is.tohoku.ac.jp)

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Abstract
Flexible continuum robots have considerable potential for use in exploring intricate spaces, and their ability to make large body shape deformations can increase the inspection area. We previously proposed a jet-actuated flying continuum robot for extinguishing fires. The main challenge in implementing large shape deformations is accommodating the twisting of the body that results from the deformation. To address this problem, we proposed a two-dimensional passive rotating nozzle unit that can expand the directionality of net force against torsion; however, it has not yet been tested on a flying robot. In this study, we achieved the large shape deformations of a jet-actuated flying continuum robot using an improved passive rotating nozzle unit that can handle three-dimensional (3D) force. First, we developed a model of the improved nozzle unit and confirmed that the unit can increase the net force direction. Herein, the design strategy for the rotary damper to handle the instability that arises from motor limitations is discussed. The stabilized flight controller was applied to a continuum robot with the nozzle unit. Simulation results showed that the 2 m robot could perform large head bends (from 0° to 135°). Although the previous fixed nozzle unit twisted by approximately 40°, which made the extra movable range of the nozzles effectively zero, the proposed nozzle unit maintained the movable range to avoid twisting. We experimentally confirmed that the nozzle unit can expand the direction of the 3D net force, and that a large shape bending of approximately ±90° can be achieved using a 1.6 m flying robot.

Index Terms
Fluid jet, continuum robot, mechanism design, dynamics.

I. INTRODUCTION
Flexible continuum robots are useful for exploring intricate spaces, and their large body shape deformations would allow them to inspect large areas. Many researchers have applied continuum robots to inspection tasks, such as in debris or pipes [1]–[5]. Some of these robots are commercially available. Continuum robots are also suitable for surgery tasks [6], [7] because they can enter the human body through small, minimally-invasive holes.

In recent years, various shape-control mechanisms have been proposed for continuum robots, such as tendon driven mechanisms, pneumatic actuators, and concentric tubes; however, these mechanisms are not effective for producing large shape changes. Tendon-based robots, which deform through a flexible backbone by pulling wires from the end of their body, were developed chiefly by OC Robotics [8] and NASA [9]. Continuum robots, which are actuated by distributed pneumatic actuators, have also been widely developed [10], [11]. However, these two types of actuators require a large force to generate a large bending moment for large shape deformations. This is because they apply forces on the surface of the thin robot, which is a little far from the
center of the curve. A different type of continuum robot is composed of flexible concentric tubes. The tubes rotate and translate with respect to each other [12]. However, in these robots, large shape deformations are still difficult because the bending shape is predetermined by the components.

In this study, the recently proposed fluid jet actuators were employed to control the shape of a continuum robot. These actuators are amenable to large deformations. The thrust generated by fluid jets is used to control the shape. For example, a long continuum robot whose head is controlled by three water jets has been developed; this robot can be used for the inspection of nuclear power plant [13] and surgical applications [6], [7]. Similarly, an idea of long flying hose for firefighting was proposed, and the jet nozzle was developed [14]. We have proposed an active scope camera whose head is controlled by the directional control of an air jet [15]–[17]. We have also developed a jet-actuated continuum robot, the Dragon Firefighter (DFF), which has several nozzle units on its flexible body, inside of which pressurized water flows [18]–[21]. The nozzle units release multiple water jets in a controlled direction to generate a translational net force for flying. A similar concept was also proposed in [22]. These jet-actuation methods enable a large shape deformation with a comparatively small force, because the force can be applied far from the root of the robot in the longitudinal direction.

The challenge in performing large shape deformations is how to handle the twisting of the body caused by the deformation. Owing to geometric constraints, a flexible long robot needs to twist its body to change its posture in three-dimensional (3D) space. Although the nozzle unit connected to the hose is also twisted, the nozzle must always maintain its jet in the desired direction. For example, the DFF requires a vertical force against gravity, regardless of the twist, as illustrated in Fig. 1. However, this is difficult to implement because of the limitations of the nozzle’s injection range. The nozzle movement range of the conventional nozzle unit is limited by the interference between the jet and the body. To address this problem, we previously proposed a passive rotating nozzle unit that can expand the direction of the net force against torsion [19]; however, we have not yet applied it to a jet-actuated flying continuum robot. Moreover, the previous passive rotating nozzle unit could generate a force only on two-dimensional (2D) plane.

The present study introduces a jet-actuated flying continuum robot capable of large shape deformations via a passive rotating nozzle unit that expands the direction of the 3D net force. First, we developed a model of a passive rotating nozzle unit that controls the 3D net force. Stability analysis confirmed that the nozzle unit can increase the range of the net force direction. We also formulated a design strategy for a rotary damper to expand the stable region of the robot. The stabilized flight controller was then applied to the continuum robot with the nozzle unit. The simulation results verified that the robot could achieve large shape deformations in a stable flight. We experimentally confirmed that the nozzle unit can expand the direction of the net force, and that large shape deformations can be achieved with an 1.6 m flying robot.

The contributions of the study are as follows. (1) The design and development of a passive rotating nozzle unit that can expand the direction range of the 3D net force. The feasibility of the design was confirmed through experiments. (2) The achievement of the large shape deformations of a jet-actuated continuum robot using the designed passive nozzle unit.

II. OVERVIEW OF THE DEVELOPED CONTINUUM ROBOT

In this study, we developed an 1.6 m continuum robot with a passive rotating nozzle unit at the tip (Fig. 2A). The robot can make large shape deformations during stable flight by controlling the magnitude and direction of the net force generated by the nozzle unit. The net force is generated by controlling the injection angles of multiple water jets. Note that our robot...
uses water as the energy source because we aim to use it for firefighting in the future.

The passive rotating nozzle unit extends the range of the achievable net force. The unit comprises four actively rotating nozzles (two roll rotating and two pitch rotating) with a central passive joint around the roll axis (i.e., the longitudinal axis of the continuum body), as shown in Fig. 2B. If the two roll nozzles inject inward to generate the net force, the roll posture of the nozzle unit automatically rotates to the direction of the net force. This is an extension of the principle of our previous study [19] from a 2D plane to a 3D context. We explain this principle using the model in Section III. By expanding it to 3D, the proportional gain (P gain) of the posture feedback increases. We discuss the design methods for handling this problem in the later sections.

