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Design of a Closed-Loop Error-in-Variable System Controller and Its Application in Quadrotor UAV

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ABSTRACT

In view of the fact that the output is only disturbed by error in most of the current system studies, this article proposes a closed-loop variable system model with error (both input and output signals are disturbed by noise) and designs the controller of the system. In this study, minimum variance controller and self-correcting minimum variance controller are designed using minimum variance control. Then an example is given to evaluate the performance of the designed controller using minimum variance performance evaluation. Finally, the closed-loop variable error system is combined with the quadrotor UAV (unmanned aerial vehicle), and the position controller in the position control loop of the quadrotor UAV is designed. The experimental results show that the controller has good performance and can well meet the design needs.

KEYWORDS

Closed-Loop System, Errors-in-Variables, Minimum Variance Controller, Performance Evaluation, Quadrotor UAV, Self-Tuning

1. INTRODUCTION

The system with error-in-variable refers to the system whose input and output are destroyed by external interference noise, which is usually abbreviated as EIV (error-in-variable). At present, due to various reasons, only the case of output error and open-loop variable error are considered in the study of control

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system. However, in real life, the vast majority of systems are closed-loop variable with error system, so the study of closed-loop variable with error system is very meaningful. Due to the limitations of current technology, when a small part is combined to form a complete system, there will always be a variety of interference. Therefore, it is necessary to consider these interference factors in the equipment with high precision requirements. Especially in many high-precision instruments, such as high-precision medical and surgical equipment, aircraft, etc., even a little error will cause difficult to estimate the consequences. In this paper, a closed-loop variable with error model is proposed to study the case that the input and output are damaged by noise. After considering the input and output errors, the designed system will be more accurate. This paper presents a closed-loop variable error system model, designs and studies its controller, and applies it to the position control of a quadrotor UAV.

Professor Torsten SöDerströM's team at the Uppsala University has made a significant contribution to the identification of error models for dynamic variables. The book Errors-in-Varibles Methods in System Identification, published in 2018, summarizes the findings of Professor Torsten S öderströ in the field from years of research, the book examines “The in-depth and extensive analysis of EIV modeling for Linear dynamical system, the process of identification, model selection and (parameter) estimation, and its statistical properties”. Professor Torsten Söderström won the IFAC TC 1.1 Prize for 2021 Systems Recognition for this book, in recognition of the outstanding contributions made by Professor Torsten S öderström in the field of systematic identification by publications (journals, papers, book chapters or scientific monographs) that appeared six years before the award year. This problem has been studied from different angles for a typical system with errors-in- variable. Statistically valid maximum likelihood methods can be used, which are computationally complex, but computationally simple methods are generally inaccurate. Subspace fitting methods are more accurate when the amount of computation is large (Stoica et al.,1995; Cedervall et al.,1996), and (Mahata & Söderström, 2002) reports a significant improvement in accuracy when the amount of computation is low. The processing of unperturbed input in (Söderström & Hong, 2005) is periodic. In (Söderström et al., 2005), the local convergence characteristics of bias elimination least squares (BELS) algorithm for EIV identification are studied. A simplified BELS method is proposed in (Hong, et al., 2007). A new method called extended compensation least squares (ECLS) is proposed and further analyzed in (Ekman, 2005; Ekman, et al., 2006). In (Söderström, et al., 2006), some methods of continuous-time modeling in EIV identification are discussed. Studies (Söderström, 2010; & Söderström, 2011) show how to embed all of these methods into a joint framework (called a generalized instrumental variable estimator, GIVE), some selection of algorithm parameters can lead to different special cases previously referred to as specific methods. Xiao Deyun et al put forward an identification method which decomposes the variable error output error model by UD, and then compensates the error (Deyun, et al., 2018). Chen Hanfu studies the variable error output error model with the system input being ARMA process and proves the convergence of the proposed recursive algorithm (Chen & Yang, 2005). From the current research status, the research of variable with error system focuses on the open-loop variable with error and the identification of variable with error system. Therefore, the controller of closed-loop variable system with error is studied in this paper.

In this paper, the minimum variance control is chosen to design the controller. The minimum variance control is a control method to keep the fluctuation variance of the output of the system with random noise to a minimum. The minimum variance control method can be applied to many industrial processes control. The solution and implementation of the minimum variance control are simpler and more convenient to apply. The basic idea of minimum variance control is as follows: due to the D-step delay of the channel in the system, the current control effect cannot affect the output until D sampling periods. Therefore, to obtain the minimum output variance, it is necessary to predict the output D steps in advance, and then calculate the appropriate adjustment effect according to the predicted value. In this way, the steady-state variance of the output can always be kept to a minimum through continuous forecasting and adjustment (Jianhong, & Daobo, 2011; Wei, & Xueming, 2010; Jianhong et al., 2014; Dezhi et al.,2011; Guili, & Zekai, 2011). In order to make the actual output infinitely close to the ideal output through the controller, the minimum variance control can achieve this purpose well. The control system occupies a very important position in the modern industrial production process (Daraz et al., 2022, 2021; Ibraheem et al., 2020a,b; Abdul-Adheem et al., 2020a,b; Soliman et al., 2020; Gorripotu et al, 2021, 2019; Meghni et al., 2017, 2018). In actual production, a production process may have thousands of control loops working together, and these loops contain various types of controllers (Mahdi et al., 2022; Sain et al., 2022; Fekik et al., 2022a,b, 2021a,b,c,d, 2020a,b; Ali et al., 2022, 2021a,b; Acharyulu et al., 2021; Ajel et al., 2021). In the actual production process, the control system can be put into use in early often show the good performance, but after running for a period of time, because of the production equipment wear and tear, regular maintenance and maintenance is not timely, and the causes of system failure and so on, may make the control system of the performance degradation, therefore control performance assessment is very important.

