Research on inertial stabilization platform on mobile carrier in complex environment

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Abstract. The inertial stabilization platform on the mobile carrier has been widely used in military and civilian fields, such as modern satellite TV receiving and broadcasting, mobile satellite communication for vehicles and ships, as well as cash transport vehicles, public security, fire protection, disaster relief, environmental monitoring and many other industries. The platform needs the ability to isolate the effects of carrier motion, and to ensure the interception, identification and tracking of the target signal under various meteorological conditions. We choose the platform of photodetector component. It uses the electromechanical to control detector according to the instructions, automatically identifying and capturing the target. In the working process, the servo system is the key guarantee of the high performance of the platform. According to the high precision, fast response, wide frequency band and strong robust performance requirements of the system, we propose a single neuron adaptive PI+DOB (Proportional Integral+Disturbance Observer) control strategy, a method for continuous nonsingular terminal sliding mode control and a improved statistical model adaptive filtering algorithm. Through theoretical research and experimental analysis, our method improves the performance parameters based on the original system, and provides theoretical support for future researchers to develop high-precision inertial stabilization platform.

1. Introduction
The control accuracy, dynamic performance and low speed stability of the inertial stabilization platform on the mobile carrier are the main design indicators [1]. At present, researches in this area at home and abroad mainly focus on servo loop control [2], multi-axis nonlinear decoupling control [3], system friction compensation[4] and tracking delay [5]. In foreign countries, inertial platforms on mobile carriers were firstly used in handheld telescopes. Since the 1950s, Double stabilizers have been widely used in tanks. In the 1980s, the tracking system was heavily equipped in various observation and camera systems of the troops. In China, research on inertial stabilization platforms on mobile carriers started late. It was only in the 1980s that the development of a stabilization platform for sights began. Until the early 1990s, the development of an inertial stabilization platform for mobile carriers was launched. Since some key technologies have not made breakthroughs, such as the chattering problem caused by friction under low-speed tracking [6], the error caused by shafting coupling under
large declination [7] and the time delay caused by target recognition [8]. With the development of weapons and equipment level, higher requirements are imposed on the rapid response and maneuverability of equipment and the ability to stabilize, track and strike in the maneuver. The high performance of the servo system is its key guarantee. According to the performance requirements of high precision, fast response, wide frequency band and strong robustness of the system, the servo control part of the inertial stabilization platform on the mobile carrier and the problem and tracking of the convergence mode and chattering of the terminal sliding mode control algorithm are respectively studied. The methods of a single neuron adaptive PI [9] control strategy based on disturbance compensation, a continuous non-singular fast terminal sliding mode control method [10] and an adaptive filtering algorithm in the existing statistical model are proposed respectively. In this paper, the composition and working principle of the stabilization platform system are introduced in detail in the third part. In the experimental analysis of the fourth part, a large number of performance comparison experiments are shown to illustrate the effectiveness of our method. I hope the method of this paper can provide theoretical support for future researchers to develop high-precision inertial stabilization platforms on mobile carriers.

2. Related work

Regarding the research of servo loop control strategy, in this paper, the basic inertial stabilization platform on mobile carrier is the traditional theory. In recent years, a variety of advanced control methods have been gradually applied to the stability control of inertial stabilization platform on mobile carriers. Hilker. JM et al. systematically analyzed and summarized the adaptive control methods that can be used for inertial stabilization platforms on mobile carriers, and obtained practical adaptive control techniques [11]. Chen et al. proposed a new adaptive variable structure scheme for model reference adaptive control (MRAC) problems for plants with unmodeled dynamic and output disturbance [12]. Wang Lianming et al. used the self-learning characteristics of the neural network to propose an adaptive neural network control method for the opto-electronic stability platform [13]. Qi Jie et al. used a fuzzy controller with a correction factor to control the servo system of the shipborne radar stability platform [14]. The controller can overcome better the influence of nonlinear factors, and has good robustness and satisfactory control accuracy, but the methods only give the simulation results, and the actual application results have yet to be further verified. We propose a single-neuron adaptive PI+DOB control method based on disturbance compensation for inertial stabilization platform on mobile carrier, which guarantees the ability of the platform to stably track the target under external disturbance and system parameter changes, and improves the platform adaptability and robustness.

