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RESEARCH ARTICLE

Research on Uncertain Stochastic Nonlinear System Based on Piecewise Loosely Constrained Nonlinear Characteristics and Backstepping Design Through Memristor Mode

FANG WANG[1,2], LONGCHUAN GUO[3], AND JIAQI PAN[3]
[1]School of Information and Electrical Engineering, Hangzhou City University, Hangzhou 310015, China
[2]Science and Technology on Underwater Vehicle Technology Laboratory, Harbin Engineering University, Harbin 150001, China
[3]School of Mechanical Engineering, Hangzhou Dianzi University, Hangzhou 310018, China

Corresponding author: Longchuan Guo (glc1988@126.com)

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ABSTRACT In this paper, we mainly study the output feedback control problem of stochastic nonlinear system based on loose growth conditions and applies the research results to the electric vehicle control system of underwater oil and gas pipelines, which can improve the speed and stability of the equipment system. Firstly, the concept of randomness is introduced to study the tracking control problem of the system, which meet the more general polynomial function growth conditions. A combination of static and dynamic output feedback practices is proposed. The tracking controller makes all the states of the system, which meet boundedness and ensures that the tracking error of the system converges to a small neighborhood of zero. Secondly, the system is extended to the parameter uncertain system, the controller with complete dynamic gain is constructed by proving the boundedness of the system state and gain. Furtherly, the nonlinear term of the system satisfies the more relaxed power growth condition, combined with the inverse method to construct a set of Lyapunov functions and obtain the controller to ensure that the system is asymptotically probabilistic stability in the global scope. Finally, through the ocean library in the Simulation X software, the controller design results are imported into the underwater electro-hydraulic actuator model to verify the effectiveness.

INDEX TERMS Complex uncertain nonlinear systems, system growth conditions, feedback control with dynamic and static.

I. INTRODUCTION

The underwater Electric Vehicle system is proposed relative to the surface mining technology (such as fixed platforms and floating production facilities.), which is a development technology that has been widely used in underwater oil and gas(UOG) fields. Underwater production system are increasingly becoming an efficient development of UOG fields and important technical means for offshore marginal oilfields. A typical subsea production system is shown in Figure 1. The continuous enrichment of development modes puts forward higher requirements for the underwater control system accordingly, which further promotes the technological innovation of the under-water control system from composite electro-hydraulic control to all-electric under-water control system.

As an important equipment to control the normal production of underwater oil-fields, the underwater control system shoulders the important task of ensuring the production of UOG, which is the bridge between the underwater production

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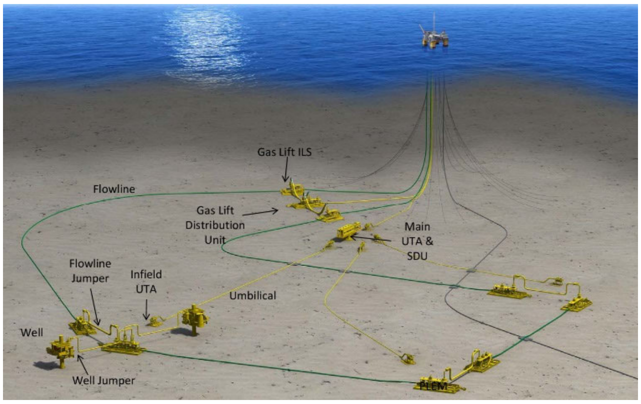

FIGURE 1. Typical subsea production control system.

system and the superstructure. Nowadays, the basic function requirements of the underwater production system for the underwater control system mainly include the following main aspects:

(1) During normal operation, the opening and closing of underwater valves can be remotely controlled according to production needs;

(2) Monitoring the operating parameters of the subsea production system;

(3) Complete underwater emergency shutdown;

(4) Adjust subsea production and injection nozzles;

(5) Switch the position of the flow-through (TFL) tool diverter;

(6) Chemical injection.

It is particularly worth noting that, in the field of UOG development, the under-water electro-hydraulic valve actuator is affected by different components in the pipe-line. The system model of valve opening process presents a system model based on Hölder constraints. Research on piecewise linear systems has been achieved a series of results [5], [11], [12], [13], for example, the piecewise linearization of linear time-varying systems is discussed. In [12], its stability is studied; in [6], the robust stability problem of piecewise linear systems with uncertain parameters is studied; in [5], the author studies the design of robust output feedback controllers for piecewise linear systems with uncertain parameters. The design of state filters for piecewise linear systems with variable delays is studied in [11]. In [13], the author studies the robustness of piecewise linear systems with distributed delays in combination with sliding mode control theory and stick control problem. In recent years, the application of memristor in chaotic circuits and logic gate circuits has also received more and more attention and research [7], [8], [9], [10]. Piecewise linear systems, as an important class of nonlinear systems, are widely used to practical engineering. Piecewise linear systems are composed of a series of linear time-invariant subsystems. The research on piecewise linear systems is mainly based on the following two considerations:

(1) In some practical systems, there are components with piecewise linear characteristics [1], [2], [3]. For example, paper [1] studies a robust control problem for a memristor loop with piecewise linear properties; literature [2] studies a NASA aerospace vehicle test system with piecewise linear properties and a piecewise linear mechanical system et al [3].

(2) Many nonlinear systems can be approximated by piecewise linear systems [4]. Piecewise linearity provides a reliable and effective method for the analysis and control of nonlinear systems.

In today's world, with the development of science and technology, the application fields of underwater robots have been continuously expanding worldwide, such as ocean research, scientific exploration, ocean development and underwater engineering, ocean environmental monitoring, ocean geoscience data collection, and seabed re-source survey. As an important carrier for underwater transportation technology, autonomous underwater vehicles (AUVs) have become a research hotspot in various countries around the world. In the late 1950s, the University of Washington in the United States began planning to develop the world's first cableless underwater robot ''SPURV''. The successful development of this underwater robot marked the beginning of the era of cableless underwater robots. However, due to technological limitations in the early stages, AUVs at that time had varying degrees of shortcomings, including low efficiency, high cost, and excessive volume [9]. With the development of science and electronics technology, the research and design of AUVs has gradually entered an era of rapid development. By the 1990s, AUVs had been able to achieve many predetermined goals and had simple operational systems. AUV technology has gradually moved from academic research to mainstream commercial fields in the ocean, including many associations established internationally, such as the IEEE Ocean Engineering Society, The IEEE Robotics and Automation Society and others have made varying degrees of contributions to promoting the development of underwater robot technology. The research on underwater robots in China started relatively late, and it was not until 1970 that large-scale research on underwater vehicles began. After more than 20 years of research, various types of underwater robots with rescue and lifesaving capabilities were successfully developed. These studies have made China's level of underwater robots reach a leading international level. Until the 1990s, significant breakthroughs were made in the development technology of deep-sea diving robots in China, including various submersibles represented by the Explorer, which enabled China to efficiently, accurately, and comprehensively investigate, measure, and store information in about 96% of the ocean area (outside the trench), and complete real-time transmission, This has laid a solid foundation for the large-scale exploration and exploitation of deep ocean resources in China in the future.

