Realizing Positive Gait Stability of a Quadruped Robot Walking on Sloping Surface

Jung–Min Yang
Sch. Electronics Engr.
Kyungpook National Univ.
Daegu, Korea
jmyang@ee.knu.ac.kr

Seong Woo Kwak
Dept. Electronic Engr.
Keimyung Univ.
Daegu, Korea
ksw@kmu.ac.kr

P. M. Pathak M. M. Gor
Robotics & Control Lab
IIT, Roorkee
Uttarakhand, India
pushpfme@iitr.ernet.in

A. K. Samantaray
Dept. Mechanical Engr.
IIT, Kharagpur
West Bengal, India
samantaray@lycos.com

***Abstract*—A fault-tolerant gait planning of a quadruped robot is presented. The considered robot has static walking and suffers from a locked joint failure. Especially, the quadruped robot is equipped with the moving appendage onto the body. By controlling the moving appendage, the robot can adjust the effective position of the center of gravity. Incorporating the adjustment of the moving appendage along the leg and body sequence, the fault-tolerant gait can have positive stability margin. Based on gait study, we address theoretical analyses on the proposed fault-tolerant gait planning for the quadruped robot to walk over a slope. We also conduct 3D simulation studies on a synthetic quadruped robot to show the applicability of the proposed scheme.**

Keywords—fault-tolerant gaits; quadruped robots; moving appendage; uneven terrain

I. INTRODUCTION

Fault tolerance in engineering systems is referred to as the capability that enables a system to continue its intended operation, possibly at a reduced level, rather than failing completely, when some part of the system fails [6]. Legged robots with static walking must also have fault tolerance against various kinematic and dynamic faults, as they often work in remote or hazardous environments where repair by human is nearly impossible [5],[8]. *Fault-tolerant gaits* [15] are referred to as gait patterns that make the robots continue their walking after the occurrence of a leg failure, possibly with degraded performance. Fault-tolerant gaits utilize the inherent redundancy in the number of legs: even though a leg fails during locomotion, the whole system of the legged robot does not fall into total breakdown as long as the rest legs work normally.

In the past, fault tolerant gaits are developed mainly to overcome a leg kinematic fault termed *locked joint failures* [4]. The locked joint failure causes a leg joint to be locked in a known place. The degree of freedom of the failed leg thus decreases by one, constraining the robot motion. The authors proposed fault-tolerant gaits against locked joint failures for dealing with walking of hexapod robots over even terrain [15]. The result has been expanded to quadruped robots with straight line motion [11] and crab walking [12], hexapod robots with crab and turning gaits [13], and quadruped robots with discontinuous gaits [14]. For other related studies on locked joint failures in gait study, the readers are referred to [2],[1],[9].

In this paper, we present a novel fault-tolerant gait planning for a quadruped robot subject to locked joint failures. In particular, the considered robot is equipped with the moving appendage. A moving appendage is a mechanical apparatus attached onto the robot body that moves according to posture control by the accompanying actuator [7]. The purpose of using the moving appendage is to adjust the equivalent position of the center of gravity (cg) of the robot body whenever necessary. By incorporating the control of the moving appendage, we can overcome the drawback of the former fault-tolerant gait that it has the marginal stability margin when the robot has tripod, i.e., when one leg is in the transfer phase while the rest three legs support the robot body [11],[12]. Notice that a similar study is addressed in the authors' previous work [16]. The present study extends the result of [16] by applying the adjustment of the moving appendage to uneven terrain.

This paper is organized as follows. In Section 2, we present a model of the considered quadruped robot. Dynamic model of the attached moving appendage is also addressed. In Section 3, we review basic features of fault-tolerant gaits for quadruped robots in the case that the robots walk over perfectly even terrain. In Section 4, a novel fault-tolerant gait planning is proposed. We focus our concern on two main considerations as follows:

i) First, we present a control scheme of the moving appendage. In the leg sequence of the fault-tolerant gait, the position of the moving appendage is adjusted so that the robot can have positive static stability margin.
ii) Secondly, the robot is supposed to walk over a slope, i.e., even terrain that is at an angle. The effective cg of the robot on a slope will be displaced by gravity. The latter restraint must be reflected on the adjustment of the moving appendage in the gait planning.

