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Gait synthesis for hexapod robots with a locked joint failure

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SUMMARY
This paper presents a strategy for generating fault-tolerant gaits of hexapod walking robots. A multi-legged robot is considered to be fault-tolerant with respect to a given failure if it is capable of continuing its walking after the occurrence of a failure, maintaining its static stability. The failure concerned in this paper is a locked joint failure for which a joint in a leg cannot move and is locked in place. The kinematic condition for the existence of fault-tolerant gaits is derived for straight-line walking of a hexapod robot on even terrain. An algorithm for generating fault-tolerant gaits is described and, especially, periodic gaits are presented for forward walking of a hexapod robot with a locked joint failure. The leg sequence and the stride length formula are analytically driven based on gait study and robot kinematics. A case study on post-failure walking of a hexapod robot with the wave gait is shown to demonstrate the applicability of the proposed method.

KEYWORDS: Hexapod robots; Gait study; Locked joint failure; Fault-tolerant walking.

I. INTRODUCTION

Legged robots with static walking have inherent fault tolerance capability against a failure in a leg, since a failed leg for itself does not cause fatal breakdown nor instability to walking motions.[1,2] This means that for a given type of failure, the problem of finding fault-tolerant gaits can be formulated with which legged robots can continue their walking after the occurrence of a failure, maintaining static stability. Nevertheless, the research on fault diagnosis and tolerance has been given little attention in the field of gait study for the past few decades.

In the author's previous studies, a general fault detection scheme for legged robots was established in a logical setting,[3,4] and fault-tolerant gaits of quadruped robots were proposed for a locked joint failure,[5] in which a joint of a leg is locked in a known place. As one of common failures that can be frequently observed in dynamics of robot manipulators, the locked joint failure reduces the number of degrees of freedom of the robot manipulator by one and consequently its workspace to a certain limit.[6] To establish the fault-tolerance scheme, the reduction of the workspace of a failed leg should be interpreted and reflected based on gait study.

The objective of this paper is to develop the fault-tolerant gait algorithm for a locked joint failure when the model of legged robots is hexapod. Compared with the previous result on quadruped robots,[5] this paper has the following contributions: 1) Unlike quadruped robots which have only tripod gaits in static walking, hexapod robots can have tripod, quadruped and pentaped gaits. We show that fault tolerance can be realized for walking with any gait and, especially, periodic gaits can be generated for straight-line walking on even terrain. 2) The previous result did not take into account kinematic constraints of the failed leg in developing fault-tolerant gait planning. We verify that for the existence of fault-tolerant gaits, the configuration of the failed leg must be within a prescribed range of kinematic constraints.

This paper is organized as follows: In Section II, a hexapod prototype is described with conditions on walking mechanism. The configuration of the locked joint failure and the kinematic constraints for the existence of fault-tolerant gaits are provided in Section III. In Section IV, a general scheme for fault-tolerant gait planning is proposed for straight-line walking of a hexapod robot over even terrain. In particular, periodic gaits are derived from the proposed scheme with formulations of the stride length and stability margin. In Section V, a post-failure walking example is addressed in which a hexapod robot walking with the wave gait before a failure could realize fault tolerance by the proposed scheme. Finally, some concluding remarks are given in Section VI.

II. HEXAPOD PROTOTYPE

This paper studies a general hexapod model shown in Figure 1. C is the center of gravity of the robot and the origin of the robot body's coordinate system X-Y, and six legs are attached to the body 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. Though the legs's reachable working areas can be any shape so long as they can be approximated to straight sided polygons, the conventional rectangular layout[7] is used in this paper for convenience. 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, that is, the working area of a leg is adjacent with those of neighboring ipsilateral legs, as shown in the figure. W is the distance between the working area and the robot body. Some specific

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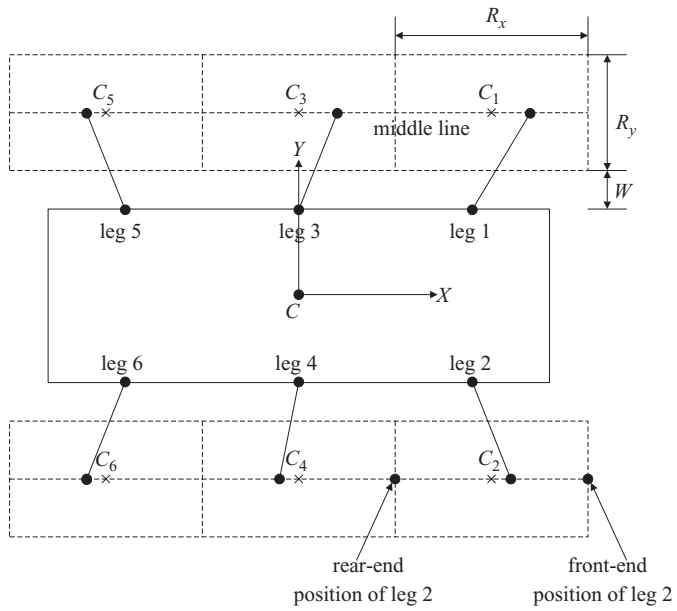


Fig. 1. Hexapod representation for gait synthesis.