For stabilized flight and shape deformation, the net force is adjusted as control input. Specifically, the controller comprises a constant force vector that determines the shape of the robot and the velocity feedback term that dampens the body oscillation [18]. To realize the net force, the rotating nozzle angles are calculated using an optimization method and achieve inward injection. Through simulations, we demonstrate that stable flight and large deformations can be achieved with this controller.

III. DESIGN OF THE 3D PASSIVE ROTATING NOZZLE UNIT

This section introduces the 3D passive rotating nozzle unit and verifies that the nozzle unit directs to the net force direction.

A. GEOMETRICAL STRUCTURE OF THE 3D PASSIVE NOZZLE UNIT

The allocations of the rotating nozzles and the passive joint on the nozzle unit are shown in Fig. 3. The unit has two pairs of rotating nozzles: one rotates around a pitch axis, and the other rotates around the roll axis. We define the nozzle coordinate $\Sigma_n$ on the passive joint. The $x_n$ and $y_n$ axes corresponds to the directions of the passive joint and pitch rotating nozzle axes, respectively. The angles of the nozzles are defined as $(\phi_1, \phi_2, \phi_3)$. The angles of the pitch nozzles are the same. The other parameters $d_{1-4}$, which represent the positions of nozzles, are shown in Fig. 3. The center of mass (CoM) is on the axis of the passive joint.

The nozzle unit can generate a net force by adjusting the nozzle direction. The force $f_n$ and torque $\tau_n$ that the nozzle unit generates at the CoM are expressed as follows:

$$f_n = \begin{bmatrix} 2R_p \sin \phi_3 + R_c \\ -R_p \cos \phi_1 - R_c \cos \phi_2 \\ 2R_p \cos \phi_3 - R_c \sin \phi_1 - R_c \sin \phi_2 \end{bmatrix},$$

(1)

$$\tau_n = \begin{bmatrix} d_1R_e \sin \phi_1 - d_1R_\phi \sin \phi_2 \\ d_4R_p \cos \phi_3 + d_3R_t \sin \phi_1 + d_2R_t \sin \phi_2 \\ -d_1R_e \cos \phi_1 - d_1R_\phi \cos \phi_2 \end{bmatrix},$$

(2)

where $R_p$, $R_r$, and $R_c$ represent the forces generated by the jet from the pitch nozzle, the jet from the roll nozzle, and the force applied by the fluid flowing into the nozzle unit, respectively. These forces are determined by the pump pressure.

B. PRINCIPLES OF THE POSTURE ADJUSTMENT MECHANISM

Theoretical analysis confirmed that the passive rotating nozzle unit can direct the net force direction to increase the range of the net force.

1) MODEL

Because the rotation along the passive joint ($x_n$ axis) can be investigated on plane $O - y_nz_n$, we designed a 2D nozzle unit model (Fig. 4) under the following assumptions.

(A1) The root of the passive joint is fixed on the inertial coordinate for simplification. Subsequently, the inertial coordinate $O - xy$ can be defined on the plane.

(A2) The nozzle unit comprises a passive joint in the center and two roll rotating nozzles. The pitch nozzles apply the normal force $R_m (= 2R_\phi \cos \phi_3)$ on the joint. The unit is a rigid body (mass: $m$), and the mass of the nozzles is ignored.

(A3) The situation wherein the nozzle unit generates a constant net force in the inertial coordinate is considered. In this case, the net force on $O - xy$ is constant (magnitude: $F > 0$, direction: $\theta_f$). In addition, the normal force $R_m$ is also constant to generate a constant $x_n$ direction force by the pitch nozzle.

(A4) The jet can be rotated by each rotational nozzle, (reaction force: $R_\gamma > 0$) without any dynamics. The angles of the nozzles are $\phi_1$ and $\phi_2$. 

FIGURE 3. Geometrical structure of the nozzle unit.

FIGURE 4. Definition of the model and variables.
We set the posture of the nozzle unit, inertia of the unit around the joint, damping coefficient of the joint, and distance between the nozzle and joint as \( \theta \), \( J > 0 \), \( D > 0 \), and \( l > 0 \), respectively. The gravity term does not affect the operation of the nozzle unit because the CoM corresponds to the joint. The generalized coordinates of the model are \( \theta \), and the control inputs are the nozzle directions \( \phi_1 \) and \( \phi_2 \).

Next, we define the ranges of the parameters. The nozzle posture satisfies \(-\pi/2 < \theta - \theta_f < \pi/2\) to avoid breaking the inward relationship of the rotating nozzles. The net forces satisfy \( \max(F - R_m, \sqrt{F^2 + R_m^2}) < 2R_t \) to be achievable by the forces of rotating nozzles \( R \) and \( R_m \). We also set \( F > R_m \) to direct the jets against the direction of \( F \).

2) CONTROLLER
The key design consideration for a passive rotating nozzle is to expel the jets inwardly [19]. The inward nozzle directions (magnitude: \( F \), direction: \( \theta_f \)) can be calculated as follows:

\[
\phi_1 = \frac{\pi}{2} - \theta + \theta_f + \phi + \arccos \left( \frac{A}{2R_t} \right),
\]

\[
\phi_2 = \frac{\pi}{2} - \theta + \theta_f + \phi - \arccos \left( \frac{A}{2R_t} \right),
\]

where

\[
A = \sqrt{F^2 + R^2_m - 2FR_m \cos(\theta - \theta_f)} > 0,
\]

\[
\sin \phi = \frac{-R_m \sin(\theta - \theta_f)}{A}, \quad \cos \phi = \frac{F - R_m \cos(\theta - \theta_f)}{A}.
\]

Note that the relationship \( \pi > \phi_1 - \phi_2 > 0 \) ensures inward injections in the range \(-\pi/2 < \theta - \theta_f < \pi/2\). The range of \( \phi_i \) is ignored for simplicity.

