Fault-Tolerant Locomotion of a Quadruped Walking Robot

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Abstract: The fault tolerant locomotion of legged robots, in static gait, is a gait which maintains its stability even if a fault event occurred to one of their legs. This paper presents a strategy for generating fault tolerant locomotion of a quadruped robot. The failure considered in this paper is a locked joint failure. The kinematic condition of fault tolerant locomotion is derived for straight line walking of quadruped robot on even terrain. An algorithm for fault tolerant locomotion in straight line is described.

Keywords: fault, quadruped, walking, robot, locomotion.

1. INTRODUCTION

In the past, there have been many studies on legged robots with more than four legs. It is recognized that legged robots have many advantages in the mobility characteristics over wheeled or tracked vehicles. One of the most important advantages of these robots is their mobility and terrain adaptability, which is superior in comparison to wheeled mobile robots.

The legged robots require only a series of discrete footholds along the locomotion path. This property enables these robots to go over surfaces difficult for wheeled mobile robots. Another significant advantage of legged robots is their robustness to damages to legs (in specially, in static walking). Legged robots are able to continue to walk against a fault in a leg. They may maintain static stability even if a leg is broken so that is cannot support the robot body.

Adaptation to a leg failure is one of the most important requirements for robust walking of legged robots, because the repair of the failed leg is almost impossible after legged robots have been launched in most applications. From their characteristics of having multi-legs, walking robots have inherent fault tolerance capability against a leg failure since a failed leg for itself may not cause catastrophic failure or instability in static walking. Among various leg failures, a locked joint failure is one of common failures that can be frequently observed in dynamics of robot manipulators, Chen et al. (1999).

If failed joints are supposed to be locked individually, a single joint failure reduces the number of degrees of freedom of the robot manipulator by one and reduces its workspace to a certain limit.

In this paper, we focus our concern on the problem of kinematic constraints of the failed leg in fault-tolerant gaits for a locked joint failure. As a case study, we propose a quadruped robot walking with the straight-line gait on even terrain and first join locked.

2. QUADRUPED ROBOT MODEL

A two-dimensional model of a quadruped robot is shown in following figure (Fig. 1) Estremera et al. (2002), Lee et al. (2002). The four legs are placed symmetrically about the longitudinal axis and have rectangular working areas with the length D_x and the width D_y. C_i is the centre point of leg i working area.

The robot body is also in the shape of a rectangle with $2U$ width and distant from working areas by d. C is the centre of gravity of the body and the origin of the robot coordinate system X–Y.

We assume that the robot body is kept parallel to the flat ground and does not change its altitude throughout walking. In addition, all the mass of the leg is assumed to be lumped into the body and the contact between a foot and the ground is made on a point.

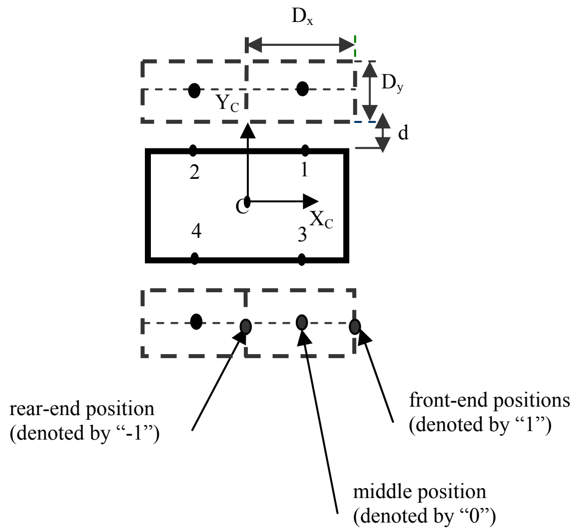

Fig. 1. Bidimensional model of quadruped robot.

A leg attached to the quadruped robot has the geometry of the articulated arm (Fig. 2). This model has two rigid links and three revolute joints; the lower link is connected to the upper link via an active revolute joint and the upper link is connected to the body via two active revolute joints, one parallel with the knee joint and the other parallel with the body's longitudinal axis. Hence the foot point has three degrees of freedom with respect to the body and the overall walking can be driven in any direction.

