

Walking Posture Control of Transmission Line Single Arm Inspection Robot

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Abstract. To control the walking posture according to transmission line single arm inspection robot, the robot is divided into normal walking and climbing walking two state, and gives the definition, then based on the state space method of state variable feedback and PD control method is used to control the two states, two kinds of control method of simulation by using Matlab, in the end, the two control methods proposed is validated in the actual circuit structures. The results show that, the proposed control method is rapid and effective, and can meet the needs of practical application.

1. Introduction

The electricity sector in order to grasp the running state of line, find fault equipment in time, At present, they mainly used to monitor the line on the line of the manual inspection line, This paper describes the design of a compact, high reliability, double arm inspection robot for the single span line between two towers.

Single arm inspection robot to large span wire for driving path. Under the influence of gravity, the line will present an opening up of a parabolic shape, Therefore, in the process of continuous walking, the robot will inevitably encounter the situation of downhill and uphill, which will show an opening to the parabolic shape. In addition, affected by the structure of the robot arm, robot in walking, center of gravity can not always maintain in the perpendicular bisector of the two wheel shaft connection, leading to the robot due to the instability and attitude in uncontrolled phenomenon.

The problem for the analysis of the attitude control of robot, the domestic and foreign scholars have made some research. The literature on the control of the state of the body is rarely seen. Literature [1-4] about the line tracking robot is analyzed and found robot in the process of obstacle, line grasping arm would swing along the ground, Therefore, a PD control method based on the minimum energy consumption is proposed.

The method can effectively control the swing angle of the robot to return to the equilibrium point quickly and smoothly. In this paper, the PD control method is simulated and analyzed, but the practical application is not given. Literature [5] has carried out some research on the deflection of the designed three arm line inspection robot, by adding a center of gravity adjustment mechanism on the robot to eliminate the robot's overall deflection caused by the moving of the center of gravity, this way has achieved certain results, but increase the burden of the system but also reduces the efficiency of robot. Literature [6] patrol robot for an additional obstacle resistant tension tower bridge, the real-time



positioning of the sensor based control, but does not take into account the deflection between the arm and the ground line grasping, cannot reflect the attitude of robot arm at the end of the execution.

Literature [7] on the two arms and three arms of the robot obstacle navigation process, just made some simulation research. In the literature [8], the phenomenon of posture instability appeared in the application of a wide range of boom type inspection robot in the cable accessories is studied, from the perspective of institution and developed the corresponding pitch instability self balancing mechanism, lateral buckling self balancing mechanism, and analyzes its working principle.

In this paper, a power transmission line inspection robot walking wheel arm charged on attitude control. Firstly, the climbing ability of the robot is analyzed, and the maximum climbing angle of the robot is given. Secondly, the dynamic model of the robot's walking is established, taking into account that the robot can be divided into normal walking posture and walking posture. After the analysis of normal walking posture, the robot is designed by using the control method based on state feedback to design the attitude controller of the robot. After the analysis of the climbing walking posture, the system has a strong nonlinear, simple linear processing can not meet the needs of climbing attitude control, So the attitude controller of the robot climbing walking is designed by using the PD control method. Finally, the effectiveness of the two attitude controllers is verified by experiments.

2. Static analysis of robot climbing

Two wheeled robot arm as shown in Figure 5, Figure 1 static model for climbing, Among them, I is the robot's walking wheel, II is the pressing wheel, III is the control box of the robot. In order to increase the climbing ability of the robot, a pressing wheel mechanism is designed on the arm, which is used to increase the positive pressure of the walking wheel, thereby increasing the friction force.