We also present a simulation study in Section 4 to demonstrate the applicability of the proposed scheme. Finally, Section 5 concludes this paper.

II. MODEL OF A QUADRUPED ROBOT

A. Robot Kinematics

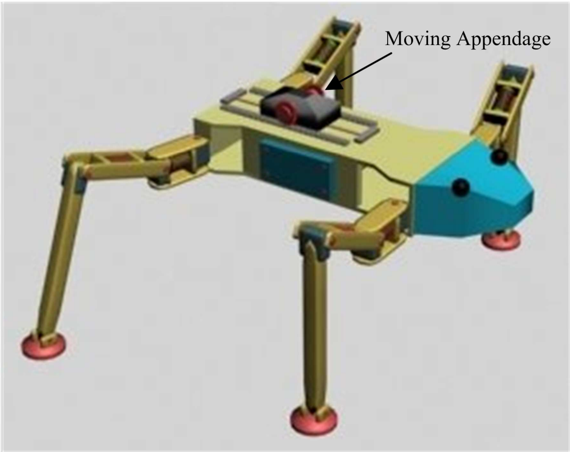

Fig. 1. Quadruped robot with the moving appendage.

Fig. 1 illustrates a 3D image of the quadruped robot under consideration. Drawing from the major premises of gait study [10], we characterize the motion feature of the quadruped robot as follows.

1) The robot is assumed to walk over a slope with even ground and thus have a periodic gait to generate the maximum speed.
2) The robot body is kept parallel with the slope throughout walking. The projection of cg on the ground will be determined by the slope angle.
3) Mass of each leg is negligible compared with the robot body and the moving appendage, and the foot projection onto the ground is regarded as a point.

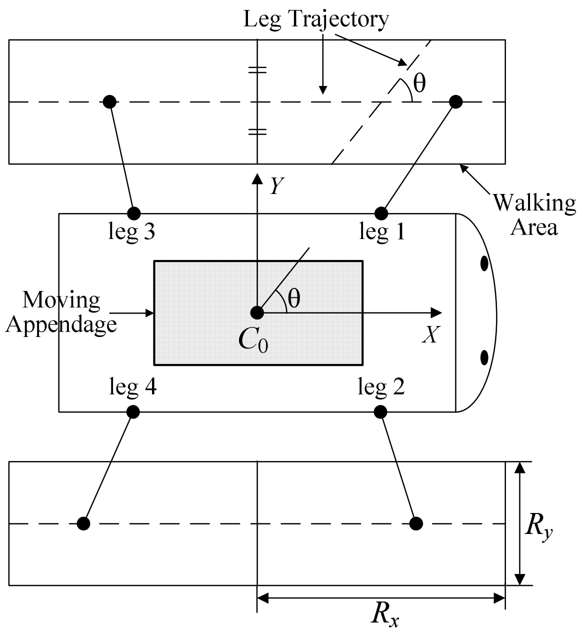

Fig. 2. Two dimensional projection of the quadruped robot with relevant parameters.

Fig. 2 is the two-dimensional projection of the quadruped robot of Fig. 1 on the ground. C_0 denotes the position of cg of the robot body, to which the body coordinate system *X-Y-Z* is attached. Each leg has a rectangular working area with length R_x and width R_y where the foot of the leg can be placed. Though the reachability of the foot position on the ground is larger, we reduce the working area to prevent the interference between two adjacent legs [15]. The robot walks along a straight-line that serves as the trajectory of the body cg. If the direction of the trajectory is the same as the longitudinal axis of the body, or the *X*-axis in Fig. 2, the robot is said to have a straight-line motion. Otherwise, it has crab walking with the crab angle θ. In this study, we assume θ=0 throughout walking.