There are many control loops in the current control system, and the single input single output control loop is the most classical and basic control loop in the control system (Toumi et al., 2022; Saidi et al., 2022; Serrano et al., 2022; Humaidi et al., 2022, 2020; Hamida et al., 2022; Ben Njima et al., 2021; Ghoudelbourk et al., 2021; Pilla et al., 2021a,b; Ajeil et al. 2020a,b; Azar and Serrano, 2015). In 1989, Harris proposed a control system performance evaluation method based on minimum variance minimum variance benchmark for single input single output system. This method only uses the normal output data under the closed-loop operation condition, so when evaluating the system performance, there is no additional disturbance to the normal operation of the system. In order to estimate the minimum variance reference value of the loop, it is necessary to know the operating data of the system and the knowledge of the delay of the object, but there is no requirement for the model of the control object, and there is no need to impose additional model identification experiments, so the method has been widely used. Using the minimum variance as a benchmark for evaluating system performance can provide valuable information for technicians, such as judging the difference between the current operating state of the system and the ideal state according to the solved performance indicators. If the value of the performance indicator is close to 1, it indicates that the current controller can meet the needs of the production process, and it is not necessary to reset or design the controller parameters. When the performance indicator is poor, it is necessary to reset or design the controller parameters to improve the system performance.

Some control systems can be made more accurate by studying the controller of closed-loop variable system with error (Mittal et al., 2021; Al-Qassar et al., 2021a,b; Ammar et al., 2020, 2019, 2018; Vaidyanathan et al., 2019, 2018a,b, 2017a,b,c; Radwan et al., 2018; Abdelmalek et al., 2018; Ouannas et al., 2020, 2017a,b,c,d, 2016a,b; Azar et al., 2018a,b; Singh et al., 2021, 2017). Unmanned aerial vehicles (UAVs) or drones have recently proven to be a potent instrument for reshaping more and more sectors with increased efficiency and productivity. Many techniques to controller design have been considered for UAVs (Kazim et al., 2022, 2021a,b; Najm et al., 2021a,b, 2020).

In this paper, the quadrotor UAV is selected as the research object, and the closed-loop variable error system is applied to the position control of the UAV, so as to make the control of the quadrotor UAV more accurate. Four-rotor UAV can also be regarded as a helicopter, but also vertical take-off and landing, and does not need a runway, it has many similarities with helicopters. Unlike traditional helicopters, which rely on electric motors to drive their propellers to provide lift, the four-rotor UAV's attitude and position are controlled by the speed of its four propellers, the helicopter is controlled by the tail. The mechanical structure of the four-rotor UAV is very simple, it is mainly composed of three parts: frame, power system, command and control system. The simple structure of the four-rotor brings a lot of convenience, first of all, it is very simple to control, even if you have never been in contact with the four-rotor UAV, you can get the UAV in a few minutes after the skilled operation of the UAV; Second, its maintenance cost is very low, most parts can be removed and replaced. In contrast, it has obvious disadvantages, such as poor load capacity and endurance compared with other aircraft. Due to the excellent characteristics of the four-rotor UAV, it has been widely used in all walks of life. In particular, the introduction of the Phantom UAV in DJI, users can do to fly, and its very low price after the development of the four-rotor UAV ushered in a blowout of development. In 2013, after Professor Andrea showed off the incredible capabilities of the quadrotor drone at TED, the potential of the drone was seen to be limitless, and the quadrotor began to shine in all sorts of fields. Whether it is in natural disaster response, military training exercises or aerial photography, pesticide spraying, delivery of small express delivery and other fields can see the four-rotor UAV active figure. Faced with the wide market and demand, the development of four-rotor UAV is more and more fast, and towards the direction of intelligent, mass development, UAV lighting performance is indeed amazing. The first rotorcraft dates back to 1907, when the Breguet brothers flew their multi-rotorcraft for just 1.5 meters, a significant step in helicopter history. The multi-rotor helicopter designed by Etienne Oemichen took off in 1923 and flew for 14 minutes, setting a world record for a helicopter at the time. In 1956, Marc Adman Kaplan designed the first true four-rotor Convertawings Model “A”. However, due to the material and technology constraints at that time, resulting in the slow development of multi-rotor, people do not pay attention to him. The multi-rotor reappeared in the early 1990s with the emergence of the Keyence Gyrosaucer as a toy. Under the stimulation of the broad market, and with the progress of the times, materials and technology have been greatly developed, various types of multi-rotor began to emerge like mushrooms. In the 2002, Jugend forscht competition, the Silverlit-XUFO quad-rotor UAV won. In 2006, German Microdrones GmbH company launched Md4-200, has achieved unprecedented success. The MD4-1000 system, introduced in 2010, was a benchmark for the four-rotor UAV industry at the time. Since 2005, scholars of various countries have paid more and more attention to multi-rotor, and published a large number of academic articles. In 2007, an article published in the Business Journal Nature analysed the commercial potential of UAVs, further spurring the development of multi-rotors. AR 2010. The Drone quadcopter is spreading rapidly in all walks of life because of its advanced technology, good handling and excellent entertainment. In 2012, Professor Wager Al-karmah demonstrated the maneuverability and collaboration of micro air vehicle formations at TED, a talk that opened up the possibilities of multiple rotors. In 2013, at Ted, professor Raffaello d’Andrea shows the movement of machines with multiple rotors, including catching balls, balancing and more. In June 2015, the journal Nature’s Machine Intelligence Column published an article summarizing the challenges of small autonomous UAVs in design, manufacturing, perception, control, and research trends. At present, the UAV industry is developing rapidly, and China has become a major producer of consumer-grade UAV. DJI UAV launched in the Spirit series of UAV, and then launched a series of” Wu”,” Yu”, “Xiao” UAV, so that the rapid development of UAV. With the rapid development of the UAV industry, the consumer market reached saturation in 2017, so UAV manufacturers began to move into other industries. DJI launched the M200 series UAV for power patrol, security patrol and emergency rescue and other fields, launched such as the wind series, for the logistics field. Jifei turned to the field of agricultural plant protection and achieved great success. Militaries around the world have also conducted in-depth research in the field of UAVs, and now you can see on many screens that the military is sending out UAVs to spy on and fight the enemy. UAV has been widely used in both military and civil fields. The appearance of drones has brought great convenience to life, so this paper selects the quadrotor UAV as the research object. In this paper, the position control of the quadrotor UAV is studied by combining the closed-loop variable error system and the quadrotor UAV. Position control can be divided into three types: fixed-point control, trajectory tracking and path following. The desired position is a fixed point, and the control objective is to design a controller to make the actual position of the UAV infinitely close to the desired position, so that the fixed-point control does not need to consider the problem of flight trajectory. However, trajectory tracking, and path tracking need to be considered. The difference between them is that trajectory tracking is time-dependent. Trajectory tracking needs to follow the target’s trajectory in real time, while path tracking does not. Path following is also known as 3D tracking, and trajectory tracking is also known as 4D tracking because it has more time dimensions than path following. In other words, path following is a special case of trajectory tracking, which becomes trajectory tracking after adding time constraint. When the desired fixed points are connected one by one, it becomes a trajectory, so trajectory tracking becomes a fixed-point control after adding the desired trajectory constraints. Therefore, the fixed-point control room in all the special cases of position control, and fixed-point control is the most widely used, so this paper chooses to fixed-point control controller design. In the application of the quadrotor UAV, it is often hoped that it can fly to a specified location, but there is always a more or less gap. With the addition of closed-loop variable error system, this error can be greatly reduced, so that the quadrotor UAV can fly to the specified position more accurately.

