Active disturbance rejection control of indoor inspection robot in intelligent substation based on monocular vision

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Abstract. In order to improve the autonomous digging ability of the inspection robot, an auto disturbance rejection control method based on monocular vision is designed for the indoor inspection robot in the intelligent substation. Through tracking and detecting the end position and posture changes of the robot in the x-z plane during the operation of the robot in the intelligent substation, and mining the abnormal data, and combining with the PID control principle, the inspection robot single view automatic disturbance rejection control method is designed. The visual interference information is cleaned and denoised to realize the auto disturbance rejection and autonomy of the indoor inspection robot monocular vision pan-tilt. Due to the adjustment of the operating parameters of the pan-tilt active disturbance rejection controller based on monocular vision of the indoor inspection robot, it is difficult to set the parameters due to the interaction between the parameters. Furthermore, the parameters of the ADRC are adjusted and optimized to meet the research requirements of the effective control of the pan-tilt active disturbance rejection of the indoor inspection robot in the substation. Finally, the experimental results show that compared with the traditional methods, the control accuracy and strong robustness of the indoor inspection robot in the substation are significantly improved, which fully meets the research requirements.

1. Introduction
Traditionally, there are camera internal parameter calibration, robot kinematics parameter calibration and hand-eye relationship calibration based on system calibration technology. The accuracy of hand-eye relationship calibration directly affects the final control performance of the system. In order to overcome the shortcomings of traditional calibration methods, people gradually focus on non-calibration methods[1]. Compared with the traditional method, the uncalibrated hand eye coordination method has no obvious limitations in the operation environment and robot motion control. It has strong anti-interference, which is helpful to improve the adaptability of the robot. However, because there are many adjustable parameters in this method, the calibration process and effect of this method and motoman-sv3xl robot are relatively mature, which can realize the uncalibrated robot well.

2. Active disturbance rejection control of inspection robot based on monocular vision
2.1. monocular vision pan-tilt interference information mining for indoor inspection robot
The application of indoor inspection robot is more and more widely. It is of great significance to improve the performance index of auto disturbance rejection control of monocular vision pan-tilt for inspection robot. Based on this, the active disturbance rejection control (ADRC) technology is studied. By analyzing the motion principle of the inspection robot, its kinematics model is established[2]. Using
Lagrange quadratic equation and Newton-Laplace equation as state variables, the dynamic model of position control and attitude angle state control of inspection robot is established. The active disturbance rejection control technology of monocular vision pan-tilt is analyzed, and the interference parameter tuning principle of single visual pan-tilt is discussed. Based on the virtual control variables, the active disturbance rejection control law for the position and yaw angle of the ground omnidirectional inspection robot is designed. Without considering the small angle, this paper analyzes and simplifies the robot motion model, and mines the interference characteristic information of monocular vision platform of indoor inspection robot, so as to estimate and compensate the internal and external interference in the process of system operation in real time. Active disturbance rejection controller (ADRC) is a simplified control strategy based on Active Disturbance Rejection Control[3]. It has a second-order control structure.

Based on the second-order control module of monocular visual pan-tilt of inspection robot, the interference data of pan-tilt are mined. In order to solve the contradiction between rapidity and overshoot, linear tracking differential link (LTD) is introduced[4]. After given the input tracking signal and its differential signal, the corresponding interference detection equation is obtained.

\[
\begin{align*}
    v_1 &= v_2 \\
    v_2 &= -r^2 (v_1 - v_0) + 2rv_2
\end{align*}
\]

Furthermore, the extended disturbance state observer is simplified to high gain linear ESO to improve the sensitivity of abnormal disturbance data mining, and the collected characteristic data are optimized to mine state, model uncertainty and external disturbance information. The algorithm equation is as shown in formula (2).

\[
\begin{align*}
    e &= v_i z_1 - y \\
    z_1 &= v_z z_2 - \beta_0 e \\
    \dot{z}_2 &= v_z z_3 - \beta_0 e + bu \\
    z_3 &= -\beta_0 e / rv_2
\end{align*}
\]

