Study on Control of Two Axis Linkage of Live-working Robot for Power Transmission Lines

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Abstract: A two axis linkage dynamic control method for joint space of a live-working robot for power transmission lines is presented in order to solve the problem of that the working efficiency of the live-working robot is low in single joint serial connection working. This paper established a global dynamical equation during obstacle-crossing through the Newton-Euler approach, providing the basis for establishing any two-axis linkage dynamic equation; analyzed and determined joints of the robot capable of two axis linkage, presenting a group of common dynamical equations for two axis linkage joints; and designed a PD control method with a gravity model. Simulation and experimental results show that the two axis linkage method is feasible and capable of increasing working efficiency of the robot.

1. Introduction

The live-working robot for power transmission lines developed by this paper can fulfill working tasks of live replacement of suspension insulators and live current plate bolt tightening by replacing working ends. The working object (current plate bolt) is small and the working space is compact so that many working steps of the robot are required, and therefore two axis linkage can effectively increase the working efficiency of the robot.

At present, linkage control strategy is widely applied to machine tools [1-2], and some researches have been also done on inspection robot for power transmission lines. In essence, the studies on linkage of line inspection robot for power transmission lines according to references [3-5] were intended to analyze and solve the problem of motion coordination of two arms without establishing a dynamical model thereof, thus accuracy control can not be achieved. References [6-9] only established a two axis linkage dynamical equation for the gravity adjusting joint and the arm lifting joint of the line inspection robot, without taking the common two axis linkage dynamical modeling approach. References [10-11] introduced a two axis linkage approach which mainly focus on linkage study of the gravity adjusting joint and the arm lifting joint of the line inspection robot, but the gravity adjusting joint is a relatively independent joint which is not coupled to arm staggering joint motion, therefore this method can not be popularized to other two axis linkage control of the robot. In addition, references [12] studied linkage of the gravity adjusting joint and other joints of the line inspection robot.

In conclusion, there are only few researches on two axis linkage control of live-working robot for power transmission lines at present. A two axis linkage approach applicable to the live-working robot...
is in urgent need so as to save the working time of the robot and increase the working efficiency of the robot.

This paper established a global dynamical equation during obstacle-crossing through the Newton-Euler approach [13], providing the basis for establishing any two-axis linkage dynamic equation; then designed a corresponding PD control law for two axis linkage and proved stability of the control system after the designed control law is involved; and then carried out simulated analysis on the control law with Matlab, and determined the optimal PD parameters; and finally verified validity of the approach presented in this paper through experiments.

2. Kinematic and dynamic model establishment of double working arm of robot

The robot strokes along a line, stops moving after detecting collision detection sensor signals, then fixes the mechanical arms with the line through a clamping mechanism, and then live working can be completed through the two working arms.

Figure 1. Robot structure diagram

The robot studied in this paper, as shown in Figure 1, is equipped with two working arms and capable of fulfilling working tasks of live replacement of suspension insulators and live current plate bolt tightening by replacing ends of the two working arms. The left working arm has 3 degrees of freedom while the right working arm has 4. D-H coordinate systems are established for the two working arms, the coordinate system of the left working arm is X'Y'Z' and the coordinate system of the right working arm is XYZ, as shown in Figure 2. Corresponding link parameters are listed in Table 1 and Table 2.

Table 1. The D-H parameters of the right working arm of the live-working robot.

| i  | \( \theta_i \) | \( \alpha_{i-1} \) | \( a_i \) | \( d_i \) | Variable range of joint |
|----|----------------|----------------|-------|-------|-------------------------|
| 1  | 0°            | 0°            | 0     | \( d_i(0) \) | 0 ~ 260(mm)           |
| 2  | \( \theta_i(0°) \) | 90°           | \( a_i \) | \( d_2 \) | \(-180° ~ 180°\)      |
| 3  | 0°            | \(-90°\)      | \( a_2 \) | \( d_3(445) \) | 445 ~ 645(mm)         |
| 4  | 0°            | 90°           | \( a_3 \) | \( d_4(-120) \) | \(-120 ~ 0\)(mm)      |