The main structure of this paper consists of four parts. In the second part of this paper, a closed-loop variable model with error is proposed, and each part of the system is explained. In the third part, minimum variance controller and self-tuning minimum variance controller are designed for closed-loop variable systems with errors. In the fourth part, the performance of the designed controller is evaluated by using the minimum variance performance index. In the fifth part, the position controller is designed by combining the closed-loop variable error system with the fixed-point control in the four-rotor UAV position control.

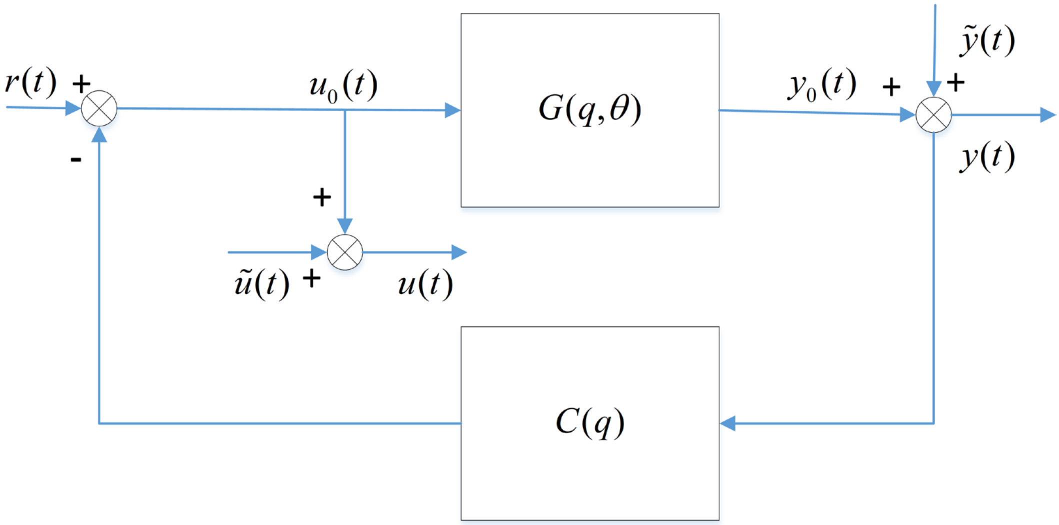
2. PROBLEM DESCRIPTION

In daily production and life, it is often encountered that given an ideal value, and then need to pass a series of operations, so as to make the actual output value infinitely close to the ideal value. For example, fixed-point control of quadrotor UAV, that is, it is hoped that the quadrotor UAV can fly to the designated place. In practical applications, most of them belong to fixed-point control. In this problem, the given point is the expected value, and the ideal state is that the actual output is infinitely close to the expected value. In order to achieve this goal, this paper designs the controller based on the closed-loop variable error system. By considering the actual situation where both input and output are disturbed by noise, the designed controller will be more accurate, so that the actual value is infinitely close to the ideal value.

In this paper, the closed-loop variable with error system whose input and output are disturbed by noise is analyzed. The closed-loop variable with error model is shown in Figure 1.

In this model, $r(t)$ is a reference signal independent of noise. $u(t)$ and $y(t)$ are input and output signals respectively. Input data and output data can be acquired by physical equipment, such as

Figure 1.
Errors-in-variables closed-loop model



oscilloscope. The noiseless input is denoted by $u_0(t)$, and the interference-free output is denoted by $y_0(t)$. The observation results are damaged by additional noises $\tilde{u}(t)$ and $\tilde{y}(t)$. For the convenience of research, it is assumed that both $\tilde{u}(t)$ and $\tilde{y}(t)$ meet the following requirements:

$$\tilde{y}(t) = H(q)e(t)\,,\ \tilde{u}(t) = H(q)e(t)$$

$e(t)$ is white noise with mean 0 and variance 1, $H(q)$ is a filter, and its expression is as follows:

$$H(q) = 1 + h_1 q^{-1} + \cdots h_{n_h} q^{-n_h}$$

$H(q)$ is the stable polynomial, and n_h is the order of the polynomial. The closed-loop system transfer model is denoted by $G(q,\theta)$, and it is assumed that G is known, $G(q,\theta) = \dfrac{B(q)}{A(q)}$. In the simulation part, a specific quadrotor UAV will be substituted for the experiment. Where $A(q)$ and $B(q)$ are respectively:

$$A(q) = 1 + a_1 q^{-1} + \cdots a_{n_a} q^{-n_a}$$
$$B(q) = b_1 q^{-1} + \cdots b_{n_b} q^{-n_b}$$

n_a and n_b are orders of polynomials. θ is the parameter in $A(q), B(q)$:

$$\theta = \left[a_1, \ldots, a_{n_a}, b_1, \ldots b_{n_b}\right]$$

The feedback controller is denoted by $C(q)$. The feedback in this system is:

$$u_0(t) = r(t) - C(q)y(t)$$

It is reasonable to assume that both $r\left(t\right)$ and $C\left(q\right)$ are unknown, and the purpose of this paper is to design the controller. q time shift operator satisfies:

$$q^{-1}u(t) = u(t-1)$$

To simplify writing, write $y(t)$ as y, $u(t)$ as u, $r\left(t\right)$ as r, $u_0(t)$ as u_0, $y_0(t)$ as y, $G(q,\theta)$ as G, $\tilde{y}\left(t\right)$ as $\tilde{y}$, $\tilde{u}(t)$ as $\tilde{u}$, and $C\left(q\right)$ as C.