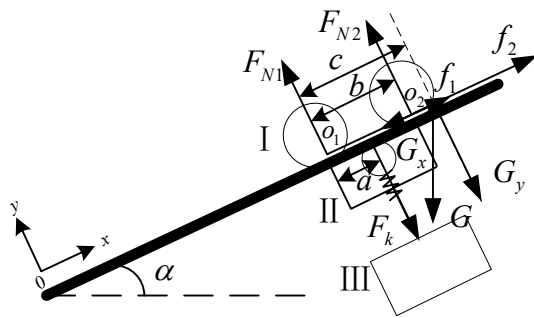


Figure 1. Static model of robot climbing.

Static equation of robot climbing:

$$G_x = G \sin \alpha \quad (1)$$

$$G_y = G \cos \alpha \quad (2)$$

$$f = f_1 + f_2 \quad (3)$$

$$f - G_x \geq 0 \quad (4)$$

$$f = \mu(F_{N1} + F_{N2} + F_k) \quad (5)$$

$$F_k = -kx \quad (6)$$

$$F_k a - F_{N2} b + G_y c = 0 \quad (7)$$

$$F_{N1} b - F_k (b - a) + G_y (c - b) = 0 \quad (8)$$

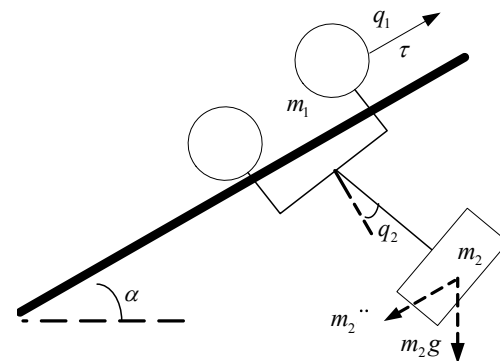


Figure 2. Dynamic model of robot climbing.

Above the formula, α stands for slope; G is the gravity of the robot, N ; F_{N1} for the support of the line on the left wheel, N ; F_{N2} for the support of the line on the right wheel, N ; F_k for pressing wheel by the line pressing force, N ; f_1 for the left running wheel by the friction, N ; f_2 for the right running wheel by the friction, N . G_x is a component of Gravity G acting on the x axis, N ; G_y is a component of Gravity G acting on the y axis, N ; f for the robot to be the total friction, N ; μ for friction factor; k as elastic, x for spring deformation, m ; the maximum deformation of the spring is a x_m , Above the formula $x \in (0, x_m)$; a is F_k and o_1 between the force arm, m ; b is F_{N2} and o_1 between the force arm, m ; c is G_y and o_1 between the force arm, m . From formula (7) and (8) can be seen, F_{N1} and F_{N2} are not equal, combined (1) to (8) can be obtained (9):

$$\cos(\alpha + \arctan(1/\mu)) \leq \frac{2\mu kx}{G\sqrt{1+\mu^2}} \quad (9)$$

From the formula (9) can be seen, under the condition of not considering the driving ability of the driving wheel, the biggest factors influencing the climbing of the robot are the positive pressure exerted by the pressing wheel. Taking into account the maximum deformation of the compression spring is a x_m , we can get the maximum climbing angle of the robot α_{\max} is:

$$\alpha_{\max} = \arccos\left(\frac{2\mu kx_m}{G\sqrt{1+\mu^2}}\right) - \arctan(1/\mu) \quad (10)$$

3. Dynamic analysis of robot walking

The robot dynamics model is shown in Figure 2, the formula (11) can be obtained by analyzing the force of the walking direction of the system, and the torque of the pendulum is obtained by the formula (12).

$$m_1\ddot{q}_1 + m_2l\ddot{q}_2 + c_1\dot{q}_1 + (m_1 + m_2)g \sin \alpha = \tau \quad (11)$$

$$m_2l\ddot{q}_1 + m_2l^2\ddot{q}_2 + c_2\dot{q}_2 - m_2gl \sin(q_2 + \alpha) = 0 \quad (12)$$

