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Full paper

Crab walking of quadruped robots with a locked joint failure

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Abstract—Fault tolerance is an important aspect in the development of control systems for multi-legged robots since a failure in a leg may lead to a severe loss of static stability of a gait. In this paper, an algorithm for tolerating a locked joint failure is described in gait planning for a quadruped robot with crab walking. A locked joint failure is one for which a joint cannot move and is locked in place. If a failed joint is locked, the workspace of the resulting leg is constrained, but legged robots have fault tolerance capability to continue walking maintaining static stability. A strategy for fault-tolerant gaits is described and, especially, a periodic gait is presented for crab walking of a quadruped. The leg sequence and the formula of the stride length are analytically driven based on gait study and robot kinematics. The adjustment procedure from a normal gait to the proposed fault-tolerant crab gait is shown to demonstrate the applicability of the proposed scheme.

Keywords: Quadruped robot; fault tolerance; crab gait; locked joint failures; gait study.

1. INTRODUCTION

There is a growing need for legged robots to traverse rough terrain in applications such as agriculture, underwater [1], as well as planetary and volcanic exploration [2]. In these demanding applications, fault tolerance capability is a critical requirement for the legged robots because repairing failed parts is practically impossible during walking. From natural multi-pedal features, legged robots with static walking have fault tolerance capability against a failure in a leg, i.e. they can continue walking even though a leg is injured or mutilated. Until recently, this advantage, nevertheless, has attracted little attention in the field of gait study. Among few works, are there a robust distributed neural network controller for hexapod robots [3], energy-based stability measures for reliable locomotion [4] and fault-tolerant quadruped gaits for hexapod robots [5]. In Ref. [6], we have proposed a

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general scheme of fault tolerance for a locked joint failure, in which a joint of a leg is locked in place [7]. A locked joint failure reduces the workspace of the failed leg and consequently limits the scope of gait planning. In Ref. [6], it was found that quadruped robots having straight-line motion on even terrain can continue their walking with a failed leg and can have a periodic gait after a locked joint failure.

In this paper, the study will focus on fault tolerance in crab walking of a quadruped robot. Crab walking is defined as a walking motion with the direction of locomotion different from the longitudinal axis of the robot body. It is very important to an omni-directional walking robot, especially to a quadruped, since the four legs are symmetrical about the body vertical axis. With adequate implementation of crab gaits, a quadruped could have the same agility in both longitudinal and lateral directions [8]. In this paper it is supposed that a leg has the geometry of the articulated arm [9] which has three revolute joints — two hip joints and one knee joint. The foot of such a leg will have a three-dimensional workspace and thus overall walking can be driven in any direction. If a joint of a leg is locked from failure, the leg mechanism is partially operated and the failed leg may not be either lifted, swung or placed depending on the characteristics of the locked joint. In this paper, based on the general scheme proposed in Ref. [6], fault-tolerant gaits of a quadruped robot are derived for crab walking on even terrain. The constrained motion of the quadruped after a locked joint failure is described in the frame of gait study and it is shown that the crab gaits can be analyzed as was done to the forward gaits in Ref. [6]. A periodic crab gait is presented in which the quadruped has the maximum stride length after a locked joint failure occurs in a leg. The adjustment procedure from a normal wave-crab gait to the proposed fault-tolerant gait is shown to demonstrate the applicability of the proposed scheme.

2. DESCRIPTION OF A QUADRUPED ROBOT

A simplified model of the quadruped robot is shown in Fig. 1. C is the center of gravity of the robot and the origin of the robot body's coordinate system $X-Y$. The legs are placed symmetrically about the longitudinal axis X. Dashed rectangles are working areas of legs, which represent pre-specified regions where each leg can reach at the present position of the body. Although the legs' reachable working areas can be any shape so long as they can be approximated to straight sided polygons, the conventional rectangular layout is used in this paper for convenience. C_i is the center of the workspace of leg i, and R_x and R_y are the length and width of a working area, respectively. It is assumed that the stroke pitch of a leg is the same as the length of a working area R_x, i.e. the working area of a leg is adjacent with those of neighboring ipsilateral legs, as shown in Fig. 1. W is the distance between the working area and the robot body. α is the crab angle defined as the angle between the longitudinal axis of the robot body and the direction of crab walking. α_1 is defined as the angle between the off-diagonal and the base of the working area.

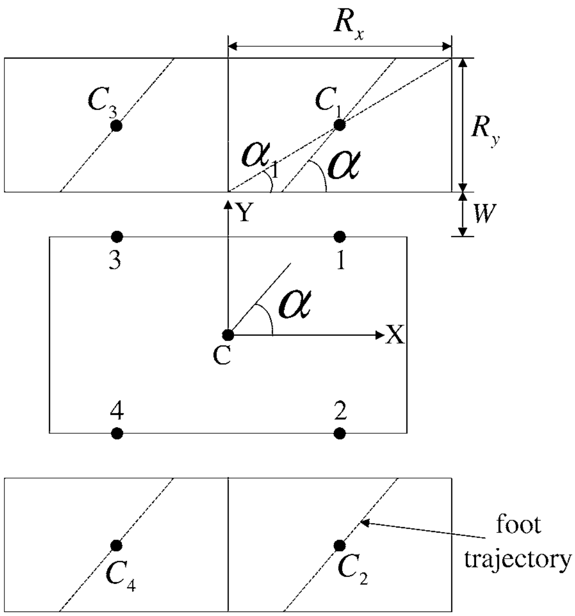

Figure 1. A general model of a quadruped robot.