Table 2. The D-H parameters of the left working arm of the live-working robot.

| i  | \( \theta_i' \) | \( \alpha_{i-1}' \) | \( a_i' \) | \( d_i' \) | Variable range of joint |
|----|----------------|----------------|-------|-------|-------------------------|
| 1  | \( \theta_i'(0°) \) | 0°            | 0     | 0     | \(-180° ~ 180°\)      |
| 2  | 0°            | \(-90°\)      | \( a_1' \) | \( d_1'(425) \) | 425 ~ 625(mm)         |
| 3  | 0°            | \(-90°\)      | \( a_2' \) | \( d_2'(120) \) | 0 ~ 120(mm)          |

By means of the kinematic model of the robot, the dynamic model of the robot’s working can be established conveniently. In addition, the Newton-Euler approach has the advantages of facilitating
programming with the computer language and having an algorithm pattern itself, thus this paper established the dynamic mode of the robot with the Newton-Euler approach.

The dynamic issues refer to calculating required joint torque or force $\tau$ of the joints according to displacement, velocity and accelerated velocity ($\theta, \dot{\theta}$ and $\ddot{\theta}$). The entire algorithm consists of step 1 performing outward recursion to calculate velocity and accelerated velocity of each link and working out inertia force and torque of each link with the Newton-Euler approach; and step 2 performing inward recursion on interaction force and torque of each link as well as joint driving force or torque.

1) The whole dynamic equation is shown in formula (1): ($i:0 \rightarrow n-1$)

$$
\begin{align*}
\dot{\omega}_i^{i+1} &= \left[ \dot{\omega}_i^{i+1} + \omega_i^{i+1} \times \dot{z}_{i+1}^{i+1} \right] \\
\ddot{\omega}_i^{i+1} &= \left[ \ddot{\omega}_i^{i+1} + \omega_i^{i+1} \times \ddot{z}_{i+1}^{i+1} \right] \\
\dot{v}_i^{i+1} &= \dot{v}_i^{i+1} + \omega_i^{i+1} \times \dot{r}_{c(i+1)}^{i+1} \\
\ddot{v}_i^{i+1} &= \ddot{v}_i^{i+1} + \omega_i^{i+1} \times \ddot{r}_{c(i+1)}^{i+1} \\
I_{f(i+1)} &= m_{i+1} \dot{v}_i^{i+1} \\
N_{c(i+1)} &= \left( \dot{r}_{c(i+1)}^{i+1} \right) \times \left( \dot{r}_{c(i+1)}^{i+1} \right) \\
T_{c(i+1)} &= \left( \dot{r}_{c(i+1)}^{i+1} \right) \times \left( \dot{r}_{c(i+1)}^{i+1} \right)
\end{align*}
$$

In formula (1), $\omega_i^{i+1}$ is the angular velocity of of the link $i+1$ in the coordination system $i+1$, $\dot{\omega}_i^{i+1}$ is the joint angular velocity of link $i+1$, $\dot{v}_i^{i+1}$ is the velocity of link $i+1$ in the coordination system $i+1$, $\ddot{v}_i^{i+1}$ is the displacement of link $i+1$, $I_{f(i+1)}$ is the force of the barycenter of the link $i+1$, $N_{c(i+1)}$ is the torque of the link $i+1$, $T_{c(i+1)}$ is the inertia tensor of the barycenter of the link $i+1$.

2) The joint dynamic equation is ($i:n-1 \rightarrow 0$)
In formula (2), \( f_i \) is force of link \( i \) in the coordination system \( i \), \( N \); \( f_{i+1} \) is force of link \( i+1 \) in the coordination system \( i+1 \), \( N \); \( R_{i+1}^i \) is transformation matrix from link \( i+1 \) to link \( i \); \( n_i \) is torque of link \( i \) in coordination system \( i \), \( Nm \); \( n_{i+1} \) is torque of link \( i+1 \) in coordination system \( i+1 \), \( Nm \); \( \tau_i \) is torque of barycenter of link \( i \) in coordination system \( i \), \( Nm \); \( \tau_{i+1} \) is sector radius of barycenter of link \( i+1 \) in coordination system \( i+1 \), \( m \); \( p_{i+1} \) is sector radius of link \( i+1 \) in coordination system \( i \); \( \tau_i \) is torque of link \( i+1 \) in coordination system \( i+1 \), \( Nm \); \( z_i \) is torque \([0,0,1]^T\).