The nonlinear error disturbance information feedback is simplified to linear programming:

\[
\begin{align*}
    e_1 &= v_i - z_1 \\
    e_2 &= v_z - z_2 \\
    u &= (k_1 e_1 + k_2 e_2 - z_3) / b
\end{align*}
\]

It is further assumed that \( x \) is a group of random variables of PTZ jamming information, where \( N \) is the jamming signals, \( y \) is the frequency range of each group of PTZ jamming signals, and \( M \) is the constant threshold of PTZ jamming energy. If the spectrum amplitude and frequency corresponding to each random variable are the same, formula (4) can be obtained.

\[
R = \frac{m \times y \cdot xu}{z_n \oplus \{p\}}
\]

In formula (4), \( p \) is an extended code sequence of PTZ interference information. Assuming that \( d \) is the spectrum statistical characteristics of the PTZ interference signal of the inspection robot, and \( k \) is the state change of the PTZ signal position of the inspection robot, then here is formula (5).

\[
d = \frac{x(f)}{r} \cdot k - o
\]

In formula (5), \( r \) and \( o \) are the transformation parameters of the time-domain interference signal of the inspection robot pan-tilt control. In the inspection work, using the above algorithm to collect the interference information from the pan-tilt of inspection robot can not only carry out manual inspection flexibly and intelligently, but also overcome and make up for some defects and deficiencies of manual inspection, so as to better meet the actual needs of intelligent and unattended in the current development.
2.2. Error correction algorithm for pan-tilt control of inspection robot

Because of nonlinear factors and internal and external interference, the trajectory of the inspection robot appears deviation in the actual moving process. Therefore, in the control process of inspection robot, it is necessary to use a linear active disturbance rejection controller to achieve the consistency between the actual trajectory and the expected trajectory\cite{6-7}. The sine wave inversion algorithm of active disturbance rejection control (ADRC) for inspection robot is optimized.

\[
\text{TD} \hat{z}_1 = -rsat\left(z_1 - v_0, \delta_0\right)
\]

\[
e = z_2 - y
\]

ESO:

\[
\hat{z}_2 = z_3 - \beta_{01}fal(e, \alpha, \delta) + b_0 u
\]

\[
\hat{z}_3 = -\beta_{22}fal(e, \alpha, \delta)
\]

NLSEF:

\[
\begin{align*}
\dot{e}_1 &= z_1 - z_2 \\
\dot{u} &= gfal(\delta_1, a, \delta) - z_3 / b_0
\end{align*}
\]

In the above algorithm, the parameters of auto disturbance rejection control of inspection robots usually need to be adjusted. Due to the large initial error of pan-tilt controller of inspection robot, overshoot is easy to be caused, and further optimization is needed\cite{9}. Based on this, when the adaptability of the PTZ of the inspection robot is higher than the average level of the group, the PC and PM of the PTZ of the inspection robot are reduced to protect the ADRC information of the next generation inspection robot PTZ. The convergence speed of the active disturbance rejection control algorithm of the inspection robot is guaranteed. The calculation formulas of \( P_c \) and \( P_m \) are shown in (9) and (10).

\[
P_c = \begin{cases} 
P_{cl} - \left(\frac{P_{el} - P_{e2}}{f_{max} - f_{avg}}\right) & \\
\left(\frac{f_{max} - f_{avg}}{P_{cl} - P_{e2}}\right) & \\
\end{cases}
\]

\[
P_m = \begin{cases} 
P_{ml} - \left(\frac{P_{m1} - P_{m2}}{f_{max} - f_{avg}}\right) & \\
\left(\frac{f_{max} - f_{avg}}{P_{m1} - P_{m2}}\right) & \\
\end{cases}
\]