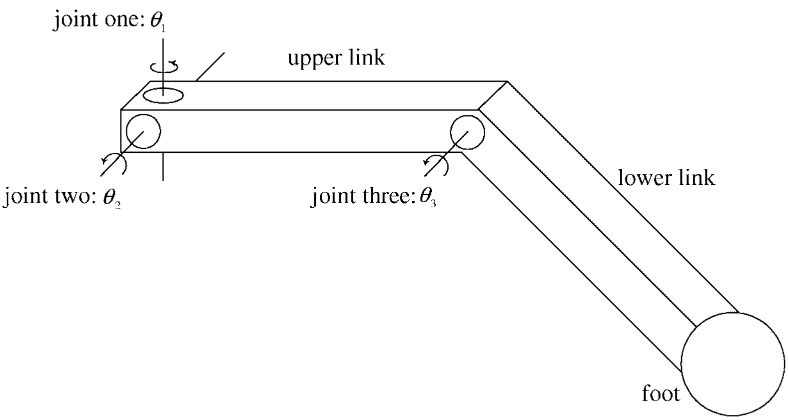

Figure 2. Three-joint leg model.

Figure 2 is a perspective view of a leg attached to the considered quadruped. A leg is composed of two rigid links. 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 longitudinal axis. Hence the foot point has 3 d.o.f. with respect to the body. 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, respectively. Figure 3 shows the local coordinate system of leg i

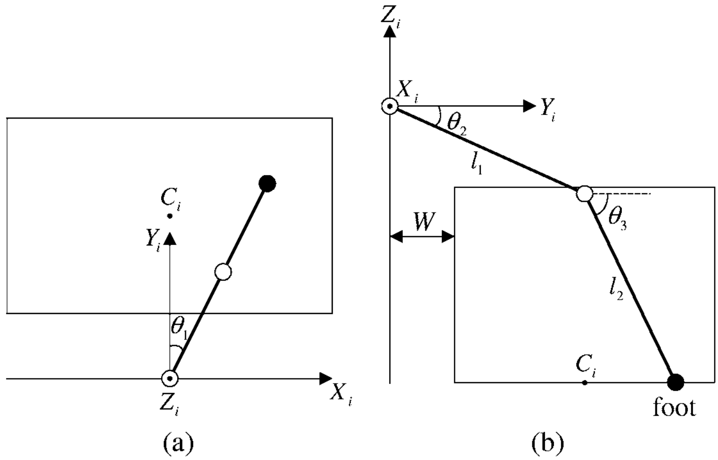

Figure 3. Leg coordinate system: (a) $X_i - Y_i$ view and (b) $Y_i - Z_i$ view.

where the origin is attached on the hip joint of the leg. l_1 and l_2 are the length of the upper and lower link, respectively.

In this paper, the quadruped robot is supposed to have the following mechanism:

(i) The quadruped walks on a straight line with a constant crab angle α ($0 < \alpha \leqslant 90^\circ$) on even terrain.

(ii) The trajectories of all the four feet move through their workspace centers as shown in Fig. 1.

(iii) The robot body is kept horizontal and, unless specified otherwise, the altitude of the body is not changed.

(iv) All the mass of the legs is lumped into the body, and the contact between a foot and the ground is a point.

Point (i) implies that only the crab gaits of the $+x$ type [10] are considered in this paper. Other gaits with different directions could be easily derived by symmetry of the quadruped. Points (ii) and (iii) rule out any irregular motion such as walking over uneven terrain, etc. Thus, for developing fault-tolerant gaits for irregular motions, the strategy that will be presented with these assumptions should be extended taking into account the characteristics of irregular motions.

3. LOCKED JOINT FAILURE

When a locked joint failure occurs in a leg, a joint of the failed leg is locked in a known position. This failure may be directly due to the failure itself, the indirect result of a very high gear ratio on an actuator that has lost power or due to brakes that have been applied by implemented failure detection software [11]. A single joint failure reduces the number of d.o.f. in the leg by one. Because the leg model considered has three-dimensional motions in a normal state, a locked joint failure will result in two-dimensional motion of the leg. We investigate constrained motions of the failed leg and obtain kinematic conditions required for continuing crab walking with the failed leg. For simplicity of presentation, we assume that a locked joint failure occurs in leg 1. The cases of failures in other legs could be deduced from symmetry.