Transformation matrix between links is shown in the formula as follows.

\[
R_{i+1}^i = \begin{bmatrix}
c_{s_{i+1}} & -s_{i+1} & 0 \\
s_{s_{i+1}} & c_{s_{i+1}} & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

In this formula, \( R_{i+1}^i \) is transformation matrix from link \( i+1 \) to link \( i \); \( R_{i}^{i+1} \) is transformation matrix from link \( i \) to link \( i+1 \); suppose mass of links of the robot concentrate on ends of the links \( p_{i+1} = r_{i+1} \). Kinematic parameters, dynamic parameters and initial conditions when the robot starts working are shown in the following formula.

\[
\begin{align*}
p_{i+1}^{(i)}(t) &= a_i x_i \\
l_i &= 0 \\
f_j &= 0, n_j = 0(j = 3, 4) \\
w_0 &= 0, \dot{w}_0 = 0 \\
\dot{v}_0 &= g y_0
\end{align*}
\]

By means of the above preparation, velocity, accelerated velocity and force of each link can be calculated according to the adopted algorithm with the tools of Matlab.

3. Design of two axis linkage control law

After the overall dynamic model of the robot is established in a Matlab environment with the Newton-Euler approach, the two axis linkage dynamic equation of the robot can be calculated conveniently.

During two axis linkage, the dynamic equation of the robot can be expressed as follows.

\[
\tau = D(q)\ddot{q} + h(q, \dot{q}) + G(q)
\]

In this formula, \( \tau \) is joint force, \( N \); \( D(q) \) is mass matrix; \( \ddot{q} \) is joint acceleration, \( m/s^2 \); \( h(q, \dot{q}) \) is joint force matrix; \( G(q) \) is gravity compensation \( N \).
The two axis linkage control law is designed as follows.

\[ \tau = k_p e - k_d \dot{q} + G(q) \]  

(6)

In this formula, \( e \) is position error, \( m/s \); \( \dot{q} \) is joint velocity, \( m/s \); \( k_p \), \( k_d \) are position and velocity diagonal gain matrices respectively. A loop system can be obtained through formula (5) and formula (6):

\[ D(q)\ddot{q} + h(q, \dot{q}) + k_d \dot{q} + k_p q = k_e q_d \]  

(7)

In this formula, \( q_d \) is expected displacement, \( m \). Global asymptotic stability of this system can be proved with the Lyapunov theory, and the constructed Lyapunov function is shown as below.

\[ v = \frac{1}{2} \dot{q}^T D(q) \dot{q} + \frac{1}{2} e^T k_e e \]  

(8)

Function (8) is non-negative because the mass matrix \( D(q) \) and the position gain matrix \( k_p \) are both positive definite. According to derivation of formula (8), it can be calculated that

\[ \dot{v} = \frac{1}{2} \dot{q}^T D(q) \dot{q} \dot{q} + \dot{q}^T D(q) \dot{q} - e^T k_e \dot{q} = -\dot{q}^T k_e \dot{q} \]  

(9)

Provided \( k_d \) is positive definite, \( v \) is non-negative, by which the global stability of the control law (9) can be proved. The following is a plurality of controllers of two axis linkage design of the robot with a gravity model.

Each elmo driver adopted by the live-working robot can at most drive 4 motors in a part-time drive mode. The total number of of joints of the two working arms is no more than 4, thus each elmo driver drives one motor of a working arm, as shown in Table 3. In theory, any joint positioned on either working arm can realize two axis linkage.