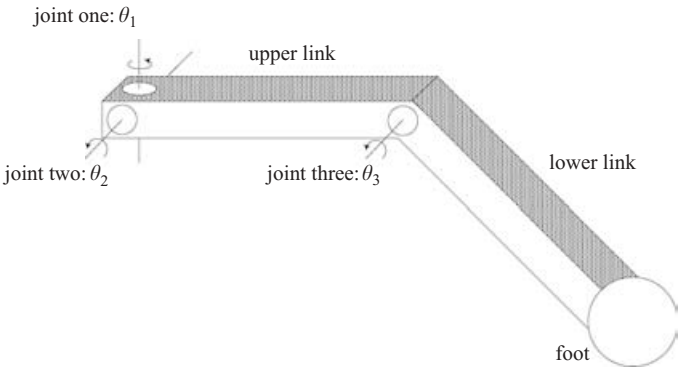


Fig. 2. Three-joint leg model.

foothold positions on a working area are designated: C_i, the center of the working area of leg i, the front-end position and the rear-end position.

As a leg model attached to the hexapod prototype, we use the articulated manipulator model[8] of which a perspective view is shown in Figure 2. This leg model 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 three degrees of freedom with respect to the body and the overall walking can be driven in any direction. Since other legs models with different mechanisms[9,10] have also three degrees of freedom, the leg model used in this paper can be said to be general. We designate 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.

To limit the scope of the study reported here, it is assumed that the robot body remains parallel to the ground, and that the ground is flat over the region affecting the robot workspace. The dimension of the working area of each leg is thus kept the same throughout walking. Moreover, it is assumed that the hexapod robot has static walking in which dynamic effects of legs and the body are negligible. All the mass of the legs is supposed to be lumped into the body and the orientation of the support surface with respect to the gravity vector is irrelevant. Because walking on uneven terrain is precluded in the study, we properly suppose that the hexapod robot has straight-line walking with a regular gait, that is, each leg tracks on the middle line of its working area (see Figure 1), paralleled with the trajectory of the center of gravity.

III. FAILURE CONFIGURATION

A locked joint failure is a failure mode in which a joint of a leg is locked in a known position. The immobilization of a joint 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 an implemented failure detection software.[11] A single joint failure reduces the number of degrees of freedom 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 motions of the leg. While the previous study[5] investigated constrained motions of a failed leg in detail, it did not take into account kinematic constraints necessary for the existence of fault-tolerant gaits. In this section, we show that there is a range of kinematic constraints which the configuration of a failed leg should satisfy for guaranteeing the existence of fault-tolerant gaits.

III.1. Failure of joint one

In the first, let us 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 as shown in Figure 3(a), 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 shown in Figure 3(b). The failed leg can place its foot on the one and only foothold position, denoted by P, the intersection point of the foot trajectory (middle line of the working area) and the reachable line. For such an intersection point to exist, locked angle $\hat{\theta}_1$ must be in the range of

$$\hat{\theta}_{1,\min} \le \hat{\theta}_1 \le \hat{\theta}_{1,\max}$$

as shown in Figure 3(b), 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

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

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

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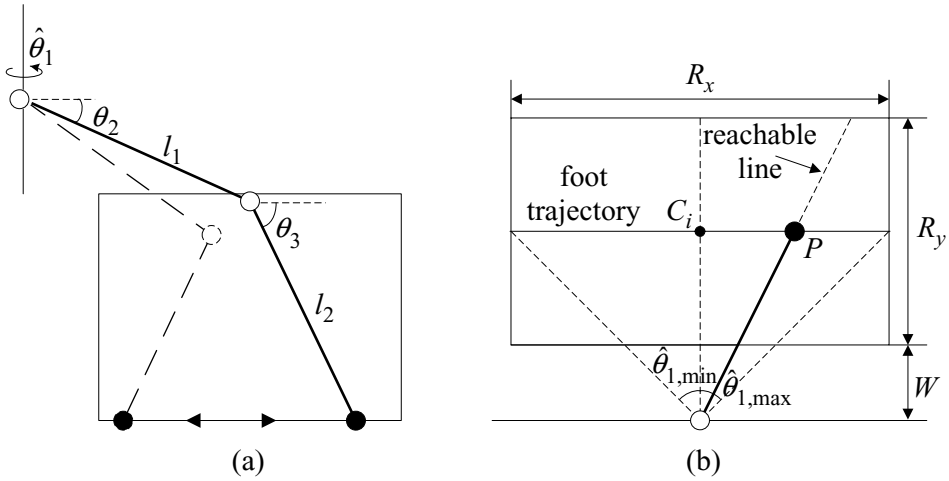


Fig. 3. Locked failure at joint one in straight-line walking: (a) lateral view and (b) kinematic constraint.

