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Research on Gait Planning of Quadruped Search Robot Based on Non-fragile Reliable Control Strategy with the D-stability

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Abstract

The problem of gait planning for the quadruped search robot is described as an uncertainty discrete system. According to the basic gait elements of the quadruped search robot, the periodic gait of the robot is analyzed on the basis of gait timing diagram. The non-fragile control theory is proposed for gait planning control of quadruped search robot. A non-fragile reliable adaptive controller is designed for adaptive gait transition with the D-stability, which makes the gait planning to be regular, causal and D-stable. The condition of controller is given based on robust control theory, which include theorem 1 and theorem 2. And the approaches of designing the controller are given in terms of linear matrix inequalities. The results given by linear matrix inequalities indicate that the proposed non-fragile reliable robust controller is correct and effective.

Keywords: *quadruped robot; gait planning; Non-fragile reliable adaptive control; D-stabilit*

1. Introduction

Nowadays, the quadruped walking robot has been making great progress, but there is still some distance to the utility [1-3]. The quadruped search robot has the huge advantages in environmental adaptability, kinematics dexterity and efficiency in nature, which is able to move in almost any ground on the earth [4]. The quadruped robot is the optimal form among the multi-legged robots considering all the factors [5-7], like manufacturing cost, controlling complexity and stability and so on.

The gait of quadruped search robot is the swing sequence and the relative position relationship of legs [8]. The gait planning is to satisfy the search motion requirements and design a reasonable order of lifting leg [9]. Gait analysis is an important walking ability feature of the quadruped search robot. When the quadruped search robot is in the plane, most of its gait performance is the fixed mode to orderly lift leg [10-12]. In the unstructured environment, the fixed mode can not fully meet the terrain changes, so the necessary multi mode gaits must be need to switch and adjust the center of robot gravity.

According to D stability condition for uncertain discrete singular systems of adaptive gait transition, the D stability control is studied in the case of system parameter uncertainties [13-15]. The quadruped search robot works in the unstructured environments, the type of terrain features is different from the smooth and hard indoor environment [16-18]. It makes the traditional design method is not able to meet gait planning of the quadruped search robot [19]. The previous research theoretical results are difficult to be applied in the complex system parameters and control parameters. In this sense, the state of gait transition should be described as the equations. They are to

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establish the controller for the gait planning. Based on the quadruped search robot gait model, the non-fragile reliable adaptive control law is designed. It can get the parameters of the controller with linear matrix inequality. Finally, the test results prove the effectiveness of the design.

2. Planning of Periodic Gait

When the quadruped search robot walks, each leg has two states. There are the swing phase and support phase. The swing phase is that the leg swings in quadruped search robot motion state. The support phase is that the leg supports and plays a supporting role. There is a completed process of lift, swing, and landing in each leg of the quadruped search robot. It is a periodic gait *T*. In a gait cycle, the duration of each leg of the quadruped robot land with the ratio of a gait cycle. It is known as the duty cycle β_i ($0 \le \beta_i \le 1$).The land time t_1 of the first leg is selected as a fixed reference when the quadruped search robot walks. The ratio between the time difference of t_1, t_i and the gait cycle *T* is called relative phase that denoted as φ_i. The leg motion event of the quadruped search robot is description as shown in formula 1.

$$\psi_i = \begin{cases} \varphi_i + \beta_i, \varphi_i + \beta_i < 1 \\ \varphi_i + \beta_i - 1, \varphi_i + \beta_i \ge 1 \end{cases} \tag{1}$$

2.1. The Low Speed Gait Model

The quadruped search robot has three legs in the support phase and one leg in the swing phase at the same time. The lifting legs of slow gait are in a certain order. The left front leg of the quadruped search robot is called leg 1. In clockwise sequence, leg 2, leg 3 and leg 4 are shown in Figure 1. Four legs position of the quadruped search robot is divided into four sections.

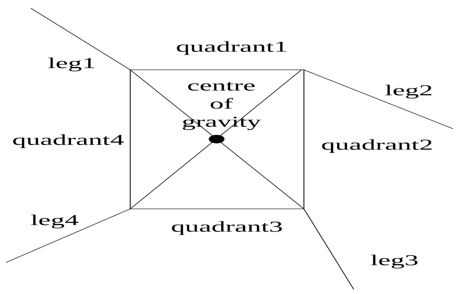

Figure 1. The Lift Leg Order of the Quadruped Search Robot

If the center of gravity of the quadruped robot is in the first quadrant, the robot cannot lift legs 1 and leg 2, only lift leg 3 and leg 4 to keep the stability. If the leg 4 swing and is not on ground, leg 1, leg 2 and leg 3 can still form a stable regional triangle to keep the center of gravity. If the leg 3 swing and it is not on ground, leg 1, leg 2 and leg 4 can still form a stable regional triangle to keep the center of gravity. Along with the motion of quadruped search robot, the body center of gravity moves. Because the low speed gait keeps three support phases, a stable regional triangle is formed. Therefore, it can guarantee the stable walking of the quadruped robot. The leg 1 is the initial landing leg, $\varphi_2 = 0$, $\varphi_4 = 0.25$, $\varphi_1 = 0.5$