3. MINIMUM VARIANCE CONTROLLER

In this part, firstly, the controller of closed-loop variable system with error is designed by using minimum variance control, and then the performance of the controller is evaluated. Finally, in order to meet the practical needs, the self-correcting minimum variance controller is designed.

3.1 Minimum Variance Controller Design

The expression for the output y can be obtained from Figure 1:

$$y = G(u - \tilde{u}) + \tilde{y} \tag{1}$$

In order to simplify the operation, assuming that $\tilde{y}$ and $\tilde{u}$ are the same, Equation (1) can be rewritten as:

$$y = Gu + (1 - G)He \tag{2}$$

Substitute $G(q) = \dfrac{B(q)}{A(q)}$ into Equation (2) to obtain:

$$\begin{aligned} y &= \frac{B}{A}u + (1 - \frac{B}{A})He \\ &= \frac{B}{A}u + \frac{\left(A - B\right)H}{A}e \end{aligned} \tag{3}$$

In order to ensure that the real output at each time is close to the ideal value, the output at time $t + d$ is deduced, as shown in Equation (4):

$$y(t + d) = \frac{B}{A}u(t + d) + \frac{\left(A - B\right)H}{A}e(t + d) \tag{4}$$

Combined with Diophantine equation:

$$H = AF + q^{-d}P \tag{5}$$

where:

$$\begin{aligned} F &= 1 + f_1 q^{-1} + \cdots f_{n-1} q^{-(d-1)} + f_{n_f} q^{-n_f} \\ P &= p_0 + p_1 q^{-1} + \cdots p_{n-1} q^{-(d-1)} + p_{n_p} q^{-n_p} \\ n_f &= d - 1 \\ n_p &= \max\left\{n_a - 1, n_f - d\right\} \end{aligned} \tag{6}$$

Substituting Equation (5) into Equation (4):

$$y(t + d) = \frac{P}{H}y + \frac{BFq^d}{H}u + (A - B)Fe(t + d) \tag{7}$$

Substitute Equation (7) into the minimum variance prediction performance index J_p:

$$\begin{aligned} J_p &= E\left\{\left[y(t+d) - y^*(t+d \mid t)\right]^2\right\} \\ &= E\left\{\left[\frac{P}{H}y + \frac{BFq^d}{H}u + (A-B)Fe(t+d) - y^*(t+d \mid t)\right]^2\right\} \end{aligned} \tag{8}$$

where $y^*(t+d \mid t)$ represents the predicted value of output at time t to time $t+d$.

When Equation (9) is satisfied, the minimum variance prediction performance index reaches the minimum:

$$y^*(t+d \mid t) = \frac{P}{H}y + \frac{BFq^d}{H}u \tag{9}$$

In this case, the minimum variance performance prediction index can be expressed as:

$$J_p = E\left\{\left[(A-B)Fe(t+d)\right]^2\right\} = (A-B)^2\left(1 + \sum_{i=1}^{d-1} f_i^2\right)\sigma^2 \tag{10}$$

Substitute Equation (9) into Equation (7) to obtain:

$$y(t+d) = y^*(t+d \mid t) + (A-B)Fe(t+d) \tag{11}$$

After obtaining the real output value at time $t+d$, an objective function is constructed by subtracting the ideal value from the real value to minimize the objective function, so as to meet the requirements. Let the ideal output value at time $t+d$ be $y^*(t+d)$, and the objective function is shown in Equation (12):

$$\begin{aligned} J &= E\left\{\left[y(t+d) - y^*(t+d)\right]^2\right\} \\ &= E\left\{\left[y^*(t+d \mid t) + (A-B)Fe(t+d) - y^*(t+d)\right]^2\right\} \end{aligned} \tag{12}$$

where E represents the operation of taking expectation. When (13) is satisfied, J can be minimized:

$$y^*(t+d \mid t) = y^*(t+d) \tag{13}$$

In this case, the ideal output value is:

$$y^*(t+d) = \frac{P}{H}y + \frac{BFq^d}{H}u \tag{14}$$

The minimum variance control law can be obtained by Equation (13). In a quadrotor UAV, its ideal value is a three-dimensional coordinate: x, y in the horizontal position and h in the altitude.

Only the x-channel x is analyzed here, and the analysis process of the horizontal position channel is consistent with that of the height channel. In this case, let equation (14) be equal to x, and the control law can be obtained:

$$y^*(t+d) = \frac{P}{H}y + \frac{BFq^d}{H}u = x \tag{15}$$

The control law can be obtained by deformation of Equation (15):

$$u = \frac{Hx}{FBq^d} - \frac{P}{FBq^d}y \tag{16}$$

By summarizing the above process, the general process of the minimum variance controller can be obtained:

Step 1: Determine the order of A and B in Diophantine equation according to the specific model of the controlled system.
Step 2: Solve the polynomial coefficients of A and B according to Diophantine equation.
Step 3: The minimum variance control law is solved according to the expression (14), and the optimal C is further obtained according to the minimum variance control law.

3.2 Design of Self-Correcting Minimum Variance Controller

After the general controller is obtained, a self-correcting controller is further designed to better meet the actual situation.