We denote the joint at the main actuator as joint one, the joint at the lifting actuator as joint two and the joint at the knee actuator as joint three. θ_1, θ_2 and θ_3 are values of each joint angle, and l_1 and l_2 are lengths of the upper and lower links, respectively.

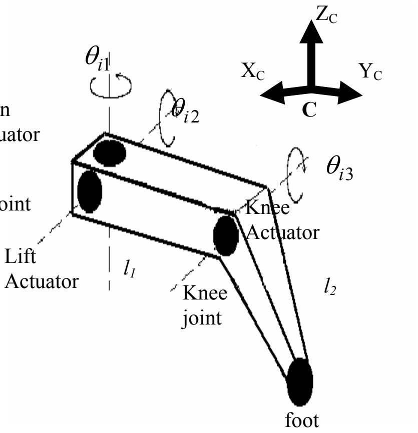

Fig. 2. Generalized coordonations of quadruped leg.

3. KINEMATIC CONSTRAINT

In this section, we show that there exists a range of kinematic constraints which the configuration of the failed leg should satisfy for guaranteeing the existence of the previous fault-tolerant gait. We assume that a locked joint failure occurs to any joint of leg 1.

3.1 Failure of Joint One

We consider the case where joint one is locked from failure. The failed leg in this case cannot take longitudinal swing with respect to the body and can take only lateral swing using the remaining normal joints (Fig. 3), where $\hat{\theta}_1$ is the locked angle of joint one, and l_1 and l_2 are the length of the upper and lower link, respectively. The motion of such a leg becomes that of a two-link revolute joint manipulator. Its workspace is reduced to the plane made of the links and the reachable region of the foothold position in the working area is projected onto a straight-line (Fig. 4). The failed leg can place its foot on the one and only foothold position, denoted by P, the intersection point of the foot trajectory and the reachable line. For such an intersection point to exist, locked angle $\hat{\theta}_1$ must be in the range of $\hat{\theta}_{1\min} < \hat{\theta}_1 < \hat{\theta}_{1\max}$, (Fig. 4), where all the angles are measured from the bisecting line of the working area in the clockwise direction. $\hat{\theta}_{1\min}$ and $\hat{\theta}_{1\max}$ are calculated as:

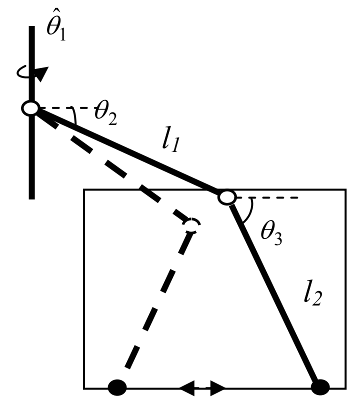

Fig. 3. Locked failure at joint one in straight-line walking (lateral view)

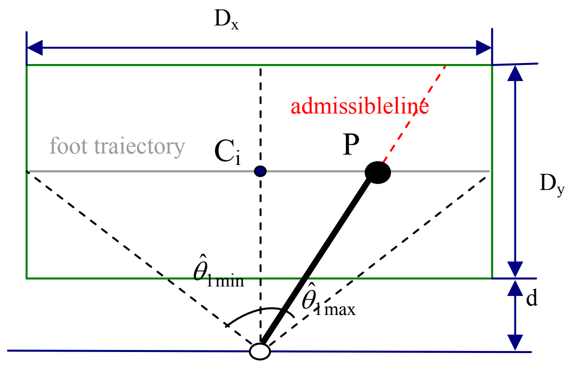

Fig. 4.Kinematic constraint of the quadruped leg

$$\hat{\theta}_{1\min} = -\arctan\left(D_x / D_y + 2d\right) \quad (1)$$

$$\hat{\theta}_{1\max} = \arctan\left(D_x / D_y + 2d\right) \quad (2)$$

3.2 Failure of Joint Two

When joint two of leg is locked because failure, the leg can swing only the second link by the knee joint in the lateral direction. Therefore, at a given value of joint one and the altitude of the hip joint, the failed leg can have two possible foothold positions. The resulting reachable region is thus of an arc shape (Fig. 5).