3) EQUATION OF MOTION
The equation of motion can be derived as follows:

\[
J\ddot{\theta} + D\dot{\theta} = \tau,
\]

where \( \tau \) is the torque along the passive joint and is expressed as:

\[
\tau = R_tl (\sin \phi_2 - \sin \phi_1).
\]

By substituting (3) into \( \phi_i \) in (7), the following equation is obtained:

\[
\tau = -\frac{1F}{A} \sqrt{4R_t^2 - A^2 \sin(\theta - \theta_f)}.
\]

4) EQUILIBRIUM POINT
The equilibrium of the system \( \theta^* \) can be derived by substituting \( \tau = 0 \) into (8). Because \( 4R_t^2 - A^2 > 0 \) is in the range \(-\pi/2 < \theta - \theta_f < \pi/2\), equilibrium can be derived as \( \theta^* = \theta_f \).

5) LINEAR STABILITY
The equation of motion can be linearized using a small deviation \( \Delta \theta = \theta - \theta^* \) as

\[
J\Delta \ddot{\theta} + D\Delta \dot{\theta} = -K \Delta \theta,
\]

\[
K = l\sqrt{4R_t^2 - (F - R_m)^2} \frac{-F}{F - R_m}.
\]

Because \( l, F, F - R_m, \) and \( 4R_t^2 - (F - R_m)^2 \) are all positive, \( K > 0 \) always holds. \( J \) and \( D \) are also positive. Thus, linear stability can be ensured for all ranges of the above parameters. The 3D nozzle unit can also stably direct the net force.

6) SIMULATION
The parameters used in the simulation are listed in Table 1. The value of the damper coefficient was set to \( D = 0.238 \text{ Nm/(rad/s)} \), which is the sum of those of the swivel joint and damper with a gear ratio of 50:30. Based on the experiment, the magnitudes of the net force \( F \), \( R_m \), and \( R_t \) were set as \( F = 39.2 \text{ N}, R_m = 23.9 \text{ N} \), and \( R_t = 17.6 \text{ N} \). Simulation was performed using MATLAB and conducted via the 4th-order Runge–Kutta method, with an integration step of 0.001 s.

We investigated the posture change when the net force direction \( \theta_f \) was altered from 0° to 15° as a step input. We repeated the procedure by altering the proportional gain \( K \) with the geometric parameter \( l \).

Fig. 5 shows the time response of the posture \( \theta \) against the step input of \( \theta_f \) for various P gains (colored lines), demonstrating that the nozzle unit automatically follows the net force direction, and its responsiveness can be tuned by geometrical parameters.

C. SELECTION OF DAMPING COEFFICIENTS
Although the nozzle unit can automatically direct the net force direction, while maintaining linear stability, the value of \( K \) approaches infinity when \( F \sim R_m \). In this case, the
posture of the actual nozzle unit may diverge if there are speed limitations in the motors of the rotating nozzles. Thus, in this section, we discuss how to select the parameters, particularly the joint damping coefficient, to ensure stability even in the presence of motor speed limits.

1) SIMULATION SET UP

The speed limit and operating range of the rotating nozzle were added to the simulation. Specifically, the maximum speed of the rotating nozzle was set to 67 rpm, and the operating ranges were set to \( \phi_1 \in [0, 21\pi/12] \) and \( \phi_2 \in [3\pi/12, \pi] \). In each calculation step of the Runge–Kutta method, the values \( \phi_1 \) and \( \phi_2 \) were modified to the nearest boundary if they exceeded the limits. The other physical parameters were the same as those in Table 1.

The simulation analyzed the posture response (convergence and convergence time) when the directional command of the net force changed by 15° from the vertical direction (step input), for three different parameters. Specifically, the damping coefficient \( D \) was changed for six conditions: 0.05, 0.1, 0.2, 0.3, 0.4, and 0.5 Nm/(rad/s). The magnitude of the net force \( F \) and the force \( R_m \) from the pitch nozzle were varied from 0 to 10 N in increments of 0.5 N.

2) SIMULATION

Simulation results are shown in Fig. 6. The six graphs correspond to the six damping coefficients \( D \). Each graph represents whether the posture converges (circle) or not (red crosses) depending on \( F \) and \( R_m \). The color of the circles indicates convergence time, which increases from blue to yellow. As the damping coefficient \( D \) increases, the area of convergence expands monotonically, and convergence time decreases over most of the range. However, when the damping coefficient exceeds 0.4 Nm/(rad/s), convergence time increases in the region where \( F \) is small.

These results suggest that an appropriate selection of the damper can stabilize the posture, even if the speed and range of the rotating nozzle are limited. In this study, we selected a damper with a damping coefficient of 0.30 Nm/(rad/s) because the values of \( F \) and \( R_m \) change significantly depending on the robot motion, and we prioritized the uniformity of convergence time.

The convergence time is large when \( F \) is small at high damping coefficient. This is because in this condition, rotating nozzles need to spray more inward to cancel out the opposing force, which can lead to the nozzles rotating to their rotational limits. This limit prevents the nozzle unit from producing sufficient torque to rotate against the damper with a high damping coefficient.

IV. STABLE FLIGHT WITH THE NOZZLE UNIT

We conducted simulations to verify that the nozzle unit can make the robot deform largely while maintaining a stable float.

A. MODEL AND EQUATION OF MOTION

A model was formulated to verify that the proposed passive rotating nozzle unit can achieve the large deformation of robot body without being affected by the torsion caused by the deformation. To date, various models of continuum robots have been proposed, ranging from continuous to discrete models [23]–[27]. In this study, a multiple rigid-link model was selected to approximate the continuum robot because the model can also reproduce the situation of torsion occurring with body deformation. We derived the equation of motion of the DFF with the nozzle unit under the following assumptions.

(B1) The flexible continuum body is approximated by multiple rigid links connected by springy joints. Each joint has two degrees of freedom, along the pitch and yaw axes.

(B2) The head nozzle unit is modeled as a rigid body connected to the body with a passive roll axis joint. We ignored the mass and dynamics of the active rotating nozzles.

(B3) The fluid effect on the flexible body part is ignored.