B. Dynamics of the Moving Appendage

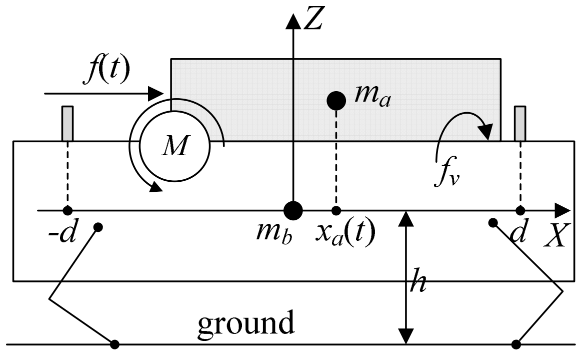

Fig. 3. Dynamic model of the moving appendage.

The moving appendage is referred to as a payload that, attached to the robot body, is controlled by an actuator to adjust the effective position of the body cg. In our study, we use a moving appendage having one degree of freedom along the *X*-axis of the robot body. Fig. 3 shows a schematic diagram of the moving appendage employed in this paper. m_a and m_b are the mass of the moving appendage and the robot body, respectively, and f_v is the coefficient of viscous friction that exists between the surfaces of the moving appendage and the robot body. Initially, the moving appendage stays at the origin of *X*-axis. According to the designed fault-tolerant gait planning, the actuator *M* displaces the appendage along the *X*-axis. $x_a(t)$ is the displacement of the moving appendage at time *t*. The displacement range of m_a is bounded by a limit value $\pm d$ ($d>0$). $f(t)$ denotes the force component in the *X*-axis direction generated by *M*, and *h* is the height of cg of the robot body measured from the ground.

When the quadruped robot walks over a slope as well as the moving appendage is adjusted by a control scheme, the position of the effective cg of the robot changes accordingly. Assume first that the robot walks over perfectly even terrain. If the moving appendage stays at its initial position $x_a(t)=0$, C_0, the coordinate of the body cg, would be unchanged. On the other hand, if we displace the position of the moving appendage toward ±*X*-direction, the effective position of cg would be changed by the distribution of m_a and m_b. Denote by $c(t)$ the position of cg in the X-coordinate made of m_a and m_b at time t. By simple mathematics, $c(t)$ is written as

$$c(t) = m_a x_a(t)/(m_a+m_b)$$

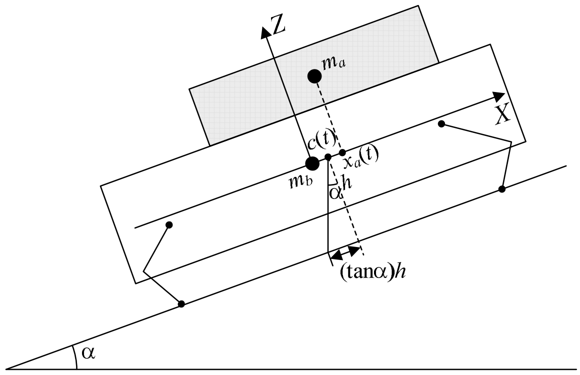

Fig. 4. Position of the effective cg on a slope.

Assume now that the quadruped robot climbs over a slope with the angle α (0<α<90°). Referring to Fig. 4, we know that the effective position of the body cg is adjusted to $c(t)$ by moving average of m_a and m_b, where m_a has the coordinate $x_a(t)$ in the X-axis. Further, as the robot is walking over the slope, the projection of $c(t)$ on the ground will lag behind the original position by the angle α. A slight examination leads to that the real position of the body cg is (tanα)h behind the original position, where h is the height of cg. Measured along the X-axis projected on the slant ground, the body cg has new coordinate $c_\alpha(t)$ such that

$$c_\alpha(t) = m_a x_a(t)/(m_a+m_b) - (\tan\alpha)h \qquad (1)$$

The slope angle causes additional restraint on the fault-tolerant gaits. As will be shown later, the fault-tolerant gait for locked joint failure has the drawback that it has marginal stability margin when walking on even terrain, i.e., the cg is placed on the boundary of the support pattern. If no adjustment scheme is applied to the robot body (or the moving appendage), the projection of cg would be outside the support pattern in walking over a slope due to the offset value –(tanα)h. Hence, the robot must activate a control scheme for displacing the moving appendage to avoid unstable situation caused by the slope angle.