With the application and popularization of intelligent trap science and technology such as scientific and technological automation and wireless communication technology, the functions of intelligent underwater vehicles in China will be more scientific and intelligent, and the corresponding development trends are mainly shown in the following aspects:

1. Intelligent development of robots: due to the difficulty of under-water operations, it is necessary to improve the learning ability of the intelligent system of the entire underwater vehicle, Enhance the robot's ability to cope with position-al environments underwater, ensuring that it can handle marine development work in various environments;

2. Achieving high precision of underwater robot navigation: In order to achieve the requirements of navigation and positioning of underwater robot operation and its own motion recognition, new underwater robot motion diving technology needs to be developed in time. There are many high-precision navigation matching technologies, such as underwater terrain matching navigation technology and other geophysics navigation technologies. Among them, underwater terrain matching navigation technology has high navigation precision The advantage of high efficiency has led to the widespread application of submarine equipment by the US Navy;

3. Development towards high energy density: Underwater robots have gradually had a great demand not only for armaments, but also for civilian use. Therefore, durable endurance has become a key trend and problem that needs to be solved in the development of underwater robots. Due to the limited energy storage space of under-water robots, it is even more necessary to use energy tightly and efficiently, while reducing the total carrying capacity, try to increase the time for advancement as much as possible;

4. Development towards modular and standardized production: In order to ensure the widespread application and promotion of underwater robots, while ensuring the operational performance of equipment, it is necessary to achieve batch and programmed production of underwater robots. This requires the establishment of standard specifications and modular production lines.

From simple piecewise linear systems to piecewise linear systems including time-delay terms and uncertain parameters, which into the piecewise linear systems research. But in practical applications, piecewise linear systems include uncertain parameter disturbances, time-delay links and disturbances [14]. As one of the robust control strategies, the sliding mode variable structure controller has a good effect on dealing with uncertain parameters and disturbances. Sliding mode variable structure control has been widely used in complex dynamic system control problems, such as time-delay systems [15], [16], [17], [20], parameter uncertain systems [15], stochastic systems [16] and Markovian jumping systems [17].

The design of the sliding mode variable structure controller mainly consists of the following two steps: first, design the sliding mode surface of the system, so the system state has ideal stability and motion performance on the sliding mode surface [18]; second, design a reasonable controller satisfies the reachability condition of system sliding mode control [7].

Therefore, in this paper the research question mainly considers the following three points:

(1) Design a reasonable sliding mode surface for an uncertain piecewise linear timedelay system and the stability conditions satisfy the sliding mode control;

(2) The new method should select a reasonable Lyapunov function for the state-lag piecewise linear time-delay system;

(3) Based on the stability of the sliding mode control of the system, the control law is designed in combination with the controller parameters to ensure that the sliding mode control of the piecewise linear system meets the accessibility conditions.

The traditional control method model has relatively strong constraints. In this paper, we relax the constraints. The control method based on the reverse thrust output feedback is applied to the underwater equipment to make it run stably. Based on the above analysis, this paper will introduce the research system. By introducing the transfer function and the linear matrix inequality condition, the piecewise linear system exists in the sliding mode sur-face stability condition. The control law is designed to make the system meeting the sliding mode control accessibility. Chaotic circuit based on piecewise linear characteristic memristor will be analyzed in this paper. By simulating and analyzing the sliding mode controller verify the effectiveness of the controller design.

All functions of the underwater control module are achieved through its reliable internal hardware configuration and hardware based software configuration. The implementation of the data collection function provides a data source for the underwater control module to control normal production underwater, and the data is collected through the communication interface to the SEM inside the underwater control mod-ule. The specific communication scheme and interface form are shown in the communication scheme chapter. The underwater control module sends control commands based on real-time collected data, drives the hydraulic control valve to control the conduction and closure of the hydraulic channel, and switches the working status of the underwater actuator, thereby controlling the underwater valve. In order to prevent the failure of the underwater control system due to the functional failure of the underwater control module itself, it is necessary to diagnose its working status in re-al-time during the development process of the underwater control module to ensure that the control system can receive and issue correct control commands. The above functional requirements of the underwater control module are based on stable hydraulic power and power supply, and the design of the underwater control module must consider power supply and distribution as important factors.

For the output feedback control problem of nonlinear systems under relaxed growth conditions. Scholars have conducted extensive research work and achieved numerous research results. In [23], for the output feedback control problem of nonlinear systems under the action of complex factors, the author obtained a controller that meets specific performance indicators with the help of stability theory and related controller design tools: 1. Design a nonlinear system output feedback controller that meets the power growth condition; 2.Output feedback control of nonlinear systems satisfying polynomial function growth conditions; 3.Output feedback tracking control for stochastic nonlinear systems with parameter uncertainties satisfying polynomial growth conditions; 4.For the output feedback problem of a class of stochastic nonlinear systems, under the assumption that such systems are exponentially growing, time varying delay factors are introduced, and the output feedback control problem of such problems is studied by using the stability analysis principle; 5.The output feedback controller is designed for high-order stochastic nonlinear systems with time-varying delays that satisfy the power growth condition.

NN [26], [27] estimators are used to deal with nonlinear dead zones and unknown dynamics in servos. Develop and incorporate new variables into controller designs to improve transient and steady-state performance. A finite-time filter is introduced to remove the complexity phenomenon in traditional backstepping [30]. Observers with adaptive control capabilities, such as neural networks (NNs) [28] and fuzzy logic systems, have been studied for various nonlinear systems. Some methods that do not converge may cause slow control system response and complicate parameter tuning. The goal of this paper is to propose a new design method to replace the adaptive estimation error adaptive control. The parameter estimation errors are extracted with the new control law [29]. The convergence error of parameter estimation and tracking can be achieved by this new method. The proposed learning algorithm is further proven to guarantee finite-time convergence.

II. DESCRIPTION OF DEEPWATER INTELLIGENT SENSOR NETWORK CONTROL SYSTEM AND MEMRISTOR MODE

Deepwater Electric Vehicle valves and actuators are essential equipment for UOG development, which are widely used in underwater production systems [19]. Compared with onshore valves, deepwater valves involve external environmental influences such as seawater corrosion, deepwater pressure and deepwater temperature. At the same time, the influence of these external factors also requires valves to have higher reliability and longer service life. The composition of deepwater valve and actuator is shown in Figure 2 (1-indicator pointer; 2-pressure compensator; 3-hydraulic injection port; 4-deep water gate valve; 5-actuator body; 6-ROV interface), which is including hydraulic cylinder, ROV (underwater robot) operation interface, mechanical transmission mechanism, valve position indicator and pressure compensation structure for balancing seawater static pressure.

Electro-hydraulic control systems are widely used in aerospace systems, vehicle systems, artillery launch base control and oil extraction. The system has a wide range of applications in actual production and processes. In this section, we consider an ap-plication to the offshore oil and gas production process. Electro-hydraulic valve position control system [20], [22], [25] mainly focuses on the output practical tracking controller design for a class of complex stochastic nonlinear systems with unknown control coefficients. Literature [21] provides a solution for increasing the nonlinear constraint conditions for this paper, which is just suitable for underwater control valve systems.

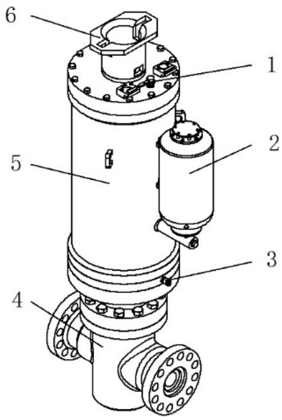

FIGURE 2. Deepwater gate valve actuator.

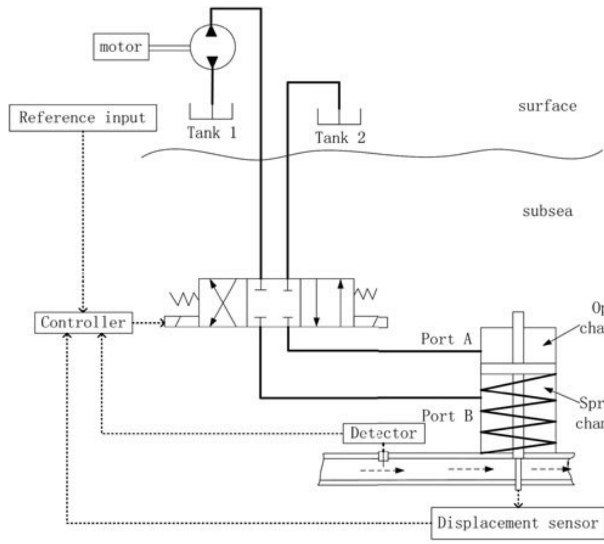

FIGURE 3. Deepwater intelligent sensor network control system and Memristor mode.