The model comprises \( N \) rigid links on \( \Sigma_0 \), as shown in Fig. 7, where the coordinate \( \Sigma_0 \) is defined as the inertial coordinate. The direction of gravity acceleration is \(-g\), and its magnitude is \( g \). Each link \( i \) is a rigid body (mass: \( m_i \), inertia matrix: \( J_i \), length: \( l_i \)), and we define the coordinate \( \Sigma_i \) whose origin and \( x_i \) axis are joint \( i \) and the longitudinal axis of link \( i \), respectively. For convenience, we set \( \Sigma_0 \equiv \Sigma_{N+1} \). Link 1 is the head and contains joint 1, which can rotate along the \( x_1 \) axis (passive joint of the nozzle unit). The angle of joint 1 is represented by \( \theta_1 \). The other joint \( i \) has two degrees of freedom for rotation along the pitch and yaw axes. The joint angles are represented by Euler angles \( \theta_i = [\theta_{i1} \theta_{i2}]^T \) (pitch and yaw angles), and the orientation of \( \Sigma_i \) is derived by two rotations: rotating \( \Sigma_{i+1} \) at an angle of \( \theta_{i2} \) along the \( z \) axis and then rotating the new frame at an angle of \( \theta_{i1} \) along the \( y \) axis. Each joint \( i \) has a rotational spring with a damper.
The positions of the CoM of link \( i \) and joint \( i-1 \) (the tip position for \( i = 1 \)) are represented as \( s_i \) and \( p_i = [l_i, 0, 0]^T \) on \( \Sigma_i \), respectively. The angular-velocity vector of link \( i \) relative to \( \Sigma_j \) is defined as \( \omega_{ij} = [\omega_{ij1}, \omega_{ij2}, \omega_{ij3}]^T \) on \( \Sigma_i \). Note that these vectors are represented boldfaced as \( s_i, p_i, \omega_{ij} \) on the inertial coordinate \( \Sigma_0 \). The external force and torque applied to the CoM of link \( i \) are denoted by \( f_i = [f_{i1}, f_{i2}, f_{i3}]^T \) and \( \tau_i = [\tau_{i1}, \tau_{i2}, \tau_{i3}]^T \) on \( \Sigma_0 \), respectively.

We define the coordinate transformation matrices \( A_{1,2} \) and \( A_{i,i+1} \) for \( i = 2 \ldots N \) as

\[
A_{1,2} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{11} & s_{11} \\ 0 & -s_{11} & c_{11} \end{bmatrix}, \quad A_{i,i+1} = \begin{bmatrix} c_{i1} & c_{i2} & s_{i1} \\ -s_{i2} & c_{i2} & 0 \\ c_{i2}s_{i1} & s_{i2}s_{i1} & c_{i1} \end{bmatrix},
\]

where the abbreviations \( c_{ij} = \cos \theta_{ij} \) and \( s_{ij} = \sin \theta_{ij} \).

Let vector \( a \) be defined on \( \Sigma_0 \) and vector \( a \) be represented as \( a^i \) on \( \Sigma_i \). \( A_{i,i+1} \) relates the vectors on \( \Sigma_i \) and \( \Sigma_{i+1} \) as \( a^i = A_{i,i+1}a^{i+1} \). In addition, the following relationships are satisfied: \( A_{i,i+1} = A_{i+1,i}^T \) and \( a = A_{0,i}a_i \), where \( A_{0,i} = A_{i,i+1}A_{i+1,i+2} \ldots A_{N-1,N} \).

The angular velocity \( \omega_{ij+1} \) can be expressed as \( \omega_{ij+1} = B_i \dot{\theta}_i \), using the Euler angles \( \theta_i \), where \( B_1 \) and \( B_i \) for \( i = 1 \ldots N \) are represented as follows:

\[
B_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \quad B_i = \begin{bmatrix} 0 & -s_{i1} \\ 1 & 0 \\ 0 & c_{i1} \end{bmatrix}.
\]

Using the above relationships, the position and velocity of the CoM of link \( i \) on \( \Sigma_0 \) (\( r_i \) and \( \dot{r}_i \), respectively) are derived as the functions of \( \theta_1, \theta_2, \ldots, \theta_N \) and \( \dot{\theta}_1, \dot{\theta}_2, \ldots, \dot{\theta}_N \) as follows:

\[
\begin{align*}
\underline{r}_i &= \sum_{j=1+1}^{N} (A_{0,j}p_j) + A_{0,i}s_i, \\
\dot{\underline{r}}_i &= \sum_{j=1+1}^{N} (A_{0,j}\dot{p}_j) + A_{0,i}\dot{s}_i \omega_{ij}.
\end{align*}
\]

where \( \omega_{ij} = \sum_{j=1}^{N} A_{ij} \omega_{ij} \) and the cross-product operator \( \hat{\times} \) is defined as \( \hat{\times} = \begin{bmatrix} 0 & a_2 & -a_3 \\ -a_3 & 0 & a_1 \\ a_2 & -a_1 & 0 \end{bmatrix} \).

Kinetic energy \( T \), potential energy \( V \), and the dissipation function \( U \) are expressed as follows:

\[
\begin{align*}
T &= \frac{1}{2} \sum_{j=1}^{N} \left( \dot{r}_j^T m_j \dot{r}_j + \omega_j^T f_j \dot{\omega}_j \right), \\
V &= \sum_{j=1}^{N} \left( r_j^T m_j \dot{g} + \frac{1}{2} \dot{\theta}_j^T K_j \dot{\theta}_j \right), \\
U &= \sum_{j=1}^{N} \left( \frac{1}{2} \dot{\theta}_j^T D_j \dot{\theta}_j \right),
\end{align*}
\]

where \( K_j = \text{diag}(k_j) \) and \( D_j = \text{diag}(d_j) \). The Euler–Lagrange equation can be derived using \( L = T - V \) as follows:

\[
\frac{d}{dt} \frac{\partial L}{\partial \dot{\theta}} - \frac{\partial L}{\partial \theta} + \frac{\partial U}{\partial \theta} = (X^T f)^T + \tau,
\]