C. Maintaining the Integrity of the Specifications

The template is used to format your paper and style the text. All margins, column widths, line spaces, and text fonts are prescribed; please do not alter them. Also, do not alter the contents of the footer which are specific to this conference and *do not include* page number(s) in the final version of the manuscript that you submit.

III. FAULT-TOLERANT GAITS ON EVEN TERRAIN

A single locked joint failure occurring to a robot manipulator decreases the number of degrees of freedom by one [4]. Hence, a robot leg with three degrees of freedom will be given two dimensional motions of the leg after a fault occurrence and thus will forbid the failed leg to have normal swing in the transfer phase or backward movement in the support phase. Nevertheless, unlike free-swinging failure [3] and mutilation failure, a locked joint failure does not take away body-supporting ability from the failed leg. The fault-tolerant gait for a locked joint failure employs this feature: In the support phase, the failed leg does not have active swing and just participates in body supporting work. In the transfer phase, once being lifted off, the failed leg goes through passive movement along with the displacement of the robot body, i.e., its relative position with respect to the robot body does not change; refer to the former studies [11],[14] for detailed derivation of the fault-tolerant gait.

Fig. 5 shows the gait sequence in a period of the fault-tolerant gait developed in the former studies. The quadruped robot is supposed to walk over perfectly even terrain on a straight-line trajectory, that is, the crab angle θ is 0° in Fig. 1. Assume that a locked joint failure has occurred to a joint of leg 1 and the foothold position on the leg trajectory is determined to be x_1 ($0<x_1< R_x/2$) in the X-coordinate. By symmetry of the quadruped robot, fault-tolerant gaits for locked joint failures occurring to other legs can be easily derived from Fig. 5. $\lambda(x_1)$, the stride length of the fault-tolerant gait with leg 1 in failure, is determined by x_1, the fixed foothold position of leg 1, as follows.

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

Note that owing to the passive swing of the failed leg, the stride length of the fault-tolerant gait cannot exceed $R_x/2$, i.e., half the length of the working area. Being a discontinuous gait, the gait of Fig. 5 is characterized by the sequential motion of legs and the robot body as follows.

Swing leg 4 → Swing leg 2 → Swing leg 3
→ Lift off leg 1 and move m_b

Fig. 5(a) is the initial state to which the robot must adjust the foot positions after detecting a fault occurrence. The feet of leg 2 and leg 3 are on the center point of each working area, and leg 4 is placed onto $-x_1-\lambda(x_1)$ in the X-coordinate. In Fig. 5(b), leg 4 swings forward by $\lambda(x_1)$, placing onto the next foothold position $-x_1$ in the X-coordinate. As marked in Fig. 5(b) by a dot-dashed line, the foothold positions of leg 1 and leg 4 make the rear boundary of the support pattern, onto which C_0 is placed. This allows the next leg to enter into the transfer phase while maintaining gait stability; since C_0 is on the boundary of the support pattern, the gait has marginal stability margin. In Fig. 5(c) and (d), leg 2 and leg 3 follow the motion of leg 1 respectively, transferring forward by $\lambda(x_1)$. Finally, in Fig. 5(e), leg 1 undergoes passive swing with the help of the robot body. It is lifted off in synchronization with the start of body motion and is moved passively by the translation of the body. For clarify, we fix the positions of working areas in Fig. 5(e) the same as Fig. 5(a)~(d). In fact, they will move according to the translation of the robot body.