When the state of system is in the sliding phase, due to the action of the switching item, the system closed loop response exhibits strong anti-disturbance and robustness. Traditional sliding mode control method uses linear hyperplane [10]. Due to multiple-source disturbances, frame dynamic characteristics of aerial inertially stabilized platform (ISP) changes, leading to nonlinear and time-varying position loop error. Therefore, conventional PID control with fixed parameters can't bring performance of high accuracy and fast response [15]. Wu et al. proposed a terminal sliding mode control design scheme for uncertain dynamic systems in the pure-feedback form, this design employs a recursive procedure which utilizes a set of switching manifolds to realize finite time convergence [16]. In order to solve the problems of convergence speed and chattering, we use a continuous non-singular fast terminal sliding mode control method. The combination of the coefficient double power approach rate and the non-singular fast terminal sliding mode surface improves the convergence speed of the system state in the approaching and sliding phases. Compared with the traditional method, the proposed control rate is continuous, so the chattering is suppressed and the control precision is higher. The simulation results verify the effectiveness of the algorithm.

With respect to tracking time-delay compensation, in the inertial stabilization platform, signal needs from the target imaging to the off-target output, and through photoelectric conversion, signal processing, data acquisition and storage, multiple tracking algorithm operations and transmission, etc., Multiple time delays will cause overall system performance degradation. Many time delay
compensation methods have appeared. Tian et al. put forward a networked control system random time-delay compensation method based on time-delay prediction and improved implicit generalized predictive control (GPC) [17]. Park et al. proposed scheme estimates the time delay using the difference between the Q-axis stator current command and the time-delayed actual Q-axis stator current in a synchronous reference frame, then compensates the time delay in the voltage and current using the angular displacement of a DQ transformation [18]. In this paper, an improved statistical model adaptive filtering algorithm is proposed to compensate for the delayed target signal. By adaptively adjusting the maneuver frequency and the acceleration variance, the state information of the target is predicted in advance, thereby achieving the purpose of compensating for the time delay.

The main contributions of this paper are as follows,

- We introduce the working mechanism of the photoelectric search system in depth. The dynamic equation of the photoelectric search system is derived. The mathematical model of each component of the servo system is established. The influencing factors of the system stability accuracy and tracking accuracy are analyzed in detail.
- Aiming at the core problem of how to improve the anti-interference ability of the optical search system, a single neuron adaptive PI+DOB control strategy based on disturbance compensation is proposed.
- In order to solve the problems of convergence speed and chattering in the existing terminal sliding mode control algorithm of photoelectric search system, a continuous non-singular fast terminal sliding mode control method is proposed.
- About the time delay of the photoelectric tracker in the photoelectric search system, an improved statistical model adaptive filtering algorithm is proposed to compensate the delayed target signal.

3. Methods
In this part, we will introduce separately the mechanism of photoelectric search system, single neuron adaptive PI+DOB control strategy based on disturbance compensation, continuous non-singular fast terminal sliding mode control method, and an improved statistical model adaptive filtering algorithm.

3.1. Photoelectric search system
The servo control system consists of six parts: Gyro stabilization tracking turntable [19], turntable electronic control system, main control computer, camera, power supply and swing test turntable. Power supply, the system uses a linear power supply to power the system. Camera, this system uses the composition of visible light CCD camera and camera lens. The sway test turret is used to test and verify the gyro stabilization platform index, it consists of an azimuth axis and a pitch axis system, which can simulate the attitude of the carrier in both azimuth and pitch directions.
Figure 1. System work flow chart

Firstly, we need to initialize the camera and system, keep it pointing the camera's boresight to the specified airspace. After the moving target enters the camera field of view, the system realizes the capture tracking of the target according to the operation result of the image processor, and simultaneously displays the image on the main control computer interface, which can realize single frame saving. During the system operation, three kind system functions were designed: manual positioning function, stability function and automatic tracking function, is shown in Figure 1.