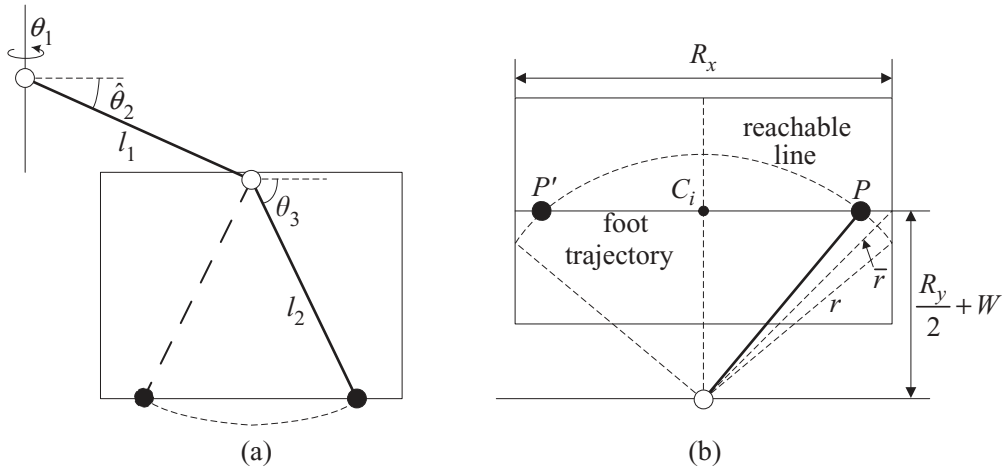


Fig. 4. Locked failure at joint two in straight-line walking: (a) lateral view and (b) kinematic constraint.

III.2. Failure of joint two

When joint two is locked from failure, the failed leg can move only the lower link by joint three for vertical swing. Depending on the configuration at the moment of failure, the failed leg can be placed on the inner foothold position or the outer position as shown in Figure 4(a). The resulting reachable region on the working area is thus projected onto a line of arc shape shown in Figure 4(b). Unlike the case of joint one where there is only one foothold position, the failed leg in this case can place its foot on one of two possible foothold positions, P and P', in the foot trajectory. The kinematic constraint for guaranteeing such foothold positions can be described as

$$\frac{R_y}{2} + W \le r \le \bar{r} \tag{1}$$

where r is the radius of the arc and $\bar{r}$ is the distance between the leg attachment point and the front-end(or rear-end) position 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 (1) in terms of joint angles and robot parameters, let us rewrite $\bar{r}$ and r as

$$\bar{r} = \frac{1}{2}\sqrt{R_x^2 + (R_y + 2W)^2} \tag{2}$$

$$r = l_1 \cos\hat{\theta}_2 + l_2 \cos\theta_3 \tag{3}$$

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 be fixed in failure mode (see Figure 4(a)). Substituting (2) and (3) into (1) leads to

$$\frac{R_y}{2} + W \le l_1 \cos\hat{\theta}_2 + l_2 \cos\theta_3 \le \frac{1}{2}\sqrt{R_x^2 + (R_y + 2W)^2}.$$

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.

Consider the case of a locked failure at joint three as a remark. The constrained motion of the failed leg is almost identical to the case of joint two. If joint three is locked from

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failure, the leg is reduced to an one-link manipulator with two revolute joints,[8] and the restricted reachable region projected onto the working area is of arc shape too. Therefore, the kinematic constraint for the existence of the fault-tolerant gait is the same as the case of joint two:

$$\frac{R_y}{2} + W \leq l_1 \cos\theta_2 + l_2 \cos\hat{\theta}_3 \leq \frac{1}{2}\sqrt{R_x^2 + (R_y + 2W)^2}$$

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

IV. FAULT-TOLERANT GAIT PLANNING

IV.1. Review of general scheme

In the previous research, we have described constrained motions of a leg when a locked joint failure occurs to each of the three joints, respectively, and proposed the following principles of fault-tolerant gait planning:

Principles of Fault-Tolerant Gait Planning for a Locked Joint Failure[5]

a) When the failed leg is in the support phase, the robot body does not translate because the failed leg cannot maintain the current foothold position.
b) When the failed leg is in the transfer phase, it does not have active swing with respect to the body motion and is moved only passively by the translation of the body.

Let us examine the meaning of the above principles. When the robot body translates in legged locomotion, the configurations of all the supporting legs should be simultaneously changed to maintain the current foothold positions. If a locked failure occurs to a joint of a leg, however, 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, the robot body should not translate when the failed leg is in the support phase (Principle a). Furthermore, the forward movement of a leg with respect to the robot body is inexecutable with a locked joint. For instance, if joint one of a leg is locked from failure, the failed leg cannot take active swing with respect to the robot body (see Figure 3). On the other hand, if joint two or three is locked from failure, the accessible area where the failed leg could place its foot is reduced to only a partial region of the working area (see Figure 4), which forbids normal straight-line walking with continuous leg swing. Therefore, it is prescribed that the failed leg is moved only passively by the translation of the body (Principle b).

