IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 3, 2019, accepted January 4, 2020, date of publication January 13, 2020, date of current version January 21, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2966037

Nonlinear Error Feedback Positioning Control for a Pneumatic Soft Bionic Fin via an Extended State Observer

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This work was supported by the National Science Foundation of China under Grant 91748123.

ABSTRACT This paper presents a nonlinear error feedback controller for a pneumatic soft bionic fin based on an extended state observer. Manufacturing process is shown for a bionic stingray with the pneumatic soft bionic fin. A test experiment is carried out for a driving part in the pneumatic soft bionic fin by upper chamber inflated and lower chamber inflated with different internal pressures. A dynamic nonlinear system is established for the pneumatic soft bionic fin by test experiment results and kinematic modeling. Total disturbances of the dynamic nonlinear system are estimated and compensated by the extended state observer and the nonlinear error feedback controller, respectively. Moreover, both the convergence of the extended state observer and stability of the dynamic nonlinear system are proved by Lyapunov approach. Finally, simulation results are shown to verify the effectiveness of the proposed control method for the pneumatic soft bionic fin.

INDEX TERMS Bionic stingray, soft bionic fin, kinematic modeling, extended state observer.

I. INTRODUCTION

Since a study of soft robots becomes a burgeoning hotspot, numerous robots with soft mechanisms are created for many fields [1]. Due to the advantages of soft mechanisms for safety operation, cleanliness, excellent flexibility and so on, soft actuators of the soft robots are popular, such as shape memory alloy-actuated multiple degrees of freedom soft robot [2], twisted and coiled polymer-based elastomer soft robot [3]. In addition, fabrications and designs are common for bionic soft robots. For example, snake-like locomotion is obtained by bidirectional fluidic elastomer actuators in [4] for a fluidic soft robot. And a robot arm is built in [5] based on an artificial muscular hydrostat inspired by octopuses. Moreover, some bionic fishs are made using soft materials, such as a fast-moving soft electronic fish [6], an autonomous soft robotic fish [7] and a soft fluidic elastomer robot [8]. It is worth mentioning that stingrays with good motion stability becomes one of numerous bionic fishs objects [9]. Some works on bionic stingray are introduced by researchers in recent years [10]–[12]. In this paper, a kind of bionic stingray is introduced, which is made by soft materials. As a kind of soft robot, the bionic stingray faces a same problem as many soft robots, that is, designs of control method are difficult for soft robots. Accurate models and system states are obtained difficultly for soft robots due to strong nonlinearity and lack of sensors [13]. Therefore, it makes a practical sense for soft robots to choose appropriate control method.

Active disturbance rejection control, which was proposed by Jingqing Han in 1990s, is a model-free control method [14]. As a core of active disturbance rejection control, extended state observer usually is used to estimate nonlinear terms, external disturbances and unmodeled dynamics as total disturbances for dynamic nonlinear systems. The extended state observer is successfully applied in many fields [15], such as wearable hand rehabilitation robot control system [16], multi-agent control systems [17] and pneumatic control systems [18]. The total disturbances estimated by the extended state observer can be compensated in error feedback controller [19]. In generally, nonlinear error feedback controller is better than linear error feedback controller in improving control performance of the dynamic nonlinear

The associate editor coordinating the review of this manuscript and approving it for publication was Ludovico Minati.

system [20]. Therefore, the nonlinear error feedback controller based on the extended state observer may be an effective method to deal with total disturbances in the dynamic nonlinear system of soft robots. This problem is interesting and challenging in both theory and practice, which motivated us carry on this research work.

In this paper, a bionic stingray is introduced with twelve pneumatic soft bionic fins. For realizing desired movement of the bionic stingray, positioning control is considered for a single pneumatic soft bionic fin. By experimental testing, a dynamic nonlinear system is established for the pneumatic soft bionic fin based on kinematic model. Due to properties of soft for the pneumatic soft bionic fin, some nonlinear functions are present in the dynamic nonlinear system. The nonlinear functions are extended as total disturbances and estimated by an extended state observer. Then estimation of the total disturbances are compensated by a nonlinear error feedback controller for improving control performance. Both convergence of the extended state observer and stability of the dynamic nonlinear system are proved by Lyapunov approach. Finally, simulation results are shown to verify the effectiveness of the proposed control method for the dynamic nonlinear system. The main research works of this paper are summarized as below:

- A bionic stingray with twelve pneumatic soft bionic fins are introduced, and a test experiment is carried out for a driving part in the pneumatic soft bionic fin.
- A dynamic nonlinear system is established for the pneumatic soft bionic fin, in which five nonlinear functions caused by soft material features are considered.
- A nonlinear error feedback controller based on an extended state observer is designed to deal with total disturbances caused by the nonlinear functions.

II. PROBLEM STATEMENT AND PRELIMINARIES

A. MANUFACTURE OF BIONIC STINGRAY

As shown in Fig. 1, a bionic stingray is introduced with twelve pneumatic soft bionic fins. By observations of stingray swimming in water, bionic stingray is designed using a bionic fin surface, a bionic fish body and dozen bionic fins. Through the following operation process, the bionic stingray is manufactured with a size similar to that of a real fish using soft materials.