The electro-hydraulic composite valve position control system is composed a water equipment part and an underwater equipment part (as shown in Figure 3). The water part includes liquid supply unit, hydraulic station, power units and other control units; the underwater part includes electromagnetic reversing valve, hydraulic actuator and the electronic control unit that controls the electromagnetic reversing valve, the inside of the electronic control unit is the controller logic design.

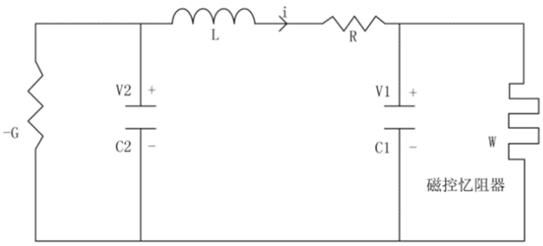

FIGURE 4. Memristor mode.

III. ROBUST SLIDING MODE CONTROLLER DESIGN FOR INTELLIGENT SENSOR NETWORK SYSTEMS

Consider the following stochastic nonlinear intelligent sensor network systems:

$$\begin{cases} dx_i = x_{i+1}dt + \phi_i(x)\,d\omega \\ \qquad\qquad i = 1, \cdots, n-1, \\ dx_n = udt + \phi_n(x)\,d\omega \\ y = x_1 \end{cases} \tag{1}$$

where $x = (x_1, \cdots, x_n) \in R^n$, $u \in R$ and $y \in R$ are the states, the control input and the measurable output of the system, respectively. Here, we introduce a stochastic process for the system: ω is an m - dimensional standard Wiener process defined on the complete probability space (Ω, Γ, P) with Ω being a sample space, Γ being a filtration, and P being a probability measure. Observable state $x_2, \cdots, x_n$ is not measurable. $\phi_i : R^n \to R^r, i = 1, \cdots, n$ is satisfied a power growth conditions and is local Lipschitz.

Assumption 1: for each $1 \le i \le n$, there exists the known positive constants $d \ge 0$ such that $|\phi_i(x)| \le d(|x_1|^p + |x_2|^p + \cdots + |x_i|^p)$, where p is any positive integer.

Remark 1: the design of the sliding mode variable structure observer and con-troller of the piecewise linear time-delay system with unmeasurable state variables of the system is considered. By considering the sliding mode surface design of the observer of the piecewise linear system, the stability of the sliding mode motion of the system is carried out. Through the analysis, the robust sliding mode H∞ stability conclusion of the piecewise linear time-delay system is obtained. At the same time, the control law is designed to make the system possess the robust sliding mode H with the given "sliding mode" motion characteristics and parameter disturbances at the same time.

Since $x_2, \cdots, x_n$ are unmeasured, the following observer is introduced:

$$\begin{cases} \dot{\hat{x}}_i = \hat{x}_{i+1} + K^i h_i\left(x_1 - \hat{x}_1\right), \\ \qquad\qquad i = 1, \cdots, n-1, \\ \dot{\hat{x}}_n = u + K^n h_n\left(x_1 - \hat{x}_1\right) \end{cases} \tag{2}$$

where $\hat{x}_i$ is the estimated value of x_i, $K \in \hat{E}R_+$ is the observer gain to be determined, $h_i > 0$ $i = 1, \cdots, n$ are chosen such that matrix $A = \begin{pmatrix} -h_1 & \\ \dots & I_{n-1} \\ -h_n & 0 \ \dots \ 0 \end{pmatrix}$ is asymptotically stable, thus there exists a positive definite matrix P satisfying $A^TP + PA = -I$. Let $\tilde{x} = (\tilde{x}_1, \cdots, \tilde{x}_n)^T$, where $\tilde{x}_i = \frac{(x_i - \hat{x}_i)}{K^{i-1}}$ for each $i = 1, \cdots, n$. By (1) and (2), we can get error system:

$$d\tilde{x} = KA\tilde{x}dt + \Phi(x)\,d\omega \tag{3}$$

where $\Phi(x) = \left(\phi_1(x), \frac{\phi_2(x)}{K}, \cdots, \frac{\phi_n(x)}{K^{n-1}}\right)^T$.

Now we give the backstepping controller design procedure,

Step 0: Choosing the zeroth Lyapunov function $V_0(\tilde{x}) = (n+1)\tilde{x}^T P\tilde{x}$, applying $(a+b)^2 \le 2(a^2+b^2)$, $\sum_{i=1}^{n}|a_i|^2 \le \left(\sum_{i=1}^{n}|a_i|\right)^2$, $\left(\sum_{i=1}^{n}a_i\right)^2 \le n\sum_{i=1}^{n}a_i^2$, *Lemma 1*, *Assumption 1* and (2), we can lead to

$$\begin{aligned} LV_0 &= -(n+1)K|\tilde{x}|^2 + (n+1)Tr\left(\Phi^T(x)P\Phi(x)\right) \\ &\le -(n+1)K|\tilde{x}|^2 + (n+1)\|P\|\left(\sum_{i=1}^{n}\left|\frac{\phi_i(x)}{K^{i-1}}\right|^2\right) \\ &\le -(n+1)K|\tilde{x}|^2 + (n+1)\|P\|d^2\left(\sum_{i=1}^{n}\frac{1}{K^{i-1}}\right)^2 \\ &\quad \times\left(|x_1|^p + \frac{|x_2|^p}{K} + \cdots + \frac{|x_n|^p}{K^{n-1}}\right) \\ &\le -(n+1)K|\tilde{x}|^2 + 2^{2p-1}nd^* \\ &\quad \times\left(\sum_{i=1}^{n}\left(\frac{\hat{x}_i^p}{K^{i-1}}\right)^2 + \sum_{i=1}^{n}\left(K^{(i-1)p-(i-1)}\tilde{x}_i^p\right)^2\right) \\ &\le -\left((n+1)nK - 2^{2p-1}nd^*\sum_{i=1}^{n}\left(K^{(i-1)p-(i-1)}\right)^2\right) \\ &\quad \times\|\tilde{x}\|_\infty^{2p} + 2^{2p-1}nd^*\left(\hat{x}_1^{2p} + \frac{\hat{x}_2^{2p}}{K^2} + \cdots + \frac{\hat{x}_n^{2p}}{K^{2n-2}}\right) \end{aligned} \tag{4}$$

where

$$\begin{aligned} d^* &= (n+1)\|P\|d^2\left(\sum_{i=1}^{n}\frac{1}{K^{i-1}}\right)^2 \\ &= \frac{(n+1)\|P\|d^2\left(\sum_{i=0}^{n-1}(i+1)K^i + \sum_{i=n}^{2n-2}(2n-i-1)K^i\right)}{K^{2n-2}} \end{aligned} \tag{5}$$

and $\|\tilde{x}\|_\infty = \max_i |x_i|$.