, $\varphi_3 = 0.75$ are got in Figure 1. In accordance with formula 1, $\psi_2 = 0.8$, $\psi_4 = 0.3$, $\psi_1 = 0.05$, $\psi_3 = 0.55$ can be calculated. The sequence of every leg is $(\varphi_2, \psi_4, \varphi_4, \psi_{21}, \varphi_1, \psi_3, \varphi_3, \psi_2)$.

2.1.1. The Low Speed Intermittent Gait Model. The body movement timing diagram of the quadruped robot for low-speed intermittent walking gait is as shown in Figure 2. The RF, LB, LF and RB respectively represent the right fore leg, the left back leg, the left fore leg and the right back leg of the quadruped robot. CF represents the center of gravity of the quadruped robot. t_1, t_2, t_4, t_5, t_6, t_7, t_8, t_9 represent the time of landing and leg lift to the right fore leg, the left back leg, the left fore leg and the right back leg of the quadruped robot. t_{10}, t_{11}, t_{12}, t_{13} represent the second land time of the right fore leg, the left back leg, the left fore leg and the right back leg of the quadruped robot. t_3 represents the adjustment time for the body center of gravity moving.

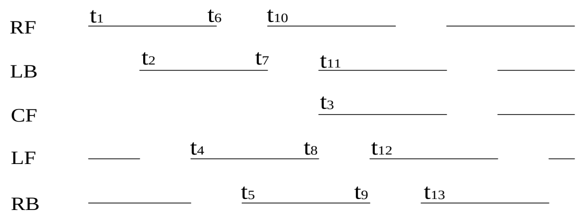

Figure 2. The Gait Timing Diagram of Low-Speed Intermittent Walking

The low-speed intermittent walking gait is only one action to achieve the body forward in a gait cycle, so this limits the speed of robot walking gait in a certain extent. The average speed of intermittent slow gait is in formula 2.

$$\bar{v} = \frac{LG\sin\theta}{T} \tag{2}$$

Where, L is leg length of the quadruped robot. θ is swinging angle of stride legs.

The sequence of the low-speed intermittent walking gait is shown in Figure 3.

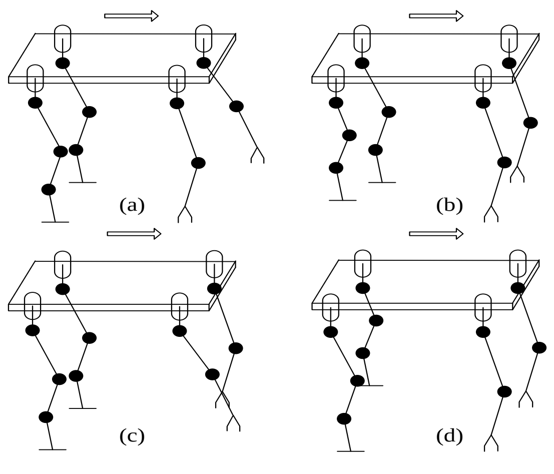

Figure 3. The Sequence Figure of Low-Speed Intermittent Gait

2.1.2. The Low Speed Coordination Gait Model. The low speed coordination walking is the general walking mode of the quadruped robot. In order to speed up the whole body walking and improve the whole robot coordination and consistency, the body can do the corresponding move to match the robot moving in each leg swing at the same time. It greatly reduces adjustment time of the quadruped robot to the body center of gravity. The low speed coordination gait is a continuous motion type and it is at the expense of stability margin.

The body movement timing diagram of the quadruped robot for low-speed **coordination** walking gait is as shown in Figure **4**. The RF, LB, LF and RB respectively represent the right fore leg, the left back leg, the left fore leg and the right back leg of the quadruped robot. CF represents the center of gravity of the quadruped robot. t_i , t_{i+4} (i =1, 2, 3, 4, 5) represent the time of landing and leg lift to the right fore, the left back, the body center of gravity, the left fore and the right back leg of the quadruped robot. t_{i+8} (i =1, 2, 3, 4, 5) represent the second land time of the right fore, the left back, the body center of gravity the left fore and the right back leg of the quadruped robot. The every action of the **low speed coordination** walking gait makes the body to go forward in a gait cycle. It increase walking speed and walking coordination for a certain level. The sequence of the low-speed coordination walking gait is shown in Figure 5.