The quality of m_1 for two walking wheels in the formula, kg ; m_2 is the quality of the robot arm and control box, kg ; l is the length of the robot arm, m ; τ is the driving wheel drive power, N ; $c = [c_1 \ c_2]^T$ is the coefficient of friction; q_1 is the displacement of the robot, m , is the input variable of the system; \dot{q}_1 is the robot moving speed, m/s ; \ddot{q}_1 is the acceleration of robot motion, m/s^2 ; q_2 is the robot arm swing angle, but also the output variable of the system moving acceleration; \dot{q}_2 is the angular velocity of the robot arm swing, rad/s ; \ddot{q}_2 is the robot arm swing angular acceleration, rad/s^2 ; g is gravity constant coefficient. $|q_2 + \alpha| \leq \alpha_d$, α_d takes 15° in this paper; α is for line slope.

According to the line slope size, in the case of slope $|\alpha| \leq 8^\circ$, the dynamic equations of the robot can be partially linearized, and the equations can be controlled by modern control theory; in the case of slope $|\alpha| > 8^\circ$, control using PD control method. Therefore, in order to facilitate the discussion, the two controllers are designed to facilitate the discussion, and the following two definitions are given for the convenience of the discussion:

Definition 1 Normal walking: The robot walked on the ground which is less than or equal to 8 degrees.

Definition 2 Climbing walking: The robot walked on the ground which is greater than or equal to 8 degrees.

3.1. Normal walking controller design

When the robot walked on the ground, $c \approx 0$, $\alpha \approx 0$, because the swing angle q_2 is very small, so we can deal with the linear approximation of the system equation. Besides,

$$x = [q_1 \quad \dot{q}_1 \quad q_2 \quad \dot{q}_2]^T, \dot{x} = [\dot{q}_1 \quad \ddot{q}_1 \quad \dot{q}_2 \quad \ddot{q}_2]^T.$$

Combined (11) to (12) can be obtained:

$$m_1 \dot{x}_2 + m_2 l \dot{x}_4 = \tau \quad (13)$$

$$\dot{x}_2 + l \dot{x}_4 - g x_3 = 0 \quad (14)$$

Combined formula (13) formula (14), elimination of \dot{x}_4 , can be obtained:

$$(m_1 - m_2) \dot{x}_2 + m_2 g x_3 = \tau \quad (15)$$

Combined formula (13) formula (14), elimination of \dot{x}_2 , can be obtained:

$$(m_1 - m_2) l \dot{x}_4 - m_1 g x_3 + \tau = 0 \quad (16)$$

As a result, we can get the following 4 first order differential equations.

$$\dot{x}_1 = x_2 \quad (17)$$

$$\dot{x}_2 = -\frac{m_2 g}{m_1 - m_2} x_3 + \frac{1}{m_1 - m_2} \tau \quad (18)$$

$$\dot{x}_3 = x_4 \quad (19)$$

$$\dot{x}_4 = \frac{m_1 g}{(m_1 - m_2) l} x_3 - \frac{1}{(m_1 - m_2) l} \tau \quad (20)$$

Taking into account that when the robot is walking, only the displacement of q_1 can be measured directly by the encoder, q_1 as the only output of the system $y = x_1$. Combined formula (17) - (20) the state space equation of the robot when the robot is walking:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\tau \quad (21)$$

$$y = \mathbf{C}\mathbf{x} \quad (22)$$

Where
$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & -\frac{m_2 g}{m_1 - m_2} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{m_1 g}{(m_1 - m_2) l} & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 \\ \frac{1}{m_1 - m_2} \\ 0 \\ -\frac{1}{(m_1 - m_2) l} \end{bmatrix}, \quad \mathbf{C} = [1 \quad 0 \quad 0 \quad 0].$$

After actual measurement, the parameters of the system are $m_1 = 2\text{kg}$, $m_2 = 10\text{kg}$, $l = 0.4\text{m}$. Therefore, the determinant value of the controllability matrix P_c and the observability matrix P_o of the system are respectively given by formula (23) and formula (24):

$$|P_c| = |\mathbf{A} \quad \mathbf{AB} \quad \mathbf{A}^2\mathbf{B} \quad \mathbf{A}^3\mathbf{B}| = 20.6670 \neq 0 \quad (23)$$

$$|P_o| = |\mathbf{C} \quad \mathbf{CA} \quad \mathbf{CA}^2 \quad \mathbf{CA}^3|^T = 2401 \neq 0 \quad (24)$$

By the formula (23) and (24) we can know that the system is controllable and observable.