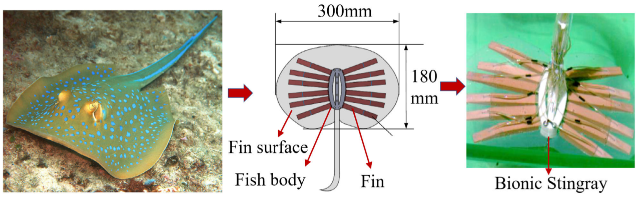

FIGURE 1. Bionic stingray with pneumatic soft bionic fin.

As shown in Fig. 2, preparations of casting materials for the pneumatic soft bionic fin need three operating processes: mixing, stirring and vacuum pumping.

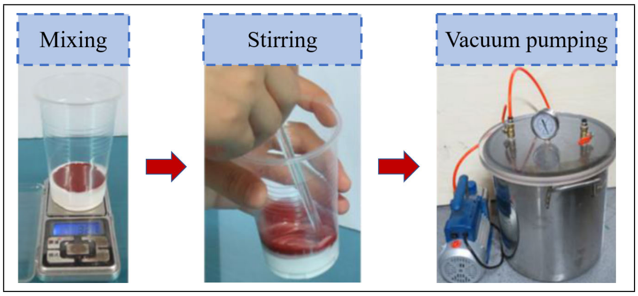

FIGURE 2. Preparations of casting materials.

Material mixing is proportioned with M4601-A and M4601-B at a ratio of 9 to 1. Material stirring with a glass rod until color is uniform for the casting material. To keep the casting material free of air bubbles during casting, a vacuum pumping operation is requested by a vacuum bucket. Then the casting materials can be used to cast the pneumatic soft bionic fin using specific moulds of bionic fin.

Shape of the bionic fin surface is made into by cutting a transparent silica gel plate, which is shown in Fig. 3. Moreover, in twelve pneumatic soft bionic fin positions, twelve hollow surfaces are cut out to avoid influences of the transparent silica gel plate on movements for the pneumatic soft bionic fins.

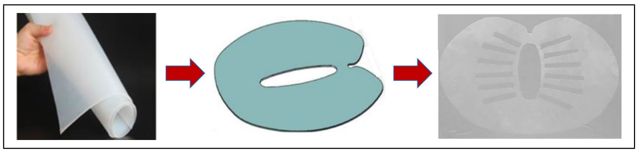

FIGURE 3. Certain shape of bionic fin surface.

As shown in Fig. 4, moulds of the pneumatic soft bionic fin are printed with photosensitive resin materials by a laser rapid prototyping technology. In addition, the bionic fish body is also manufactured by the laser rapid prototyping technology. According to the Fig. 4, the pneumatic soft bionic fin is

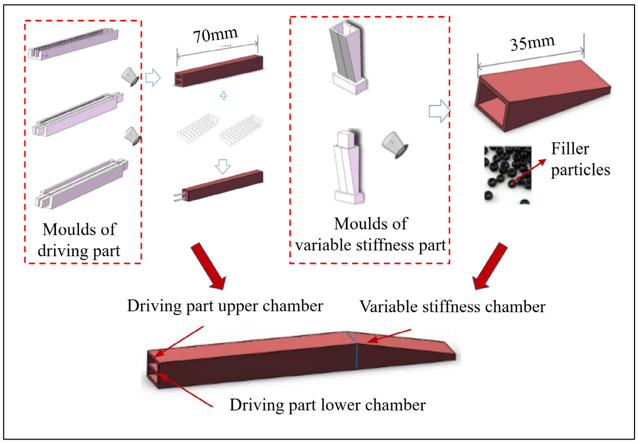

FIGURE 4. Fabrication of the pneumatic soft bionic fin.

composed of the driving part and the variable stiffness part. Lengths of the driving part and the variable stiffness part are designed as 70mm and 35mm, respectively. Twice castings are carried out for the driving part during manufacture process. After the first casting and solidification, fibre threads are wound around the driving part to limit its circumferential expansion. Then second casting is carried out to obtain a complete driving part with two air pipes installed in a upper driving chamber and a lower driving chamber. Functions of the variable stiffness part is considered to be accomplished by blocking technique.

The blocking is a physical process, in which a material consisting of many particles changes from a flexible state to a solid state. Therefore, some annular filler particles with 2mm are filled in the variable stiffness chamber. When filler particles mix with air in the variable stiffness chamber, flexible state is embodied in the variable stiffness part. When different negative pressures are adjusted in the variable stiffness chamber, loose filler particles are squeezed together, different solid states are obtain to change stiffness of the variable stiffness part.

Finally, the pneumatic soft bionic fin is obtained by adjoining the variable stiffness part and the driving part together. Stiffness of the variable stiffness part is changed by adjusting different negative pressures in the variable stiffness chamber. Upward and downward bending deformations of the pneumatic soft bionic fin are realized by adjusting positive internal pressures in the upper driving chamber and the lower driving chamber, respectively.

B. EXPERIMENTAL TEST OF PNEUMATIC SOFT BIONIC FIN

In this paper, control of the driving part are considered only for the pneumatic soft bionic fin. Variable stiffness control of the variable stiffness part in the pneumatic soft bionic fin will be considered in the future work.

To know motion attitudes of the pneumatic soft bionic fin under different control quantities, a test experiment is carried out in this section. Schematic diagram on control structure is shown in Fig. 5 for the pneumatic soft bionic fin.