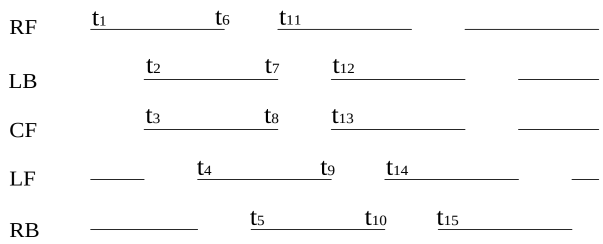

Figure 4. The Gait Timing Diagram of the Quadruped Robot in Low-Speed Coordination Walking

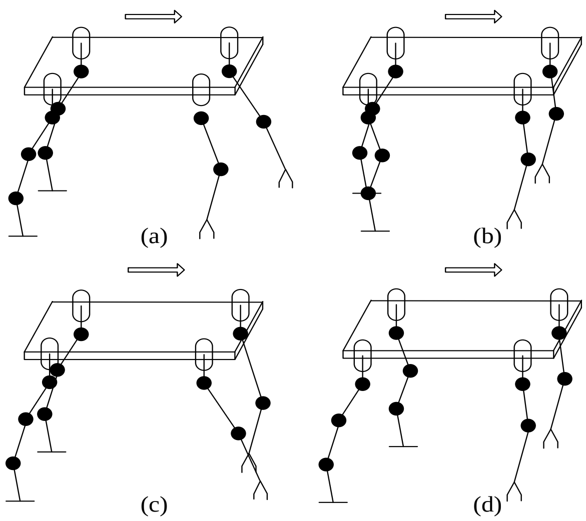

Figure 5. The Sequence Figure of Low-Speed Coordination Gait

2.2. The Medium Speed Gait Model

The diagonal two legs are in the swing phase, the other two are in the support phase angle at the same time. This gait is a diagonal gait. The duty cycle β_i is $0.3 < \beta_i \leq 0.5$. $\varphi_2 = 0$, $\varphi_4 = 0.25$, $\varphi_1 = 0.5$, $\varphi_3 = 0.75$ are got in Figure 1. In accordance with formula 1, $\psi_2 = 0.4$, $\psi_4 = 0.9$, $\psi_1 = 0.65$, $\psi_3 = 0.15$ can be calculated. The sequence of the quadruped robot every leg is $(\varphi_2 = 0, \psi_3 = 0.15, \varphi_4 = 0.25, \psi_2 = 0.4, \varphi_1 = 0.5, \psi_2 = 0.5, \varphi_3 = 0.75, \psi_1 = 0.9)$.

2.2.1. The Medium Speed Intermittent Gait Model. The RF, LB, LF and RB respectively represent the right fore leg, the left back leg, the left fore leg and the right back leg of the quadruped robot. CF represents the center of gravity of the quadruped robot. The body movement timing diagram of the quadruped robot for medium speed intermittent walking gait is as shown in Figure 6. The sequence of the medium speed intermittent walking gait is shown in Figure 7.

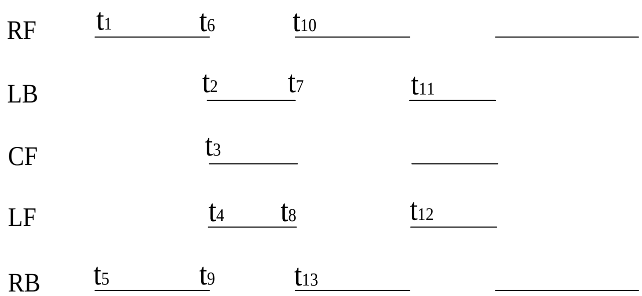

Figure 6. The Gait Timing Diagram of Quadruped Robot in Medium Speed Intermittent Walking

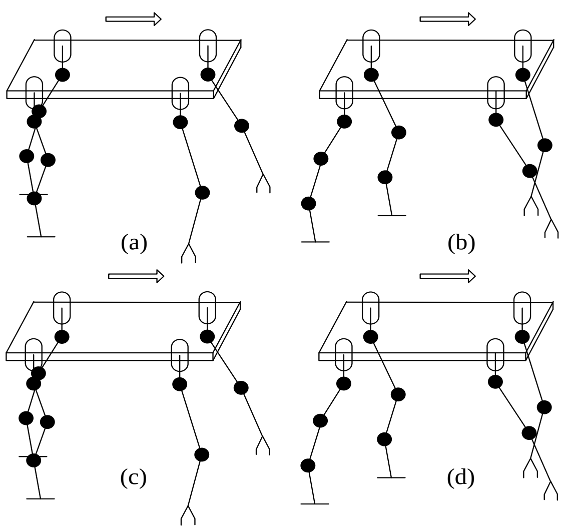

Figure 7. The Sequence Figure of Medium Speed Intermittent Gait

2.2.2. The Medium Speed Coordination Gait Model. The coordination gait of the quadruped robot with medium speed can walk more rhythm, more continuous, and walking speed is greatly improved. The body movement timing diagram of the quadruped robot for medium speed coordination walking gait is as shown in Figure 8. The sequence of the medium speed coordination walking gait is shown in Figure 9.