3.1. Failure of joint one

When joint one is locked from failure, the motion of the 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 line as shown in Fig. 4a, where joint one is locked at angle $\hat{\theta}_1$. The failed leg cannot take lateral swing with respect to the body and can take only vertical swing, as shown in Fig. 4b, using the remaining joints. Thus the leg has at most one possible foothold position on the foot trajectory, as P in Fig. 4a. The existence of P depends on the values of the crab angle α and the locked angle $\hat{\theta}_1$. Figure 5 illustrates the range of $\hat{\theta}_1$ for the existence of the foothold position. Let us calculate the boundary of the range, $\hat{\theta}_{1,\min}$ and $\hat{\theta}_{1,\max}$. First, consider the case of $\alpha_1 < \alpha \leqslant 90°$. For the failed leg to be placed on the foot trajectory of crab walking, the locked angle $\hat{\theta}_1$ must be in the range of $\hat{\theta}_{1,\min} \leqslant \hat{\theta}_1 \leqslant \hat{\theta}_{1,\max}$ as shown in Fig. 5a. $\hat{\theta}_{1,\min}$ and $\hat{\theta}_{1,\max}$ can be expressed as:

$$\begin{aligned}\hat{\theta}_{1,\min} &= \arctan\left(\frac{-x_1}{W}\right),\\ \hat{\theta}_{1,\max} &= \arctan\left(\frac{x_1}{R_y + W}\right).\end{aligned} \tag{1}$$

From Fig. 5a, x_1 is calculated as:

$$x_1 = \frac{R_y}{2\tan\alpha}. \tag{2}$$

Using (2), (1) gives:

$$\begin{aligned}\hat{\theta}_{1,\min} &= -\arctan\left(\frac{R_y}{2W\tan\alpha}\right),\\ \hat{\theta}_{1,\max} &= \arctan\left(\frac{R_y}{2(R_y + W)\tan\alpha}\right).\end{aligned} \tag{3}$$

Next, consider the case of $0 < \alpha \leqslant \alpha_1$. Referring to Fig. 5b, $\hat{\theta}_{1,\min}$ and $\hat{\theta}_{1,\max}$ can be expressed as:

$$\begin{aligned}\hat{\theta}_{1,\min} &= \arctan\left(\frac{-R_x}{2y_2}\right),\\ \hat{\theta}_{1,\max} &= \arctan\left(\frac{R_x}{2y_1}\right).\end{aligned} \tag{4}$$

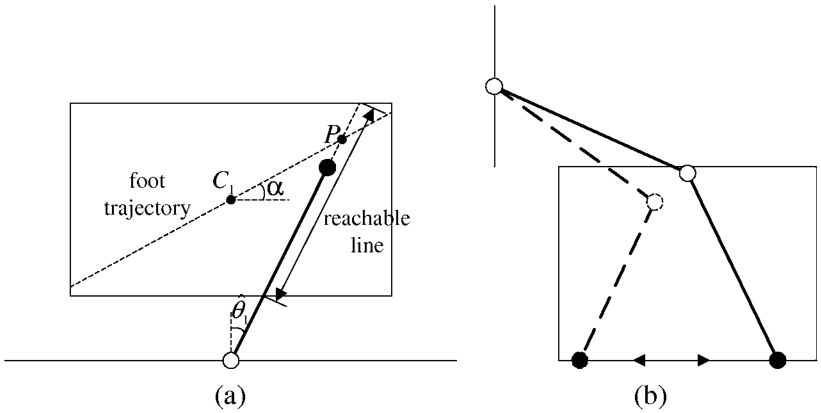

Figure 4. Locked failure at joint one: (a) plane view and (b) lateral view.

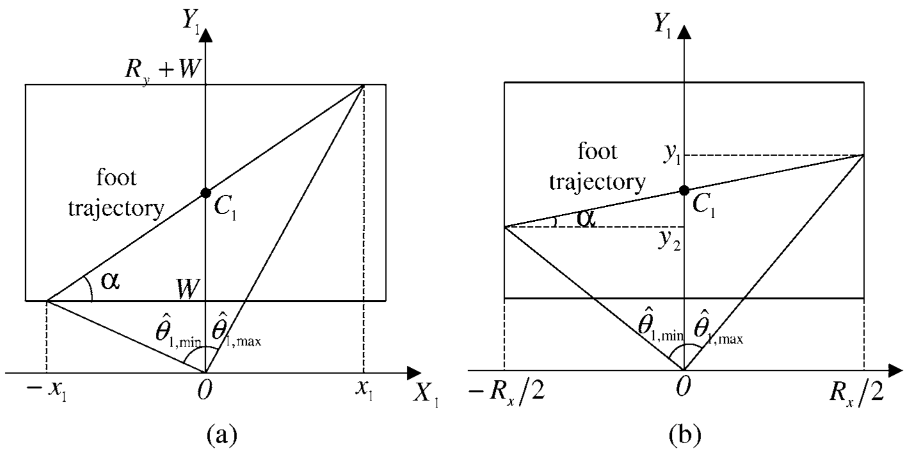

Figure 5. Range of $\hat{\theta}_1$ for the existence of the foothold position: (a) $\alpha_1 < \alpha \leqslant 90°$ and (b) $0 < \alpha \leqslant \alpha_1$.