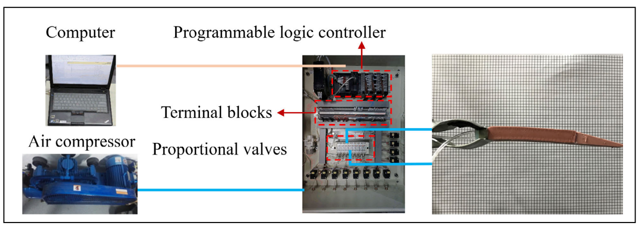

FIGURE 5. Control structure of the pneumatic soft bionic fin.

In the control structure of the pneumatic soft bionic fin, compressed air is produced as power source by the air compressor (TONGYI, TYW-1). By an analog output module (OMRON, CJ1W-DA08V) of programmable logic controller, control signals produced by a computer are used to control two proportional valves (SMC, ITV0050-3ML). Then internal pressures in the upper driving chamber and the lower driving chamber of the pneumatic soft bionic fin are adjusted by the two proportional valves.

Under the control structure shown in Fig. 5, upper chamber inflated and lower chamber inflated are carried out in turn for the pneumatic soft bionic fin. Then attitudes of pneumatic soft bionic fin are shown in Fig. 6 under the case of uninflated, upper chamber inflated and lower chamber inflated with different internal pressures.

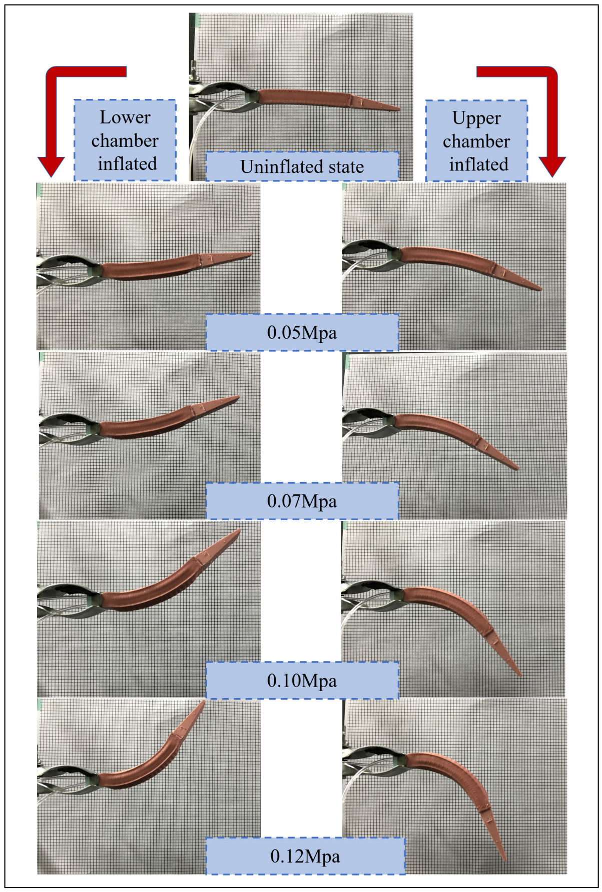

FIGURE 6. Attitudes of pneumatic soft bionic under different internal pressures.

III. DYNAMIC NONLINEAR SYSTEM

By controlling each pneumatic soft bionic fin to complete different motions, a desired motion is achieved for the bionic stingray. Therefore, an appropriate control method is required to carry out precise control for the pneumatic soft bionic fin. To make the pneumatic soft bionic fin complete a desired movement, a dynamic nonlinear system is required to describe trajectory position of the pneumatic soft bionic fin. Then appropriate control method can be designed on the basis of the dynamic nonlinear system to improve positioning precision for the pneumatic soft bionic fin.

A. KINEMATIC MODEL

According to attitudes of the pneumatic soft bionic fin shown in Fig. 6 under uninflated, upper chamber inflated and lower

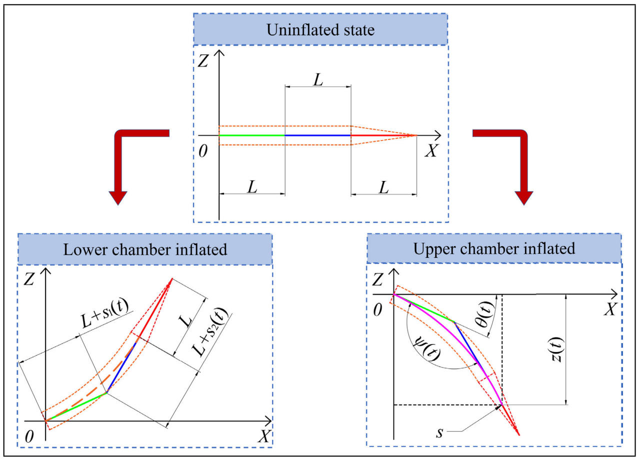

FIGURE 7. **Motion attitudes diagram for the pneumatic soft bionic fin.**

chamber inflated, a schematic diagram is given in Fig. 7 for motion states of the pneumatic soft bionic fin.

In Fig. 7, a coordinate system is established with a central point in end of the pneumatic soft bionic fin is treated as an origin of coordinate. Driving part is average divided two retractable slender rods with functions representing length contraction $s_1(t)$ and $s_2(t)$, $L = 35$mm, $\psi(t)$ is the obtuse angle between two slender rods, $\theta(t)$ is the angle between the pneumatic soft bionic fin and positive direction of X-axis, s represents the distance from a starting point to a specific point on the pneumatic soft bionic fin, $z(t)$ is the coordinate value on Z-axis of the specific point.