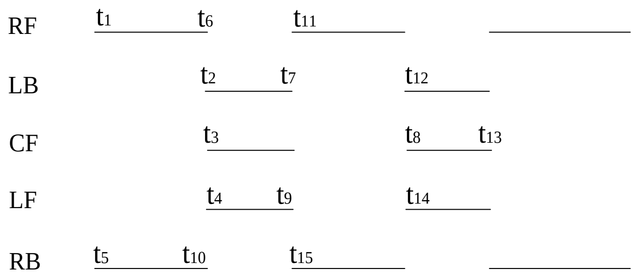

Figure 8. The Gait Timing Diagram of Quadruped Robot in Medium Speed Coordination Walking

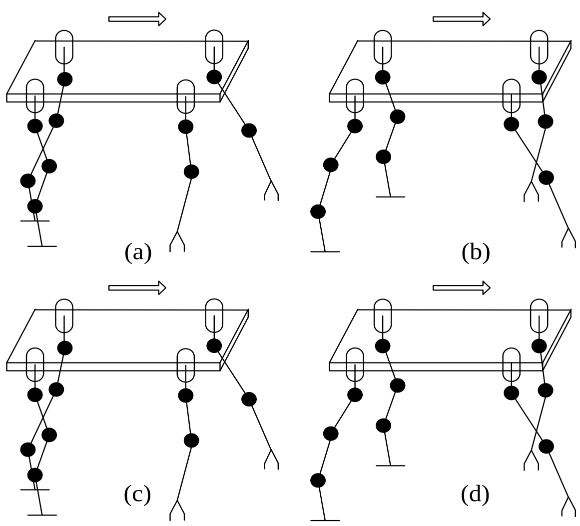

Figure 9. The Sequence Figure of Medium Speed Coordination Gait

2.3. The Fast Speed Gait Model

The left fore leg and the right fore leg are in the swing phase, the left back leg and the right back leg are in the support phase angle at the same time. This gait is a diagonal gait. The duty cycle β_i is $0 \le \beta_i \le 0.3$. $\varphi_2 = 0$, $\varphi_4 = 0.25$, $\varphi_1 = 0.5$, $\varphi_3 = 0.75$ are got in Figure 1. In accordance with formula 1, $\psi_2 = 0.5$, $\psi_4 = 0$, $\psi_1 = 0.75$, $\psi_3 = 0.25$ can be calculated. The sequence of the quadruped robot every leg is $(\varphi_2 = \psi_4 = 0, \varphi_1 = \psi_3 = 0.25, \varphi_4 = \psi_2 = 0.5, \varphi_3 = \psi_1 = 0.75)$.

2.3.1. The Fast Speed Intermittent Gait Model. The RF, LB, LF and RB respectively represent the right fore leg, the left back leg, the left fore leg and the right back leg of the quadruped robot. CF represents the center of gravity of the quadruped robot. The body movement timing diagram of the quadruped robot for fast speed intermittent walking gait is as shown in Figure 10. The sequence of the fast speed intermittent walking gait is shown in Figure 11.

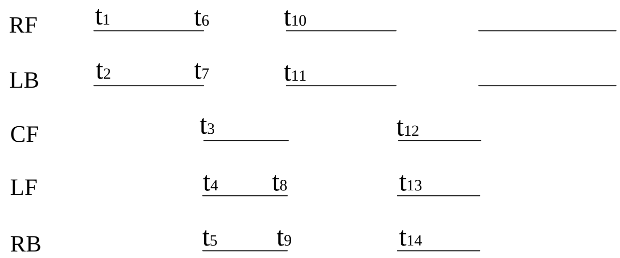

Figure 10. The Gait Timing Diagram of the Quadruped Robot in Fast Speed Intermittent Walking