We introduce a series of coordinate changes as follows:

$$\begin{aligned} w_1 &= \hat{x}_1 \\ w_i &= \hat{x}_i - \beta_{i-1}\left(\hat{x}_{[i-1]}\right) \end{aligned} \tag{6}$$

where $\beta_{i-1}\left(\hat{x}_{[i-1]}\right)$ $(i = 2, \cdots, n)$ is the virtual control law to be designed

Step 1: Constructing the 1st Lyapunov function:

$$V_1(\tilde{x}, w_1) = V_0(\tilde{x}) + \frac{1}{p+1} w_1^{p+1} \tag{7}$$

using (1), (2), (4)~(7) and Young's inequality, we can obtain

$$\begin{aligned} LV_1 \le & -\left((n+1)nK - 2^{2p-1}nd^*\left(\sum_{i=1}^{n} K^{(i-1)p-(i-1)}\right)^2\right) \\ & \times \|\tilde{x}\|_\infty^{2p} + 2^{2p-1}nd^*\left(\frac{\hat{x}_3^{2p}}{K^4} + \cdots + \frac{\hat{x}_n^{2p}}{K^{2n-2}}\right) \\ & + 2^{2p-1}nd^* w_1^{2p} + 2^{2p-1}nd^*\frac{\hat{x}_2^{2p}}{K^2} + w_1^p w_2 + w_1^p \beta_1 \\ & + K\tilde{x}_1^2 + \frac{K}{4}h_1^2 w_1^{2p} \end{aligned} \tag{8}$$

Applying (6) and Lemma 1, choosing $K \ge 2^{2p}nd^*$, we can get

$$\begin{aligned} & 2^{2p-1}nd^* w_1^2 \le \frac{K}{2} w_1^2 \\ & 2^{2p-1}nd^*\frac{\hat{x}_2^{2p}}{K^2} \le 4^{2p-1}nd^*\frac{1}{K^2}w_2^{2p} + 4^{2p-1}nd^*\frac{1}{K^2}\beta_1^{2p} \end{aligned} \tag{9}$$

which one substitutes in (8) to obtain

$$\begin{aligned} & LV_1 \\ & \le -\left((n+1)nK - 2^{2p-1}nd^*\left(\sum_{i=1}^{n} K^{(i-1)p-(i-1)}\right)^2\right) \\ & \quad \times \|\tilde{x}\|_\infty^{2p} + 2^{2p-1}nd^*\left(\frac{\hat{x}_3^{2p}}{K^4} + \cdots + \frac{\hat{x}_n^{2p}}{K^{2n-2}}\right) \\ & \quad + 2^{2p-1}nd^* w_1^2 + 4^{2P-1}nd^*\frac{1}{K^2}w_2^{2p} \\ & \quad + 4^{2p-1}nd^*\frac{1}{K^2}\beta_1^{2p} + w_1^p w_2 + w_1^p\beta_1 + K\tilde{x}_1^2 + \frac{K}{4}h_1^2 w_1^{2p} \\ & \le -\left(((n+1)n-1)K - 2^{2p-1}nd^*\left(\sum_{i=1}^{n} K^{(i-1)p-(i-1)}\right)^2\right) \\ & \quad \times \|\tilde{x}\|_\infty^{2p} + 2^{2p-1}nd^*\left(\frac{\hat{x}_3^{2p}}{K^4} + \cdots + \frac{\hat{x}_n^{2p}}{K^{2n-2}}\right) \\ & \quad + 4^{2p-1}nd^*\frac{1}{K^2}w_2^{2p} \\ & \quad + 4^{2p-1}nd^*\frac{1}{K^2}w_1^{2p} + w_1^p w_2 + w_1^p\beta_1 + K\left(\frac{1}{2} + \frac{h_1^2}{4}\right)w_1^{2p} \\ & \le -\left(((n+1)n-1)K - 2^{2p-1}nd^*\left(\sum_{i=1}^{n} K^{(i-1)p-(i-1)}\right)^2\right) \\ & \quad \times \|\tilde{x}\|_\infty^{2p} + 2^{2p-1}nd^*\left(\frac{\hat{x}_3^{2p}}{K^4} + \cdots + \frac{\hat{x}_n^{2p}}{K^{2n-2}}\right) - nKw_1^{2p} \\ & \quad + 4^{2p-1}nd^* v_1^{2p}\sqrt{\underbrace{w_1^{2p}\cdots\cdot w_1^{2p}}_{2p}} + 4^{2p-1}nd^*\frac{1}{K^2}w_2^{2p} + w_1^p w_2 \\ & \le -\left(((n+1)n-1)K - 2^{2p-1}nd^*\left(\sum_{i=1}^{n} K^{(i-1)p-(i-1)}\right)^2\right) \\ & \quad \times \|\tilde{x}\|_\infty^{2p} + 2^{2p-1}nd^*\left(\frac{\hat{x}_3^{2p}}{K^4} + \cdots + \frac{\hat{x}_n^{2p}}{K^{2n-2}}\right) \\ & \quad - nKw_1^{2p} + 4^{2p-1}nd^* v_1^{2p}\sqrt{\left(2pw_1^{2p}\right)^2} \\ & \quad + 4^{2p-1}nd^*\frac{1}{K^2}w_2^{2p} + w_1^p w_2 \\ & = -\left(((n+1)n-1)K - 2^{2p-1}nd^*\left(\sum_{i=1}^{n} K^{(i-1)p-(i-1)}\right)^2\right) \\ & \quad \times \|\tilde{x}\|_\infty^{2p} + 2^{2p-1}nd^*\left(\frac{\hat{x}_3^{2p}}{K^4} + \cdots + \frac{\hat{x}_n^{2p}}{K^{2n-2}}\right) \\ & \quad - \left(nK - 2^{4p-1}pnd^* v_1^{2p}\right)w_1^{2p} + 4^{2p-1}nd^*\frac{1}{K^2}w_2^{2p} \\ & \quad + w_1^p w_2 \end{aligned} \tag{10}$$

by choosing the 1st virtual control law

$$\begin{aligned} \beta_1 &= -Kv_1 w_1^p \\ v_1 &= \frac{1}{2} + \frac{h_1^2}{4} + n \end{aligned} \tag{11}$$

Step 2: Using (2), (6) and (10), we can get

$$\begin{aligned} dw_2 &= \left(\hat{x}_3 + K^2 h_2 \tilde{x}_1 + Kv_1 p w_1^{p-1}\left(\hat{x}_2 + Kh_1\tilde{x}_1\right)\right)dt \\ &= \left(\hat{x}_3 + K^2 h_2 \tilde{x}_1 + K^2 h_1 v_1 p w_1^{p-1}\tilde{x}_1 \right. \\ & \quad \left. + Kv_1 p w_1^{p-1}\left(w_2 + \beta_1\right)\right)dt \end{aligned} \tag{12}$$

Constructing the 2nd Lyapunov function

$$V_2\left(\tilde{x}, w_{[2]}\right) = V_1(\tilde{x}, w_1) + \frac{1}{K^2}\cdot\frac{1}{p+1}w_2^{p+1} \tag{13}$$

Applying (6), (10)~(13), $K \ge 2^{2p}nd^*$, *Lemma 1* and Young's inequality [19], we obtain

$$\begin{aligned} & LV_2 \\ & \le -\left(((n+1)n-1)K - 2^{2p-1}nd^*\left(\sum_{i=1}^{n} K^{(i-1)p-(i-1)}\right)^2\right) \\ & \quad \times \|\tilde{x}\|_\infty^{2p} + 2^{2p-1}nd^*\left(\frac{\hat{x}_4^{2p}}{K^6} + \cdots + \frac{\hat{x}_n^{2p}}{K^{2n-2}}\right) \\ & \quad - \left(nK - 2^{4p-1}pnd^* v_1^{2p}\right)w_1^{2p} \\ & \quad + 4^{2p-1}nd^*\frac{1}{K^2}w_2^{2p} + w_1^p w_2 + 2^{2p-1}nd^*\frac{\hat{x}_3^{2p}}{K^4} \\ & \quad + \frac{1}{K^2}w_2^p\left(\hat{x}_3 + K^2 h_2\tilde{x}_1 + K^2 h_1 v_1 p w_1^{p-1}\tilde{x}_1\right. \\ & \quad \left. + Kv_1 p w_1^{p-1} w_2 - K^2 v_1^2 p w_1^{2p-1}\right) \\ & \le -\left(((n+1)n-1)K - 2^{2p-1}nd^*\left(\sum_{i=1}^{n} K^{(i-1)p-(i-1)}\right)^2\right) \end{aligned}$$