According to the Fig. 7, a kinematics model of the pneumatic soft bionic fin is obtained as follows:

$$z(t) = f(t) + \mathrm{sign}(u(t)) \begin{cases} \bar{z}_1, & 0 \le s < L \\ \bar{z}_2, & L \le s < 2L \\ \bar{z}_3, & 2L \le s \le 3L \end{cases} \tag{1}$$

where $f(t)$ indicates unknown external disturbances and unmodeled dynamics, $u(t)$ is the control law, $u(t) > 0$ and $u(t) < 0$ represent lower chamber inflated and upper chamber inflated for the pneumatic soft bionic fin, respectively. An absolute value of $u(t)$ is a control voltage of proportional valve. Moreover, expressions of $\bar{z}_1$, $\bar{z}_2$ and $\bar{z}_3$ are given as follows:

$$\begin{aligned} \bar{z}_1 &= (s + s_1(t)s/L)\sin(\theta(t)), \\ \bar{z}_2 &= (L + s_1(t))\sin(\theta(t)) \\ &\quad + (s - L)(1 + s_2(t)/L)\sin(\psi(t) - \theta(t)), \\ \bar{z}_3 &= (L + s_1(t))\sin(\theta(t)) \\ &\quad + (s - L + s_2(t))\sin(\psi(t) - \theta(t)). \end{aligned}$$

Due to functions $\theta(t)$, $\psi(t)$, $s_1(t)$ and $s_2(t)$ are related to $u(t)$, the following expressions are established as:

$$\theta(t) = f_\theta(t)u(t), \tag{2}$$
$$\psi(t) = 180^\circ + f_\psi(t)u(t), \tag{3}$$
$$s_1(t) = f_{s1}(t)u(t), \tag{4}$$
$$s_2(t) = f_{s2}(t)u(t). \tag{5}$$

Note that $f(t)$, $f_\theta(t)$, $f_\psi(t)$, $f_{s1}(t)$ and $f_{s2}(t)$ are five unknown continuous nonlinear functions.

B. DYNAMIC NONLINEAR SYSTEM

Taking a derivative of $z(t)$ (1), a dynamic nonlinear system is obtained that:

$$\dot{z}(t) = \dot{f}(t) + \mathrm{sign}(u(t)) \begin{cases} \dot{\bar{z}}_1, & 0 \le s < L \\ \dot{\bar{z}}_2, & L \le s < 2L \\ \dot{\bar{z}}_3, & 2L \le s \le 3L \end{cases} \tag{6}$$

where

$$\begin{aligned} \dot{\bar{z}}_1 &= [(s + s_1(t)s/L)\cos(\theta(t))f_\theta(t) + f_{s1}(t)\sin(\theta(t))]\dot{u}(t) \\ &\quad + [(s + s_1(t)s/L)\cos(\theta(t))\dot{f}_\theta(t) + \dot{f}_{s1}(t)\sin(\theta(t))]u(t), \\ \dot{\bar{z}}_2 &= [(L + s_1(t))\cos(\theta(t))f_\theta(t) + f_{s1}(t)\sin(\theta(t)) \\ &\quad + (s - L - s_2(t)(s - L)/L)\cos(\theta(t) - \psi(t))(f_\psi(t) - f_\theta(t)) \\ &\quad + f_{s2}(t)\sin(\theta(t) - \psi(t))(s - L)/L]\dot{u}(t) \\ &\quad + [(L + s_1(t))\cos(\theta(t))\dot{f}_\theta(t) + \dot{f}_{s1}(t)\sin(\theta(t)) \\ &\quad + (s - L - s_2(t)(s - L)/L)\cos(\theta(t) - \psi(t))(\dot{f}_\psi(t) - \dot{f}_\theta(t)) \\ &\quad + \dot{f}_{s2}(t)\sin(\theta(t) - \psi(t))(s - L)/L]u(t), \\ \bar{z}_3 &= [(L + s_1(t))\cos(\theta(t))f_\theta(t) + f_{s1}(t)\sin(\theta(t)) \\ &\quad + (s - L - s_2(t))\cos(\theta(t) - \psi(t))(f_\psi(t) - f_\theta(t)) \\ &\quad + f_{s2}(t)\sin(\theta(t) - \psi(t))]\dot{u}(t) \\ &\quad + [(L + s_1(t))\cos(\theta(t))\dot{f}_\theta(t) + \dot{f}_{s1}(t)\sin(\theta(t)) \\ &\quad + (s - L - s_2(t))\cos(\theta(t) - \psi(t))(\dot{f}_\psi(t) - \dot{f}_\theta(t)) \\ &\quad + \dot{f}_{s2}(t)\sin(\theta(t) - \psi(t))]u(t). \end{aligned}$$

Setting $z_1(t) = z(t)$, an item $\dot{f}(t) - b_0u(t) + \mathrm{sign}(u(t))\{\cdots$ is treated as total disturbances and extended a new state $z_2(t)$, then the dynamic nonlinear system (6) for the pneumatic soft bionic fin is rewritten as follows:

$$\begin{cases} \dot{z}_1(t) = z_2(t) + b_0u(t), \\ \dot{z}_2(t) = h(t, Z), \\ y(t) = z_1(t). \end{cases} \tag{7}$$

where $y(t)$ is the output of the dynamic nonlinear system (7), $h(t, Z)$ is a derivative of $z_2(t)$, Z is a variable associated with states $z_1(t)$ and $z_2(t)$. b_0 is an adjustable parameter,which is a rough approximation of uncertain input gain for $u(t)$. Moreover, the derivatives of $z_2(t)$ in the dynamic nonlinear system (7) are bounded. Therefore, the following inequalities are obtained as:

$$h(t, Z) \le \Delta_1, \tag{8}$$

where Δ_1 is the positive constant. Due to limitation of practical moving range of the pneumatic soft bionic fin, it is reasonable to limit a rate of change for $z_2(t)$ in the dynamic nonlinear system (7).