IV.2. Periodic gait planning

In terms of mobility, it would be more advantageous that the robot walking with a periodic gait before a failure could preserve its periodicity (with a different gait pattern) even after a fault event. Based on the principles of fault-tolerant gait planning, we propose fault-tolerant periodic gaits for hexapod robots. Among the periodic gaits hexapod robots can have in static walking, quadruped gaits and tripod gaits are proposed in this section. The generation procedure of pentaped gaits, in which five legs are always in the support phase during walking, are similar to the other cases and omitted.

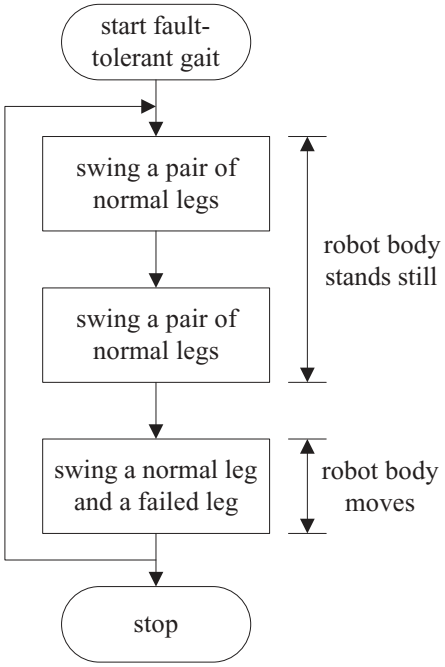


Fig. 5. Algorithm of the fault-tolerant qaudruped gait.

IV.2.1. Quadruped gait. In quadruped gaits, two legs are always in the transfer phase. Figure 5 shows the algorithm of the fault-tolerant quadruped gait. Since a pair of legs is simultaneously lifted off and placed, the quadruped gait resulting from the algorithm belongs to a singular gait. Provided that there is no timing gap between movements of two pairs of legs, the number of supporting legs always remains four. There are three movements of a pair of legs during the cycle time and the robot body advances only after a failed leg is lifted off. According to the principles of fault-tolerant gait planning, the final pair of leg in the transfer phase, including a failed leg, do not take active swing while the robot body moves.

Let us determine the leg sequence and the stride length formula based on the algorithm in Figure 5. The leg sequence with which a quadruped gait can have the maximum longitudinal stability margin[13] in straight-line walking is known to be (2,5)-(3,4)-(1,6) when the hexapod robot has the prototype shown in Figure 1.[14] In other words, lifting two legs in the symmetric positions with respect to the center of gravity guarantees the maximum stability to the resulting support pattern. The leg stroke, the distance through which the foot is translated relative to the body during the support phase,[13] should be equal to the stride length if the gait is periodical. Therefore, if the stride length of the robot body is chosen, the leg stroke is determined equally.

Figure 6 illustrates the proposed quadruped gait with stride length λ for a locked joint failure at leg 1. Quadruped gaits for a failure at other legs can be derived by symmetry of the hexapod. Black circles denote foothold positions of supporting legs and white circles denote the previous locations of foothold positions. Dash-dotted rectangles are support patterns obtained from lifting two legs. Without loss of generality, the periodic gait sequence is supposed to start with all the six legs set to be in the support phase on the

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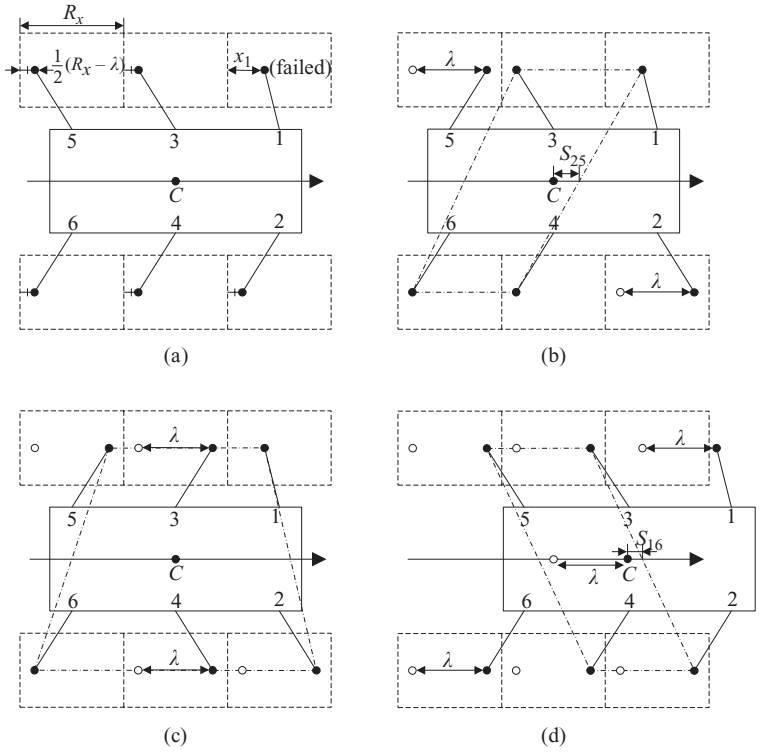