$$\times \|\tilde{x}\|_\infty^{2p} + 2^{2p-1} nd^* \left(\frac{\hat{x}_4^{2p}}{K^6} + \cdots + \frac{\hat{x}_n^{2p}}{K^{2n-2}} \right) - \left(nK - 2^{4p-1} pnd^* v_1^{2p} \right) w_1^{2p} + 4^{2p-1} nd^* \frac{1}{K^2} w_2^{2p} + w_1^p w_2 + 2^{2p-1} nd^* \frac{\hat{x}_3^{2p}}{K^4} + \frac{1}{K^2} w_2^p \hat{x}_3 + w_2^p h_2 \tilde{x}_1 + w_2^p h_1 v_1 p w_1^{p-1} \tilde{x}_1 + \frac{1}{K} w_2^{p+1} v_1 p w_1^{p-1} - v_1^2 p w_1^{2p-1} w_2^p$$

$$\leq -\left(((n+1)\, n-1)\, K - 2^{2p-1} nd^* \left(\sum_{i=1}^{n} K^{(i-1)p-(i-1)} \right)^2 \right) \times \|\tilde{x}\|_\infty^{2p} + 2^{2p-1} nd^* \left(\frac{\hat{x}_4^{2p}}{K^6} + \cdots + \frac{\hat{x}_n^{2p}}{K^{2n-2}} \right) - \left(nK - 2^{4p-1} pnd^* v_1^{2p} \right) w_1^{2p} + 4^{2p-1} nd^* \frac{1}{K^4} w_3^{2p} + 4^{2p-1} nd^* \frac{1}{K^4} \beta_2^{2p} + \frac{1}{K^2} w_2^p w_3 + \frac{1}{K^2} w_2^p \beta_2 + \left(w_2^p \left(h_2 + h_1 v_1 p w_1^{p-1} \right) \right) \tilde{x}_1 + 4^{2p-1} nd^* \frac{1}{K^2} w_2^{2p} + w_1^p w_2 + \frac{1}{K} w_2^{p+1} v_1 p w_1^{p-1} - v_1^2 p w_1^{2p-1} w_2^p$$

$$\leq -\left(((n+1)\, n-1)\, K - 2^{2p-1} nd^* \left(\sum_{i=1}^{n} K^{(i-1)p-(i-1)} \right)^2 \right) \times \|\tilde{x}\|_\infty^{2p} + 2^{2p-1} nd^* \left(\frac{\hat{x}_4^{2p}}{K^6} + \cdots + \frac{\hat{x}_n^{2p}}{K^{2n-2}} \right) - \left(nK - 2^{4p-1} pnd^* v_1^{2p} \right) w_1^{2p} + 4^{2p-1} nd^* \frac{1}{K^4} w_3^{2p} + 4^{2p-1} nd^* \frac{1}{K^4} \beta_2^{2p} + \frac{1}{K^2} w_2^p w_3 + \frac{1}{K^2} w_2^p \beta_2 + \left(w_2^p \left(h_2 + h_1 v_1 p w_1^{p-1} \right) \right) \tilde{x}_1 + \left(\frac{1}{4nd^*} - 1 \right) w_2^{2p} + w_1^{2p} + \frac{1}{4} w_2^2 + \frac{1}{K} w_2^{2p+2} \tag{14}$$

then we can get the 2nd virtual control law

$$\beta_2 \left(\hat{x}_{[2]} \right) = -K^2 v_2 w_2^p, \quad v_2 = \frac{h_2^2}{4} + \frac{v_1^2 h_1^2}{4} + \frac{v_1^4}{4} + v_1 + 1 + n - 1 \tag{15}$$

which satisfies

$$LV_2 \leq -\left(((n+1)\, n-2)\, K - 2^{2p-1} nd^* \left(\sum_{i=1}^{n} K^{(i-1)p-(i-1)} \right)^2 \right) \times \|\tilde{x}\|_\infty^{2p} + 2^{2p-1} nd^* \left(\frac{\hat{x}_4^{2p}}{K^6} + \cdots + \frac{\hat{x}_n^{2p}}{K^{2n-2}} \right) - \left((n-1)\, K - 2^{4p-1} pnd^* v_1^{2p} \right) w_1^{2p} - \frac{1}{K^2} \left(\left(n - 4^{p-1} \right) K - 2^{4p-1} pnd^* v_2^{2p} \right) w_2^{2p} + 4^{2p-1} nd^* \frac{1}{K^4} w_3^{2p} + \frac{1}{K^2} w_2^p w_3 \tag{16}$$

Remark 2: The backstepping method has unique advantages in dealing with nonlinear system control problems, and its core is to combine the selection of Lyapunov function with controller design to lead to virtual control. The basic idea is to decompose the nonlinear system into several subsystems (note that the number of subsystems should not exceed the order of the original system), construct the Lyapunov function of each subsystem separately, Version July 10, 2022 submitted to Journal Not Specified 9 of 16 and then design the corresponding subsystem virtual controller to ensure the subsystem has a certain stability. In the next subsystem, the virtual controller of the previous subsystem is used as the tracking target of the subsystem at this moment, and the corresponding virtual controller is obtained again. The controller, and finally through the Lyapunov stability theory to ensure the stability of the closed-loop system.

Step i: Suppose at $(i-1)$th, there are a set of virtual control laws $\beta_1 \left(\hat{x}_1 \right), \cdots, \beta_{i-1} \left(\hat{x}_{[i-1]} \right)$:

$$\begin{aligned} \beta_1 \left(\hat{x}_1 \right) &= -K v_1 w_1^p, \quad v_1 = \frac{1}{2} + \frac{h_1^2}{4} + n \\ \beta_2 \left(\hat{x}_{[2]} \right) &= -K^2 v_2 w_2^p, \quad v_2 = \frac{h_2^2}{4} + \frac{v_1^2 h_1^2}{4} + \frac{v_1^4}{4} + v_1 + 1 + n - 1 \\ &\cdots\cdots \qquad \cdots\cdots \\ \beta_{i-1} \left(\hat{x}_{[i-1]} \right) &= -K^{i-1} v_{i-1} w_{i-1}^p, \\ v_{i-1} &= \frac{1}{4} \left(h_{i-1} + v_{i-2} h_{i-2} + v_{i-2} v_{i-3} h_{i-3} + \cdots + v_{i-2} v_{i-3} \cdots v_1 h_1 \right)^2 + \cdots + \frac{1}{4} \left(v_{i-3} v_{i-2} - v_{i-2}^2 \right)^2 + v_{i-2} + 1 + n - (i-2) \end{aligned} \tag{17}$$

which $v_j > 0 (j = 1, \cdots, i-1)$ being independent of K such that the ith Lyapunov function:

$$V_{i-1} \left(\tilde{x}, w_{[i-1]} \right) = V_0(\tilde{x}) + \frac{1}{p+1} \sum_{j=1}^{i-1} \frac{1}{K^j} w_j^{p+1} \tag{18}$$

which satisfies

$$LV_{i-1} \leq -\left(((n+1)\, n - (i-1))\, K - 2^{2p-1} nd^* \times \left(\sum_{i=1}^{n} K^{(i-1)p-(i-1)} \right)^2 \right) \|\tilde{x}\|_\infty^{2p} + 2^{2p-1} nd^* \times \left(\frac{\hat{x}_{i+1}^{2p}}{K^{2i}} + \cdots + \frac{\hat{x}_n^{2p}}{K^{2n-2}} \right)$$

$$
\begin{aligned}
&-\sum_{j=1}^{i-1}\frac{1}{K^{2j-2}}\left(\left(n-4^{(p-1)(j-1)}\right)K-2^{4p-1}pnd^{*}v_j^{2p}\right)w_j^{2p}\\
&+4^{2p-1}nd^{*}\frac{1}{K^{2(i-1)}}w_i^{2p}+\frac{1}{K^{2(i-2)}}w_{i-1}^{p}w_i \qquad (19)
\end{aligned}
$$