Here we introduce the working mechanism of the servo control system. Taking the common optoelectronic stability platform as an example, it is based on the DSP motion control module [20] for electronic control system. The system runs fast and has strong computing power, which can meet the real-time performance requirements of advanced control algorithms. It provides an effective simulation platform for the research and verification of related servo control algorithms. The structure of the basic optoelectronic servo control system was selected in this paper, as is shown in Figure 2. From the inside to the outside, the current loop, speed loop and position loop form a cascade control system. The current loop of the system is realized by analog circuit, it is integrated in the drive. The speed loop and position loop use a digital servo. The workflow of the system is as follows, when the system receives the stabilization command $\omega_r$, the command signal directly differs from the gyro feedback signal as the input of the speed loop, and then the torque motor is rotated by the current loop. When the input signal is the search command, the deviation signal from the search command $\theta_r$ and the viewing angle $\theta_l$ is used as the input of the search regulator, then the signal enters the speed loop and the current loop in turn, the torque motor is rotated by it. When receiving the stabilization tracking command, the image processor gives the miss target signal $\Delta \theta$ as the tracking regulator, The motor is driven by signal through the speed loop and the current loop.
For the speed loop digital model, unlike the conventional servo control system, the servo control system use the angular velocity of inertial space that was measured by the gyroscope to form a speed closed loop, which is a core loop for realizing the visual axis stability of the detector. The speed loop can effectively suppress the influence of disturbance caused by the attitude of the carrier, and it can make the visual axis of the detector on the platform remain stable in the inertial space. It also makes the platform follow the angular velocity command of the inertial space to run smoothly. The speed loop can reduce the time constant of the forward path, improve the dynamic characteristics of the loop, and improve the low-speed stability of the servo control system. The speed loop model is shown in Figure 3.

In Figure 3, $\omega_i$ is the input, command angular velocity, $\omega_b$ is the external carrier interference angular velocity, and $\omega_j$ is the visual axis angular velocity, $C_i(s)$ is the speed loop controller, $K_{PWM}$ is a PWM amplification factor, $K_g$ is the transfer function of the gyro.

For the position loop digital model, the position loop is used to achieve fast and accurate tracking of the target command. The digital model is shown in Figure 4. When the input signal is a search command, the deviation signal of the search command and the visual axis angle is used as the input of the search loop regulator, and the motor is rotated by the speed loop and the current loop in turn. When the input signal is the tracking command, the image processor gives the miss distance deviation as an input to the tracking regulator, then the motor is driven through the speed loop and current loop.
In Figure 4, \( \theta_{\text{tar}} \) is the position of the target position, \( K_{TV} \cdot e^{-\tau s} \) is the tracker model, \( \Delta \theta \) is the off-target amount, \( C_p(s) \) is the position loop controller, when the system works in the tracking mode \( C_p(s) = C_{na}(s) \), when the system works in the search mode \( C_p(s) = C_{soa}(s) \).

This part firstly analyzes the principle of the basic servo control system selected in this paper. Since the current loop uses analog circuit, this paper only introduces the digital circuit of speed loop and position loop in detail. The detailed theoretical will provide a theoretical basis for that we improved the servo control system.

3.2. Single Neuron Adaptive PI+DOB Control System

In the actual modeling process of the photoelectric search system, the influence of many uncertain factors is often ignored, and the system model is impossible to be completely consistent with the actual system, and the system characteristics will also change with the external environment and external conditions, if the carrier is in different postures, it will cause the gravity center of the platform to change, the coupling of the shaft system will also affect, the nonlinear friction between the shafts and the wind resistance torques may change, in addition to these, there are other factors, the characteristics of the actual control object may be different from the characteristics of the object on which the calibration link is designed, it is difficult to achieve the desired control effect.