where \( \theta = [\theta_1, \theta_2^T, \ldots, \theta_N^T, f = [f_1^T, \ldots, f_N^T]^T, \tau = [\tau_1^T, \ldots, \tau_N^T]^T \). X is defined such that \( \dot{\theta} = X \dot{\theta} \) for \( r = [r_1^T, \ldots, r_N^T]^T \), using (11). Solving (12) based on previous studies [28], [29] yields the final form of the equation of motion as follows:

\[
\ddot{\theta} + \ddot{\theta} - \dddot{\theta} + \dot{V} + BD\ddot{\theta} + BK\theta + \dddot{\theta}^T L^T \dot{\theta} + \dddot{\theta}^T L^T f + \tau \quad (13)
\]

where \( R = H^T (L^T ML + J)HB, P = AMLHB\dot{\theta}, K = \text{diag}([k_1^2, k_2^2, \ldots, k_N^2]^T), D = \text{diag}([d_1^2, d_2^2, \ldots, d_N^2]^T), M = \text{diag}(m_1, m_1, \ldots, m_N, m_N) \), \( m = [0, 0, m_1, \ldots, 0, 0, m_N]^T \).


| Elements                  | Values | Elements                  | Values | Elements                  | Values |
|---------------------------|--------|---------------------------|--------|---------------------------|--------|
| \(I_{1-10}\)              | 0.200  | \(I_{3y}\)               | 0.0162 | \(J_{xx}\)               | 0.0155 |
| \(J_{xy}\)               | 0.0162 | \(J_{zz}\)               | 0.0308 | \(J_{xzz}\)              | -0.000255 |
| \(J_{yxy}\)              | 0      | \(d_{1}\)                | 0.238  | \(k_{1}\)                | 0      |
| \(m_{2-10}\)             | 0.345  | \(J_{2y-10}\)            | 0.000177 | \(J_{2y-10y}\)          | 0.00124 |
| \(J_{2z-10}\)            | 0      | \(k_{2-10}\)             | 18.7   | \(d_{2-10}\)             | 0.250  |

The rotating nozzle angles \(\phi_{1,2,3}\) determine the net force and torque applied to link 1 (nozzle unit) as \(f_{1} = A_{0}f_{n}\) and \(\tau_{1} = A_{0}\tau_{n}\) using (1), respectively. In addition, \(f_{i} = \tau_{i} = 0\) for \(i \neq 1\).

### B. CONTROLLER

To fly the robot with stability, we used the control method of the net force proposed in [18]. The targeted net force \(f_{1}^{d}\) of the nozzle unit was controlled as follows:

\[
f_{1}^{d} = F_{n} - D_{n}\dot{r}_{1},
\]

where \(F_{n}\) and \(D_{n} \geq 0\) are a constant vector and a positive semi-definite matrix, respectively. The first term, \(F_{n}\), determines the shape of the robot (equilibrium), while the second term is the damping term, used to suppress vibrations.

The rotating nozzle angles \(\phi_{1,2,3}\) are determined to realize \(f_{1}^{d}\) using an optimization method. Although \(\phi_{1,2}\) were theoretically derived in Section III, we use a quadratic optimization method here to minimize the error from the desired net force [20]. Let the desired net force on \(\Sigma_{n}(= \Sigma_{1})\) be \(f_{1}^{d}\); then, the evaluation function to be minimized \(\Phi(\phi_{1}, \phi_{2}, \phi_{3})\) is expressed as:

\[
\Phi(\phi_{1}, \phi_{2}, \phi_{3}) = (f_{1}^{d} - f_{n})^{T} A_{r}(f_{1}^{d} - f_{n}) + b_{r} \sum_{i=1}^{3} (\phi_{i} - \phi_{0i})^{2},
\]

where \(f_{n}\) is the generated force for the angles \((\phi_{1}, \phi_{2}, \phi_{3})\) on \(\Sigma_{n}(= \Sigma_{1})\) from (1). \(\phi_{0}^{i}\) represents the previous command angle of the rotating nozzle \(i\). Matrix \(A_{r}\) and the scalar variable \(b_{r}\) are the weights of evaluation elements. \(A_{r}\) specifies the preferred accuracy of the generated net force. Normally, the forces in \(y_{n}\) and \(z_{n}\) directions have high priority to achieve that in \(x_{n}\) direction to generate sufficient force to float and change in lateral directions. \(b_{r}\) ensures a continuous change in the nozzle inputs. The optimization problem is solved under the following constraints:

\[
\phi_{i}^{\text{min}} \leq \phi_{i} \leq \phi_{i}^{\text{max}} \quad i = 1, 2, 3
\]

\[
\phi_{1} - \phi_{2} > 0,
\]

where \(\phi_{i}^{\text{min}}\) and \(\phi_{i}^{\text{max}}\) are the minimum and maximum nozzle angles, respectively. The second inequality ensures inward injection.

### C. SETUP FOR SIMULATION

Based on the actual robot, we set the physical parameters as in Table 2. We modeled the 2-m-long flexible hose body using \(N = 10\) links. The physical parameters of the nozzle unit (link 1) were estimated using a CAD model. The inertia of the hose body was approximated using a uniform cylinder. The spring stiffness and damper coefficients of joints were theoretically derived in Section III, we use a quadratic optimization problem to achieve the desired static and dynamic properties of the hose (0.4 m). Note that \(s_{1-10} = [0.2, 0, 0]^{T} m\). The control parameters were set as \(R_{t} = 13.8, R_{p} = 10.4, R_{c} = 21.8 N\). The feedback gain was set as \(D_{n} = 5\). The parameters for nozzle angle optimization were set as \(A = \text{diag}(0.0130, 0.0651, 0.0651)\) and \(b = 1\). The ranges of rotating nozzles were set as \(\phi_{1} \in [0, 21\pi/12], \phi_{2} \in [3\pi/12, \pi], \) and \(\phi_{3} \in [0, \pi/2]\).

The equation of motion (13) was numerically solved using the 4th order Runge–Kutta method with a time step of 0.0007 s. Force and torque \((f_{n} \text{ and } \tau_{n})\) were calculated by solving the optimization problem at each time step. The optimization problem was solved using the \texttt{fmincon} function of MATLAB.