Using the following control law:

$$\tau = Kx \quad (25)$$

Through the analysis, we can know that there are two zeros point in the open loop poles of the 4 order system and the critical is very stable. The closed-loop poles of the system can be configured on the $\lambda = [-8+6j \quad -8-6j \quad -0.4+0.3j \quad -0.4+0.3j]$, to meet the requirements of the system regulating time and absolute stability, the feedback gain matrix K should be able to satisfy the following formula:

$$\det(\lambda I - (A - BK)) = (\lambda + 8 \pm 6j)(\lambda + 0.4 \pm 0.3j) \quad (26)$$

We can first calculate the $K = [1.7 \quad 5.8 \quad 342.9 \quad 56.1]$. In our practical system, the state variable is only measured by displacement x_1 , so it is needed to design the observer for the system to provide the estimated value of the state variable which can not be measured directly. The actual control law is given by formula (27):

$$\tau = K\hat{x} \quad (27)$$

The state variable estimate \hat{x} is given by the formula (28):

$$\dot{\hat{x}} = A\hat{x} + B\tau + L(y - C\hat{x}) \quad (28)$$

L is the observer gain, which is related to the pole of the observer, and satisfies the formula:

$$\det(\lambda I - (A - LC)) = ((\lambda + \lambda_1)(\lambda + \lambda_2))^2 \quad (29)$$

In application, the closed-loop poles of the system and the poles of the observer should be guaranteed to be 10 to 2 times. After repeated testing, the observer poles are determined to be $-16 \pm 21.3j$.

The observer gain matrix of this system is determined by using Ackerman's formula $L = [64 \quad 2437.3 \quad 918.9 \quad 9974.4]^T$.

3.2. Design of climbing walking controller

The dynamic equations of the robot can be expressed as follows:

$$M\ddot{q} + G(q) = \begin{bmatrix} \tau - c_1\dot{q}_1 \\ -c_2\dot{q}_2 \end{bmatrix} \quad (30)$$

Above the formula, $M = \begin{bmatrix} m_1 & m_2l \\ m_2l & m_2l^2 \end{bmatrix}$ is a constant positive definite matrix. $G(q) = \begin{bmatrix} m_1gq_1 \sin \alpha \\ -m_2gl \sin(q_2 + \alpha) \end{bmatrix}$.

The formula (31) to construct auxiliary function:

$$P(q) = \frac{1}{2}m_1gq_1^2 \sin \alpha + m_2gl \cos(q_2 + \alpha) \quad (31)$$

Lyapunov function is defined as follows:

$$V(q, \dot{q}) = \frac{1}{2}\dot{q}^T M\dot{q} + P(q) + \frac{1}{2}k_p q_1^2 \quad (32)$$

In the formula, the position gain $k_p > 0$, we know that $V(q, \dot{q})$ is globally positive definite.

The formula (11) and the formula (12) describe the system in $|\alpha| > 8^\circ$ when using the following control law:

$$\tau = -k_p q_1 - k_v \dot{q}_1 \quad (33)$$

In the formula, the velocity gain is $k_v > 0$.