In the above algorithm, \( P_{el} = 0.19, P_{e2} = 0.16, P_{m1} = 0.11, P_{m2} = 0.1001, f_{max} \) and \( f_{avg} \) are the average fitness between the two individuals, \( f_{avg} \) is the cross fitness between the two individuals, and \( f \) is the average fitness of the population\cite{10}. PID control principle is adopted in the pan-tilt controller of inspection robot. If the output error of PTZ is \( y \), the error has certain inertia and no jump output. The output of v-jump is represented by \( y' \), which overcomes the traditional method. The disadvantage of PID control method is that there is still a short transition process and no overshoot when tracking the step signal. In the process of robot control, the continuous audible signal is reasonably extracted from the noiseless or noiseless signal, so that the reference displacement is given, the reference speed and acceleration are automatically planned, and the research requirements of auto disturbance rejection control error correction for inspection robot pan-tilt table are realized.

2.3. Realization of auto disturbance rejection control for inspection robot

Further inheriting the essence of PID control idea and combining mode theory with control theory, an auto disturbance rejection control method for inspection robot pan-tilt is proposed. The error between the data conversion process and the ESO observation value is combined in a linear or non-linear way, so as to obtain the standard parameters and control parameters of the pan-tilt active disturbance rejection control of the inspection robot. The ADRC control value \( u_0 \) is obtained by combining the compensation
with the total interference. If the parameter $b$ in the mathematical expression is adjustable, the active disturbance rejection control coefficient can be calculated:

$$u = u_0 - \frac{z}{b} (P_d - P_m)$$  \hspace{2cm} (11)$$

Taking the adjustable wave convergence value of auto disturbance rejection control (ADRC) of the inspection robot as $z$, the stable tracking function of inspection robot is $a$, and the hierarchical joint standard system of auto disturbance rejection control (ADRC) of inspection robot can stably track the inspection route of robot, and the ADRC algorithm of route control is set as follows:

$$\begin{align*}
\dot{x}_1(t) &= x_2(t) \\
\dot{x}_2(t) &= a(t) + b(u_0(t) - z_3(t)/b) \\
y(t) &= x_3(t)
\end{align*}$$  \hspace{2cm} (12)$$

In nonlinear functions than function is used to control the state error feedback of auto disturbance rejection control of PTZ of inspection robot, so that the parameters of auto disturbance rejection control of SEF inspection robot pan-tilt can be expressed intuitively. According to the display results, the damping coefficient $C$ and $D$ are subjected to second-order vibration reduction, so as to increase the damping of PTZ ADRC of inspection robot and reduce the overshoot of auto disturbance rejection control of PTZ of inspection robot:

$$\begin{align*}
e_1 &= \dot{x}_1(t)(v_1 - z_1) \\
e_2 &= \dot{x}_2(t)/v_2 - z_2 \\
u_0 &= -y(t)(e_1, ce_2, r, h)
\end{align*}$$  \hspace{2cm} (13)$$

The pan-tilt of inspection robot is driven by four motors, and there are only three attitude control modules. Therefore, there are control coupling problems in the process of auto disturbance rejection control of inspection robot pan-tilt. Therefore, the pan-tilt controller of inspection robot can be used to track OMR and adjust yaw angle. In order to achieve the purpose of control and disturbance rejection, it is necessary to change the auto disturbance rejection control variables of the inspection robot, so that the inspection robot can run on three independent channels, $x$, $y$. According to the dynamic level and motion level of control, the control of inspection robot is divided into inner loop control and outer loop control.

Because the PID controller only uses the error elimination to control the process, and does not estimate the process itself $(a(T))$, it is difficult to directly compensate the $a(T)$ integral part, so the robustness is poor. In order to solve this problem, an ESO module is constructed in the controller, which uses ESO to estimate the state and uncertainty of the system in real time and compensate the uncertainty. Finally, ADRC with the ability of self-interference rejection is obtained. This method does not need accurate mathematical model, and optimizes the auto disturbance rejection control steps of inspection robot PTZ, as shown in figure 1.
Based on the linear active disturbance rejection control, an anti-saturation active disturbance rejection controller based on error compensation is designed to realize the trajectory tracking control of the robot and improve the accuracy of the pan-tilt active disturbance rejection control of the inspection robot.