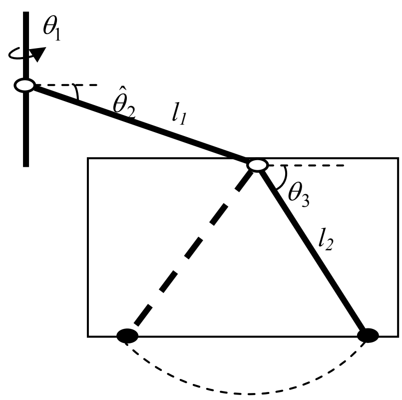

Fig. 5. Locked failure at joint two in straight-line walking (lateral view)

Depending on the features of its lateral motion, the leg can be placed on the inner foothold position P' or the outer position P (Fig. 6), or cannot be placed on the ground in the worst case.

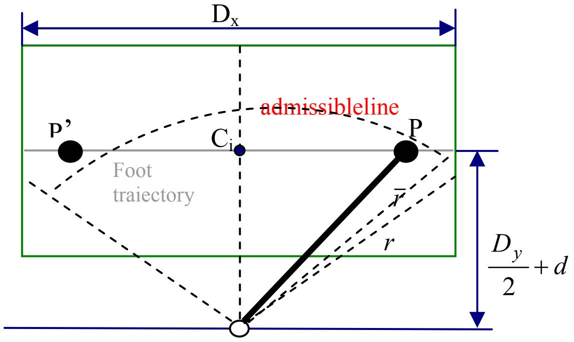

Fig. 6. Kinematic constraint of the quadruped leg

The kinematic constraint for guaranteeing such foothold positions can be described as

$$(D_y/2)+d \le r \le \bar{r} \quad (4)$$

where r is the radius of the arc and $\bar{r}$ is the distance between the leg attachment point and the front (or rear) boundary of the foot trajectory projected onto the X–Y plane.
If the radius of the arc r is in the above range, there exists at least one intersection point of the arc and the foot trajectory. For describing (4) in terms of joint angles and robot parameters, let us rewrite $\bar{r}$ and r as

$$\bar{r} = \frac{1}{2}\sqrt{D_x^2 + (D_y + 2d)^2} \quad (5)$$

$$r = l_1 \cos\hat{\theta}_2 + l_2 \cos\theta_3 \quad (6)$$

where $\hat{\theta}_2$ is the locked angle of joint two. Note that r is identical to the length of the leg projection onto the working area. Since the robot body is supposed to have a constant altitude, the angle of joint three θ_3 should also remain the same in the support phase. Substituting (5) and (6) into (4) leads to

$$(D_y/2)+d \le l_1 \cos\hat{\theta}_2 + l_2 \cos\theta_3 \le \frac{1}{2}\sqrt{D_x^2 + (D_y + 2d)^2} \quad (7)$$

The above result prescribes the kinematic constraint of locked angle $\hat{\theta}_2$ which guarantees the existence of the fault-tolerant gait for straight-line walking proposed in Yang (2002), Yang (2003).

3.3 *Failure of Joint Three*

The motion of leg in the case of a locked failure at joint three is almost similarly as that of a locked failure of joint two. If joint three, or the knee joint, is locked because of failure, the leg is reduced to a manipulator with one link and two revolute joints. The reduced reachable region in the working area is an arc (Fig. 7).

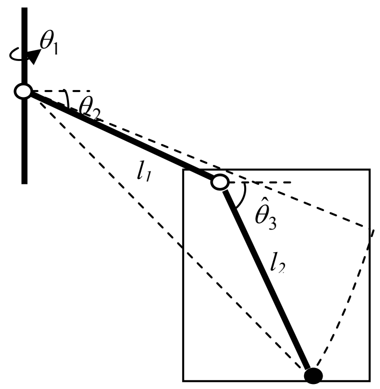

Fig. 7. Locked failure at joint three in straight-line walking (lateral view)

The next figure shows the lateral motion of the failed leg, in which the leg is moved only by joint two and the second link is passively lifted associated with the lift-off of the first link.