**Table 3. Driver and motor distribution**

| Working arm       | Motor No.          |
|-------------------|--------------------|
| Left working arm  | 1 Left rotary joint|
|                   | 2 Left telescopic joint |
|                   | 3 Left traversing joint |
| Right working arm | 4 Right vertical moving joint |
|                   | 5 Right rotary joint |
|                   | 6 Right telescopic joint |
|                   | 7 Right traversing joint |

4. Simulation and program implementation of two axis linkage

4.1. Two axis linkage simulation

Joint variables of the right vertical moving joint of the right working arm \( d_1 = 0 \), \( \dot{d}_1 = 0 \), \( \ddot{d}_1 = 0 \), joint variables of the right rotary joint of the right working arm \( \theta_2 = 90^0 \), \( \dot{\theta}_2 = 0 \), \( \ddot{\theta}_2 = 0 \), joint variables of the right traversing joint of the right working arm \( d_4 = -120^0 \), \( \dot{d}_4 = 0 \), \( \ddot{d}_4 = 0 \); and joint variables of the joint of the left working arm \( d_2' = 425^0 \), \( \dot{d}_2' = 0 \), \( \ddot{d}_2' = 0 \) are plugged in the global dynamic equation of the robot, and a dynamic equation of during linkage of the rotary joint of the left working arm \( (\theta_1) \) and the telescopic joint of the right working arm \( (d_3) \) can be achieved.
the average torque and velocity of the two joints are obtained, providing two more references for selection of PD parameters.

In Table 4, the system vibrates violently when \( k_p > 400 \), the adjustment time is in this table refers to the time that required by the response curve to reach and permanently keep within an error range 5% of the steady-state value. When \( k_p = 500 \), the adjustment time of the system is only 13% of that when \( k_p = 100 \), and other performance parameters have no obvious defects, hence \( K_p = 500 \) is used.

Table 4. Proportional gain adjustment of the right arm telescopic joint motor

| \( k_p \) | \( k_d \) | Average torque (N m) | Average velocity (m/s) | Adjustment time (s) | Overshoot (1) |
|------|------|----------------|----------------|----------------|-------------|
| 4000 | -50  | 86.4987        | 0.5623          | 0.325           | 21.05%      |
| 3000 | -50  | 84.2741        | 0.4989          | 0.265           | 19.28%      |
| 2000 | -50  | 81.7470        | 0.4266          | 0.305           | 16.69%      |
| 1000 | -50  | 76.7580        | 0.3446          | 0.305           | 12.06%      |
| 500  | -50  | 74.7120        | 0.3176          | 0.435           | 7.71%       |
| 100  | -50  | 69.5132        | 0.3658          | 3.465           | 0.36%       |
| 50   | -50  | 61.4962        | 0.3913          | 3.990           | 0           |

In Table 5, when \( k_d < -150 \), overshoots of the system are all zero, indicating that control variables converge in a very smooth manner to the target value, but the adjustment time is long, which is 1.73s. Based on overall consideration, differential gain \( k_d = -150 \) is selected, although the overshoot is 0.23%, the adjustment is only 0.595s.

\[
14\ddot{\theta}_1 - 5.7d_3 + 0.21\dot{\theta}_1^2 - d_3(1.6\dot{\theta}_1 + 5.7\dot{\theta}_1 - 10d_\theta \dot{\theta}_1' - 20d_\theta \dot{\theta}_1' + 10g \sin \theta_1' - 5.7\ddot{\theta}_1' + 10d_\theta + 1.6\dot{\theta}_1^2 - 10d_\theta \dot{\theta}_1' + 10g \cos \theta_1' + 4.1d_\theta \dot{\theta}_1' - 3.2d_\theta \dot{\theta}_1' - 17g \cos \theta_1' = 3.8g \sin \theta_1' + 7.3d_\theta \dot{\theta}_1' - 0.21\dot{\theta}_1 \dot{\theta}_1' = \tau_1
\]