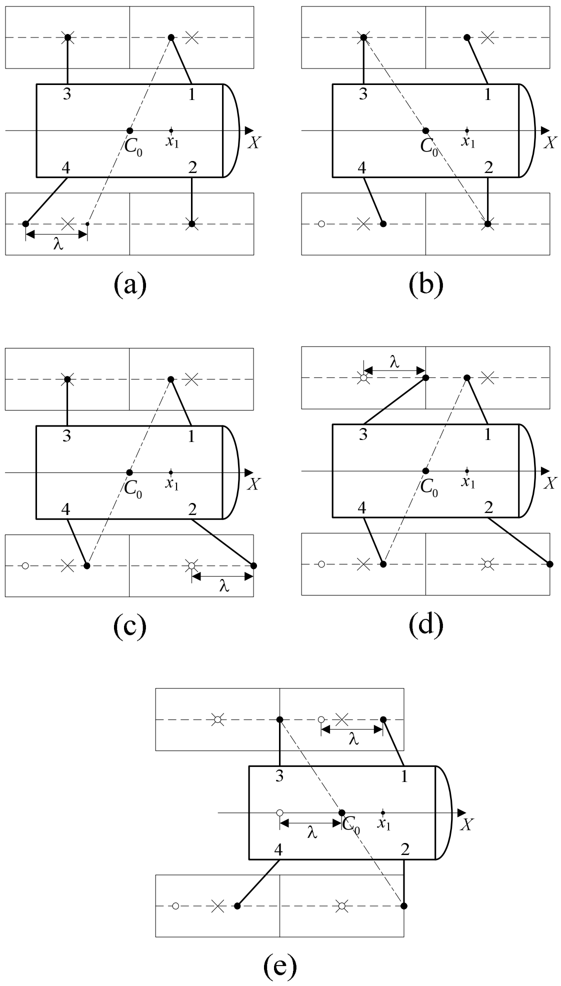

Fig. 5. Fault-tolerant periodic gait with leg 1 in failure, crab angle θ=0, and $0<x_1\le R_x/2$: (a) initial state, (b) swing leg 4, (c) swing leg 2, (d) swing leg 3, and (e) lift off leg 1 and move the robot body [11].

As mentioned before, dot-dashed lines in Fig. 5 denote the boundary of the support pattern, a polygon made of the foot positions of all supporting legs [10]. We can see that C_0 is onto the boundary whenever a leg is in the transfer phase. In terms of gait study for static walking, the robot is said to have the marginal stability margin with this gait. With the marginal stability margin, the robot may suffer from falling unstable by adverse influences such as tilting of the robot body by outer disturbances, position errors from ill-measured sensor data, involved force/torque on the center of gravity, etc.

IV. Walking over a Slope

After the text edit has been completed, the paper is ready for the template. Duplicate the template file by using the Save As command, and use the naming convention prescribed by your conference for the name of your paper. In this newly created file, highlight all of the contents and import your prepared text file. You are now ready to style your paper; use the scroll down window on the left of the MS Word Formatting toolbar.

A. *Control of the Moving Appendage*

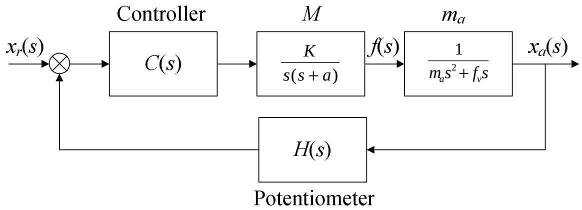

Fig. 6. Position control system of the moving appendage.

To have positive stability margin by moving the position of the body cg inside the support pattern, we must control the moving appendage in a desirable way. Fig. 6 illustrates the position control system of the moving appendage. From Fig. 3, we derive the dynamic equation for the position $x_a(t)$ of the moving appendage as

$$m_a\, d^2x_a(t)/dt^2 + f_v\, dx_a(t)/dt = f(t)$$

where $f(t)$ is the external force generated by the actuator M. Thus the transfer function for the input $f(s)$ and the output $x_a(s)$ is $1/(m_a s^2+f_v s)$. Following the characteristics of DC motors, we define the transfer function of the actuator M as $K/[s(s+a)]$, where K and a are the input gain and the pole, respectively. $C(s)$ is the controller for the system and $H(s)$ represents the potentiometer. $x_r(s)$ is the reference trajectory of the moving appendage. In our case study, we have employed the following PID controller $C(s)$ to accomplish the position control of the moving appendage:

$$C(s) = K_c(s+z_1)(s+z_2)/s$$

where the parameters K_c, z_1, and z_2 are determined according to kinematics of the given quadruped robot.

As the measure of the stability margin, we use the longitudinal stability margin [10]. Let $S(t)$ be the stability margin of a gait at time t. The moving appendage plays a key role in enhancing the stability margin of the fault-tolerant gait. Referring to Fig. 5, assume that the quadruped robot has the state (a), i.e., having a tripod in which leg 4 is in the transfer phase. Further, assume that the robot has been walking over a slope with the angle α.