For a constant input \(F_{n}\), we assume that the system reaches equilibrium when the state variables \((\theta, \dot{\theta})\) remain in the range of 10\(^{-3}\) for 1 s. For equilibrium, we numerically evaluated linear stability by calculating the Jacobian matrix. Let \(z = [\theta^{T} \dot{\theta}^{T}]^{T} \in \mathbb{R}^{(4N-2)\times 1}\) be the state vector of the system. Then, equation (13) can be rewritten as follows:

\[
\frac{dz}{dt} = g(z),
\]

where \(g \in \mathbb{R}^{(4N-2)\times 1}\) is a nonlinear vector function. If equilibrium is derived as \(z^{*} (0 = g(z^{*}))\), then the Jacobian matrix \(J_{e}\) is defined as

\[
J_{e} = \left. \frac{\partial g}{\partial z} \right|_{z = z^{*}}.
\]

The eigenvalues of the Jacobian matrix specify the linear stability of the system [30]. If the maximum real parts of all eigenvalues are less than zero, the equilibrium points of the system are linearly stable. In addition, the real parts of the eigenvalues specify the damping. Note that \(J_{e}\) is numerically calculated using a small deviation \(2\Delta(= 10^{-2}\) in our simulation).

\[
(J_{e})_{ij} = \frac{g_{i}(z^{*} + \Delta e_{j}) - g_{i}(z^{*} - \Delta e_{j})}{2\Delta},
\]

where \(e_{j} \in \mathbb{R}^{(4N-2)\times 1}\) is the unit vector in the \(j\) direction.
D. DEMONSTRATION OF A LARGE DEFORMATION

To demonstrate a large deformation, we simulated the movement of the DFF when a direction of constant input $F_n$ changes along the yaw axis. Specifically, we changed $F_n$ as follows:

$$F_n = [F \cos \psi_p \cos \psi_y, F \cos \psi_p \sin \psi_y, F \sin \psi_p]^T,$$

where $\psi_y$ oscillates as $\psi_y(t) = (3\pi/4) \sin(\pi t/50)$, $\psi_p = 30^\circ$, and $F = 47$ N. To compare the result with the case where no passive joint is present, we also conducted the simulation by constraining $\theta_1 = 0$. In this case, we selected the outward injection (i.e., changed the constraint for the optimization (16) as $\phi_1 - \phi_2 < 0$) to increase the achievable range of force.

Simulation results are shown in Fig. 8. Figures 8A and B show the results with and without the proposed passive rotating nozzle unit, respectively. Figure 8A0 shows how the shape changed with time. Figures 8A1 and B1 show the time responses of the nozzle unit postures. The dotted line represents the yaw angle of the input force, $\psi_y$. Figures 8A2 and B2 show the rotating nozzle angles $\phi_1, 2, 3$ and their maximum and minimum values.

We found that the DFF can bend its shape up to approximately 135$^\circ$, and the passive nozzle unit did not twist. Although the roll posture of the nozzle unit without the proposed passive rotating joint twisted significantly (approximately 40$^\circ$) with the deformation of the flexible body (Fig. 8B1), the proposed nozzle unit maintained its roll posture at approximately zero by automatically rotating the passive joint (Fig. 8A1). Because of this posture adjustment, the rotating nozzle angles were always in the actuation range for the proposed nozzle unit (Fig. 8A2), whereas the angles reached the limits for the nozzle unit without the passive rotating joint (Fig. 8B2).

E. EQUILIBRIUM POINTS AND STABILITY

To quantify the advantages of the proposed nozzle unit, we investigated the equilibrium points and stability for various $\psi_p$ and $\psi_y$ in (20) and $F = 47$ N. As in the previous simulation, we also investigated the case without a passive joint.

Simulation results are shown in Fig. 9. Figures 9A1 and A2 correspond to the cases with the proposed nozzle unit, and Figures 9B1 and B2 correspond to the cases without the proposed nozzle unit. Figures 9A1 and B1 present the stability (i.e., the maximum real parts of the eigenvalues of the Jacobian matrix) of the equilibrium points by color. Figures 9A2 and B2 display the minimum actuation margins of the rotating nozzle (i.e., the minimum distance of $\phi_i$ from their rotating limits).

From the results presented in Figs. 9A1 and B1, it can be deduced that the proposed nozzle unit ensured a stabilized flight with a fixed nozzle unit. Furthermore, the proposed nozzle unit offered improved stability for a large yaw input. This is because the nozzle unit can maintain the nozzle actuation margin even for a large yaw input, whereas the fixed nozzle cannot ensure the margin because of twisting, as shown in Figs. 9A2 and B2.

From these results, it is concluded that the proposed nozzle unit has the advantage of increasing the nozzle actuation range, especially when the shape deforms significantly. If the damping coefficient of the passive joint is adjusted properly, shape deformation does not impede the linear stability of the flight.

V. EXPERIMENT

In this study, two experiments were conducted. The first evaluated the basic performance of the proposed 3D passive rotating nozzle unit, and the second demonstrated a large deformation of the robot while maintaining the actuation range of its rotating nozzle.

A. DEVELOPED NOZZLE UNIT AND THE 2-M-LONG DFF

The developed passive rotating nozzle unit is shown in Fig. 2B. It has four actively rotating nozzles actuated by servo motors (Dynamixel MX-28AR, ROBOTIS). The passive
rotating joint comprises a rotating channel (swivel joint, custom-made) and a rotary damper (FRT-D2-152: FUJI LATEX CO., LTD.). The physical parameters were the same as in Table 1. A microcomputer with an inertia-measurement-unit (IMU: ICM-20948, TDK Corporation) sensor was attached to the top of the nozzle unit to control nozzle angles and calculate the posture. The data from the sensor were acquired at 1 kHz and transformed into a posture (roll, pitch, and yaw angles) via a filter [31].