Derivative of the formula (31):

$$\dot{V}(\mathbf{q}, \dot{\mathbf{q}}) = \dot{\mathbf{q}}^T \dot{\mathbf{M}} \dot{\mathbf{q}} + \frac{1}{2} \dot{\mathbf{q}}^T \dot{\mathbf{M}} \dot{\mathbf{q}} + \dot{\mathbf{P}}(\mathbf{q}) + k_p q_1 \dot{q}_1 \quad (34)$$

Into the formula (30) can be obtained:

$$\dot{V}(\mathbf{q}, \dot{\mathbf{q}}) = \dot{q}_1 (\tau + k_p q_1) - c_1 \dot{q}_1^2 - c_2 \dot{q}_2^2 \quad (35)$$

τ in the formula (33) into the formula (35) can be obtained:

$$\dot{V}(\mathbf{q}, \dot{\mathbf{q}}) = -(k_v + c_1) \dot{q}_1^2 - c_2 \dot{q}_2^2 \leq 0 \quad (36)$$

The global stability of the control law type (30) is proved.

4. Simulation analysis and experiment

According to the preamble design of two kinds of controller, the actual parameters of measuring robot, using Matlab simulation platform is built, respectively, given two kinds of controller system initial parameters, using the designed control law, the robot in different conditions of walking posture control simulation.

4.1. Normal walking simulation analysis

The simulation conditions are as follows: the initial value of the given state variable x_0 and the state error e_0 , $x_0 = [1 \ 0 \ 0 \ 0]$, $e_0 = [0.5 \ 0 \ 0 \ 0]$. The simulation platform is Matlab, which provides the basis for the actual control of the robot. The simulation results are shown in figure 3.

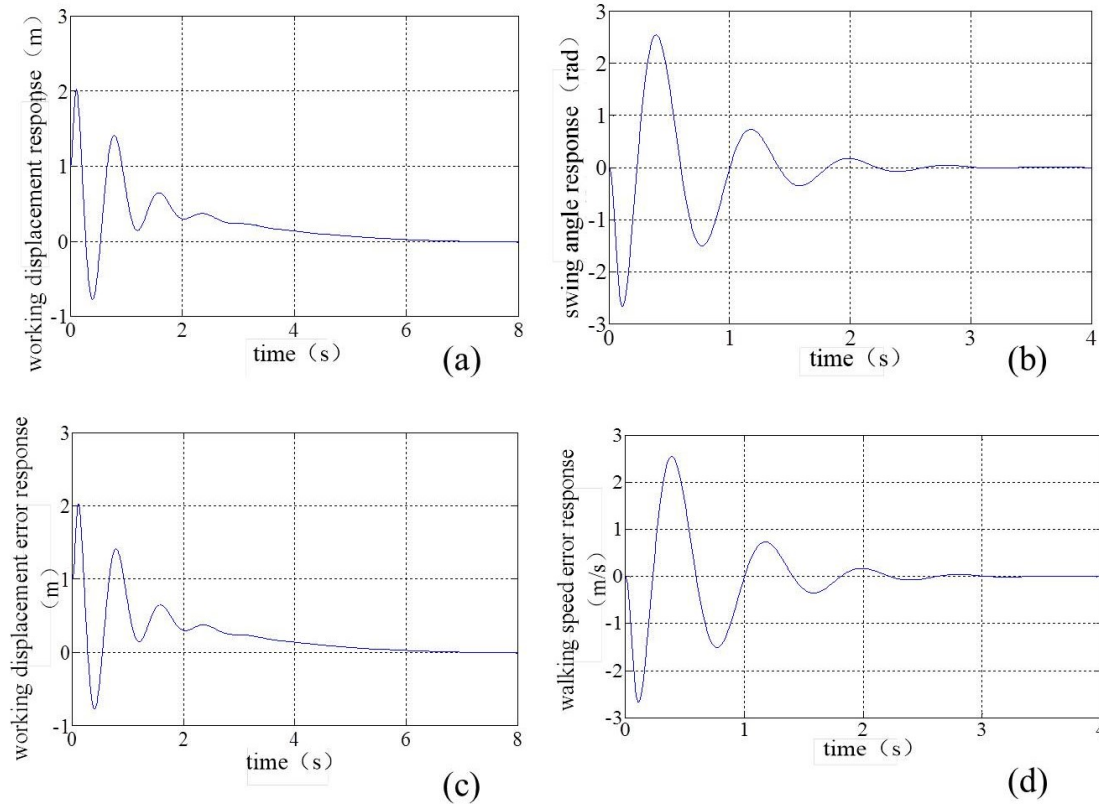


Figure 3. Robot normal walking simulation.