In the sequel, we will prove that (19) still holds for

$$
V_i\left(\tilde{x},w_{[i]}\right)=V_{i-1}\left(\tilde{x},w_{[i-1]}\right)+\frac{1}{p+1}\cdot\frac{1}{K^i}w_i^{p+1} \qquad (20)
$$

Using (6) and (17), a direct calculation leads to

$$
\begin{aligned}
dz_i=&\left(\hat{x}_{i+1}+K^ih_i\tilde{x}_i+Kh_{i-1}pw_{i-1}^{p-1}\left(\hat{x}_i+K^{i-1}h_{i-1}\tilde{x}_1\right)\right.\\
&+K^2v_{i-1}v_{i-2}pw_{i-2}^{p-1}\left(\hat{x}_{i-1}+K^{i-2}h_{i-2}\tilde{x}_1\right)\\
&\left.+\cdots+K^{i-1}v_{i-1}v_{i-2}\cdots v_1pw_1^{p-1}\left(\hat{x}_2+Kh_1\tilde{x}_1\right)\right)dt
\end{aligned} \qquad (21)
$$

Using $K\ \ge\ 2^{2p}nd^{*}$, Lemma 1, Young's inequality, (6) and (19) $\sim$ (21), we obtain

$$
\begin{aligned}
&LV_i\\
&\le-\left(((n+1)n-(i-1))K\right.\\
&\qquad\left.-2^{2p-1}nd^{*}\left(\sum_{i=1}^{n}K^{(i-1)p-(i-1)}\right)^2\right)\\
&\quad\times\|\tilde{x}\|_\infty^{2p}+2^{2p-1}nd^{*}\left(\frac{\hat{x}_{i+2}^{2p}}{K^{2(i+1)}}+\cdots+\frac{\hat{x}_n^{2p}}{K^{2n-2}}\right)\\
&\quad-\sum_{j=1}^{i-1}\frac{1}{K^{2j-2}}\left(\left(n-4^{(p-1)(j-1)}\right)K-2^{4p-1}pnd^{*}v_j^{2p}\right)w_j^{2p}\\
&\quad+2^{2p-1}nd^{*}\frac{1}{K^{2i}}\hat{x}_{i+1}^{2p}+\frac{1}{K^{2(i-1)}}w_i^{2p}\hat{x}_{i+1}\\
&\quad+\frac{1}{K^i}w_i^p\ \left(\hat{x}_{i+1}+K^ih_i\tilde{x}_i+Kv_{i-1}pw_{i-1}^{p-1}\right.\\
&\quad\times\left(\hat{x}_i+K^{i-1}h_{i-1}\tilde{x}_1\right)+\cdots+K^{i-1}v_{i-1}v_{i-2}\cdots v_1pw_1^{p-1}\\
&\quad\left.\times\left(\hat{x}_2+Kh_1\tilde{x}_1\right)\right)\\
&\le-\left(((n+1)n-i)K-2^{2p-1}nd^{*}\left(\sum_{i=1}^{n}K^{(i-1)p-(i-1)}\right)^2\right)\\
&\quad\times\|\tilde{x}\|_\infty^{2p}+2^{2p-1}nd^{*}\left(\frac{\hat{x}_{i+2}^{2p}}{K^{2(i+1)}}+\cdots+\frac{\hat{x}_n^{2p}}{K^{2n-2}}\right)\\
&\quad-\sum_{j=1}^{i}\frac{1}{K^{2j-2}}\left(\left(n-4^{(p-1)j}\right)K-2^{4p-1}pnd^{*}v_j^{2p}\right)w_j^{2p}\\
&\quad+4^{2p-1}nd^{*}\frac{1}{K^{2i}}w_{i+1}^{2p}+4^{2p-1}nd^{*}\frac{1}{K^{2i}}\beta_i^{2p}\\
&\quad+\frac{1}{K^{2(i-1)}}w_i^pw_{i+1}+\frac{1}{K^{2(i-1)}}w_i^p\beta_i+\frac{1}{K^{2i-3}}w_i^{2p}\\
&\quad\times\left(\frac{1}{4}\left(h_i+v_{i-1}h_{i-1}+v_{i-1}v_{i-2}h_{i-2}+\cdots\right.\right.\\
&\qquad\left.+v_{i-1}v_{i-2}\cdots v_1h_1\right)^2\\
&\qquad\left.+\cdots+\frac{1}{4}\left(v_{i-3}v_{i-2}-v_{i-2}^2\right)^2+v_{i-1}+1\right)
\end{aligned} \qquad (22)
$$

then we can choose the ith smooth virtual control law

$$
\begin{aligned}
\beta_i\left(\hat{x}_{[i]}\right)&=-K^iv_iw_i^p\\
v_i&=\frac{1}{4}\left(h_i+v_{i-1}h_{i-1}+v_{i-1}v_{i-2}h_{i-2}+\cdots\right.\\
&\quad\left.+v_{i-1}v_{i-2}\cdots v_1h_1\right)^2+\cdots\\
&\quad+\frac{1}{4}\left(v_{i-3}v_{i-2}-v_{i-2}^2\right)^2+v_{i-1}+1+n-(i-1)
\end{aligned} \qquad (23)
$$

and get

$$
\begin{aligned}
&LV_i\\
&\le-\left(((n+1)n-i)K-2^{2p-1}nd^{*}\left(\sum_{i=1}^{n}K^{(i-1)p-(i-1)}\right)^2\right)\\
&\quad\times\|\tilde{x}\|_\infty^{2p}+2^{2p-1}nd^{*}\left(\frac{\hat{x}_{i+2}^{2p}}{K^{2(i+1)}}+\cdots+\frac{\hat{x}_n^{2p}}{K^{2n-2}}\right)\\
&\quad-\sum_{j=1}^{i}\frac{1}{K^{2j-2}}\left(\left(n-4^{(p-1)j}\right)K-2^{4p-1}pnd^{*}v_j^{2p}\right)w_j^{2p}\\
&\quad+4^{2p-1}nd^{*}\frac{1}{K^{2i}}w_{i+1}^{2p}+\frac{1}{K^{2(i-1)}}w_i^pw_{i+1}
\end{aligned} \qquad (24)
$$

Step n: Using repeatedly the above arguments, at the $n-1$th step, we can get

$$
\begin{aligned}
&LV_{n-1}\\
&\le-(((n+1)n-(n-1))K\\
&\qquad\left.-2^{2p-1}nd^{*}\left(\sum_{i=1}^{n}K^{(i-1)p-(i-1)}\right)^2\right)\\
&\quad\times\|\tilde{x}\|_\infty^{2p}\\
&\quad-\sum_{j=1}^{n-1}\frac{1}{K^{2j-2}}\left(\left(n-4^{(p-1)(j-1)}\right)K-2^{4p-1}pnd^{*}v_j^{2p}\right)w_j^{2p}\\
&\quad+4^{2p-1}nd^{*}\frac{1}{K^{2(i-1)}}w_n^{2p}+\frac{1}{K^{2(i-2)}}w_{n-1}^pw_n
\end{aligned} \qquad (25)
$$

where

$$
V_{n-1}\left(\tilde{x},w_{[n-1]}\right)=V_{n-2}\left(\tilde{x},w_{[n-2]}\right)+\frac{1}{K^{n-1}}\cdot\frac{1}{p+1}w_n^{2p} \qquad (26)
$$