Fig. 6. The periodic quadruped gait for a locked failure at leg 1: (a) initial state, (b) swing leg 2 and leg 5, (c)swing leg 3 and leg 4, and (d) swing leg 1 and leg 6 with the body movement.

foothold positions in Figure 6(a), where normal legs are placed $(R_x - \lambda)/2$ in front of their rear-end positions and the failed leg lands on a point with distance $x_1 (0 \le x_1 \le R_x)$ from its rear-end position. Leg 2 and leg 5 are lifted off in the first and moved as much as λ in the $+X$ direction (Figure 6(b)). Next, leg 3 and leg 4 are lifted off and moved the same distance (Figure 6(c)). Because leg 1 is in the support phase, the robot body should not move in these states. The fault tolerance is realized in Figure 6(d) where leg 1 is lifted off with leg 6 and is transferred forward by the movement of the robot body. It is noted that working areas of the initial state are drawn fixed in Figure 6(d) for the convenience of illustration. In fact, the real locations of the areas change as the body moves. By closing the behavior in Figure 6(d), one period of the leg sequence is accomplished. The longitudinal stability margin of this gait sequence is determined by the shortest of S_{25} and S_{16}, which are the longitudinal stability margins of the states obtained from lifting (leg 2, leg 5) and (leg 1, leg 6), respectively (see Figure 6(b) and (d)). S_{25} and S_{16} are calculated as

$$S_{25} = \frac{1}{4}(2x_1 + R_x - \lambda)$$

$$S_{16} = \frac{1}{2}(R_x - \lambda).$$

Therefore, longitudinal stability margin $S(\lambda)$ of the quadruped gait with stride length λ is derived as

$$S(\lambda) = \min\left[\frac{1}{4}(2x_1 + R_x - \lambda), \frac{1}{2}(R_x - \lambda)\right].$$

Restating the above equation according to the range of x_1 leads to

$$S(\lambda) = \begin{cases} (2x_1 + R_x - \lambda)/4, & x_1 < (R_x - \lambda)/2 \\ (R_x - \lambda)/2, & x_1 \ge (R_x - \lambda)/2. \end{cases} \quad (4)$$

This result implies that the stability of the fault-tolerant quadruped gait increases as the foothold position of the failed leg is more distant from the rear-end position in its working area. Because the failed leg cannot have active swing, the longest stroke which can be obtained in fault-tolerant periodic gaits is equal to R_x, the length of the working area.[5] Thus the range of the stride length should be $0 < \lambda \le R_x$. If λ is equal to R_x, $S(\lambda)$ becomes zero from (4). This complies with a corollary in gait study that a periodic gait with its maximum stride length has the marginal stability margin.

IV.2.2. Tripod gait. The tripod gait has been adopted as the standard gait for hexapod robots[15] and is regarded as the fastest gait with the minimum stability.[16] Figure 7 shows the tripod gait with stride length λ for a locked joint failure at leg 1. Like the quadruped gait, all the legs are supposed to be in the support phase with the foothold positions given in Figure 7(a). The leg sequence is (2, 3, 6)-(1, 4, 5), the same as that of the standard tripod gait on even terrain,[17] but, from the principles of fault-tolerant gait planning, the robot body has discontinuous movement.

The stability margin of the tripod gait is determined only by the stride length, regardless of the foothold position of the failed leg. This is because when the failed leg (leg 1)

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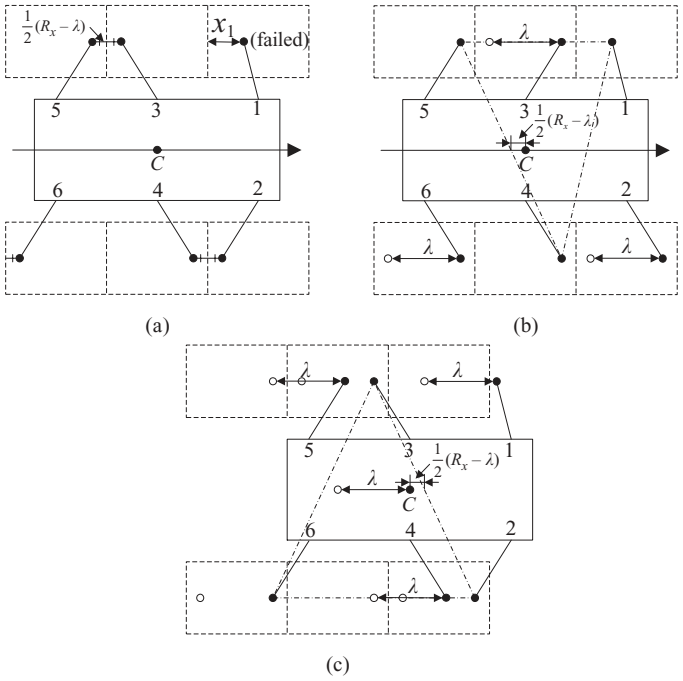