Multiply both sides of equation (9) by A to obtain:

$$Hy^*(t+d \mid t) = py(k) + FBq^d u \tag{17}$$

make:

$$H^*\left(q\right) = H\left(q\right) - 1 = h_1 q^{-1} + h_2 q^{-2} + \cdots + c_{n_h} q^{-n_h} \tag{18}$$

Then equation (17) can be rewritten as:

$$y^*(t+d \mid t) = py + FBq^d u - H^* y^*(t+d \mid t) \tag{19}$$

Substitute Equation (19) into Equation (11) to obtain:

$$y(t+d) = Py + BFq^d u - H^* y^*(t+d \mid t) + F(A-B)e(t+d) \tag{20}$$

It can be obtained by deformation of Equation (20):

$$y(t) = Py(t-d) + BFu - H^{*}y^{*}(t \mid t-d) + F(A-B)e(t) \tag{21}$$

make:

$$M = FB \tag{22}$$

where:

$$M = m_{0} + m_{1}q^{-1} + \cdots m_{n-1}q^{-(d-1)} + m_{n_{m}}q^{-n_{m}} \tag{23}$$

Then Equation (21) can be expressed as:

$$y(t) = Py(t-d) + Mu(t-d) - H^{*}y^{*}(t \mid t-d) + F(A-B)e(t) \tag{24}$$

According to Equation (13), it can be obtained:

$$y^{*}(t+d) = py + Mq^{d}u - H^{*}y^{*}(t+d \mid t) \tag{25}$$

make:

$$\begin{aligned} &\theta = \left[p_{0}, p_{1}, \cdots, p_{n_{p}}, m_{0}, m_{1}, m_{2}, \cdots, m_{n_{m}}, h_{1}, h_{2}, \cdots, h_{n_{h}}\right]^{T} \\ &\varphi(k) = \left[y(t), y(t-1), \cdots, y\left(t-n_{p}\right), u(t), u(t-1), u(t-2), \cdots, u\left(t-n_{m}\right)\right. \\ &\left.-y^{*}(t+d-1 \mid t-1), -y^{*}(t+d-2 \mid t-2), \cdots, -y^{*}\left(t+d-n_{h} \mid t-n_{h}\right)\right]^{T} \end{aligned} \tag{26}$$

According to Equation (26), Equations (24) and (25) can be expressed as:

$$\begin{aligned} &y(t) = \varphi(t-d)^{T}\theta + F(A-B)e(t) \\ &y^{*}(k+d) = \varphi(k)^{T}\theta \end{aligned} \tag{27}$$

Here, the design of the self-correcting controller is transformed into parameter identification, and the θ value of the parameter can be obtained by the least square method. However, with the increasing of the observed data, it will take a lot of time to estimate the parameter by the basic least square method, so the augmented least square method is used to solve the problem. The general expression of the augmented least square method is as follows:

$$\begin{cases} \hat{\theta}(k) = \hat{\theta}(k-1) + K(k)\left[y(k) - \hat{\varphi}(k-d)^{T}\hat{\theta}(k-1)\right] \\ K(k) = P(k-1)\hat{\varphi}(k-d) \,/\, \left[1 + \hat{\varphi}(k-d)^{T}P(k-1)\hat{\varphi}(k-d)\right] \\ P(k) = \left[I - K(k)\hat{\varphi}(k-d)^{T}\right]P(k-1) \end{cases} \tag{28}$$

After the parameter variables are obtained by the augmented least square method, the ideal output value $y^*(t+d)$ can be obtained, and then the expression of the optimal control law and controller can be derived.

To summarize the above process, the design steps of self-correcting minimum variance controller can be divided into the following four steps:

Step 1: Use physical equipment (such as oscilloscope) to measure input $u(k)$ and output $y(k)$, and store them.
Step 2: Form vectors $\varphi(k)$ and $\varphi(k-d)$ according to input and output.
Step 3: The augmented least squares method is used to obtain parameter θ.
Step 4: Obtain $u(k)$ according to Equation (27).

4. PERFORMANCE EVALUATION

After the controller is designed, a performance evaluation of the controller is required. As time goes on, the performance of the controller will gradually decline under the influence of external disturbances, so it is very important to evaluate the performance of the controller. The minimum variance performance index proposed by Harris is the mainstream of controller performance evaluation, and this method is also used in this paper (Zhan, 2010; Yinsong et al., 2021; Qingyue, 2014; Changlei, & Zhong, 2011; Desborough, & Harris, 1993) . The minimum variance performance measures are as follows:

$$\eta = \frac{\sigma_{mv}^2}{\sigma_y^2} \tag{29}$$

where σ_{mv}^2 represents the system output error variance, σ_y^2 represents the system output variance. The value of performance index is 0 ~ 1, the closer to 1, the better the performance of the controller. The closer to 0, the poor performance of the controller needs to be adjusted in time. Performance Index σ_y^2 can be obtained by specific output data, σ_{mv}^2 can be obtained by two methods: Arma (autoregressive moving average) algorithm and FCOR (filtering and correlation analysis) algorithm. This paper uses the FCOR algorithm, FCOR algorithm specific process as follows.

Assuming that the closed-loop system is stable, an infinite-order MA (moving average) model is used to represent the output, i. e:

$$y(t) = \left(f_0 + f_1 z^{-1} + f_2 z^{-2} + \cdots + f_{d-1} z^{-(d-1)} + f_d z^{-d} + \cdots\right) e(t) \tag{30}$$

The two sides of the equation (30) are multiplied by $e(t), e(t-1), \cdots, e(t-d+1)$, respectively, and then the expectation is found:

$$\begin{aligned}
\gamma_{ye}(0) &= E\left[y(t)e(t)\right] = f_0 \\
\gamma_{ye}(1) &= E\left[y(t)e(t-1)\right] = f_1 \\
\gamma_{ye}(2) &= E\left[y(t)e(t-2)\right] = f_2 \\
&\vdots \\
\gamma_{ye}(d-1) &= E\left[y(t)e(t-d+1)\right] = f_{d-1}
\end{aligned} \tag{31}$$

where $e(t)$ is a White noise with a mean of 0 and a variance of 1, so $E[e(t)e(t)]=1$, $E[e(t)e(t-i)]=0$, $i \neq 0$. γ_{ye} is the covariance function of output y and noise e.