At the end of the recursive procedure, choosing the controller

$$
u\left(\hat{x}_{[n]}\right)=-K^nv_nw_n^p \qquad (27)
$$

where $v_n>0$ satisfies (17) and is independent of K, we lead to

$$
\begin{aligned}
LV_n\le&-\left(n^2K-2^{2p-1}nd^{*}\left(\sum_{i=1}^{n}K^{(i-1)p-(i-1)}\right)^2\right)\|\tilde{x}\|_\infty^{2p}\\
&-\sum_{j=1}^{n-1}\frac{1}{K^{2j-2}}\left(\left(n-4^{(p-1)(j-1)}\right)K\right.
\end{aligned}
$$

$$-2^{4p-1}pnd^*v_j^{2p}\Big)w_j^{2p}-\frac{1}{K^{2n-5}}w_n^{2p} \tag{28}$$

where

$$V_n\left(\tilde{x},w_{[n]}\right)=(n+1)\,\tilde{x}^TP\tilde{x}+\frac{1}{p+1}\sum_{j=1}^{n}\frac{1}{K^j}w_j^{p+1} \tag{29}$$

Remark 3: On the basis of nonlinear system analysis method is considering the design problem of robust sliding mode controller for piecewise linear discrete time-delay system with uncertain parameters of state lag. Sliding mode control theory of piecewise linear time-delay system makes the system state moving along the given "sliding mode" motion trajectory. On the other hand, this paper is applying the sliding mode variable structure control theory to the valve position control system, which verify practical significance in the control theory and application of piecewise linear systems.

Theorem 1: The control law

$$u^*=-\theta K^n v_n w_n^p,\quad \theta\geq 2 \tag{30}$$

solves the problem of inverse optimal stabilization in probability for (6) by minimizing the cost function

$$J(u)=E\left\{\int_0^\infty\left[l\left(\tilde{x},\hat{x}\right)+\frac{1}{K^{2(n-1)}}\frac{v_n^{-1}\left(\hat{x}\right)}{K^n}u^2\right]dr\right\} \tag{31}$$

where

$$\bar{\phi}_1\left(\tilde{x},\hat{x}\right)=\left(\Phi^T(x),0,\cdots,0\right)^T,$$
$$\bar{\phi}_2\left(\tilde{x},\hat{x}\right)=(0,\cdots,0,1)^T,\quad V=V_n.$$

Proof: (2) and (3) can be represented as

$$\begin{pmatrix} d\tilde{x}\\ d\hat{x}\end{pmatrix}=\bar{\phi}_1\left(\tilde{x},\hat{x}\right)d\omega+\bar{\phi}_2\left(\tilde{x},\hat{x}\right)udt \tag{32}$$

where $\bar{\phi}_1$, $\bar{\phi}_2$ are identified in Theorem 2. Choosing $\gamma(r)=\frac{1}{2K^{2(n-1)}}r^2$, we can get $\left(\gamma'\right)^{-1}(r)=K^{2(n-1)}r$ and $\ell\gamma(r)=\frac{1}{2}K^{2(n-1)}r^2$. Applying Lemma 3, we get

$$\begin{aligned} u=\beta\left(\hat{x}\right)&=-R_2^{-1}\left(\hat{x}\right)\frac{1}{K^{2(n-1)}}w_n^p\frac{1}{2}K^{2(n-1)}\\ &=-\frac{1}{2}R_2^{-1}\left(\hat{x}\right)w_n^p \end{aligned} \tag{33}$$

According to Theorem 1 and Lemma 3, the inverse optimal controller can be de-signed as follows

$$\begin{aligned} u^*=\beta^*\left(\hat{x}\right)&=-\frac{\theta}{2}R_2^{-1}\left(\hat{x}\right)\frac{1}{K^{2(n-1)}}w_n^pK^{2(n-1)}\\ &=-\frac{\theta}{2}R_2^{-1}\left(\hat{x}\right)w_n^p=\theta\beta\left(\hat{x}\right)=\theta\, u,\quad \theta\geq 2 \end{aligned} \tag{34}$$

where $R_2\left(\hat{x}\right)=\frac{1}{2K^nv_n}$

Remark 4: In this paper, we study the system observer design when the state variables are unmeasured and implement the observer and controller design based on the stability theorem. The nonlinear system study contains uncertain parameter disturbances and time-delay terms.

IV. INTELLIGENT SENSOR NETWORK CONTROL SYSTEM THROUGH MEMRISTOR MODEL EXAMPLE

In actual marine engineering applications in order to ensure the stability, reliability and safety of the system, the response speed of the valve position control needs to be stable, accurate and timely. During the valve position opening/closing process, it is simultaneously affected by the hydraulic power unit from the water surface. The hydraulic driving force, the spring restoring force and the force have generated by the fluid medium inside the oil and gas pipeline during the opening process of the actuator.

Combining existing research results [23], [24], the electro-hydraulic composite valve position control system model during the valve position opening process is obtained as follows:

$$\begin{aligned} &p\left(S-S_1\right)+\rho gHS_1\\ &\quad=m\frac{d^2\tau}{dt^2}+\left(\rho gH+\frac{128\mu l_pQ}{\pi d_p^4}\right)\left(S-S_2\right)\\ &\qquad+k\left(L_0+\tau\right)+f\left(\tau,\frac{d\tau}{dt}\right)+w(t)\\ &Q_h=\upsilon\left(S-S_1\right)\left(2*\frac{\left(P_1-P_2\right)}{\rho_h}\right) \end{aligned} \tag{35}$$

In the above formula, the physical meaning of each parameter is shown in Table 1:

According to the definition of the state variable in the above formula, in practical applications, the valve displacement can be measured, but the measurement of the valve displacement velocity is difficult, which will directly affect the design of the state feedback controller; on the other hand, the valve displacement sensor has a certain transmission time delay and packet loss, which also has a certain impact on the design effect of the controller. Combined with the measurement output, namely "control fluid inlet pressure", since the monitoring and collection of "control fluid inlet pressure" is located inside the control module in the actual offshore oil and gas exploitation, it has stable measurement and fast transmission effect.

The opening and closing process of the actuator is dynamically simulated through the ocean library of the SimulationX software and the underwater valve control structure diagram, as shown in Figure 5.

The simulation results are shown in Figure 6-8. The curves clearly show the changes in the speed of the piston, the flow rate of the hydraulic chamber and the flow rate of the negative pressure chamber during the opening and closing of the actuator. It can be seen from the figure that the flow change is basically synchronized with the speed change; due to the difference in the outer diameter of the piston rod of the hydraulic chamber and the negative pressure chamber, the flow varies in size. By com-paring with the adaptive control results in [9] and [23], we can find that the backstepping control can reduce the reaction time and greatly shorten the response time of the actuator. On this basis, we can increase or decrease the relevant marine modules accordingly, and carry

TABLE 1. Variable description.

Variable	Meaning	Variable	Meaning
p	Valve opening cavity supply pressure	H	Working water depth
τ	Valve position	L_0	Spring pre-compression displacement
S	Piston area	S_1	Piston rod area
S_2	Stem area	m	Piston rod quality
ρ	Sea water density	μ	Control fluid viscosity
k	Spring coefficient of elasticity	g	Acceleration of gravity
d_p	Inner diameter of pilot hole	f	Resistance during opening of the actuator
Q_h	Control fluid flow	Q_p	Flow rate of fluid medium in pipeline
P_1	Control fluid inlet pressure	P_2	Control fluid outlet pressure
υ	Control fluid flow rate	ρ_h	Control liquid density
σ	Pressure coefficient	l_p	Control the length of the liquid guide hole
v_p	Flow rate of fluid medium in pipeline	η	Valve opening

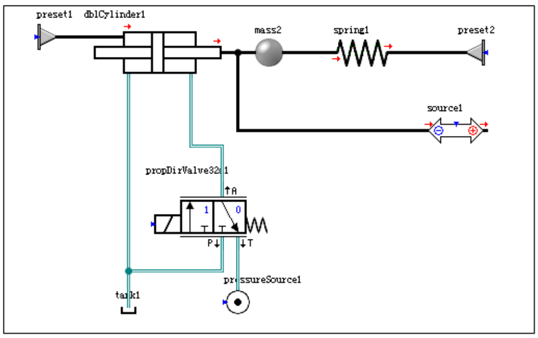

FIGURE 5. SimulationX actuator hydraulic simulation model.