Aiming at the core problem of how to improve the anti-interference ability of photoelectric search system, we propose a single neuron adaptive PI+DOB control strategy based on disturbance compensation. The block diagram is shown in Figure 5. Firstly, various disturbances are observed by the disturbance observer DOB, which is fed forward to the control input as a compensation signal to improve the anti-interference ability of the system. At the same time, the self-learning and adaptive force of the neurons are used to adjust the PI parameters online. This improvement ensures the ability of the search system to track the target stably under external disturbances and system parameter changes. The experimental results on the experimental device show that the method has strong anti-interference ability for uncertain disturbance and improves the robustness of the photoelectric search system.
3.3. Continuous non-singular fast terminal sliding mode control

In order to solve the problem of convergence speed and chattering of the existing terminal sliding mode control, we propose a continuous non-singular fast terminal sliding mode control method, it is shown in Figure 6, which adopts variable coefficient double power approaching rate $f$ and non-singular fast terminal sliding mode surface. The Lyapunov stability method [10] proves that the proposed control rate can make the state trajectory converge to a region in a finite time under the condition of disturbance, because the combined design method improves the convergence speed of the system state in the approaching sliding phases. Compared with the traditional method, the proposed control rate is continuous, so the chattering is suppressed and the control precision is higher. The simulation results verify the effectiveness of the algorithm.

3.4. Time delay compensation

In order to solve the problem of reducing the tracking accuracy due to the time lag of the photoelectric tracker, this paper proposes an improved statistical model adaptive filtering algorithm to compensate the delayed target signal. By adaptively adjusting the maneuver frequency and the acceleration variance, the state information of the target is predicted in advance, is shown in Figure 4, thereby achieving the purpose of compensating for the time lag. The effectiveness of the algorithm is verified by simulation, and the speed tracking curve with or without time delay compensation is compared on a photoelectric tracking device. The results show that the proposed algorithm effectively improves the target tracking accuracy and plays a good role in tracking time lag. After a target position is given, the system enters the automatic tracking mode. The servo control system receives the miss distance data of the azimuth and elevation directions sent by the photoelectric imaging tracker. The signal controls the motor rotation, and points the visual axis of the TV sensor to the target to reduce the amount of TV off-target. Real-time tracking of targets.

The photoelectric sensor can automatically identify and track the moving target, and the obtained off-target signal is output to the servo control system after photoelectric conversion, signal processing, data acquisition and storage. The off-target amount lags behind the target imaging time, which has a great impact on the tracking control platform. Such as, causing system phase lag, reducing system
bandwidth, reducing tracking accuracy, etc., the dynamic response of the system will be worse, if the target suddenly turns situation, it may result in the target not tracking or losing the target. Aiming at the time lag problem caused by photoelectric imaging tracker, the improved adaptive predictive filtering algorithm based on current statistical model [21-27] is used to predict the time difference of tracker delay by predicting the moving position and velocity of maneuvering target.

4. Experiment
This part consists of three parts: a single neuron adaptive PI+DOB control, continuous non-singular fast terminal sliding mode control and time delay compensation experimental results.

4.1. Speed loop is a single neuron adaptive PI + DOB control results
During the experiment, the tracking target is selected to be in a stationary state (the off-target signal is zero at this time, the photoelectric search system is required to remain stationary, and the speed and position signals are all zero). We tested the azimuthal stability performance, assuming that the simulated carrier disturbance signal was at 5°/0.5Hz and 10°/1Hz, respectively. The position loops are controlled by PID, and the speed loops are controlled by conventional PI [9], PI+DOB [28, 29], and single neuron PI+DOB control. In order to make the comparison objective, through the repeated debugging, the above three control strategies are all adjusted to the relatively optimal situation, so that the system has better dynamic and static performance, and then comparative analysis is carried out separately.

![Figure 7. Comparison of anti-disturbance performance under 5°/0.5Hz disturbance signal](image)

Figure 7 (a), (b), and (c) are the anti-disturbance performance test curves for the 5°/0.5 Hz carrier perturbation using the above three control strategies, including the position error (pos error,°/s) curve and the velocity error (vel error,°/s) curve, the x axis represents the number of sampling points. It can be seen from the experimental results that the carrier operation will have various disturbance effects on the system, especially when the carrier is changing, the shaft friction will be abrupt between the dynamic friction and the static friction, at this time, the influence on the system is most obvious, and the specific performance is the error curve shows a sharp peak here, the tracking error is the largest, and the amplitude of the glitch signal curve increases, causing chattering of the detecting device.