From Fig. 5b, we can get the following two simultaneous equations of y_1 and y_2:

$$\begin{aligned} y_1 + y_2 &= R_y + 2W, \\ y_1 - y_2 &= R_x \tan\alpha. \end{aligned} \tag{5}$$

Solving (5) gives:

$$\begin{aligned} y_1 &= \frac{R_y}{2} + W + \frac{1}{2} R_x \tan\alpha, \\ y_2 &= \frac{R_y}{2} + W - \frac{1}{2} R_x \tan\alpha. \end{aligned} \tag{6}$$

Substituting (6) into (4), $\hat{\theta}_{1,\min}$ and $\hat{\theta}_{1,\max}$ are derived as:

$$\hat{\theta}_{1,\min} = -\arctan\left(\frac{R_x}{R_y + 2W - R_x \tan\alpha}\right),$$

$$\hat{\theta}_{1,\max} = \arctan\left(\frac{R_x}{R_y + 2W + R_x \tan\alpha}\right). \tag{7}$$

Therefore, (3) and (7) determine the range of the locked angle $\hat{\theta}_1$ which guarantees the existence of the foothold position for walking with the crab angle α.

3.2. Failure of joint two

When joint two of a leg is locked from failure, the leg should move only the lower link by joint three for vertical swing. The resulting reachable region on the working area is thus projected onto an arc as shown in Fig. 6a. Depending on the configuration at the moment of failure, the leg can be placed on the inner foothold position or the outer position, or cannot be placed on the foot trajectory in the worst case. Referring to Fig. 6a, the existence condition for the foothold position on the foot trajectory can be described as:

$$d \leqslant r, \tag{8}$$

where d is the distance between the foot trajectory and the hip joint on the X_1–Y_1 plane and r the radius of the arc. d is easily derived as:

$$d = \left(\frac{R_y}{2} + W\right)\cos\alpha. \tag{9}$$

Since r is identical to the length of the leg projection onto the X_1–Y_1 plane:

$$r = l_1 \cos\hat{\theta}_2 + l_2 \cos\theta_3, \tag{10}$$

where $\hat{\theta}_2$ is the locked angle of joint two. From (8)–(10), the existence condition is derived as:

$$\left(\frac{R_y}{2} + W\right)\cos\alpha \leqslant l_1 \cos\hat{\theta}_2 + l_2 \cos\theta_3. \tag{11}$$

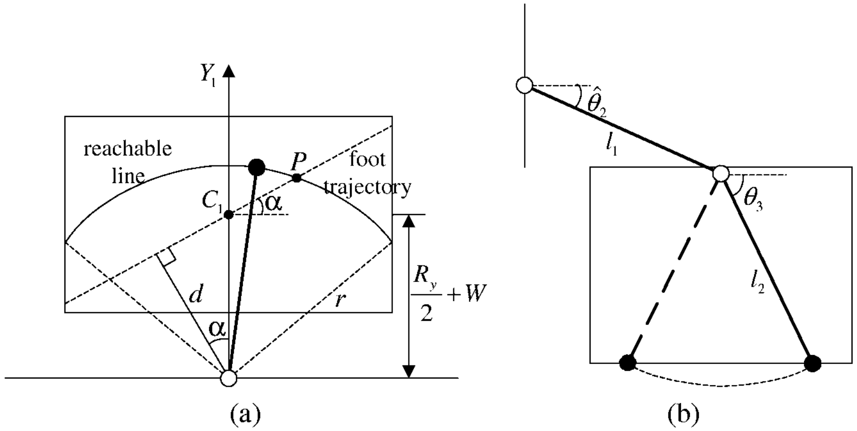

Figure 6. Locked failure at joint two: (a) plane view and (b) lateral view.

3.3. Failure of joint three

The result of a locked failure at joint three is almost identical to that of joint two. If joint three is locked from failure, the leg is reduced to an one-link manipulator with two revolute joints and the reduced reachable region in the working area becomes an arc. In this case, the failed leg is vertically swung only by joint two and the lower link is passively lifted associated with the lift-off of the upper link. By a similar calculation, the existence condition for the foothold position on the foot trajectory can be written as:

$$\left(\frac{R_y}{2} + W\right)\cos\alpha \leqslant l_1\cos\theta_2 + l_2\cos\hat{\theta}_3,$$

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

4. FAULT-TOLERANT CRAB GAIT

4.1. General scheme

When the robot body translates, the configurations of all the supporting legs should be simultaneously changed to maintain the current foothold positions. However, if a locked joint failure occurs in a joint of a leg, the rank of Jacobian of the failed leg is reduced by one [12] and there exists no solution space of the inverse kinematics with which the foothold position of the failed leg remains the same against the translation of the body. Thus, for continuing walking with a locked joint failure, the failed leg should be always lifted off before the robot body translates and be moved passively by the motion of the robot body. This leads to the following fault tolerance scheme of a quadruped robot after a locked joint failure:

(i) When the failed leg is in the transfer phase, it does not have lateral swing with respect to the robot body and is moved only passively by the motion of the body.