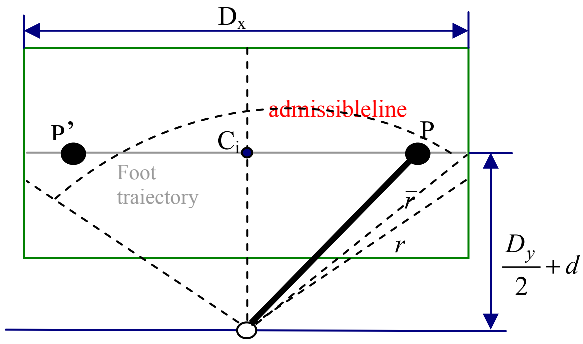

Fig. 8. Kinematic constraint of the quadruped leg

The kinematic constraint for the existence of the fault-tolerant gait is the same as the case of joint two:

$$(D_y/2)+d \le l_1 \cos\theta_2 + l_2 \cos\hat{\theta}_3 \le \frac{1}{2}\sqrt{D_x^2 + (D_y + 2d)^2} \quad (8)$$

where $\hat{\theta}_3$ is the locked angle of joint three.

4. FAULT-TOLERANT GAIT PLANNING

A. Failure of Joint One

When one of the quadruped feet has the first joint blocked appear following problems:

- cannot push the robot body in the support state, or
- have not an active swing in the transfer state for itself.

In this case, for continuing walking, the failed leg should be always lifted off when the robot body translates and be move passively by the motion of the robot body. The quadruped robot should stop walking at the moment when a locked failure at the first joint is detected and adapt its gait to obtain fault tolerance.

We purpose the follow algorithm of fault-tolerant gait for a quadruped robot with a locked failure at the first joint. The algorithm runs as follow:

Step 1: Check if $\hat{\theta}_{1i}$ is locked

- if NOT then continue the gait in normal condition (without fault)
- if YES then jump at Step 2

Step 2: Stop the movement of robot body and jump at Step 3

Step 3: Check if fault leg is in the support state

- if NOT then place the failed leg and jump at Step 5
- if YES then jump at Step 4

Step 4: Check if any leg is in the transfer state

- if NOT then jump at Step 5
- if YES then transfer forward and place the leg

Step 5: Check the support pattern, select the next leg that must begin its transfer state and jump at Step 6

Step 6: Check if selected leg is the failed one

- if NOT then swing the selected leg and jump at Step 5
- if YES then lift off the leg, move the robot body and jump at Step 5.

B. Failure of Joint Two

In the case of the failed leg due to the blocked failure of joint two, we purpose the follow algorithm of fault-tolerant gait for a quadruped robot. The algorithm runs as follow:

Step 1: Check if $\hat{\theta}_{2i}$ is locked

- if NOT then continue the gait in normal condition (without fault)
- if YES then jump at Step 2

Step 2: Stop the movement of robot body and jump at Step 3

Step 3: Check if fault leg is in the support state

- if NOT jump at Subroutine: Placing the Failed Leg (PFL)
- if YES then jump at Step 4

Step 4: Check if any leg is in the transfer state

- if NOT then jump at Step 5
- if YES then transfer forward and place the leg and jump at Step 5

Step 5: Check the support pattern, select the next leg that must begin its transfer state and jump at Step 6

Step 6: Check if selected leg is the failed one

- if NOT then lift the selected leg without robot body movement and jump at Step 5
- if YES then jump at Subroutine: Lifting the Failed Leg (LFL)

Subroutine (PFL): Check if the failed leg can be placed

- if NOT then eliminate this leg from the gait strategy
- if YES then place the failed leg by acting the joint three and adjusting the body amplitude and jump at Step 5

Subroutine (LFL): Check if the failed leg can be lifted

- if NOT then drag the leg on the ground executing a discontinuous robot body movement in regard of this
- if YES then lift the failed leg by acting the joint three

C. Failure of Joint Three

In the case of the failed leg due to the blocked failure of joint three, we purpose the follow algorithm of fault-tolerant gait for a quadruped robot. The algorithm runs as follow:

Step 1: Check if $\hat{\theta}_{3i}$ is locked

- if NOT then continue the gait in normal condition (without fault)
- if YES then jump at Step 2

Step 2: Stop the movement of robot body and jump at Step 3

Step 3: Check if fault leg is in the support state

- if NOT jump at Subroutine: Placing the Failed Leg (PFL)
- if YES then jump at Step 4

Step 4: Check if any leg is in the transfer state

- if NOT then jump at Step 5
- if YES then transfer forward and place the leg and jump at Step 5

Step 5: Check the support pattern, select the next leg that must begin its transfer state and jump at Step 6

Step 6: Check if selected leg is the failed one

- if NOT then lift the selected leg without robot body movement and jump at Step 5
- if YES then jump at Subroutine: Lifting the Failed Leg (LFL)

Subroutine (PFL): Check if the failed leg can be placed

- if NOT then eliminate this leg from the gait strategy
- if YES then place the failed leg by acting the joint two and adjusting the body amplitude and jump at Step 5

Subroutine (LFL): Check if the failed leg can be lifted

- if NOT then drag the leg on the ground executing a discontinuous robot body movement in regard of this
- if YES then lift the failed leg by acting the joint two

In this paper, as a strategy for the above algorithm, a periodic gait is proposed that has the following properties of leg sequence:

1) all the four legs are lifted off once in turn
2) all the lifted legs transfer in the forward direction along the longitudinal axis of the robot body
3) the stride length of the robot is maximized as long as 1) and 2) are held.

These properties are of great advantage to mobility of the robot. The property 1) guarantees a deadlock-free locomotion, and properties 2) and 3) imply that the derived gait sequence is optimally drive in the sense that no backward swing of the leg is necessary and that the robot body has the maximum stride length in a locomotion cycle.

For simplicity of analysis, we assume that a locked failure at join one occurs to leg 1. Fault-tolerant gaits for any other failed leg can be derived by symmetry of the quadruped robot. Any gait derived by the proposed algorithm can be described by setting the lift-off the failed by immediately before the body translation as the initial motion.

5. STRAIGHT-LINE GAIT OF QUADRUPED ROBOT WITH FAILURE OF JOINT ONE

Let x_i to be the X coordinateof the foothold position of leg i ($i=\overline{1,4}$) in the body coordinate system at the initial state. Then: $0 \le x_1, x_3 \le D_x$, $-D_x \le x_2, x_4 \le 0$, where D_x is the length of the working area. Note that x_1 is a constant value since joint one of leg 1 is locked from failure. The fault-tolerant periodic gait is defined as follow:

a) initial foothold position

a1) $(D_x/2) \le x_1 \le D_x$

$$x_2 + x_3 = 2(D_x - x_1)$$
$$x_4 = -x_1$$

a2) $0 \le x_1 < (D_x/2)$

$$x_2 = 0$$
$$x_3 = D_x$$
$$x_4 = -x_1$$

b) stride length

$$\lambda = \begin{cases} D_x - x_1, & if\,(D_x/2) \le x_1 \le D_x \\ (D_x/2), & if\,0 \le x_1 < (D_x/2) \end{cases}$$

c) gait sequence

lift and place leg 3 at distance λ $\rightarrow$ *lift and place leg 2 at distance* λ $\rightarrow$ *lift leg 1* $\rightarrow$ *move body with* λ $\rightarrow$ *place leg 1* $\rightarrow$ *lift and place leg 4 at distance* λ

The next figure (Fig. 9) illustrates an instance of the improved fault tolerant periodic crab gait in which the proposed adjustment procedure is embedded. We assume that a locked joint failure has occurred to joint one of leg 1 and the resulting kinematic constraint is beyond the reach of the present foot trajectory. Black circles denote foothold positions of supporting legs and white circles denote the previous locations of foothold positions. The dashed triangle is the support pattern in a state where a leg is in the transfer phase. Without loss of generality, all the four legs are supposed to be in the support phase in the beginning of the gait.