IV. CONTROL METHOD

As shown in Fig. 8, a schematic diagram of a control method is shown for the pneumatic soft bionic fin. The proposed control method consists of an extended state observer and a nonlinear error feedback controller.

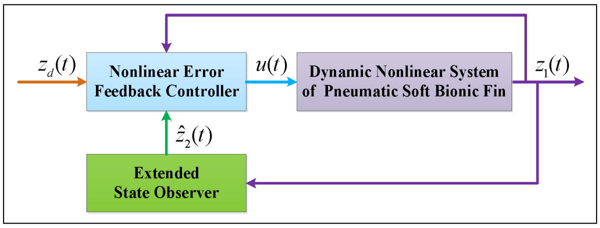

FIGURE 8. Schematic diagram on control method of this paper.

A. EXTENDED STATE OBSERVER

Considering the dynamic nonlinear system (7), an extended state observer is designed as follows:

$$\begin{cases} e_1(t) = \hat{z}_1(t) - z_1(t), \\ \dot{\hat{z}}_1(t) = \hat{z}_2(t) - \xi_1 e_1(t) + b_0 u(t), \\ \dot{\hat{z}}_2(t) = -\xi_2 e_1(t), \end{cases} \tag{9}$$

where ξ_1 and ξ_2 are two adjustable gains, $e_1(t)$ is the estimation error of $z_1(t)$, $\hat{z}_1(t)$ and $\hat{z}_2(t)$ are estimation values of $z_1(t)$ and $z_2(t)$ in the dynamic nonlinear system (7), respectively.

According to the dynamic nonlinear system (7) and the extended state observer (9), an estimation error system is obtained as:

$$\begin{cases} e_1(t) = \hat{z}_1(t) - z_1(t), \\ \dot{e}_1(t) = e_2(t) - \xi_1 e_1(t), \\ \dot{e}_2(t) = -\xi_2 e_1(t) - h(t, Z), \end{cases} \tag{10}$$

where $e_2(t)$ is the estimation error of $z_2(t)$, and an expression of $e_2(t)$ is shown as follows:

$$e_2(t) = \hat{z}_2(t) - z_2(t). \tag{11}$$

In the following, a theorem is provided for showing convergence of the extended state observer (9).

Theorem 1: Consider the extended state observer (9) for the dynamic nonlinear system (7). If there exist constants $\eta_1 > 0$, $\eta_2 > 0$ and $0 < c < \min\{\eta_1, \eta_2\}$ such that:

$$\xi_1 > 0, \tag{12}$$

$$\xi_2 = \frac{\xi_1 c + \eta_1}{\eta_2}, \tag{13}$$

then the estimation error system (10) is globally ultimately bounded. That is, the estimation values $\hat{z}_1(t)$ and $\hat{z}_2(t)$ of the extended state observer (9) track to the states $z_1(t)$ and $z_2(t)$ of the dynamic nonlinear system (7) with bounded errors, respectively. Two error boundeds of the estimation errors $e_1(t)$ and $e_2(t)$ are shown as follows:

$$|e_1(t)| \le \frac{\Delta_1 c}{\xi_1\eta_1 - c\xi_2}, \quad |e_2(t)| \le \frac{\Delta_1 \eta_2}{c}.$$

Proof 1: According to the estimation error system (10), a Lyapunov function is constructed as follows:

$$V_e(t) = \frac{1}{2}\eta_1 e_1^2(t) + \frac{1}{2}\eta_2 e_2^2(t) - c e_1(t) e_2(t).$$

The derivative of $V_e(t)$ is obtained as follows:

$$\begin{aligned} \dot{V}_e(t) &= \eta_1 e_1(t)\dot{e}_1(t) + \eta_2 e_2(t)\dot{e}_2(t) \\ &\quad - c e_2(t)\dot{e}_1(t) - c e_1(t)\dot{e}_2(t) \\ &= (c\xi_2 - \xi_1\eta_1)e_1^2(t) - c e_2^2(t) \\ &\quad - \eta_2 h(t, Z) e_2(t) + c h(t, Z) e_1(t) \\ &\quad + (\eta_1 - \eta_2\xi_2 + \xi_1 c) e_1(t) e_2(t). \end{aligned} \tag{14}$$

When two gains ξ_1 and ξ_2 of the extended state observer (9) are satisfied with (12) and (13) respectively, the following expressions are obtained as:

$$\eta_1 - \eta_2\xi_2 + \xi_1 c = 0, \tag{15}$$

$$c\xi_2 - \xi_1\eta_1 < 0. \tag{16}$$

According to the inequality (8), there exist:

$$c h(t, Z) e_1(t) \le \Delta_1 c |e_1(t)|, \tag{17}$$

$$-\eta_2 h(t, Z) e_2(t) \le \Delta_1 \eta_2 |e_2(t)|. \tag{18}$$

By expressions (15)-(18), the derivative (14) is rewritten as follows:

$$\dot{V}_e(t) < (c\xi_2 - \xi_1\eta_1)e_1^2(t) + \Delta_1 c |e_1(t)| - c e_2^2(t) - \Delta_1 \eta_2 |e_2(t)|. \tag{19}$$