By adopting the control law in formula (9), it can be calculated that

\[
\tau_1 = k_p(\dot{\theta}_1' - \dot{\theta}_1') - k_d(\dot{\theta}_1' - 10d_\theta \dot{\theta}_1') - 17g \cos \theta_1' - 3.8g \sin \theta_1' = k_p d_\theta \dot{\theta}_1' + 10d_\theta \dot{\theta}_1' + 10g \cos \theta_1' = \tau_3
\]

By plugging formula (11) in formula (3), the loop control law of the telescopic joint of the right working arm can be obtained that

\[
(-5.7 - 10d_\theta)\ddot{\theta}_1' + 10\dddot{\theta}_1 + (1.6 - 10d_\theta)\dot{\theta}_1' = \tau_3
\]
Table 5. Differential gain adjustment of the right arm telescopic joint motor

| $k_p$ | $k_d$ | Average torque ($N\cdot m$) | Average velocity ($m/s$) | Adjustment time (s) | Overshoot (1) |
|-------|-------|----------------------------|--------------------------|---------------------|--------------|
| 500   | -550  | 52.5114                    | 0.2050                   | 2.825               | 0            |
| 500   | -450  | 56.1581                    | 0.2068                   | 2.565               | 0            |
| 500   | -350  | 59.8850                    | 0.2083                   | 2.250               | 0            |
| 500   | -250  | 63.7338                    | 0.2095                   | 1.735               | 0            |
| 500   | -150  | 69.1871                    | 0.2240                   | 0.595               | 0.23%        |
| 500   | -50   | 74.7120                    | 0.3176                   | 0.435               | 7.71%        |
| 500   | -20   | 81.2558                    | 0.5466                   | 1.940               | 22.98%       |

With the same principle, expected proportional gain and expected differential gain of the rotary joint of the left working arm can be selected, suppose the expected proportional gain is $K_{pm}$ and the expected differential gain is $K_{dm}$, both of which are $2 \times 2$ matrix.

Figure 3. Right arm telescopic joint position response

Figure 4. Left arm rotation joint position response

After PD parameters of $K_{pm}$ and $K_{dm}$ of the two joints are selected with the tool of Matlab, it can be seen in Figure 3 and Figure 4 that within 4s, positions of the two joints of the working arms quickly respond to expected positions and come into stable state, indicating good control effect. In these two figures, 

$K_{pm} = \begin{bmatrix} 1000 & 0 \\ 0 & 500 \end{bmatrix}$ and $K_{dm} = \begin{bmatrix} -150 & 0 \\ 0 & -150 \end{bmatrix}$.

4.2. Program implementation of two axis linkage

In the process of two axis linkage of the robot, firstly, it must ensure that each shaft in linkage operates in its safe stroke; secondly, from the perspective of control, ensure that each shaft in linkage immediately stops after running to the expected position; and finally, ensure that the robot body can respond to instructions of a base station to stop moving when the base station gives emergency braking instructions.
To meet the three requirements mentioned above, each motor shaft in operation is subject to constrain conditions of stroke limit, counting, current abnormality and emergency brake, among which only stroke limit and counting are effective for single shaft while current abnormality and emergency brake require double shafts in motion to respond simultaneously as to guarantee safety of equipment.

In the case that two axis linkage is available, the robot calls a two axis linkage program, as shown in Figure 5. At first two linkage motors are selected and parameters of the motors are set. After the motors are enabled, velocity and stroke of the motors are set so as to drive the motors. The two axis linkage program adopts do-while statement, and takes full counting and current abnormality as termination judging conditions. In the loop of do-while of the main program, two motor motor operating threads are created so that when one motor meets termination conditions, it stops running immediately while the other motor is not affected.

5. Experiment and conclusion
The velocity of the motors of the robot is limited by a reducer. Under load condition, the motors generally runs at a velocity of 8000rpm. In order to verify validity of the approach presented in this paper, operation time of each single joint stroke of the left working arm and the right working arm of the robot, as well as period of time that the robot fulfills working tasks of live replacement of suspension insulators and live current plate bolt tightening with a single joint are counted; and then the working time under the two axis linkage control approach is calculated.