Fig. 7. The periodic tripod gait for a locked failure at leg 1: (a) initial state, (b) swing legs 2, 3 and 6, and (c) swing legs 1, 4 and 5 with the body movement.

is in the support phase, the boundary of the support pattern made of the two normal legs (leg 4 and leg 5) has always the shortest distance from the vertical projection of the center of gravity (Figure 7(b)). Referring to Figure 7(b) and (c), the longitudinal stability margin is derived as

$$S(\lambda) = \frac{1}{2}(R_x - \lambda).$$

In most cases, a gait of the hexapod robot at the moment of a locked failure may not belong to any state of the proposed periodic gaits. To change the present gait into a state of the proposed periodic gaits, some pre-adjustment of the leg position and the body movement are necessary. This issue will be discussed as a case study in the next section.

V. POST-FAILURE WALKING FOR WAVE GAIT

V.1. Normal walking: wave gait

In this section, the proposed gait planning is applied to a post-failure walking problem of a hexapod robot. We assume that the hexapod robot has been moving with the wave gait with duty factor $\beta = 2/3$ before a locked joint failure occurs to leg 1. The wave gait is a standard periodic gait of straight-line walking and mostly well known in the area of level-going.[16] Its behavior can be analyzed using the gait diagram and the stationary gait pattern. Figures 8 and 9 are the gait diagram and the stationary gait pattern of the wave gait with $\beta = 2/3$, respectively. A darkened solid line in Figure 8 represents the support phase of a leg and is cast on the leg stroke in the stationary gait pattern in Figure 9. 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

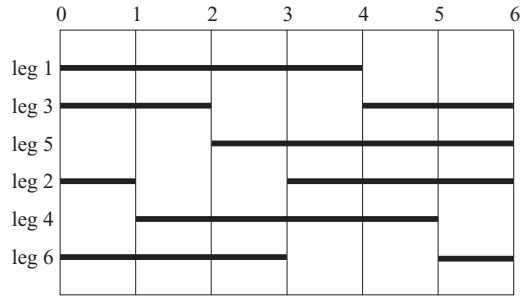


Fig. 8. Gait diagram of the wave gait with $\beta = 2/3$.

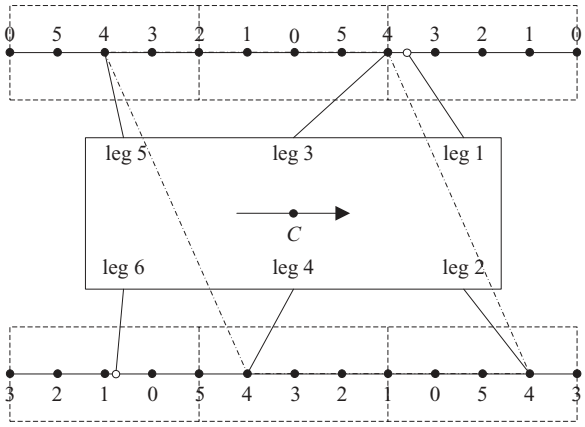


Fig. 9. The stationary gait pattern.

connecting all the segments with the same label. For example, the support pattern immediately after leg 1 is lifted off can be obtained by connecting all the segments with label 4, except that of leg 2, since leg 2 has already been lifted. The support pattern is thus the dash-dotted rectangle in Figure 9.

V.2. Post-failure walking

We investigate the adjustment procedure for the two cases, where the failed leg is in the support phase and the transfer phase at the moment of a locked joint failure, respectively. Let us denote T as the cycle time and $t_f (0 \le t_f < T)$ 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. Since the wave gait with $\beta = 2/3$ is a type of quadruped gaits, we demand that post-failure walking should also be a quadruped gait. For the simplicity of analysis, it is assumed that the fault-tolerant gait in post-failure walking has the maximum stride length. Note that when $\lambda = R_x$, all the normal legs in the fault-tolerant quadruped gait are lifted off at the rear-end positions and placed on the front-end positions in one period (refer to Figure 6).

V.2.1. Failure in the support phase. If leg 1 fails in the support phase, t_f is in the range of $0 \le t_f \le 2T/3$. As two legs are always in the transfer phase, the gait transition procedure is made by the following steps:

(i) The robot body halts the movement at the instance of failure.
(ii) If leg 6 is in the transfer phase, it is placed on the rear-end position of its working area. Other legs in the transfer phase is placed on their front-end positions.

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(iii) Find a state of the fault-tolerant quadruped gait to which the present state can be transformed with the minimum number of the change of the foothold positions, and complete the gait transition.