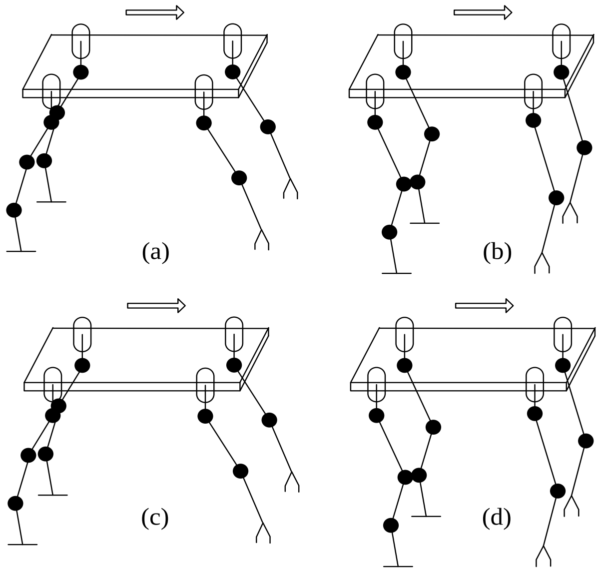

Figure 11. The Sequence Figure of Fast Speed Intermittent Gait

2.3.2. The Fast Speed Coordination Gait Model. The coordination gait of the quadruped robot with medium speed can walk more rhythm, more continuous, and walking speed is greatly improved. The body movement timing diagram of the quadruped robot for fast speed coordination walking gait is as shown in Figure12. The sequence of the fast speed coordination walking gait is shown in Figure13.

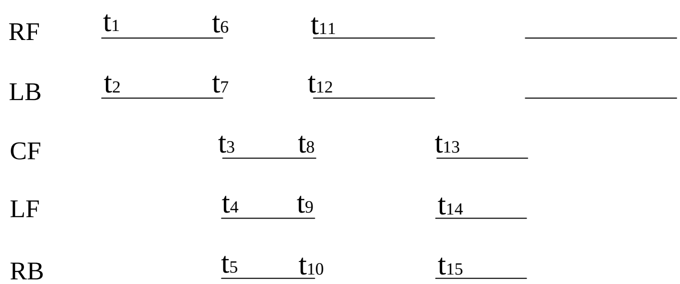

Figure 12. The Gait Timing Diagram of the Quadruped Robot in Fast Speed Coordination Walking

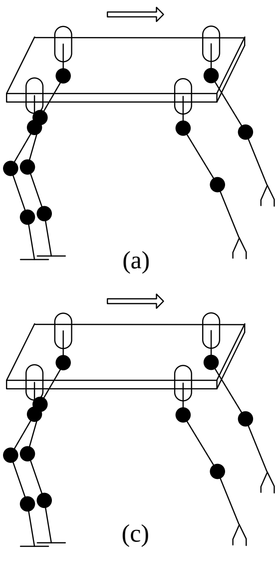

Figure 13. The Sequence Figure of Fast Speed Coordination Gait

3. Non-fragile Reliable Adaptive Control Law with the D-stability

The gait criteria of the quadruped search robot: 1. The quadruped trajectories are always periodic motion; 2. The robot body do not collide ground; 3. Gait transition control of the quadruped search robot is uncertain discrete singular system.

The adaptive gait transition state of the quadruped search robot is considered by the following equation:

$$Ex(k+1) = A_{\Delta}x(k) + B_{\Delta}u(k) \tag{3}$$

Where, $x(k) \in R^n$ is state variable of gait transition, $u(k) \in R^m$ is feedback control vector of the system stat. A and B are proper dimension of known matrix. E is known real constant matrix with the proper dimension (the motion parameters of stable walking). Guaranteed cost controller can not only guarantee the uncertain closed loop system robust asymptotic stability, and such that the closed-loop system satisfies the desired robust performance. $u(k) = kx(k)$ is a guaranteed performance control law with a performance matrix $P>0$ for system (3).

There are many kinds of gait. It is $6*6*6*6*6...$. How to ensure the controllability of gait switching?

Theorem 1: The adaptive gait transition state of the quadruped search robot is controllability.

Considering the continuous gait is nonlinear system:

$$\begin{aligned} y_1^{(s_1)} &= f_1(x) + \sum_{j=1}^{p} g_{1j}(x) u_j \\ &\vdots \\ y_1^{(s_p)} &= f_p(x) + \sum_{j=1}^{p} g_{pj}(x) u_j \end{aligned} \tag{4}$$

Where, x is gait variable, u is input gait status and y is output gait transition state. *f(x)* and *g(x)* are nonlinear function.

The above formula can be written as follows:

$$y^{(s)} = F(x) + G(x)u \tag{5}$$

The definition of gait tracking error:

$$\begin{gathered} e_1(t) = y_{d1}(t) - y_1(t) \\ \vdots \\ e_p(t) = y_{dp}(t) - y_p(t) \end{gathered} \tag{6}$$

The definition of Non-fragile gait tracking error:

$$\begin{gathered} w_1(t) = \left(\frac{d}{dt} + \lambda_1\right)^{s_1 - 1} e_1(t), \lambda_1 > 0 \\ \vdots \\ w_p(t) = \left(\frac{d}{dt} + \lambda_p\right)^{s_p - 1} e_1(t), \lambda_1 > 0 \end{gathered} \tag{7}$$

If $w_i \to 0, e_i \to 0(i = 1,2,...p)$, the control objectives are translated into $w_i \to 0(i = 1,2,...p)$.