Robot two axis linkage experiments were carried out on Phase A (right), #006 Tower, 220kV Wangpei I line, State Grid Hunan Live-working Center. Live working experiment of replacement of single insulator string is shown in Figure 6 (a), and live tightening of tension clamp current plate implemented on Phase A (right) of #003 Tower is shown in Figure 6 (b).
The result is shown in Table 6.

Table 6. Comparison of experimental results

| Working type          | Single joint motion | Two axis linkage |
|-----------------------|---------------------|------------------|
| Suspension insulator  | Number of step 180  | 139              |
|                       | Time (min) 30       | 20               |
| Current plate bolt    | Number of step 90   | 70               |
|                       | Time (min) 14       | 9                |

Conclusions drawn from the above experiments are as follows:
(1) The global dynamic equation of the robot established in this paper is correct, and the proposed two axis linkage approach is feasible, which can be spread to other live-working robots for power transmission lines.
(2) According to the two axis linkage approach presented in this paper, working steps are reduced by 20% and working time is saved by 30% compared with single joint motion.
(3) Two axis linkage can effectively increase working efficiency of the robot.

References
[1] Yue, Xi, Wang, Hong-guang and Jiang, Yi. Design of a novel locomotion mechanism of power transmission line inspection robot [J]. 2017 Applied Mechanics & Materials 10 863
[2] Dong Xin, Gao Guo-qin and Lv Yun-qi. Study on Smooth Sliding Model Control for a 6-DOF Parallel Robot on Numerical Control [J]. 2009 Machine Tool & Hydraulics 05 111
[3] Fang Li-jin, Wei Yong-le and Tao Guang-hong. Design of a Novel Dual-arm Inspection Robot with Flexible Cable [J]. 2013 Robot 03 319
[4] Xu Xian-jin, Wu Gong-ping and He Yuan. Mechanism Design of an Inspection Robot for Reformed Ground Wire [J]. 2011 Machinery Design & Manufacture 11 93
[5] Mao Xing-tao, Bao Gang and Yang Qing-jun. Joint Torque Control for the Pneumatically Robotic Manipulator with 3 Degrees of Freedom [J]. 2008 Chinese Journal of Mechanical Engineering 12 254
[6] Luo Jan-guo, He Mao-yan and Sun Xue-cheng. Design on the Control System of 5 DOF Series-parallel Robots [J]. 2009 Machanery Design 07 19
[7] Sun Cui-lian, Wang Hong-guang, Zhao Ming-yang. Comparisons in Localization Methods during Obstacle Navigation of Inspection Robot for Power Transmission Lines [J]. 2007 China Mechanical Engineering 01 4
[8] Cai Li, Li En and Liang Zi-ze. Fuzzy Control of the Inspection Robot for Obstacle-negotiation [J]. 2008 Control & Automation 34 24
[9] Zhu Xing-long, Wang Hong-guang and Fang Li-jin. Centroid Adjustment Control on Autonomous Obstacle Negotiating Inspection Robot [J]. 2006 Robot 04 385
[10] Fang Li-jin, Wang Hong-guang. Research on the Characteristics of the Movement and Obstacle-Clearing Processes of a Wire-suspended Mobile Robot [J]. 2010 Transactions on Intelligent Systems 06 492
[11] Wu Hua, Meng Ling-zhi and Liu Chang-an. Hybrid Anti-swing Control Scheme for Cable Tunnel Inspecting Robot [J]. 2013 Huazhong Univ.of Sci.&Tech. Natural Science Edition 01 440
[12] Wen Xue-feng, Dian Song-yi and Dong Hang. Study on Climbing Mechanism of Doal-arm Robot for Power Line [J]. 2013 Machinery Design & Manufacture 07 168
[13] Zhou Jun, Leng Hong-bing and Zhu Hong-jun. Analysis of Influence on Natural Characteristics of Gear by Thermal Effect [J]. 2012 Journal of Machine Design 12 25