Fig. 2B shows the developed 2-m-long DFF with the nozzle. The robot comprises the proposed nozzle at the head and a 1.6-m-long flexible corrugated tube. Multiple IMU sensors were attached to the tube at intervals of 0.4 m to measure the body shape. To estimate the position and velocity of the nozzle unit, the tube was approximated as a connection of rigid links of length 0.4 m, whose attitudes and angular velocity were measured by the IMU.

B. BASIC PERFORMANCE EVALUATION OF THE NOZZLE UNIT

1) SETUP

We designed an experimental setup without a DFF body to evaluate the performance of the nozzle unit. The experimental system comprised a portable fire extinguishing pump (VC 72 PRO 3 Limited, Tohatsu Co., Ltd.), water storage tank (maximum capacity: 2,500 L), suction hose (nominal diameter: 75 mm), hose from the pump to a measurement instrument (inner diameter: 38 mm, hose length: 2 m), flow meter (FD-R50, Keyence corporation), pressure gauge (GC31, NAGANO KEIKI Co., Ltd.), hose from the measurement instrument to the nozzle unit (inner diameter: 25 mm, hose length: 2 m), and the developed nozzle unit fixed on a frame, as shown in Fig. 10.

The step response of the nozzle unit was analyzed to confirm the following three points: (1) if the nozzle unit can rotate its posture in the direction of the net force; (2) if the posture stably converges for various gains of $K$; and (3) if the simulation is reasonable.

As the step input, the direction of the net force was changed by 15° from 0° (vertically upward). In this experiment, we maintained the supply pressure constant (0.7 MPa) (i.e., $R_{p.r.c}$ were constant), and the gain $K$ was tuned by the values of $R_m$ (the force generated by the pitch joint) and $F$. Specifically, we changed $R_m$ for the following four conditions: 12, 18, 22, and 24, and for each $R_m$, we changed $F$ for seven or eight conditions. For each parameter set, we performed the measurements five times.

2) RESULTS

As an example, we present the time response of the nozzle unit posture in Fig. 11, wherein the parameter values were $R_m = 24$ and $F = 10$. We found that the posture settled in the direction of the net force (15°) over time.

We analyzed the variation in steady-state deviation, settling time, rise time, and overshoot with respect to the gain $K$. The settling time, rise time, and overshoot were compared with those in the simulation results. The error band of the settling time was set as ±10%. We defined the rise time as the time required for the response to increase from 10% to 90%. The graph of each element is shown in Fig. 12.

From Fig. 12(a), the time response of the nozzle unit posture in Fig. 11, wherein the parameter values were $R_m = 24$ and $F = 10$. We found that the posture settled in the direction of the net force (15°) over time.

The steady-state deviation is sufficiently small for the step input of 15°, indicating that the nozzle posture approached the direction of the net force in all cases. Deviation remained approximately 2° for high gains and approximately 6° for low gains. From Fig. 12(b), the steady-state deviation, settling time, rise time, and overshoot were compared with those in the simulation results. The error band of the settling time was set as ±10%. We defined the rise time as the time required for the response to increase from 10% to 90%. The graph of each element is shown in Fig. 12.

From Fig. 12(c), the rise time obtained in the experiment showed a tendency to decrease once and then increase as the gain increased for all parameters. This tendency was similar to that observed in the simulation. From Fig. 12(d), the overshoot obtained in the experiment showed a tendency to increase once and then decrease as the gain increased for all parameters. This trend was similar to that observed in the simulation; however, the experimental values were smaller than the simulation values.

The steady-state error shown in Fig. 12(a) may have resulted from the friction of the passive rotating shaft. However, the maximum error was only approximately 6°, which was approximately 9% of the 67.5° rotation range of the roll nozzle; therefore, it is not a serious problem in practice. In Figs. 12(b) and (d), the experimental results are smaller.
than the simulation results owing to the friction of the rotating shaft. Friction is considered to improve the stability of the joint by dissipating energy; therefore, this difference is not a problem with regard to stability.

Although there were some limitations, we confirmed that the nozzle unit can rotate its posture in the direction of the net force for various gains $K$, and that the simulation is in adequate agreement with the experiments.

C. DEMONSTRATION OF A LARGE DEFORMATION OF THE 2-M-LONG DFF

We experimentally demonstrated a large shape deformation using the developed 1.6 m DFF with the proposed nozzle.

1) SETUP

In this demonstration, we changed the yaw direction of the constant input $F_n$ in the simulation. Specifically, the yaw direction $\psi_y$ was changed from $0^\circ$ to $90^\circ$, from $90^\circ$ to $0^\circ$, from $0^\circ$ to $-90^\circ$, and from $-90^\circ$ to $0^\circ$ with increments of $5^\circ$. (Fig. 13(a)). Control parameters were set as $F = 39.2$ N and $\psi_p = 30^\circ$, the pump pressure was $0.33$ MPa, and $D_n = \text{diag}(2.5, 2.5, 2.5)$.

To compare the experimental results with the simulation results, we also conducted the simulation for a large-scale shape deformation. The physical parameters in the simulation were almost the same as those in Table 2. The number of links was reduced to 8 because of the robot length being 1.6 m. To replicate the bending tendency of the real robot, the neutral angles of springy joints 2–8 were set as $(-\pi/8, -\pi/10, -\pi/10, -\pi/10, -\pi/10, 0, 5\pi/24)$ rad based on the initial shape of the real robot, respectively. Jet reaction forces were set as $R_r = 9.25$, $R_p = 6.95$, and $R_c = 14.6$ N based on the measured pressure of $0.33$ MPa. The time profile of the command force $F_n$ was the same as that of the experiment (Fig. 13(a)).

2) RESULTS

Experimental results demonstrate that the DFF can bend its head up to $\pm 90^\circ$ around the yaw direction while maintaining a roll angle of approximately zero (see supplementary video). In Fig. 13(b), the solid line represents the time responses of the attitude of the nozzle unit (roll, pitch, and yaw) and the roll angle of the IMU behind the unit (at the tip of the flexible body). The yaw angle of the nozzle unit varied up to $\pm 90^\circ$. The roll angle of the nozzle unit is approximately $\pm 20^\circ$, while that of the body varies over $50^\circ$. Fig. 13(c) shows the time responses of the rotating nozzle angles $\phi_{1,2,3}$. Both the pitch and roll nozzles could be maintained within the range of motion ($\phi_1 \in [0, 21\pi/12], \phi_2 \in [3\pi/12, \pi], \phi_3 \in [0, \pi/2]$).