According to the derivative (19), the following relationships are obtained as:

$$|e_1(t)| \le \frac{\Delta_1 c}{\xi_1\eta_1 - c\xi_2},$$

$$|e_2(t)| \le \frac{\Delta_1 \eta_2}{c}.$$

Therefore, there exist properly gains ξ_1 and ξ_2 in the extended state observer (9) such that the estimation error system (10) is globally ultimately bounded. That is, when expressions (12) and (13) are satisfied with, the estimation values $\hat{z}_1(t)$ and $\hat{z}_2(t)$ of the extended state observer (9) track to the states $z_1(t)$ and $z_2(t)$ of the dynamic nonlinear system (7) with bounded errors, respectively. The proof is completed.

B. NONLINEAR ERROR FEEDBACK CONTROLLER

Considering the dynamic nonlinear system (7) and the extended state observer (9), a nonlinear error feedback controller is designed as follows:

$$u(t) = \frac{-\hat{z}_2(t) + k fal(r(t), \alpha, \delta)}{b_0}, \quad r(t) = z_d(t) - z_1(t). \tag{20}$$

where $z_d(t)$ is the desired output of the dynamic nonlinear system (7), $r(t)$ is the error variable, k is the adjustable positive parameter, $fal(r(t), \alpha, \delta)$ is the nonlinear function to obtain good performance. An expression of $fal(r(t), \alpha, \delta)$ is given as follows:

$$fal(r(t), \alpha, \delta) = \begin{cases} \dfrac{r(t)}{\delta^{1-\alpha}}, & |r(t)| \le \delta \\ |r(t)|^{\alpha} \mathrm{sign}(r(t)), & |r(t)| > \delta \end{cases} \tag{21}$$

where $0 < \alpha < 1$ and $\delta > 0$.

To achieve better control performance of the nonlinear error feedback controller (20), different nonlinear characteristics can be obtained for the nonlinear function (21) by adjusting parameters α and δ.

For stability analysis of the dynamic nonlinear system (7), an inequality is defined as follows:

$$|\dot{z}_d(t) + e_2(t)| \leq \Delta_2, \tag{22}$$

where Δ_2 is the positive constant. Accroding to the Theorem 1, the estimation error $e_2(t)$ is bounded. Moreover, the desired output $z_d(t)$ and its derivative $\dot{z}_d(t)$ are generally bounded. Therefore, the definition of the inequality (22) is reasonable.

Then a theorem is given in the following to show the stability of the dynamic nonlinear system (7) via the nonlinear error feedback controller (20).

Theorem 2: Consider the nonlinear error feedback controller (20) for the dynamic nonlinear system (7) under the extended state observer (9). If there exists $k > 0$ in the nonlinear error feedback controller (20), then the error variable $r(t)$ is globally ultimately bounded. That is, the output $z_1(t)$ track to the desired output $z_d(t)$ with bounded errors for the dynamic nonlinear system (7). Furthermore, if the adjustable parameter k is satistied with the following inequality:

$$k \geq \Delta_2 \delta^{-\alpha}, \tag{23}$$

then the error bounded of the error variable $r(t)$ is obtained as follows:

$$|r(t)| \leq (\frac{\Delta_2}{k})^{\frac{1}{\alpha}}. \tag{24}$$

Moreover, when the adjustable parameter k is satistied with the following inequality:

$$0 < k < \Delta_2 \delta^{-\alpha}, \tag{25}$$

the error bounded of the error variable $r(t)$ is obtained as follows:

$$\delta < |r(t)| \leq (\frac{\Delta_2 \delta^{1-\alpha}}{k}). \tag{26}$$

Proof 2: According to the dynamic nonlinear system (7), a Lyapunov function is designed as follows:

$$V(t) = \frac{1}{2} r^2(t).$$

Taking a derivative of $V(t)$, it is obtained that:

$$\begin{aligned} \dot{V}(t) &= r(t)(\dot{z}_d(t) - z_2(t) - b_0 u(t)) \\ &= r(t)(\dot{z}_d(t) - z_2(t) + \hat{z}_2(t) - kfal(r(t), \alpha, \delta)) \\ &= r(t)(\dot{z}_d(t) + e_2(t)) - kr(t)fal(r(t), \alpha, \delta). \end{aligned} \tag{27}$$

By the inequality (22), there exist:

$$\dot{V}(t) < |r(t)|\Delta_2 - kr(t)fal(r(t), \alpha, \delta). \tag{28}$$

According to the nonlinear function $fal(r(t), \alpha, \delta)$ (21), two cases on the derivative (28) are considered in the following.

Case 1: $|r(t)| \leq \delta$.

In case 1, the derivative (28) of $V(t)$ is written as follows:

$$\begin{aligned} \dot{V}(t) &< |r(t)|\Delta_2 - k\frac{r^2(t)}{\delta^{1-\alpha}} \\ &< |r(t)| \left(\Delta_2 - k\frac{|r(t)|}{\delta^{1-\alpha}} \right). \end{aligned} \tag{29}$$

By the derivative (29), it is obtaind that: If the adjustable parameter k is satistied with the following inequality:

$$k \geq \Delta_2 \delta^{-\alpha},$$

then the following relationship of the error variable $r(t)$ is obtained as:

$$|r(t)| \leq (\frac{\Delta_2}{k})^{\frac{1}{\alpha}}.$$

Case 2: $|r(t)| > \delta$.