According to Newton's binomial theorem,

$$(a+b)^n = \sum_{i=0}^{n} C_n^i a^i b^{n-1} \tag{8}$$

Where, $C_n^i = \frac{n!}{(n-i)!i!}$ is the expansion coefficient of Newton's binomial theorem.

So the formula (7) can be written as follows:

$$\begin{aligned} w_i(t) &= \left(\frac{d}{dt} + \lambda_i\right)^{s_i - 1} e_i(t) = \sum_{j=0}^{s_i - 1} \frac{(s_i - 1)!}{(s_i - 1 - j)!\, j!} \left(\frac{d}{dt}\right)^j e_i(t) \lambda_i^{s_1 - 1 - j} \\ &= \sum_{j=1}^{s_i} \frac{(s_i - 1)!}{(s_i - j)!(j-1)!} \left(\frac{d}{dt}\right)^{j-1} e_i(t) \lambda_i^{s_1 - j} \end{aligned} \tag{9}$$

Then

$$\begin{aligned} \dot{w}_i(t) &= \sum_{j=1}^{s_i} \frac{(s_i - 1)!}{(s_i - j)!(j-1)!} e_i^{(j)}(t) \lambda_i^{s_1 - j} = e_i^{(s_j)} + \sum_{j=1}^{s_i - 1} \frac{(s_i - 1)!}{(s_i - j)!(j-1)!} e_i^{(j)}(t) \lambda_i^{s_1 - j} \\ &= y_{d_i}^{(s_i)} - y_i^{(s_i)} + \sum_{j=1}^{s_i - 1} \frac{(s_i - 1)!}{(s_i - j)!(j-1)!} \left(\frac{d}{dt}\right)^{j-1} e_i(t) \lambda_i^{s_1 - j} \\ &= y_{d_i}^{(s_i)} - f_i(x) - \sum_{j=1}^{i} g_{ij}(x) u_j + \sum_{j=1}^{s_i - 1} \frac{(s_i - 1)!}{(s_i - j)!(j-1)!} \left(\frac{d}{dt}\right)^{j-1} e_i(t) \lambda_i^{s_1 - j} \end{aligned} \tag{10}$$

That is

$$\dot{w}_1 = v_1 - f_1(x) - \sum_{j=1}^{p} g_{1j}(x)u_j$$
$$\vdots \tag{11}$$
$$\dot{w}_p = v_p - f_p(x) - \sum_{j=1}^{p} g_{pj}(x)u_j$$

Formula (5) can be written as follows:

$$\dot{w} = V - F(x) - G(x)u \tag{12}$$

Linear control law can be described as:

$$u = G^{-1}(x)(-F(x) + v + K_0 s) \tag{13}$$

Where, $K_0 = diag\lfloor K_{01}..., K_{0p} \rfloor$.

Then

$$\dot{w}(t) = -K_0 w(t) \tag{14}$$

That is

$$\dot{w}(t) = -K_{0i} w_i(t) \tag{15}$$

The solution of differential equation:

$$w(t) = w_i(0)e^{-K_{0i}t} \tag{16}$$

If $t \to \infty$, $w_i(t) \to 0$, $e_i(t)$ and it's $s_i - 1$ derivative are convergence to zero. The proof process is complete.

When the controller $u(k) = Kx(k)$ exists, it make the discrete generalized system (3) regular, causal and meet D-stability, Meets $\sigma(E, A) \in D(\alpha, \gamma)$ [20]. If there exists a positive definite symmetric matrix $P \in R^{n \times n}$, matrix $S \in R^{(n-r)\times n}$ and matrix Q, matrix G, Meet the following linear matrix inequality. According to the Theorem 1, we can to define a performance index for system (3):

$$\begin{bmatrix} \Psi_{11} + He\{rBG\} & \Psi_{12} + rBG & r(D_1 S + D_2 G)^T \\ \Psi_{12}{}^T + (rBG)^T & \Psi_{22} & r(D_1 S + D_2 G)^T \\ r(D_1 S + D_{2G}) & r(D_1 S + D_2 G) & -\varepsilon I \end{bmatrix} < 0 \tag{17}$$

Where, $\Psi_{11} = ((1-\alpha)^2 - r^2)EPE^T + He\{r(A-E)S\} + \varepsilon HH^T$, $\Psi_{12} = r(A-E)S + rQ^T R^T + (1-\alpha)EP - rs$, $\Psi_{22} = -rS - rS^T + P$