(ii) When the failed leg is in the support phase, the robot body should not translate, since the failed leg cannot maintain the current foothold position.

(iii) Consequently, the quadruped has a gait with discontinuous body motion. The general algorithm of fault-tolerant gait planning is as follows [6]:

   (a) As soon as a locked joint failure is detected, the quadruped robot halts the movement of the body.

   (b) If the failed leg is in the transfer phase, it is placed. Otherwise, check whether there is any leg in the transfer phase.

   (c) If there is a leg in the transfer phase, it is transferred forward and placed. Otherwise, the support pattern is checked and the next transfer leg is selected.

(d) If the selected leg is a normal leg, the leg is actively swung without any body motion. Else if the selected leg is the failed leg, it is lifted off and the robot body moves.

It is noted that the presented scheme fully utilizes the remaining ability of the failed leg. Unlike the free-swinging joint failure where actuator torque is lost and the failed leg cannot have the support phase [13], a leg with a locked joint failure can still hold up the robot body and has the constrained workspace which can be applied to walking. The basic idea of the above gait planning is to use the failed leg only in the support operation and exclude it in the forward transfer of the robot body. Hence three normal legs are first swung without body motion (iii.c) and followed by the lift-off of the failed leg and the body movement (iii.d).

Attention needs to be paid to the placement of the failed leg since the constrained motion of the failed leg differs according to the position of the locked joint. If a locked joint failure occurs in joint 1, only one point, the intersection point between the reachable line and the foot trajectory, can be the foothold position of the failed leg (see Fig. 4a). On the other hand, if a locked joint failure occurs in joints two or three, there may be two candidates for the foothold position, since the reachable line is an arc, not a straight-line (see Fig. 6a). In this case, the selection should be made such that it gives more mobility to other legs in the next cycle. In an extreme case, the locked angle might be out of the range which guarantees the existence of the foothold position on the foot trajectory. The quadruped robot then has to adapt its configuration, e.g. changing the altitude of the body, to restore reachability of the failed leg.

4.2. Periodic crab gait

Based on the general algorithm of fault tolerance, a periodic crab gait is proposed in this paper. Periodic gait planning is of great significance because it implies that, even though a failure happens, the quadruped can have a regular gait sequence which is easily implemented in a computer program. In deriving the periodic gait, the stride length will be maximized with the minimum stability. The reason for setting the stride length as the main performance criterion is to show the maximum mobility a quadruped can have against a locked joint failure. We assume that the failed leg is leg 1. Referring to the leg coordinate system in Fig. 3, let us denote x_1 as the X_1 coordinate of the foothold position of leg 1 after the failure. As the constrained motion of the failed leg is determined by the aspect of the failure, the stride length of the periodic crab gait depends on x_1. We propose the periodic crab gait for the cases of $x_1 \geqslant 0$ and $x_1 < 0$, respectively.

4.2.1. $x_1 \geqslant 0$. Figure 7 illustrates the proposed crab gait where a locked joint failure occurs in leg 1 with $x_1 \geqslant 0$. 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