If the moving appendage stays at its initial position $x_a(t)=0$, the coordinate of the body cg would be unchanged and $c_\alpha(t)$, its projection on the ground of the slope, would be $c_\alpha(t) = -(\tan\alpha)h$, which makes the fault-tolerant gait unstable (see (1)). On the other hand, if we displace the position of the moving appendage toward $+X$-direction *before* lifting off leg 4, the tripod gait could obtain a positive stability margin because the efficient position of cg would be changed by the distribution of m_a and m_b. Suppose that the fault-tolerant gait should guarantee the minimum value of stability margin S_m (S_m>0) throughout the locomotion. By (1), we have

$$m_a x_a(t)/(m_a+m_b) - (\tan\alpha)h \ge S_m$$
$$x_a(t) \ge ((\tan\alpha)h + S_m)(m_a+m_b)/m_a$$

Letting d_1 = ((tanα)h + S_m)(m_a+m_b)/m_a, we assert that the moving appendage must be controlled to the coordinate d_1 before lift-off of leg 4 for the fault-tolerant gait to have the stability margin S_m.

Analysis on the tripod with leg 2 in the transfer phase can be made in a similar manner. Referring to Fig. 5(c), the condition for having the stability margin $\underline{S_m}$ is written as

$$m_a x_a(t)/(m_a+m_b) - (\tan\alpha)h \le -S_m$$
$$x_a(t) \le ((\tan\alpha)h - S_m)(m_a+m_b)/m_a$$

Assuming (tanα)h < S_m, define a minus integer d_2 = ((tanα)h − S_m)(m_a+m_b)/m_a. Like the former case, the moving appendage should be controlled to the coordinate d_2 before lift-off of leg 2 to have $S(t)$=S_m. Including this control step before each leg swing, we refine the leg and body sequence to

Move m_a ⟶ Swing leg 4 ⟶ Move m_a
⟶ Swing leg 2 ⟶ Move m_a ⟶ Swing leg 3
⟶ Move m_a ⟶ Lift off leg 1 and move m_b

Incorporating all the discussions so far, we deduce $x_r(t)$ shown in Fig. 7 that will serve as the reference trajectory for the position control of $x_a(t)$. T_s denotes the cycle time of the gait and "(a)" ~ "(d)" means the time range assigned to the states Fig. 5(a)~(d). Clearly, the stability margin of the fault-tolerant gait is always greater than or equal to S_m as long as the position of the moving appendage $x_a(t)$ is controlled to follow the reference trajectory $x_r(t)$ of Fig. 7.

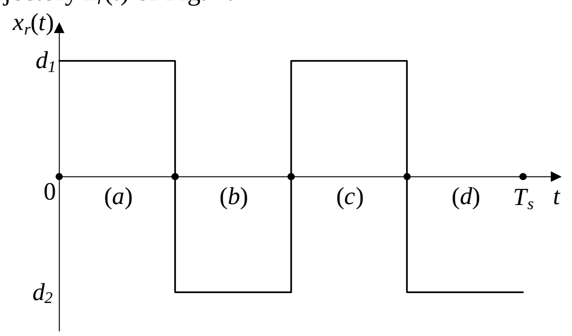

Fig. 7. Reference trajectory x_r(t) for x_a(t).

B. 3D Simulation

We conduct a case study of the proposed fault tolerant gait planning using a gait simulator. Fig. 8 summarizes the result of our 3D simulation. The quadruped robot with the moving appendage is displayed together with the projection of working areas and foothold positions of supporting legs. While circles denote the previous foothold positions of the corresponding legs. We set the relevant parameters as R_x=20cm, R_y=10cm, m_a=3kg, m_b=9kg, h=5cm, and f_v=0.5N·s/m. Suppose that the robot has been walking on a slope with the angle α=20° and the cycle time T_s=28sec, when a locked joint failure occurs to leg 1, inducing the fixed foothold position x_1=8cm. In the test, we assume that a locked joint failure has already occurred to a joint of leg 1 before the robot initiates its walking. Also, we set that the minimum stability margin is S_m=1cm.