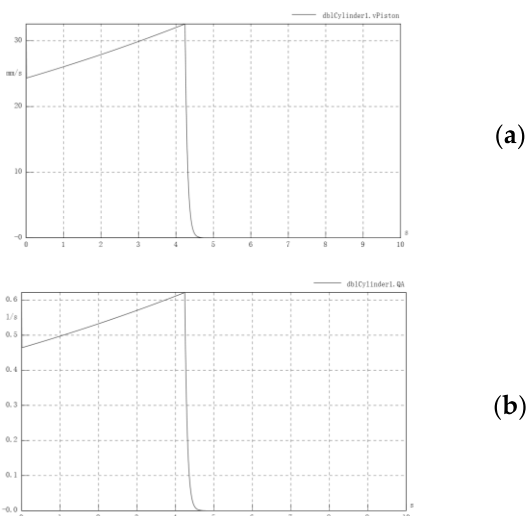

FIGURE 6. (a) Velocity curve of the piston when opening. (b) Flow curve of hydraulic chamber when opening.

out personalized optimization design through modular operation and according to the theoretical knowledge of marine engineering.

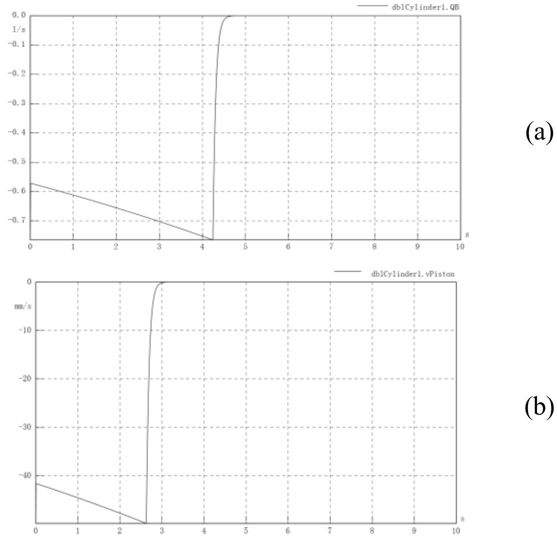

FIGURE 7. (a) Flow curve of negative pressure chamber when opening. (b) Velocity curve of the piston when closed.

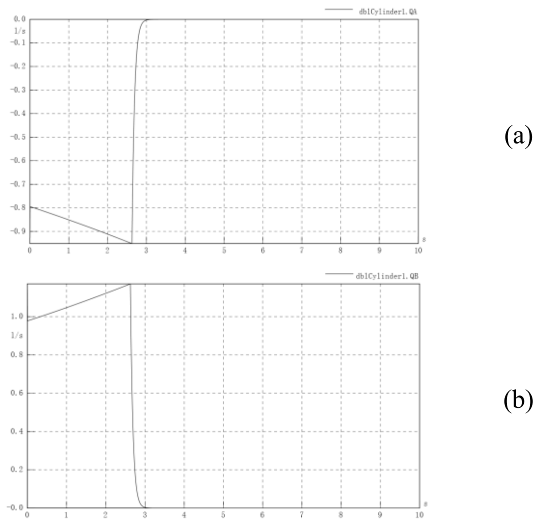

FIGURE 8. (a) Flow curve of hydraulic chamber when closed. (b) Flow curve of negative pressure chamber when closed.

V. CONCLUDING AND FUTURE PROSPECTS

In this paper, we study the design of the system observer under the condition that the state of the system is unmeasurable and the design of the system controller based on the observer. The system has uncertain parameter disturbances, time-delay terms and nonlinear terms. By introducing the error between the observation value and the actual value, combining the error equation and the closed loop of the observer-based control system, we use the Lyapunov method for stability analysis., and finally, combining the relevant theorems obtained from the stability analysis to design the observer and the controller. By using the Simulation X solve the robust controller under the given parameters and establish the valveelectro hydraulic compound valve position control model. In this paper, the valve position of actuator is analyzed through the controller designed. We study the design of system observers when state variables are unmeasurable and implement observer and controller design based on the stability theorem. The nonlinear system studied includes uncertain parameter disturbances and time-delay terms.

The nonlinear system can be described by the piecewise linear system. Therefore, it is necessary to study the control problem of the piecewise linear system. The systems studied in this thesis are all continuous systems, so it is a future research direction to study the control problems of the corresponding discrete systems. Because the underwater equipment is controlled based on computers, the data obtained are discrete. So the next step is to consider how to apply continuous systems to discrete systems. An-other limitation is that the current restraint intensity can be further relaxed to be more in line with the real underwater working environment. In the complex environment of underwater uncertain interference, no further reduction of constraints will have an impact on the stable control of underwater equipment. Further research is done based on the above two points.

The systems studied in this paper are all continuous systems, but in practical engineering applications, they are all discrete systems. Therefore, studying the control problems of corresponding discrete systems is a future research direction. As under-water equipment is based on discrete data obtained through computer control, the next step is to consider how to apply continuous systems to discrete systems. Another limitation is that the growth constraints on the current nonlinear term can be further relaxed to better match the real underwater working environment. In the complex environment of underwater uncertain interference, further reduce the impact of constraints and uncertainties on the stable control of underwater equipment.

On the other hand, in the actual research process, there is a class of nonlinear systems that can be piecewise linearized. This kind of system model can be piecewise linearized, that is, the nonlinear system is composed of finite or infinite linear subsystems. The piecewise linearization of nonlinear systems is widely used in practice. In the prcess of life and production, piecewise linearization is also an important method to solve the control problem of systems with nonlinear terms. Nonlinear systems are de-scribed as piecewise linear system. Therefore, it is necessary to transform the control problem of nonlinear systems into the research problem of piecewise linearization in future work. Future work will be further studied based on the above two points.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this articles.

DATA AVAILABILITY STATEMENT

All data generated or analyzed during this research are included in this article.

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FANG WANG received the Ph.D. degree in ship and marine engineering structure design and manufacturing from Harbin Engineering University, in 2012. She is currently a Professor with Hangzhou City University. She has hosted one General Project of the National Postdoctoral Science Foundation, two projects of the Zhejiang Provincial Natural Science Foundation, one Open Fund of the National Defense Science and Technology Key Laboratory, and multiple projects entrusted by enterprises. She has published more than 30 SCI/EI research articles and educational reform articles. Her current research interests include the autonomous takeoff and landing of flying vehicles and urban air traffic research.

LONGCHUAN GUO received the bachelor's degree in automation and the Ph.D. degree in control theory and control engineering from the China University of Petroleum, Beijing Campus (CUP), in 2011 and 2016, respectively. He is currently an Associate Professor with the School of Mechanical Engineering, Hangzhou Dianzi University. He and his team have currently developed the key equipment of the deep-sea production system-the prototype of the underwater electric actuator and the prototype of the underwater carrier communication. Their team is currently conducting research work on underwater multi-purpose robots and underwater production control system simulation platforms. His research interests include the controlling of complicated nonlinear systems and mechanical system designs, complex nonlinear systems and applications, subsea equipment control systems, and underwater robotics.

JIAQI PAN is currently pursuing the B.S. degree with Hangzhou Dianzi University, Zhejiang, China. His current research interests include motion control and path planning.