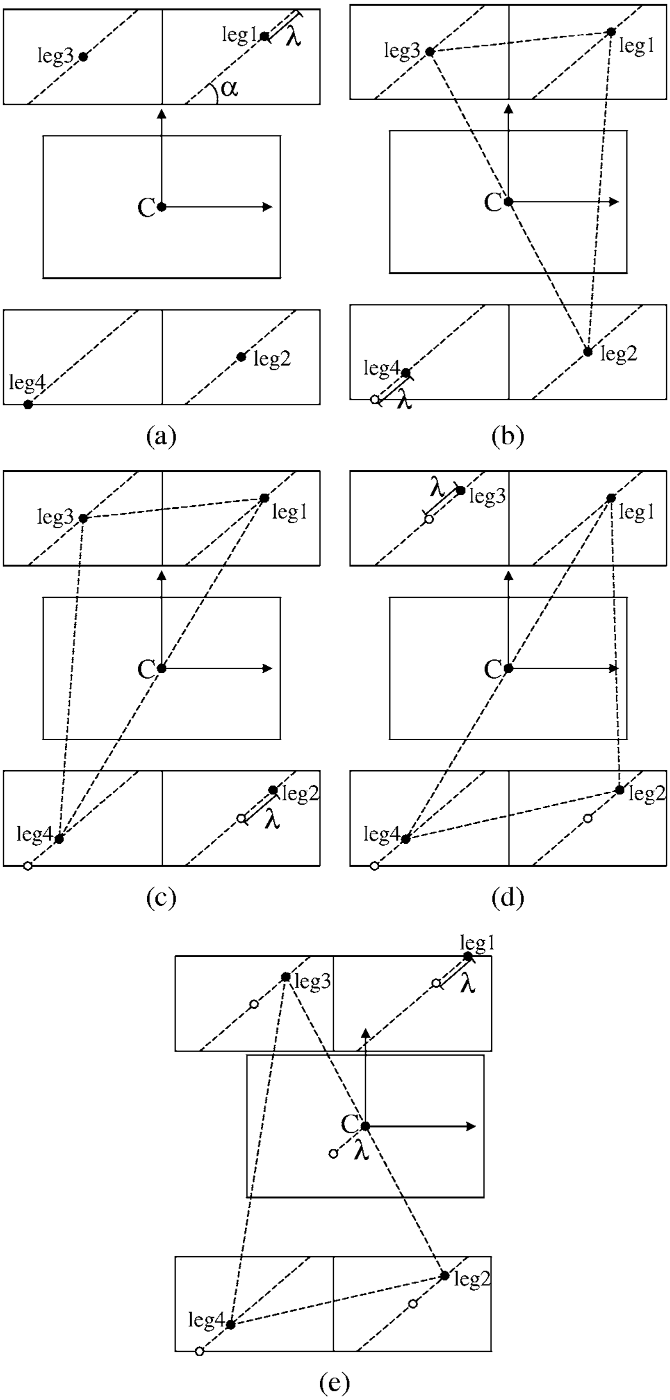

Figure 7. The periodic crab gait with a locked failure at leg 1 when $x_1 \geqslant 0$: (a) initial state, (b) swing leg 4, (c) swing leg 2, (d) swing leg 3 and (e) lift off leg 1 and move the body.

phase. Without loss of generality, all four legs are supposed to be in the support phase in the initial state as shown in Fig. 7a. Since the quadruped is prescribed to have $+x$ type gaits, the leg sequence can be $4 \rightarrow 2 \rightarrow 3 \rightarrow 1$ [10]. We select leg 4 as the first transfer leg and leg 1 the last. Legs 2 and 3 are on the center of each working area, and leg 4 is on the rear boundary of the foot trajectory in the initial state. The reason for placing leg 4 on the rear boundary is to give the maximum reachability to leg 4 for the next swing. λ is the distance between the foothold position of leg 1 and the front boundary of the foot trajectory in the working area. Figure 7b is the state where leg 4 is transferred forward. Note that leg 4 should have the stroke of length λ or be placed on the mirror point of leg 1 with respect to the center of gravity C. If the leg stroke is less than λ, leg 2 could not be lifted off in the next state because C would be out of the resulting support pattern. If, on the other hand, the leg stroke is greater than λ, leg 3 could not be lifted off for the same reason (note that the position of the center of gravity does not change until the lift-off of leg 1). From the periodicity, legs 2 and 3 also have the stroke of length λ in Fig. 7c and 7d. Finally, leg 1 is lifted off and the robot body moves along the trajectory by λ, completing a locomotion cycle. It is noted that the working areas of the initial position are drawn fixed in Fig. 7e for the convenience of illustration. In fact, the real locations of the areas change as the body moves. The fault tolerance is realized in the final state where the failed leg is lifted off and passively swung by the movement of the robot body. It can be observed that the derived leg sequence is optimally driven in the sense that the robot body has the maximum stride length and the marginal stability in a locomotion cycle.

4.2.2. $x_1 < 0$. Figure 8 shows the initial state and the final state of the periodic crab gait when $x_1 < 0$. White circles denote the initial foothold positions and black circles denote the final foothold positions. The leg sequence is the same as in Fig. 7, but the stride length is set to be $R_\alpha/2$, where R_α is the length of the foot trajectory in a working area with the crab angle α, calculated as:

$$R_\alpha = \begin{cases} \dfrac{R_y}{\sin\alpha} & \alpha_1 < \alpha \leqslant 90^\circ \\ \dfrac{R_x}{\cos\alpha} & 0 < \alpha \leqslant \alpha_1. \end{cases} \tag{12}$$

According to the stride length, the initial foothold position of leg 4 is $R_\alpha/2$ behind the mirror point of leg 1. If leg 4 would be placed on the rear boundary of the foot trajectory, as in the case of $x_1 \geqslant 0$, it could have the maximum stroke length greater than $R_\alpha/2$ in the first step, but one of legs 2 and 3 could not have the same stroke length. Because the initial positions of legs 2 and 3 should be the mirror points of each other, the most favorable case is where two legs are on the centers of their working areas in the initial state and swung on to the front boundaries of the foot trajectory, having the stroke length $R_\alpha/2$. The initial state shown in Fig. 8 realizes such an optimal leg sequence.

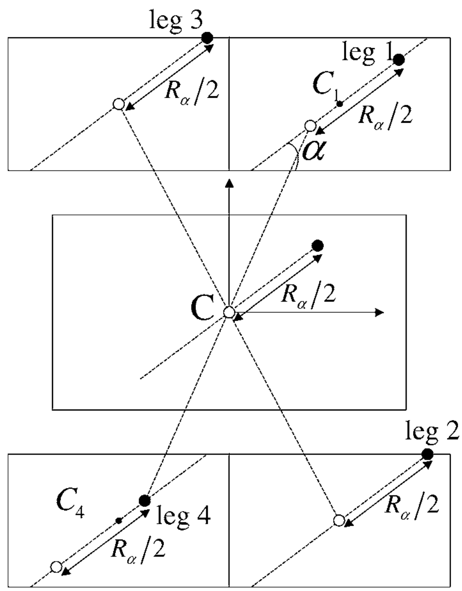

Figure 8. The initial state and the final state of the periodic crab gait when $x_1 < 0$.