Simulation results are plotted as dashed lines in Figs. 13(b) and 13(c). From Fig. 13(b), it can be inferred that the DFF can bend its head by approximately $\pm 90^\circ$ around the yaw direction while maintaining the magnitude of the roll angle small (less than $\pm 20^\circ$) in the simulation. From Fig. 13(c), both the pitch and roll nozzles were maintained...
within the movable range. These results have a similar tendency as that of the experimental results.

We also investigated the shapes of the long flexible robot at several time steps in the experiment and the simulation, as shown in Fig. 14. The black line represents the shape of the robot in the simulation, and the red points represent the measured positions of the four IMUs mounted on the robot. A large deformation of the overall shape was achieved, as shown in Fig. 14. We also confirmed that the experiment and the simulation showed similar tendencies.

Although some discrepancies were observed between the simulation and experimental results, their reasons can be explained. In Fig. 13(b), the magnitude of the roll angle of the nozzle unit in the experiment is smaller than that in the simulation, especially when the magnitude of the yaw angle is large. This is ascribed to the dry friction generated in the passive joint, which is not considered in the simulation. In Fig. 13(c), the time variation of the rotating angles of the roll nozzles do not match well with that in the simulation in two points. First, the experimental time variation oscillated at a significantly high frequency. Second, the values of the oscillation center are also different from the simulation values, especially in the ranges of 10—20 and 50—70 s. High-frequency oscillation occurs because the nozzle unit considerably oscillates due to wind (the maximum measured wind speed was 7.5 m/s). The experimental values (oscillation center) are different from simulation values because the roll postures of the nozzle unit are different in the simulation and the experiment due to the dry friction, as shown in Fig. 13(b). Despite these discrepancies, the proposed nozzle can eliminate torsion up to 60° and maintain the rotating nozzle angles in the range of motion.

VI. CONCLUSION

Herein, we achieved large shape deformations of a jet-actuated flying continuum robot by designing a passive rotating nozzle unit that can expand the direction of 3D net force. First, we developed a model of the passive rotating nozzle unit. Stability analysis confirmed that the nozzle unit can stably face the direction of net force, which increased the realized net force direction. We also identified the instability problem that arises when dealing with the 3D net force and presented a design strategy for the rotary damper to expand the stability region. The stabilized flight controller was then applied to the continuum robot with the nozzle unit. The simulation results showed that the 2 m robot can achieve a large, stable head bending (from 0° to 135°). Compared with the previous fixed nozzle unit, the proposed nozzle unit maintains the movable range of its rotating nozzles to avoid twisting. In addition, the proposed nozzle unit maintains stability, even when the robot bends significantly. We also experimentally confirmed that the nozzle unit can expand the direction of the 3D net force, and that a large shape bending of approximately ±90° can be achieved with a 1.6 m flying robot. Further, the experimental results are in good agreement with the simulation results.

In future research, large deformations should be more quantitatively compared with the simulation results. We also aim to tune the nozzle parameters based on the oscillation modes of the flexible body, which will improve the system stability.

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YU YAMAUCHI (Graduate Student Member, IEEE) received the M.S. degree in information science from Tohoku University, Miyagi, Japan, in 2019, where he is currently pursuing the Ph.D. degree in design and control of jet-actuated continuum robots.

His research interests include design and control of continuum robots.

YUICHI AMBE (Member, IEEE) received the Ph.D. degree in engineering from Kyoto University, Kyoto, Japan, in 2017.

From 2018 to 2020, he was an Assistant Professor at the Graduate School of Engineering, Tohoku University, Japan. Since 2021, he has been an Assistant Professor at the Tough Cyberphysical AI Research Center, Tohoku University. His research interests include design and control of continuum, jet-actuated aerial, legged, and rescue robots.

MASASHI KONYO (Member, IEEE) received the B.S., M.S., and Ph.D. degrees in engineering from Kobe University, Hyogo, Japan, in 1999, 2001, and 2004, respectively. He is currently an Associate Professor at the Graduate School of Information Sciences, Tohoku University. His research interests include haptic interfaces, rescue robotics, and new actuators.

YUICHI AMBE (Member, IEEE) received the Ph.D. degree in mechanical and aerospace engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 2007.

He is currently an Associate Professor at the Graduate School of Information Sciences, Tohoku University. His research interests include mechatronics, omni directional mobile robots, and rescue robots.

KENJIRO TADAKUMA (Member, IEEE) received the Ph.D. degree in mechanical and aerospace engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 2007.

He is currently an Associate Professor at the Graduate School of Information Sciences, Tohoku University. His research interests include mechatronics, omni directional mobile robots, and rescue robots.

Satoshi Tadokoro

Satoshi Tadokoro (Fellow, IEEE) graduated from The University of Tokyo, in 1984.

He was an Associate Professor at Kobe University, from 1993 to 2005. Since 2005, he has been a Professor at Tohoku University, where he was the Vice/Deputy Dean of the Graduate School of Information Sciences, from 2012 to 2014, and the Director of the Tough Cyberphysical AI Research Center, since 2019. He has been the President of the International Rescue System Institute, since 2002. He was also the President of the IEEE Robotics and Automation Society, from 2016 to 2017. He has served as a Program Manager in the MEXT DDT Project on rescue robotics, from 2002 to 2007, and a Project Manager at the Japan Cabinet Office ImpACT Tough Robotics Challenge Project on disaster robotics, from 2014 to 2019, with 62 international PIs and 300 researchers who created cyber rescue canine and dragon fire-fighter. His research team in Tohoku University has developed various rescue robots, two of which, quince and active scope camera, are widely recognized for their contribution to disaster response, including missions in the Fukushima-Daiichi NPP nuclear reactor buildings. He is a fellow of RSJ, JSME, and SICE.

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