In case 2, the derivative (28) of $V(t)$ is obtained as follows:

$$\begin{aligned} \dot{V}(t) &< |r(t)|\Delta_2 - kr(t)|r(t)|^{\alpha}\text{sign}(r(t)) \\ &< |r(t)| \left(\Delta_2 - k|r(t)|^{\alpha} \right). \end{aligned} \tag{30}$$

By the derivative (30), it is obtaind that: If the adjustable parameter k is satistied with the following inequality:

$$0 < k < \Delta_2 \delta^{-\alpha},$$

then the following relationship of the error variable $r(t)$ is obtained as:

$$\delta < |r(t)| \leq (\frac{\Delta_2 \delta^{1-\alpha}}{k}).$$

Therefore, when the adjustable parameter $k > 0$ in the nonlinear error feedback controller (20), then the error variable $r(t)$ is globally ultimately bounded. That is, the output $z_1(t)$ track to the desired output $z_d(t)$ with bounded errors for the dynamic nonlinear system (7). Moreover, if parameters k in the nonlinear error feedback controller (20) is satisfied with the inequalities (23) and (25), then the error bounded of the error variable $r(t)$ is obtained as the inequalities (24) and (26), respectively. The proof is completed.

V. SIMULATION RESULTS

In this section, two positioning control simulation results for the dynamic nonlinear system (7) of the pneumatic soft bionic fin are introduced to indicate the effectiveness for the proposed control method of this paper. In the two positioning control simulations, all sampling period is 0.01s, the specific point s is chosen as $s = 105$ in the kinematics model (1) of the pneumatic soft bionic fin.

In the first positioning control simulation, a sinusoidal signal $z_d(t)$ is given for the specific point as a given desired signal. Both a frequency and an amplitude for the given desired signal $z_d(t)$ are chosen as 0.2Hz and 70mm, respectively. Nonlinear functions $f(t), f_\theta(t), f_\psi(t), f_{s1}(t)$ and $f_{s2}(t)$ in the dynamic nonlinear system (7) are set as follows:

$$f(t) = 4\cos(0.8\pi)\text{mm},$$

$$f_\theta(t) = 40^\circ \sin(0.4\pi),$$

$$f_{\psi}(t) = -20^{\circ}\sin(0.4\pi),$$
$$f_{s1}(t) = -3.5\sin(0.4\pi)\text{mm},$$
$$f_{s2}(t) = -3.5\sin(0.4\pi)\text{mm}.$$

Moreover, adjustable parameters on the proposed control method of this paper are set listed in TABLE 1 for the first positioning control simulation.

TABLE 1. Parameters of the proposed control method.

	Parameters	
Extended state observer	$\xi_1 = 10$	$\xi_2 = 2000$
Error feedback controller	$k_1 = 50$	$\alpha = 0.75$
	$b_0 = 8000$	$\delta = 0.01$

Simulation results of the first positioning control for the pneumatic soft bionic fin are shown in Fig. 9-Fig. 10.

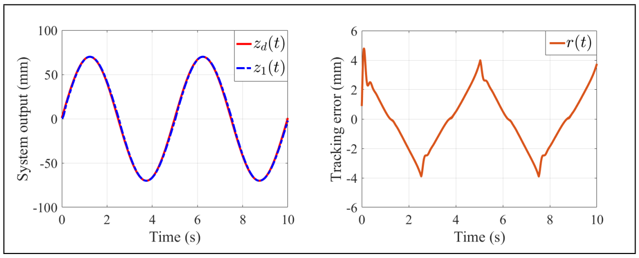

FIGURE 9. Positioning results of the pneumatic soft bionic fin.

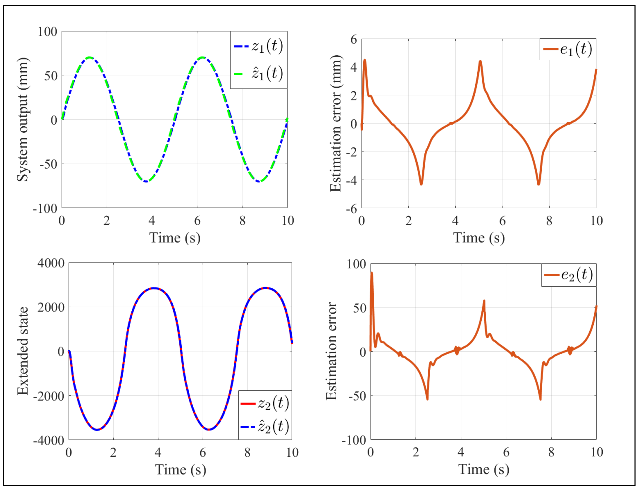

FIGURE 10. Observation results of the extended state observer.

According to the simulation results shown in Fig. 9, the output $z_1(t)$ for the dynamic nonlinear system (7) tracks the given desired signal $z_d(t)$, and the positioning error $r(t)$ is less than 5mm. Moreover, observation results of the extended state observer (9) are given in Fig. 10, according to the simulation results, the eatimation values $\hat{z}_1(t)$ and $\hat{z}_2(t)$ are almost coincident with $z_1(t)$ and $z_2(t)$, respectively.