The proposed periodic crab gaits in Figs 7 and 8 show how the kinematic limit of the failed leg can be reflected in fault tolerance in a quantitative way. From the results, it can be said that a locked joint failure which gives the foothold position further behind the front boundary of the foot trajectory is more advantageous in terms of gait mobility. In addition, in a case where there are two possible foothold positions for the failed leg, it would be more desirable to select a further position from the front boundary in order to acquire a longer stride length.

In most cases, a gait the quadruped has at the moment of a locked joint failure may not belong to any state of the proposed crab gait. In order to change the present gait into a state of the proposed periodic gait, some pre-adjustment of the leg position and the body movement is necessary. This issue will be discussed in the next section.

5. FAULT TOLERANCE IN THE WAVE-CRAB GAIT

5.1. Wave-crab gait

The adjustment procedure from a normal gait to the fault-tolerant gait is shown as an example to demonstrate the applicability of the proposed scheme. We assume that the quadruped has been moving with the wave-crab gait [8] with the duty factor $\beta = 5/6$ before a locked joint failure occurs in leg 1. The wave-crab gait is a standard periodic gait of crab walking and has analytic results similar to the forward crab gait [14]. Its behavior can be studied by the gait diagram and the stationary gait pattern. Figures 9 and 10 are the gait diagram and the stationary gait pattern of the

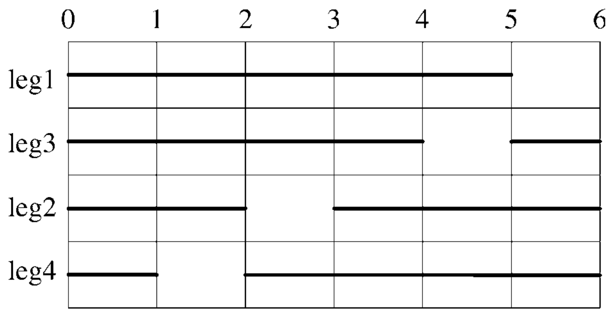

Figure 9. Gait diagram of the wave-crab gait with $\beta = 5/6$.

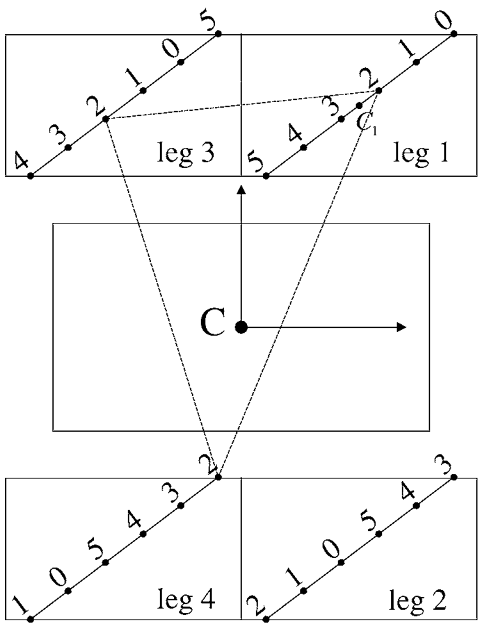

Figure 10. The stationary gait pattern.

wave-crab gait with $\beta = 5/6$, respectively. A darkened solid line in Fig. 9 represents the support phase of a leg and is cast on the leg stroke in the stationary gait pattern in Fig. 10. Each leg stroke is then divided into equal segments labeled according to the times of the corresponding argument in the gait diagram. The support pattern at any instant of time can be easily constructed by just connecting all the segments with the same label. For example, the support pattern immediately after leg 2 is lifted can be obtained by connecting all the segments with label 2 (see Fig. 9), except that of leg 2, since leg 2 has already been lifted. The support pattern is thus the dashed triangle in Fig. 10. We denote T as the cycle time and t_1 $(0 \leqslant t_1 < T)$ as the time by which the occurrence of a locked joint failure in leg 1 lags behind the contact of leg 1 on the ground.