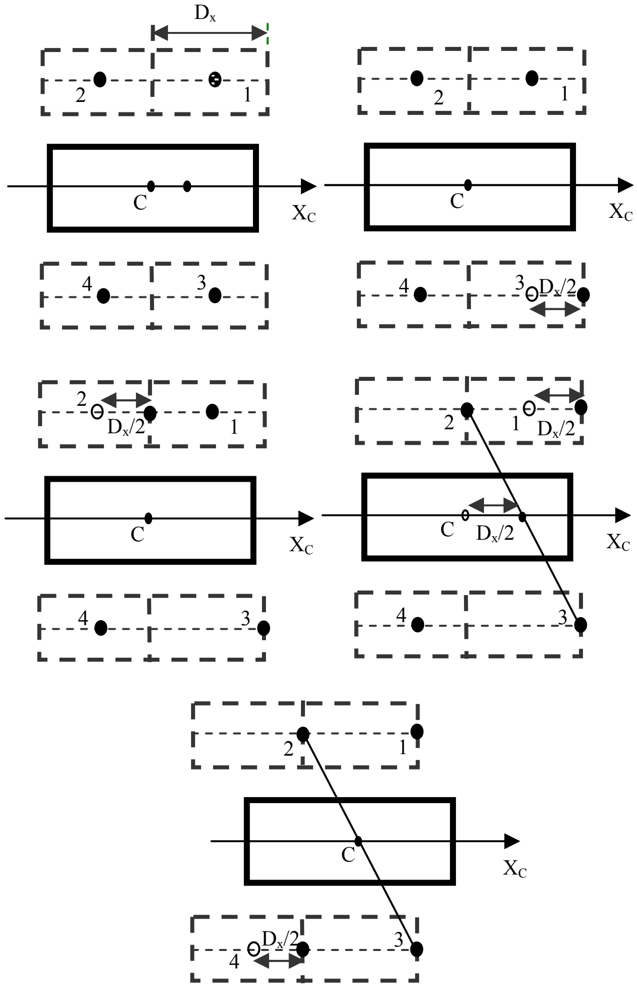

Fig. 9. Schematic top view showing foothold positions of each leg for straight-line gait with stride length $\lambda = D_x/2$

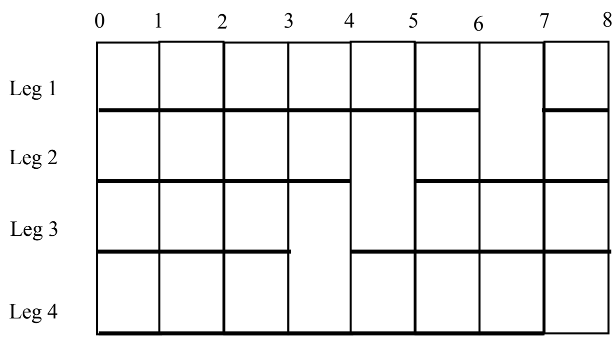

Fig. 10. Gait diagram of the proposed fault-tolerant gait

In above figure (Fig. 10) is presented the gait diagram of the proposed fault-tolerant gait for both cases of gait: straight-line a gait on flat terrain.

6. CONCLUSIONS

In this paper, a locked joint failure event was defined, and the behaviour of legged robots with a locked joint failure was examined. It was show that locked joint failure does not reduce stability of a gait but constrain the workspace of the failed leg. A fault-tolerant gait algorithm for locked joint failure (cases of one, two and three joint) was proposed in the straight-line walking of a quadruped robot over even terrain. In these algorithms, for avoiding defect caused by a locked joint failure, the robot has the discontinuous movement of the body with respect to leg swing and the failed leg is lifted and placed passively by translation of the quadruped body. The quadruped robot, with the proposed gait strategy, avoids any deadlock caused by the locked joint failure and has the maximum stride length in a cycle.

ACKNOWLEDGMENT

This work was supported by the strategic grant POSDRU/89/1.5/S/61968, Project ID61968 (2009), co-financed by the European Social Fund within the Sectorial Operational Program Human Resources Development 2007-2013.

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