3. Analysis of Experimental Results

In order to verify the effect of active disturbance rejection control (ADRC) of inspection robot PTZ and carry out experimental detection, a prototype environment for XPC main target is constructed based on xPC platform of matlab r2009a. S function is written on the host through MATLAB compiling environment to generate customized SIMULNK module. This code is automatically generated by real-time workshop, and then downloaded and run the XPC Target limited kernel on the target machine to achieve real-time control. The main components of the system hardware platform are: cpu e7200, 2 gbram; target machine resource: Pentium4, cpu 2.4 GHz, 512 MB ram; PCL-818HG analog data acquisition card; pcl-726 digital conversion control card. On the basis of MATLAB / Simulink, the simulation experiment is carried out. The model is the S-function form of Simulink model, and the S-function realization of the mathematical model is given. On this basis, the control variables, TD, ADRC, ESO, SEF are transformed to obtain the motion control law designed in Chapter 3. Based on the third-order Runge Kutta method, in the Simulink simulation environment, a fixed time interval is set and set to 0.001 s. The system is simulated by MATLAB 615, and the internal and external parameters of the camera are set as follows: f = 6 mm focal length; the scale coefficient of X and Y direction of CCD array NX = 010082, NY = 010072; the position of CCD array center in the image (unit: pixel) XC = 165, YC = 140; moving vector t = [40 10 15 0] t; rotation angle w = 80 B, H = -70 B, u = 160 B.

The active disturbance rejection control algorithm of the moving target inspection robot is as follows:

\[
\begin{align*}
\dot{x} &= 50 \sin(\theta / 5) \\
\dot{y} &= 50 \cos(\theta / 5)
\end{align*}
\]

(14)

After many simulation experiments, the range of its value is 015 ~ 315. The optimal value of auto disturbance rejection of inspection robot pan-tilt is obtained

\[
BestS = [1.3830 \quad 1.4880 \quad 1.1748 \quad 2.3566 \quad 2.1277 \quad 2.4297]
\]

(15)
The results show that the optimal adaptability of the active disturbance rejection control of the inspection robot is as follows:

$$f = 6.62 \times 10^{-3}$$  \hspace{1cm} (16)

In order to check whether the auto disturbance rejection control of the inspection robot pan-tilt is correct, the unit step input ($I = 1, 2, 3$) represented by QRI is set, $R_1 = 30$, $R_2 = 80$. Based on this, the robustness and accuracy of auto disturbance rejection control (ADRC) of inspection robot PTZ are compared and tested. The specific test results are shown in the figure 2 and figure 3.

![Figure 2](image1.png)

**Figure 2** robustness test results of active disturbance rejection control for PTZ of inspection robot

![Figure 3](image2.png)

**Figure 3** accuracy test results of active disturbance rejection control for PTZ of inspection robot

Based on the above detection results, it can be seen that the auto disturbance rejection control method of the inspection robot pan-tilt is obviously more robust and accurate in the actual application process. Through the research, it is shown that by setting the opposite noise detection points in advance, the fast detection of the field noise is realized, and the "standard detection point Library of substation intelligent detection robot" is set in advance for the detection points, and users can according to the actual situation increases or decreases the position detection point. Implement the special inspection of bad weather, defect tracking, remote abnormal alarm confirmation, remote status confirmation, safety linkage, emergency rescue, to ensure the control effect of inspection robot.

4. Conclusion

An active disturbance rejection control method for indoor inspection robot in intelligent substation based on monocular vision is proposed. The active disturbance rejection (ADRC) is realized by linearizing the state feedback and control quantity of the indoor inspection robot in the intelligent substation. Through improving the structure of the inspection robot platform, collecting interference information, effectively optimizing the control algorithm of the monocular visual pan-tilt of the indoor inspection robot in the substation, improving the auto disturbance rejection quality of the monocular visual pan-tilt of the indoor inspection robot in the substation, and ensuring the operation effect of the inspection robot.
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