In order to further compare the control effects, the amplitude and frequency of the carrier operation are gradually increased. Figure 8 (a), (b), and (c) are respectively used when the above three control strategies are used under 10°/1Hz carrier disturbance. Anti-disturbance performance test curve. It can be seen from the experimental results that after the amplitude and frequency of the carrier operation increase, the influence on the stabilization platform increases, which is manifested in the increase of position error and the more obvious speed jitter.
Figure 8. Anti-disturbance performance test curve for 10°/1Hz disturbance signal

After analysis and comparison, it is found that when the conventional PI control is used, the design index can still be achieved under the condition that the carrier disturbance amplitude and frequency are low, but as the carrier disturbance increases, the anti-disturbance performance deteriorates at 10°/1Hz. The stability isolation accuracy of carrier disturbance is >0.2°, which cannot meet the requirements of design indicators. After adding the disturbance observer, partial compensation can be realized for the system disturbance, and the system anti-disturbance performance is improved, because the PI parameter is fixed at this time, after the disturbance of the external disturbance, there is a lack of good adaptability, and the error is still too large. After the single neuron adaptive PI+DOB control, it is reflected in the interference of various frequencies and amplitudes within the test range. It has a good disturbance isolation capability. The above analysis shows that the proposed control strategy is effective and feasible in the control of the photoelectric search system, which greatly improves the anti-interference ability and system performance.

4.2. Experimental results of continuous non-singular fast terminal sliding mode control.

In order to verify the effectiveness of the proposed algorithm, the proposed CNFTSM algorithm (continuous non-singular fast terminal sliding mode control) and NTSM [26] algorithm (non-singular terminal sliding mode control) and NFTSM [27] algorithm (non-singular fast terminal sliding mode control) are respectively derived from convergence performance. Contrast simulation with control accuracy angle. The performance parameters selected in this paper are the viewing angle θ, the boresight rate ω, and the sliding surfaces.

4.2.1. Convergence performance

In the Table 1, it shows the parameters of the states θ, ω and s under different algorithms when the initial value of the system is [0.5 rad, 0.2 rad/s]T. In the presence of the interference torque Tq, the sliding mode surface s can converge to the neighborhood of s=0 in a finite time by using three control modes. The CNFTSM algorithm can achieve a faster convergence speed of the system state in the approaching phase. In addition, as can be seen from Table 1, although the NFTSM can theoretically converge the state faster than the NTSM in the sliding phase, the convergence time of the NFTSM algorithm in the state approaching phase is still greater than that of the NTSM due to the larger initial value s(0).

| Method     | Tθ (s) | Tω (s) | Ts (s) |
|------------|--------|--------|--------|
| NTSM [26]  | 1.3    | 0.5    | 0.6    |
| NFTSM [27] | 1.2    | 0.45   | 0.65   |
| CNFTSM     | 1      | 0.25   | 0.25   |

4.2.2. Disturbance suppression

When the system state reaches the steady state phase, θ and ω cannot converge to 0 due to the action of the disturbance torque Tq. The θ can converge to $0.7 \times 10^{-3}$ rad in a finite time by our method, and
the other two methods respectively converge to \(0.9 \times 10^{-3}\) rad and \(1 \times 10^{-3}\) rad, the results are shown in Table 2. It can be seen that under the same functional parameters, the CNFTSM control method can achieve higher steady-state accuracy. At the same time, when the first time reaches the lowest value of \(\omega\), the time of the three methods is \(2.75\) s, but the minimum values respectively are \(-2\times10^{-3}\) rad/s, \(-2.2\times10^{-3}\) rad/s, \(-2.3\times10^{-3}\) rad/s, respectively. Therefore, for the performance parameter \(\omega\), it has a better convergence of the method proposed in this paper.