According to Formula (7) and (14), the output error of the system can be obtained by subtracting the two formulas, and the expression is as follows:

$$\begin{aligned} y(t+d)-y^{*}(t+d) &= \frac{BFq^{d}}{H}u(t)+F(A-B)e(t+d)+\frac{P}{H}y-\left[\frac{BFq^{d}}{H}u(t)+\frac{P}{H}y\right] \\ &= F(A-B)e(t+d) \end{aligned} \tag{32}$$

Find the variance of the output error:

$$E[F(A-B)e(t+d)]=(1+f_{1}^{2}+\cdots f_{d-1}^{2})(A-B)^{2}=\sigma_{mv}^{2} \tag{33}$$

Insert the formula (31) into the formula (33):

$$\begin{aligned} \sigma_{mv}^{2} &= (1+f_{1}^{2}+\cdots f_{d-1}^{2})(A-B)^{2} \\ &= (1+\gamma_{ye}(1)^{2}+\gamma_{ye}(2)^{2}+\cdots\gamma_{ye}(d-1)^{2})(A-B)^{2} \end{aligned} \tag{34}$$

After calculating the variance of the system output error, the minimum variance performance index can be obtained:

$$\begin{aligned} \eta &= \frac{\sigma_{mv}^{2}}{\sigma_{y}^{2}} \\ &= \frac{(1+\gamma_{ye}(1)^{2}+\gamma_{ye}(2)^{2}+\cdots\gamma_{ye}(d-1)^{2})(A-B)^{2}}{\sigma_{y}^{2}} \end{aligned} \tag{35}$$

After designing the controller expression, the FCOR algorithm is used to evaluate the performance of the variable error closed-loop system shown in Figure 1. In this paper, the performance of the minimum variance controller is evaluated, and the performance evaluation of the self-tuning minimum variance controller and the minimum variance control are similar.

Here is a small example to verify the performance of the designed controller. To simplify the operation, here we take the time delay of the object $d=2$, $x=0$, and $G=\frac{1}{1-z^{-1}}$, that is, $A=1-z^{-1}$, $B=1$, and let $H=\frac{1-0.2z^{-1}}{1-z^{-1}}$. Put it into (6) and you get F and P:

$$\begin{aligned} &F=1 \\ &P=\frac{1.8q^{-1}-q^{-2}}{1-q^{-1}}q^{d} \end{aligned} \tag{36}$$

Substituting equation (36) and into Equation (17), the controller expression can be obtained:

$$C = 1 - q^{-1} \tag{37}$$

The output expression of the system is:

$$y = He + G(r - Cy) \tag{38}$$

and just to simplify things, I'm going to assume that r is 0. The concrete output expression can then be obtained:

$$y = \frac{1 - 0.2q^{-1}}{2 - 2q^{-1}} e \tag{39}$$

It can be obtained by long division of Equation (39):

$$y = 0.5e(t) + 0.4e(t-1) + \frac{0.8q}{2q - 2} e(t-2) \tag{40}$$

Because the time delay of the object is 2, under the condition of white noise with mean 0 and variance 1, the theoretical value of minimum variance can be obtained:

$$\sigma_{mv}^2 = (0.5^2 + 0.4^2) = 0.41 \tag{41}$$

The system shown in Figure 1. was built in Simulink and the concrete expressions were substituted into it. The sampling time is set to 100, and the sampling interval is 0.1. The Simulink simulation diagram is shown in Figure 2. And then you take the variance, you get $\sigma_y^2 = 0.5706$. The performance index of the system can be obtained by comparing σ_{mv}^2 with σ_y^2:

$$\eta = \frac{\sigma_{mv}^2}{\sigma_y^2} = \frac{0.41}{0.5706} \approx 0.7185 \tag{42}$$

According to the variance results, the performance index of the controller reaches 0.7185, which can better control the whole system.

The performance of the designed controller is evaluated by a small example, and it is found that the designed controller can fulfill the requirements of the work well. Therefore, in the next part of the four-rotor UAV position control of the x-channel controller design.

5. QUADROTOR UAV SIMULATION

In this section, the position controller of a four-rotor UAV is designed on the basis of a closed-loop variable error system. In order to make the experiment clearer, the model of the four-rotor UAV is simplified. In this experiment, only the x-channel is analyzed. The simplified model is shown in Figure 3 (Quan et al., 2020).

Figure 2.
Simulink simulation diagram

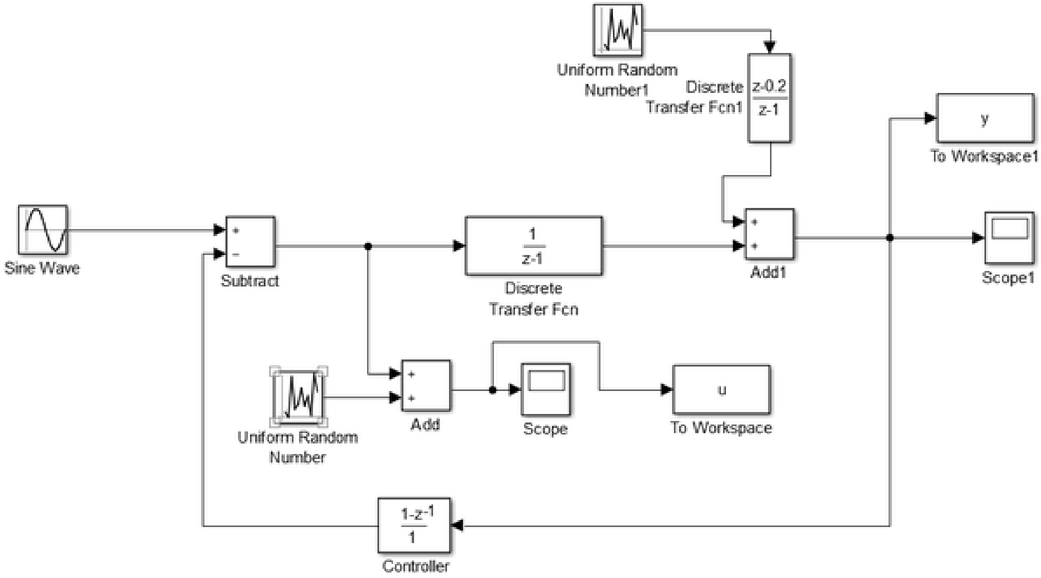
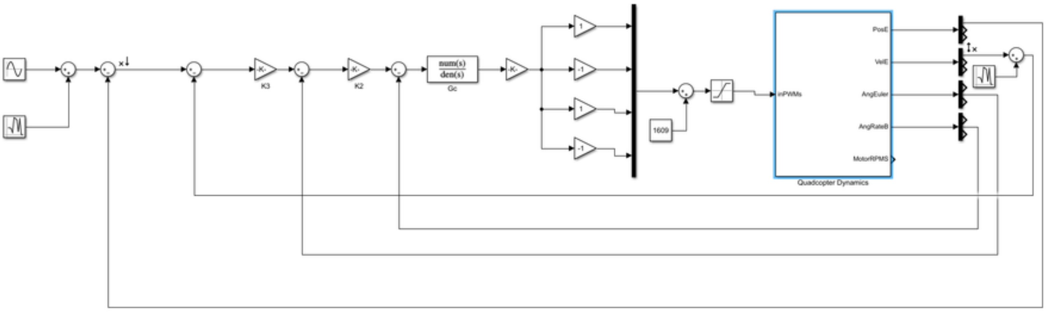