In the second positioning control simulation, a step signal $z_d(t)$ is given for the specific point as a given desired signal. An expression of the given desired signal $z_d(t)$ is given as follows:

$$z_d(t) = \begin{cases} 35, & 0 \le t < 3 \\ 70, & 3 \le t < 6 \\ 55, & 6 \le t \le 9 \end{cases} \tag{31}$$

Nonlinear functions $f(t)$, $f_{\theta}(t)$, $f_{\psi}(t)$, $f_{s1}(t)$ and $f_{s2}(t)$ in the dynamic nonlinear system (7) are set as follows:

$$f(t) = 4\text{mm}$$
$$f_{\theta}(t) = 40^{\circ}$$
$$f_{\psi}(t) = -20^{\circ}$$
$$f_{s1}(t) = -3.5\text{mm}$$
$$f_{s2}(t) = -3.5\text{mm}$$

Moreover, adjustable parameters on the proposed control method of this paper are set listed in TABLE 2 for the second positioning control simulation.

TABLE 2. Parameters of the proposed control method.

	Parameters	
Extended state observer	$\xi_1 = 10$	$\xi_2 = 2000$
Error feedback controller	$k_1 = 20$	$\alpha = 0.75$
	$b_0 = 8000$	$\delta = 0.01$

Simulation results of the second positioning control for the pneumatic soft bionic fin are shown in Fig. 11-Fig. 12. According to the simulation results shown in Fig. 11, the output $z_1(t)$ for the dynamic nonlinear system (7) tracks the given desired signal $z_d(t)$ quickly and steadily. The response time of the output $z_1(t)$ is less 0.5s and the steady-state positioning error trends to 0. Moreover, there is few overshoot phenomenon in simulation results of the positioning control for the step signal $z_d(t)$ (31).

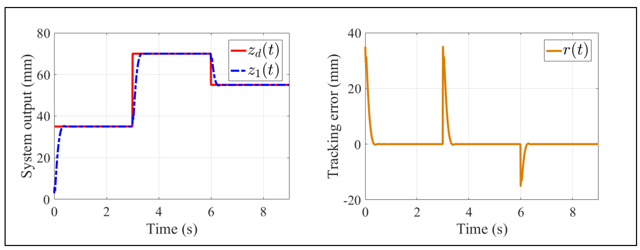

FIGURE 11. Positioning results of the pneumatic soft bionic fin.

In addition, observation results of the extended state observer (9) are given in Fig. 12, according to the simulation results, the eatimation values $\hat{z}_1(t)$ and $\hat{z}_2(t)$ are almost coincident with $z_1(t)$ and $z_2(t)$, respectively.

In sum, the effectiveness of the nonlinear error feedback controller (20) based on the extended state observer (9) is shown by two positioning control simulation results for the dynamic nonlinear system (7). That is, the two positioning

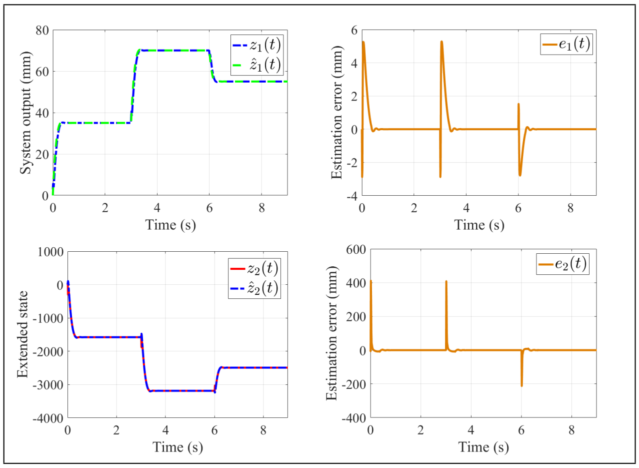

FIGURE 12. Observation results of the extended state observer.

control simulation results indicate that the proposed control method in this paper has strong advantages and practicality in positioning control for the pneumatic soft bionic fins.

VI. CONCLUSION

In this paper, manufacturing of a bionic stingray has been introduced with dozen pneumatic soft bionic fins. The pneumatic soft bionic fin has been cast by specific moulds and casting material. A test experiment has been carried out for a driving part in the pneumatic soft bionic fin by upper chamber inflated and lower chamber inflated with different internal pressures. Using results of the test experiment, a dynamic nonlinear system has been established for the pneumatic soft bionic fin based on kinematic model. A nonlinear error feedback controller has been introduced for a pneumatic soft bionic fin based on an extended state observer. Both the convergence of the extended state observer and stability of the dynamic nonlinear system have been obtained using Lyapunov approach. Finally, a sinusoidal signal and a step signal have been given as desired signals for positioning control simulation of the pneumatic soft bionic fin. And simulation results have been given to show the effectiveness of the proposed control method of this paper for the dynamic nonlinear system of the pneumatic soft bionic fin.

In the future work, positioning control physical experiments of the pneumatic soft bionic fin and the bionic stingray are considered to carry out for showing effectiveness of the proposed control method of this paper. In addition, dynamics modeling is considered for the pneumatic soft bionic fin and the bionic stingray. Moreover, the proposed control method of this paper is considered for improvement using more model information of the pneumatic soft bionic fin.

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