Table 2. Steady-state accuracy of system states \(\theta, \omega\) under different algorithms

| Method    | \(R\theta\) (/rad) \(\times 10^{-3}\) | \(R\omega\) (/rad/s) \(\times 10^{-3}\) |
|-----------|--------------------------------------|-------------------------------------|
| NTSM[26]  | 1                                    | -2.3                                |
| NFTSM[27] | 0.9                                  | -2.2                                |
| CNFTSM    | 0.7                                  | -2                                  |

4.2.3. Time delay compensation experiment results

In order to verify the effectiveness of the algorithm, the simulation is carried out in MATLAB, and the results are compared with the current statistical model based adaptive algorithm [21] (CS-KF), variance adaptive filtering algorithm [24, 25] (MACS-KF), mobile frequency adaptive filtering algorithm [30] (MFCS-KF) for comparative simulation experiments. Finally, verify it on the photoelectric search equipment. In order to ensure the rigor and reliability of the experiment, the initial conditions of all experiments were the same. In order to quantitatively compare the performance of each algorithm, the root mean square error (RMSE) is selected as the evaluation index:

\[
RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \hat{x}_i)^2}
\]

Simulation experiment 1: In the two-dimensional plane, the target starting point is \((0,0)\) m, in the \(0 \sim 50\) s, the target is moving along the x-axis at a uniform linear motion with a speed of \(50\) m/s. In the \(50 \sim 100\) s, the turning along the y-axis direction \(90^\circ\), \(a_x = a_y = 5 m / s^2\). After that, the acceleration drops to 0, when the time is \(t = 150\) s, turning is made again, the acceleration is \(-5 m / s^2\), and when \(t = 200\) s, the turning is over, the acceleration is reduced to 0 again. The sampling period is 1 s, and the x-axis and y-axis are independently observed.

Simulation parameters:

- CS-KF: \(a_{max} = 40\), \(\alpha = 0.01\), MACS-KF: \(a_{max}\) adaptive, \(\alpha = 0.01\), MFCS-KF: \(a_{max} = 40\), \(\alpha\) adaptive, MDCS-KF: \(a_{max}\), \(\alpha\) both adaptive.

Figure 9, (a), (b) and (c) are the RMSE curve of position, velocity and acceleration with different algorithms. MDCS-KF has higher estimation accuracy for target position, velocity and acceleration than the current statistical model adaptive filtering algorithm. In addition, the convergence speed at the initial moment is also better than other algorithms.
Simulation experiment 2: The experimental device is a multi-dimensional motion control experimental platform. As shown in Figure. 10, the image tracker is composed of an "area array CCD camera + lens" and a digital image processing device, and the video signal is a black and white television signal. The signal frame rate is 50 Hz. The initial value of the maneuvering frequency is $\alpha = 0.01 \, \text{rad/s}$, observe the noise array $R = \text{diag}(10^2, 10^2, 10^2)$ as the unit $\text{(°)} / \text{s}$, and the sampling period is $T = 0.01 \, \text{sec}$. During the experiment, the position of the pitch direction is kept unchanged, and the angular velocity of the azimuth direction is set to 0-50s, $\omega = 0 \, \text{°} / \text{s}$, 50-100s, $\omega = 5 \, \text{°} / \text{s}$, 100-150s, $\omega = 10 \, \text{°} / \text{s}$, 150-200, $\omega = 6 \, \text{°} / \text{s}$, 200-250s, $\omega = 2 \, \text{°} / \text{s}$ on the positioning mode interface. The speed tracking curves which we can observe in the figure 11, they are the angular velocity curve using the improved method before and after

![Figure 10. Multidimensional motion control platform](image)

![Figure 11. Angular velocity before and after compensation in 0-250s](image)

The angular velocity before and after compensation in 0-250s is shown in Figure 11. As can be seen from Figure. 11(a), the speed tracking curve without the delay compensation algorithm is delayed in time compared with the real speed, and has a large overshoot at the time of speed switching. Figure11 (b) shows that after adding the improved statistical model adaptive algorithm, the amount of time lag is well eliminated, and the overshoot is small when the speed is switched, and the prediction error accurate is $0.087 \, \text{°}$. The figure shows that in the presence of model error and uncertain measurement noise, the proposed algorithm has good predictive filtering effect and the tracking accuracy is greatly improved.