From figure 3 (a), we can see that the robot in the start stage of the displacement response to the time will be relatively large fluctuations, but after the 6S, the response tends to be stable, the displacement of the robot from the initial value of 1 to the target value of 0.

Figure 3 (b) shows the response of the robot to the time, after 2 seconds, the robot's swing angle convergence to the target value of 0.

Figure 3 (c) reflects the time response of the robot's walking displacement error, and the time is rapidly converging to 0 in a second or so.

Figure 3 (d) reveals the time response curve of the robot's walking speed error. Can be seen from the figure, in a second or so the time that convergence to 0.

4.2. Simulation analysis and experiment of hill climbing

The simulation conditions of robot climbing are: the slope is 10° , the target displacement distance is 12 m, After repeated adjustment, determine the control system of the PD parameters: $k_p=60000$, $k_v=10000$. Swing angle response as in Figure 3 as shown, figure with solid lines mark the robot swing angle of the target value of 0° , because there is no for swinging angle control design special joint, but controlled in the joint of the walking robot, so robot swing angle response shows an amplitude cosine function rule. As can be seen from the trend of the attenuation, the robot's swing angle will eventually converge to the target value of 0° .

The experiment was carried out on the set of analog circuits, as shown in figure 4, to verify the effect of this designed controller.

The experimental conditions are consistent with the simulation conditions. The robot from the same starting point for 10 consecutive times climbing walking experiment, using inclination angle sensor for robot body swing angle acquisition as per second frequency, and average of 10 times in the experimental data plotted as shown in figure 5 shows the angular response.

We can see that the inconsistent with the several intermediate response and simulation results, mainly because some parts of the line have rust, interfering with the machine swing angle response rules, but the robot actual placed the swing angle of the horn rules and simulation rules are basically the same. The practical application results show that the proposed controller can control the swing angle quickly and effectively.



Figure 4. Robot attitude control experiment.

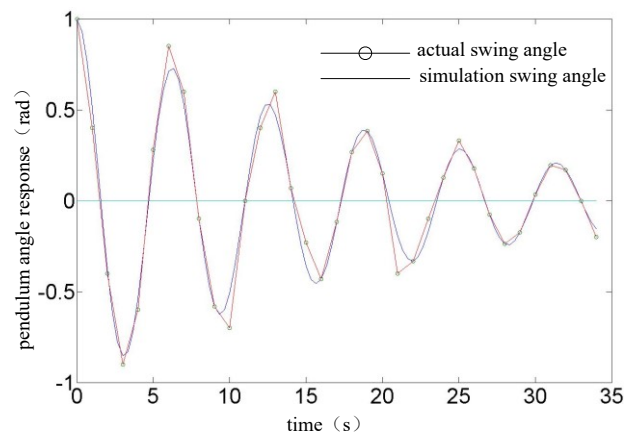


Figure 5. Pendulum angle response.

5. conclusion

We establish the static model of the single arm robot transmission line, and get the maximum climbing angle of robot. Based on the analysis of the robot's walking state, the two concepts of normal walking and climbing walking are proposed, which provide guidance for the correct and effective walking control strategy. According to the two walking strategies, the corresponding controller is designed, and the simulation is carried out by using the MATLAB tool. Finally, the effectiveness of the proposed two kinds of attitude controllers is verified by experiments, which can effectively solve the problem of robot's walking attitude control.

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