5.2. Fault tolerance procedure

5.2.1. Failure in the support phase. If leg 1 fails in the support phase, t_1 is in the range of $0 \leqslant t_1 < 5T/6$. Assuming constant speed of the body movement, the foothold position of leg 1 at the moment of failure is $6R_\alpha t_1/5T$ behind the front boundary of the foot trajectory, where R_α is defined in (12). Also, it is in front of C_1 when $0 \leqslant t_1 < 5T/12$ and behind C_1 when $5T/12 \leqslant t_1 < 5T/6$ (see Fig. 10). Therefore, from the results of the previous section, the stride length λ of the fault-tolerant periodic gait acquired with t_1 is expressed as:

$$\lambda = \begin{cases} \dfrac{6R_\alpha t_1}{5T} & 0 \leqslant t_1 < 5T/12 \\ \dfrac{R_\alpha}{2} & 5T/12 \leqslant t_1 < 5T/6. \end{cases} \tag{13}$$

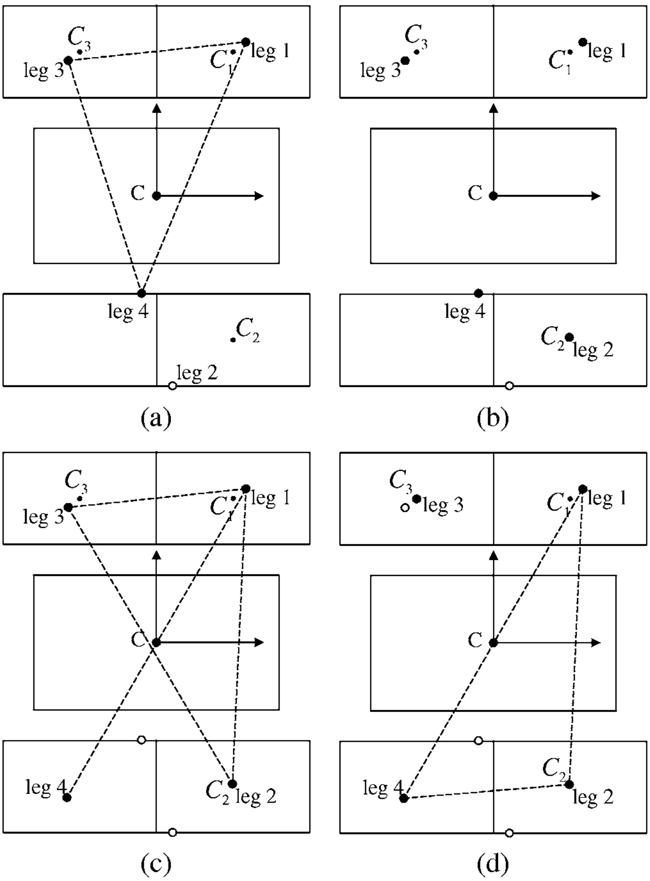

Figure 11. Adjustment procedure: (a) halt the body movement, (b) swing leg 2, (c) swing leg 4 and (d) swing leg 3.

At the instant of the failure, the current gait should be adjusted to a state of the fault-tolerant periodic gait which requires the minimum number of steps in the adjustment procedure. For example, assume that $t_1 = T/3$, i.e. a locked joint failure occurs in leg 1 immediately after leg 2 is lifted off. Figure 11 shows the adjustment procedure. As soon as the failure is detected, the quadruped halts the body movement in Fig. 11a. Leg 2, the transfer leg at the moment of failure, is swung and placed on the center of its working area C_2 in Fig. 11b. Leg 4 is swung and placed on the mirror point of leg 1 in Fig. 11c. Finally, leg 3 is swung and placed on C_3. The resulting gait is Fig. 11d, which is identical to the second state of the periodic crab gait in Fig. 7b. Note that the adjustment procedure in Fig. 11 is dead-lock free and the gait stability is guaranteed for all the states.

5.2.2. Failure in the transfer phase. If leg 1 fails in the transfer phase, t_1 is in the range of $5T/6 \leqslant t_1 < T$. According to the general scheme of fault tolerance, the quadruped should halt the body movement and place the failed leg. In this case, the exact foothold position of leg 1 cannot be resolved only by t_1, because it depends on the kind of locked joint and the dynamics of the leg in the transfer phase. However, if there are two possible candidates for the foothold positions, it would be more desirable to select one which is further behind the front boundary of the foot trajectory as proved in the previous section. The adjustment procedure from the current gait to the proposed periodic gait would be similar to the case of the support phase.

6. CONCLUSIONS

Fault-tolerant gaits have been proposed for a quadruped robot to have crab walking over even terrain. A kind of fault event, locked joint failure, was defined and the constrained motion of the failed leg with a locked joint failure was examined for the case of crab walking. The range of the locked angle is derived which guarantees the existence of the foothold position on the foot trajectory. A general strategy of fault tolerance for a locked joint failure was presented in which the quadruped has discontinuous movement of the body with respect to leg motion and the failed leg is swung passively by the translation of the body. As a special form of the proposed strategy, a periodic crab gait was proposed, and its leg sequence and the stride length were analytically formulated. By taking the proposed periodic gait, the quadruped avoids any deadlock caused by a locked joint failure and has the maximum stride length in a locomotion cycle. As an example to demonstrate the applicability of the proposed scheme, the adjustment procedure from the standard wave-crab gait to the proposed periodic gait was presented. It was shown that the transition steps from the current gait to a state of the proposed crab gait can be made maintaining the gait stability without any dead-lock.

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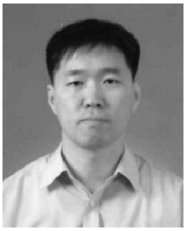

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