5. Conclusion
This paper provides theoretical support for the development of high-precision inertial stabilization platform on mobile carriers. In this paper, digital model of each component of the servo system is established. The factors affecting the stability and tracking accuracy of the system are analyzed in detail. It provides a reference for the research of the servo search algorithm and other subsequent control problems. Then, aiming at how to improve the anti-interference ability of the photoelectric search system, a single neuron adaptive PI+DOB control strategy based on disturbance compensation is proposed. Firstly, various disturbances are observed by the disturbance observer, which is fed forward to the control input as a compensation signal to improve the anti-interference ability of the
system. At the same time, the self-learning and adaptive force of the neurons are used to adjust the PI parameters online, which ensures the ability of the photoelectric search system to stably track the target under external disturbances and system parameter changes. For the problem of convergence mode and chattering of terminal sliding mode control algorithm, a continuous non-singular fast terminal sliding mode control method is proposed, which adopts the combination of variable coefficient double power approach rate and non-singular fast terminal sliding mode surface. To improve the convergence speed of the system state in the approaching and sliding phases, the result proves that the proposed control rate can converge to a region quickly in a limited time. Compared with the traditional methods, the control rate proposed in this paper is continuous, so the chattering is suppressed and the control precision is higher. The simulation results verify the effectiveness of the algorithm. Finally, in order to solve the problem of reducing the tracking accuracy of the system due to the time lag of the photoelectric tracker in the photoelectric search system, and referring to the idea of maneuvering target tracking, an improved statistical adaptive filtering algorithm is proposed to compensate the delayed off-target signal. By adaptively adjusting the maneuver frequency and the acceleration variance, the state information of the target is predicted in advance, thereby achieving the purpose of compensating for the time lag. Simulations verify the effectiveness of the algorithm. There are still some work to be done here. The verification method in this paper is mainly based on the simulation platform and through the simulation experiment. It is hoped that the theoretical research ideas can be provided for the research of relevant researchers, but the actual industrial application needs further research by future researchers.