Figure 3.
Position Ring x-axis simplified diagram



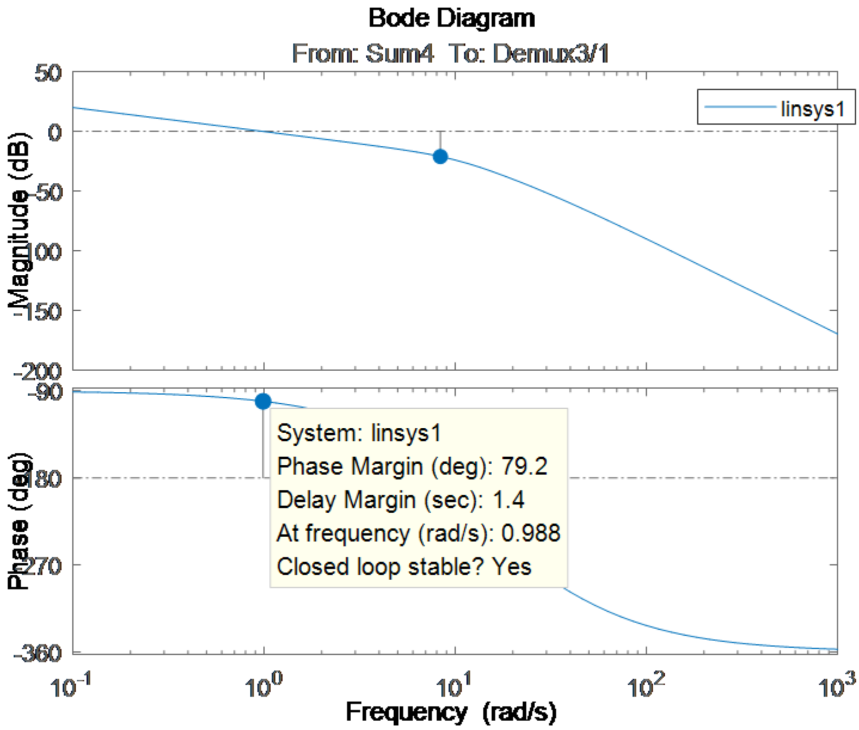
Before starting the experiment, set up the experimental indicators. It is expected that the step response error of the speed control loop is less than or equal to 0.01, the phase margin is more than 60 degrees, and the cut-off frequency is more than $2\,rad\,/\,s$. The cut-off frequency of the position control loop is greater than $1\,rad\,/\,s$, and the phase margin is greater than 60 degrees. In the experiment, the input speed is the expected speed and the output speed is the actual speed. Firstly, linear analysis is carried out and Bode diagram is generated by Simulink as shown in Figure 4.

The transfer function can be obtained from the Bode diagram as follows:

$$G=\frac{3331s^{4}+5.039e05s^{3}+2.563e07s^{2}4.486e08s+5.371e08}{s^{8}+200s^{7}+1.567e04s^{6}+6.045e05s^{5}+1.189e07s^{4}+1.154e08s^{3}+5.557e08s^{2}+5.371e08s+105.5} \quad (43)$$

Then use the control system design based on Bode diagram in MATLAB to carry on the design as shown in Figure 5.

Figure 4.
X channel Bode diagram



As shown in Figure 5, the response of the system is slow, so the response speed is improved by increasing the open-loop gain as shown in Figure 6.

From Figure 6, the response speed is greatly accelerated, and then the controller transfer function can be obtained:

$$G = \frac{26212(s + 10.3)}{s + 8.41e04} \tag{44}$$

Finally, the designed controller is put into the simplified X-channel of quad-rotor UAV, and the results are verified. As can be seen from Fig. 7, the phase margin is 73.6° and the cut-off frequency is $3.22 rad / s$, which meets the requirements.

6. CONCLUSION

At present, for various reasons, only the output error and the open-loop variable error are considered in the research of control system, but the closed-loop variable error is not studied. In this paper, the controller of closed-loop variable system with error is designed. In this paper, a minimum variance controller and a self-tuning minimum variance controller are designed by means of minimum variance control, and then the system is applied to a four-rotor UAV. In the simulation part, the controller of the x-channel of the four-rotor UAV is designed. The experimental results show that the controller can meet the experimental requirements well.