When the formula (17) has a solution, Gait transition controller of the quadruped search robot is:

$$u(k) = GS^{-1}x(k) \tag{18}$$

Theorem 2: When the controller $u(k) = MKx(k)$ exists, it make the discrete generalized system (3) regular, causal and meet D – stable, Meets $\sigma(E, A) \in D(\alpha, \gamma)$. If there exists a positive definite symmetric matrix $P \in R^{n \times n}$, matrix $S \in R^{(n-r)\times n}$ and matrix Q, matrix G, Meet the following linear matrix inequality.

$$\begin{bmatrix} \Theta_{11} & \Theta_{12} & \Theta_{31}{}^{T} & \beta BM_0 & rG^T \\ \Theta_{12}{}^{T} & \Psi_{22} & \Theta_{31}{}^{T} & 0 & rG^T \\ \Theta_{31} & \Theta_{31} & -\varepsilon I & \beta D_2 M_0 & 0 \\ \beta M_0^T B^T & 0 & \beta M_0^T D_2^T & -\beta I & 0 \\ rG & rG & 0 & 0 & -\beta I \end{bmatrix} \tag{19}$$

Where, $\Theta_{11} = \Psi_{11} + He\{rBM_0G\}$, $\Theta_{12} = \Psi_{12} + rBM_0G$, $\Theta_{31} = r(D_1S + D_2M_0G)$. Then, $u(k) = GS^{-1}x(k)$ is Non-fragile reliable adaptive control Law of gait transition for quadruped search robot.

According to the formula (17), The following formula can be established.

$$\begin{bmatrix} \Psi_{11} + He\{rBMG\} & \Psi_{12} + rBMG & r(D_1S + D_2MG)^T \\ \Psi_{12}{}^{T} + (rBMG)^T & \Psi_{22} & r(D_1S + D_2MG)^T \\ r(D_1S + D_2MG) & r(D_1S + D_2MG) & -\varepsilon I \end{bmatrix} < 0 \tag{20}$$

The above formula can be written as follows:

$$\begin{bmatrix} \Theta_{11} & \Theta_{12} & \Theta_{31}^T \\ \Theta_{12}^T & \Psi_{22} & \Theta_{31}^T \\ \Theta_{31} & \Theta_{31} & -\varepsilon I \end{bmatrix} + He\left\{ \begin{bmatrix} BM_0 \\ 0 \\ D_2M_0 \end{bmatrix} L \begin{bmatrix} rG & rG & 0 \end{bmatrix} \right\} < 0 \tag{21}$$

The following formula can be established by Schur's compensation theorem.

$$\begin{bmatrix} \Theta_{11} & \Theta_{12} & \Theta_{31}^T \\ \Theta_{12}^T & \Psi_{22} & \Theta_{31}^T \\ \Theta_{31} & \Theta_{31} & -\varepsilon I \end{bmatrix} + \beta \begin{bmatrix} B \\ 0 \\ D_2 \end{bmatrix} \begin{bmatrix} B^T & 0 & D_2^T \end{bmatrix} + \beta^{-1} \begin{bmatrix} rSK^T \\ rSK^T \\ 0 \end{bmatrix} \begin{bmatrix} rKS & rKS & 0 \end{bmatrix} < 0 \tag{22}$$

The following formula can be established by Schur's compensation theorem.

$$\begin{bmatrix} \Theta_{11} & \Theta_{12} & \Theta_{31}{}^{T} & \beta BM_0 & rG^T \\ \Theta_{12}{}^{T} & \Psi_{22} & \Theta_{31}{}^{T} & 0 & rG^T \\ \Theta_{31} & \Theta_{31} & -\varepsilon I & \beta D_2 M_0 & 0 \\ \beta M_0^T B^T & 0 & \beta M_0^T D_2^T & -\beta I & 0 \\ rG & rG & 0 & 0 & -\beta I \end{bmatrix} \tag{23}$$

Derivation is the end.

4. Numerical Examples

System (3) parameters are obtained by step simulation, the system parameters are as follows:

$$E = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad A = \begin{bmatrix} -0.1 & 0.8 & 0.01 \\ 0.9 & -1.0 & 0.2 \\ -0.15 & -0.2 & -0.3 \end{bmatrix},$$

$$B = \begin{bmatrix} 1.0 & 0.7 \\ -0.8 & 1.2 \\ 0.3 & 0.8 \end{bmatrix}, \quad R = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \quad H = \begin{bmatrix} 1.5 & 0.8 \\ 1.2 & 0.9 \\ 1.3 & 2.1 \end{bmatrix}, \quad D_1 = \begin{bmatrix} 0.010 & 0.005 & 0.010 \\ 0.018 & 0.003 & 0.010 \end{bmatrix}$$