Recall that leg 1, the failed leg, is moved passively with leg 6 in the final state of the fault-tolerant quadruped gait in Figure 6. Thus if leg 6 is in the transfer phase, it should be placed on the rear-end position for the lift-off with leg 1. Other normal legs in the transfer phase should be placed on their front-end positions for minimizing required adjustments of the foothold position before starting fault-tolerant walking.

As a specific example of applying the above transition steps, let us assume that leg 1 fails in the range of $T/6 < t_f < T/3$. Figure 10 shows the gait transition procedure for this case. Leg 2 and leg 5, the two transferring legs at the moment of failure, are placed on their front-end positions in the first, followed by the swing of leg 3 and leg 4. The resulting state in Figure 10(b) is tantamount to the state where the failed leg is about to be lifted in the fault-tolerant periodic gait, i.e., Figure 6(c). By lifting leg 1 and leg 6 and moving the robot body after the state of Figure 6(b), the fault-tolerant quadruped gait can be initiated.

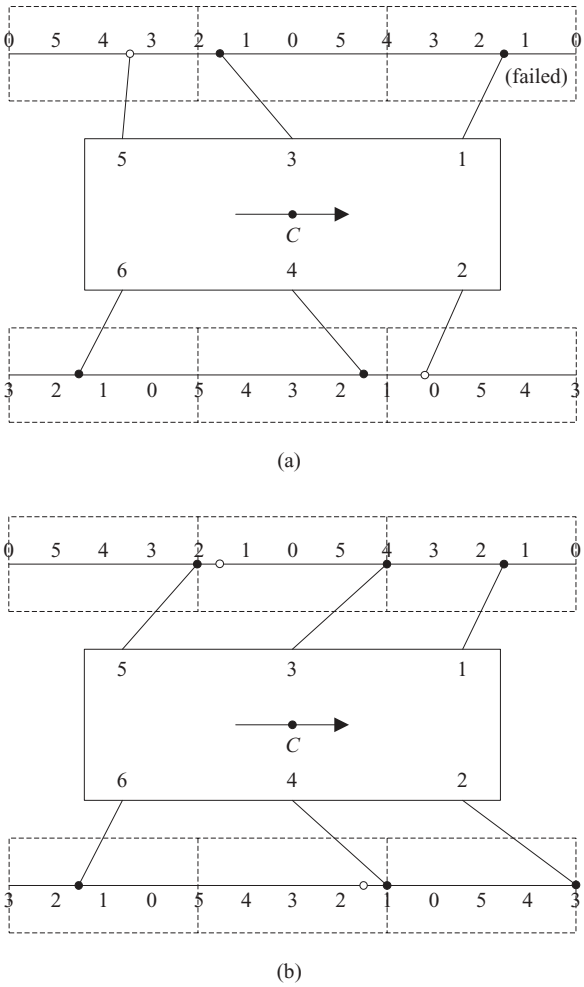


Fig. 10. Gait transition procedure when $T/6 < t_f < T/3$: (a) the state at the instance of failure, (b) place leg 2 and leg 5 and swing leg 3 and leg 4.

V.2.2. Failure in the transfer phase. If leg 1 fails in the transfer phase, t_f is in the range of $2T/3 \leq t_f < T$. In a similar manner to the case of the support phase, the robot body halts its movement at the moment of failure and two legs in the transfer phase find competent foothold positions. For example, the gait transition procedure when t_f is in the range of $2T/3 < t_f < 5T/6$ is illustrated by Figure 11. Since leg 1 and leg 6 are in the transfer phase, the initial state is