Figure 5.
Design of control system based on Bode diagram

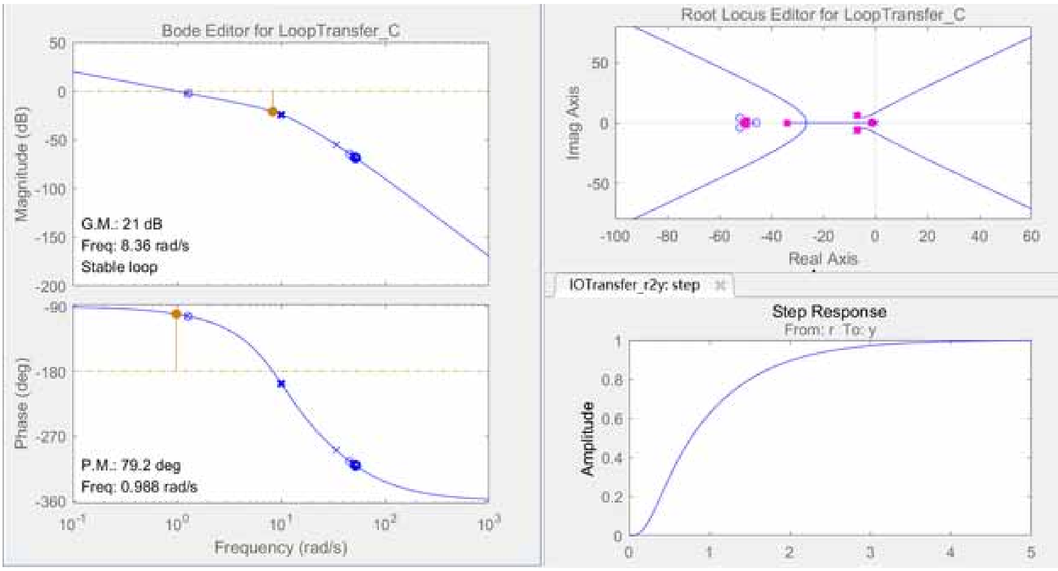
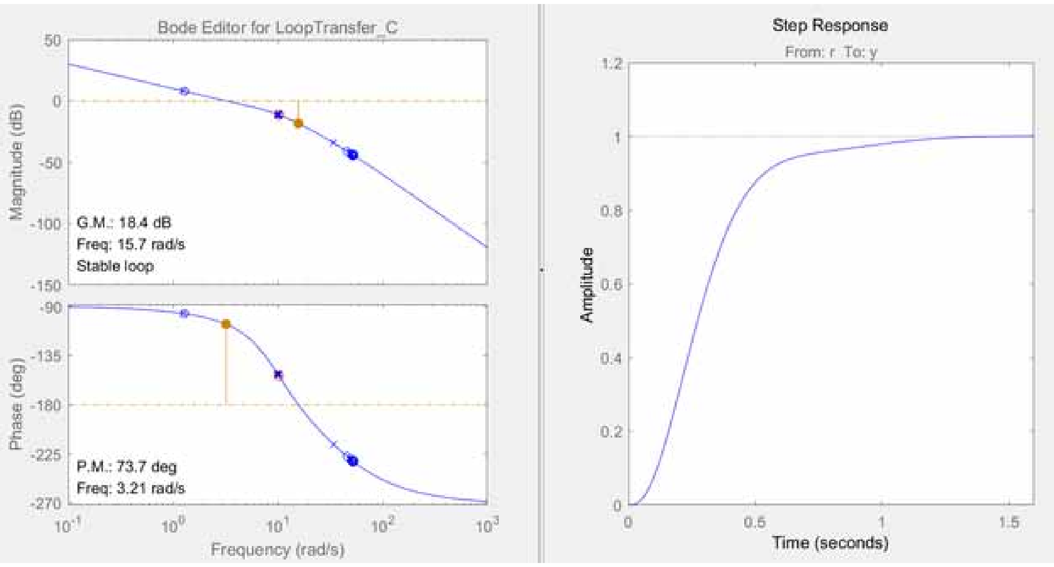
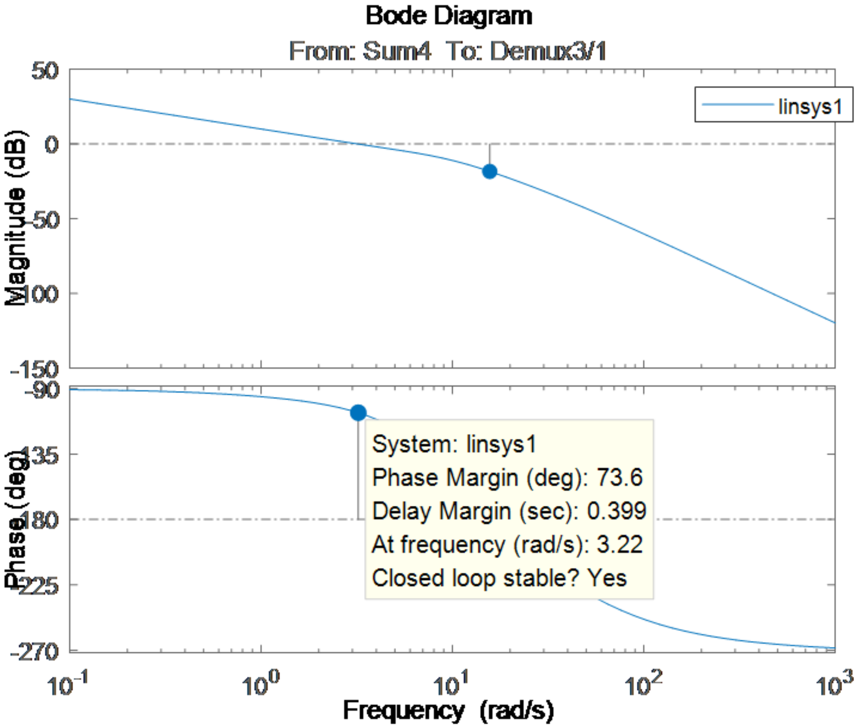


Figure 6.
Bode diagram and step response curve after increasing open-loop gain



So far, the theoretical and methodological research on the closed-loop variable with error system has not been in-depth. For the controller design of the closed-loop variable with error system in the actual process, there are still many basic problems not covered, so there are still some works to be further explored and considered: In this paper, only single-input single-output closed-loop variable error system is studied, but for daily life, it is applied to multi-input multi-output system, so it is very important to study the closed-loop variable error system of multi-input multi-output system. In this

Figure 7.
Bode diagram after adding controller



paper, we study the closed-loop variable error system under the condition of white noise with mean 0 and variance 1, but this kind of white noise exists in the ideal state, which is not in line with the reality. Therefore, the closed-loop variable system with error can be further studied under the interference of colored noise. In addition, the input and output noises are set to be the same in this paper, which is not reasonable in practice. Therefore, the next step can be to study the situation where the input and output noises are different. The ultimate goal of theoretical research in scientific research is to put it into practice. This paper only studies the position control of the four-rotor UAV, which is relatively simple compared with other systems. Therefore, how to apply the closed-loop variable system with error to the complex system needs further study. For example, autonomous driving is very promising at present, and autonomous driving is very dependent on sensors to transmit signals. In the process of transmitting signals, various disturbances will be encountered. If the unmanned driving can be combined with the closed-loop variable error system studied in this paper, the error will be greatly reduced, which will make the unmanned driving safer and make the unmanned driving more popular in the society faster. Closed-loop variable error systems can also be combined with intelligent robots, which can help robots to be more accurate.

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