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References
[1] Hamed Khodadadi; Mohammad Reza Jahed Motlagh. Mohammad Gorji. (2011) Robust control and modeling a 2-DOF Inertial Stabilized Platform, International Conference on Electrical, Control and Computer Engineering, Pahang, Malaysia. 21-22 June.
[2] Karel Jezernik; Robert Horvat; Joze Harnik. (2012) Finite-State Machine Motion Controller: Servo Drives. IEEE Industrial Electronics Magazine, Volume 6, pp. 13-23.
[3] Chun Zhao; Cungui Yu; Jianyong Ya. (2019) Dynamic Decoupling Based Robust Synchronous Control for a Hydraulic Parallel Manipulator. IEEE Access, Volume 7, pp. 30548-30562.
[4] Chao Ren, Xiaohan Li, Xuebo Yang, Shugen Ma. (2019) Extended State Observer-Based Sliding Mode Control of an Omnidirectional Mobile Robot With Friction Compensation. IEEE Transactions on Industrial Electronics, Volume 66, pp. 9480-9489.
[5] Lennart Hansson. (1989) Tracking or delay effects in microtine reproduction. Acta theriologica, Volume 34, pp. 125-132.
[6] Sabizhan Sumbekov, Ton Duc Do. Sliding Mode Controller with DOBC and MTPA Trajectory for Surface-Mounted PMSM. 2018 4th International Conference on Green Technology and Sustainable Development (GTSD),
[7] GE Yu-wen, YANG Ping, HUANG Zhe. (2016) Coupling Response Analysis of Propulsion Shafting and Hull Deformation for Large Ships. SHIP ENGINEERING, Volume 38, pp. 26-30.
[8] Tuoxin Wang, John W. M. Rogers, Krste Mitric. (2019) Analysis and Correction of Noise Injection Due to Parallel-Output-Misalignment (POM) Effects in Ring-Type Time-to-Digital Converters (TDCs), IEEE Journal of Solid-State Circuits, pp. 1-10.
[9] G.Y. Ma, W.Y. Chen, F. Cui, W.P. Zhang, X.Sh. Wu. (2010) Adaptive levitation control using single neuron for micromachined electrostatically suspended gyroscope. Electronics Letters, Volume 46, pp. 406-408.
[10] MAO J.L., LI Q., ZHU H.R. (2016) A continuous nonsingular fast terminal sliding mode control method. Control and Decision, Volume 31, pp. 1873-1878.
[11] Hilker J M. (2015) Inertially stabilized platform technology concepts and principles. IEEE Control Systems Magazine, Volume 28, pp. 26-46.
[12] Chien C.J., Fu L.C., (1999) Adaptive variable structure control. Adaptive Control Systems, Volume 22, pp. 41-62.
[13] Lianming Wang; Wenqi Ge; Mujun Xie. (2011) Neural network adaptive control method for inertial stable platform velocity loop on mobile carrier. Photoelectric engineering, Volume 28, pp.9-12.
[14] Jie Yan; Jianzhing Tang; Weixiang Shi, et al. (1999) FUZZYApplication of Control in Shipborne Radar Stabilized Platform Servo System. Journal of Ordnance Engineering, Volume 20, pp. 182-185.
[15] Zhang Y., Yang T., Li C. (2014) Fuzzy-PID control for the position loop of aerial inertially stabilized platform. Aerospace Science and Technology, Volume 36, pp. 21-26.
[16] Wu Y., Yu X., Man Z. (1998) Terminal sliding mode control design for uncertain dynamic systems. Systems & Control Letters, Volume 34, pp. 281-287.
[17] Zhong D.T., Li S.J., Wang Y.H., and Yu H.X. (2015) Networked Control System Time-Delay Compensation Based on Time-Delay Prediction and improved Implicit GPC. Algorithms. Volume 8, pp. 3-18.
[18] Chul Woo Park, Woo Hyen Kwo. (2004) Time-delay compensation for induction motor vector control system. Electric Power Systems Research, Volume 68, pp. 238-247.
[19] Cheng, Jia, Wang. (2017) Research on the Stabilization and Automatic Tracking Control in Heading Using the Electric-driven Turntable with Great Load. Proceedings of the Fifth International Symposium on Fluid Power Transmission and Control.
[20] Guo, J.M., Zhao, Y.W., Wang, H.M. (2010) DSP practical solutions for motor control using DSP-Controller, International Conference on Networking and Digital Society, 30-31 May 2010, Wenzhou, China.
[21] Sun, w., Yang, Y.J. (2017) Adaptive maneuvering frequency method of current statistical model. IEEE/CAA Journal of Automatica Sinica, Volume 4, pp. 154-160.
[22] K. Mehrotra, P R. Mahapatra. (1997) A Jerk Model for Tracking Highly Maneuvering Targets. IEEE Transactions on Aerospace and Electronic Systems, Volume. 33, pp. 1094-1105.
[23] H. Zhou, Z. Jing, P. Wang. (1991) Maneuvering Target Tracking, National Defence Industry Press.
[24] Zheng, Z.S., Zhao, H.Q. (2016) Bias-Compensated Normalized Subband Adaptive Filter Algorithm. IEEE Signal Processing Letters, Volume 23, pp. 809-813.
[25] Shilpa Suresh, Shyam Lal. (2017) Two-Dimensional CS Adaptive FIR Wiener Filtering Algorithm for the Denoising of Satellite Images, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. Volume 10, pp. 5245-5257.
[26] Feng, Y., Yu, X., Man, Z. (2002) Non-singular terminal sliding mode control of rigid manipulators. Automatica,Volume 38, pp. 2159-2167.
[27] Yu S; Yu X; Shirinzadeh B. Continuous finitetime control for robotic manipulators with terminal sliding mode. Automatica, 2005, Volume 41,pp. 1957-1964.
[28] S. Li, J. Yang, W. Chen, X. Chen. (2014) Disturbance Observer-Based Control: Methods and Applications. Boca Raton, FL, USA: CRC Press.
[29] W. Chen. (2016) Disturbance-observer-based control and related methods—An overview. IEEE Trans. Ind. Electron, Volume 63, pp. 1083-1095.
[30] J.P. Meehan, A.D. Fagan. (2000) An adaptive vector quantized flexible precoder for a dynamic continuous frequency selective mobile channel. IEEE Communications Letters, Volume 4, pp. 196-198.