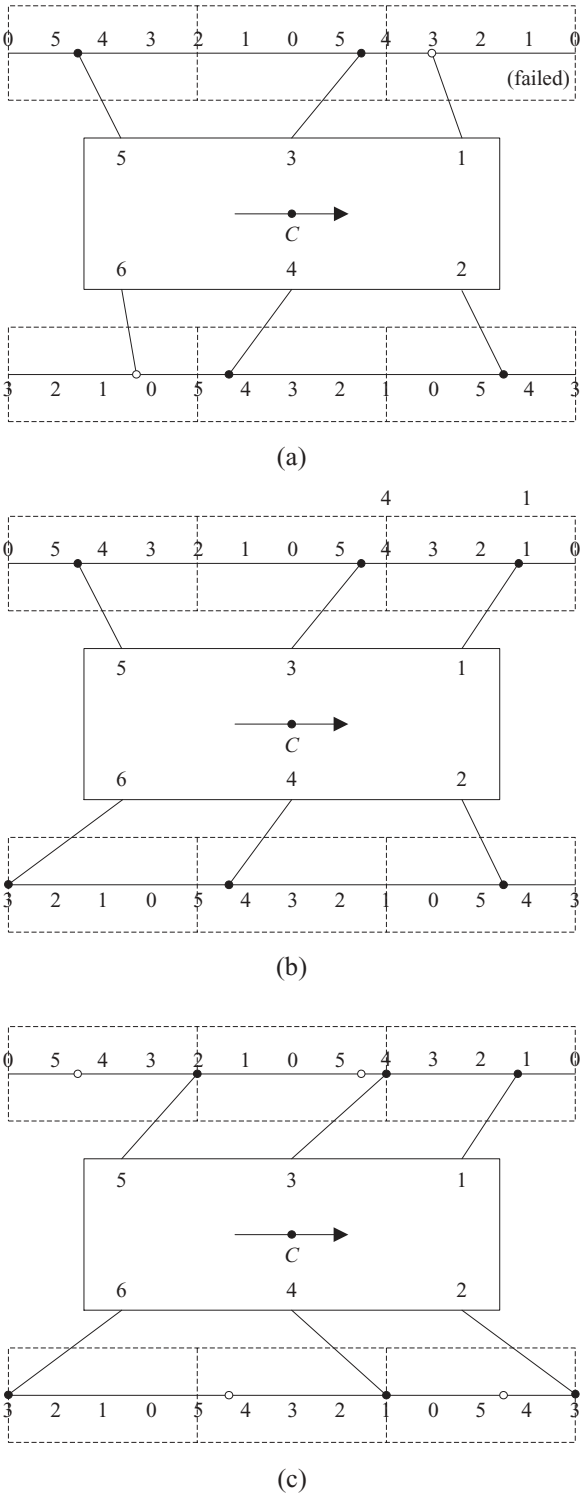


Fig. 11. Gait transition procedure when $2T/3 < t_f < 5T/6$: (a) the state at the instance of failure, (b) place leg 1 and leg 6, and (c) swing (leg 2, leg 5) and (leg 3, leg 4).

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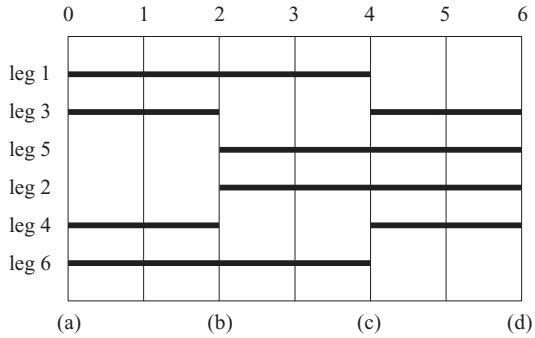


Fig. 12. Gait diagram of the wave gait with $\beta = 2/3$.

like Figure 11(a). Figure 11(b) shows the placement of the transferring legs. Leg 1, the failed leg, should be placed on a restricted position and leg 6 is placed on its rear-end position to be lifted off with leg 1 after the transition procedure. The foothold positions of the remaining normal legs are adjusted in Figure 11(c) and the hexapod is ready to start the fault-tolerant periodic gait. Note that both the transition procedures in Figures 10 and 11 are dead-lock free and guaranteed for any value of λ. They are also efficiently made in that the number of the change of the foothold positions is minimized.

V.3. Comparison of gait performance

Let us examine the change of gait performance caused by the transition to the fault-tolerant gait. Figure 12 is the gait diagram of the proposed fault-tolerant quadruped gait in Figure 6. For a clear comparison, we assume that there is no resting stage between the placement of a pair of legs and the lift-off of another pair in the quadruped gait. From the gait diagram, the duty factor is obtained as 2/3, the same as that of the wave gait. But the stride length of the fault-tolerant quadruped gait is R_x, less than $3R_x/2$ of the wave gait with $\beta = 2/3$.[16] Therefore, it can be said that the proposed fault-tolerant gait has no loss of the duty factor against a locked joint failure and its performance is degenerated only in the stride length, which is an inevitable adverse effect of the locked joint failure.

VI. CONCLUSIONS

In this paper, gait planning for static walking of hexapod robots has been considered from a different point of view. The notion of a locked joint failure is introduced and its effect on robot walking is analyzed based on manipulator kinematics and gait study. A locked joint failures does not reduce stability of a gait but constrain the workspace of the failed leg to a restricted area. We have shown that there is a range of kinematic constraint on the configuration of the failed leg which guarantees the existence of post-failure walking on the straight-line trajectory. A strategy of fault tolerance for a locked joint failure has been proposed for the hexapod robot, in which the hexapod has discontinuous movement of the body with respect to leg swing and the failed leg is swung passively by the translation of the body. As a special form of the proposed strategy, periodic quadruped and tripod gaits have been proposed and their behavior and efficiency have been investigated. By taking the proposed periodic gait, the hexapod can overcome any fault event caused by a locked joint failure and maintain static stability. The transition procedure from the standard wave gait to the proposed periodic gait has been shown as an example to demonstrate the applicability of the proposed scheme.

As a further research, fault-tolerant gait planning for other regular gaits on even terrain such as crab gaits, turning gaits, etc, and irregular gaits on uneven terrain will be proceeded.

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