,

$$D_2 = 0.2, \quad M_1 = \begin{bmatrix} 0.2 \\ 0.2 \end{bmatrix}^T, \quad N_1 = \begin{bmatrix} 0.59 & 0.25 & 0.21 \end{bmatrix}$$

Because $u(k) = GS^{-1}x(k)$ is Non-fragile reliable adaptive control Law of gait transition for quadruped search robot, solution of linear matrix inequality are as follows:

$$P = \begin{bmatrix} 0.8784 & 0.2685 & 0.3695 \\ 0.2685 & 1.2813 & 0.3271 \\ 0.3695 & 0.3271 & 0.7322 \end{bmatrix},$$

$$S = \begin{bmatrix} 1.3619 & 0.6129 & -0.2409 \\ -0.0354 & 2.0682 & -0.8126 \\ 0.9388 & 1.4611 & 0.8943 \end{bmatrix},$$

$$Q = \begin{bmatrix} -0.8812 & -3.3736 & -1.9163 \end{bmatrix},$$

$$G = \begin{bmatrix} \begin{bmatrix} 2.8120 & -12.9305 & 7.0527 \\ -4.4428 & -2.6521 & -14.6198 \end{bmatrix} \end{bmatrix}$$

Corresponding guaranteed cost for non fragile controller is:

$$K = \begin{bmatrix} 0.9442 & -7.4809 & 1.3434 \\ 4.2203 & 5.0024 & -10.6662 \end{bmatrix}$$

Set the gait state controller error $\Delta K = \begin{bmatrix} -0.2 & 0 & 0 \\ 0 & -0.2 & 0 \end{bmatrix}$ of the quadruped search robot system. The result of reliable adaptive control simulation output based on non-fragile robust controller is shown as Figure 14. Over time the state of the system tends to zero, illustrates that the system is stable. Figure 15 is its stable gait planning photo. It meets the requirements of quadruped search robot for gait transition stability.

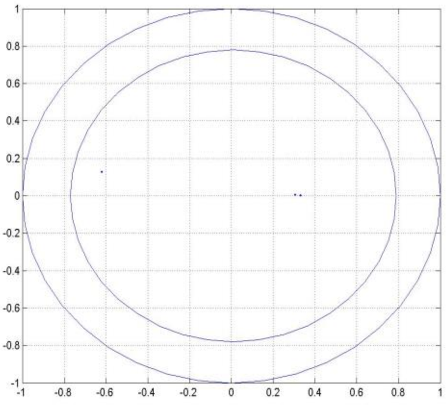

Figure 14. Pole Placement under Reliable Adaptive Control

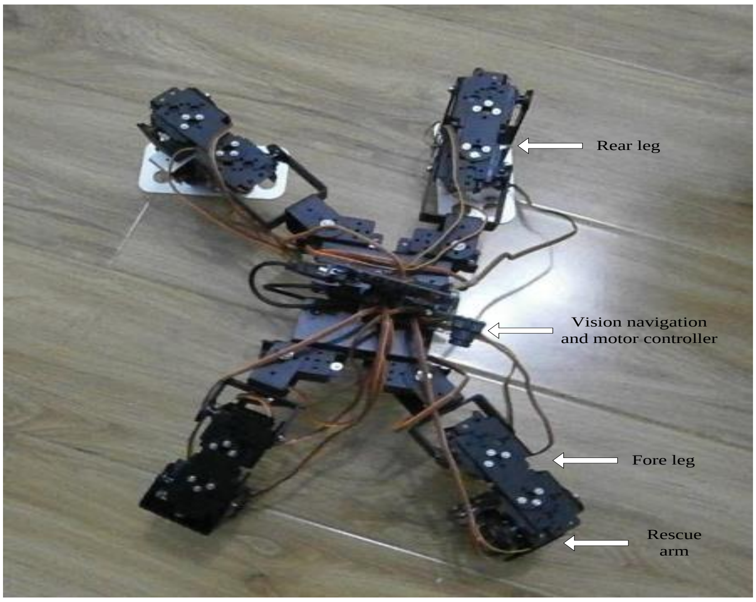

Figure 15. Stable Gait Planning of Robot

5. Conclusions

The non-fragile reliable adaptive control law with the D-stability for gait planning of the quadruped search robot is researched. Because it is non-fragile control problem, we proposed the adaptive gait transition method of non-fragile reliable controller on the basis of the D-stability. The method is given in terms of linear matrix inequalities with LMI technology. The controller can ensure that the closed-loop system is regular, causal and D- stability to solve the gait planning system and control parameters in a certain range. The conclusions are given in the form of linear matrix inequalities. After some parameter and program debugging, quadruped robot is controlled effectively. The results of the numerical simulation and robot control test show a good anticipated control performance.

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