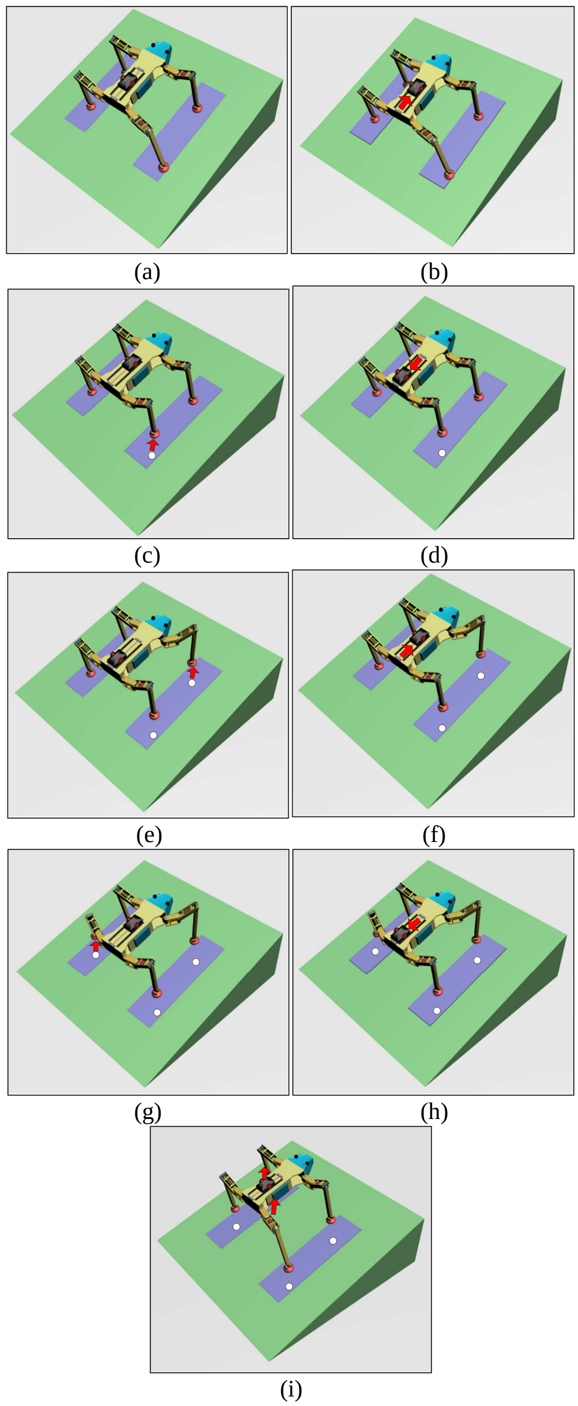

Fig. 8. 3D simulation result of the fault-tolerant periodic gait with leg 1 in failure for walking over a slope: (a) initial foothold position, (b) move m_a by d_1, (c) swing leg 4 by λ(x_1), (d) move m_a by d_2, (e) swing leg 2 by λ(x_1), (f) move m_a by d_1, (g) swing leg 3 by λ(x_1), (h) move m_a by d_2, (i) lift off leg 1 and move m_b by λ.

The specific operation of legs and the moving appendage at each gait sequence is written in the caption of Fig. 8. These operations are marked in the figure by arrows. Note that for realizing the proposed adjustment, the moving appendage should be controlled to follow a trajectory of pulse wave shown in Fig. 7. In the simulation, we have employed a PID controller $C(s)$ to accomplish the trajectory following of the moving appendage. Also, the measured stability margin $S(t)$ is found to be greater than or equal to S_m throughout the locomotion. The simulation result demonstrates that the quadruped robot could complete a cycle of the proposed fault tolerant gait with a locked joint failure at leg 1, maintaining positive gait stability

V. CONCLUSION

A novel fault-tolerant gait planning for locked joint failures is proposed. The considered quadruped robot has static walking on a slope. As a hardware redundancy, the moving appendage is utilized to adjust the cg of the robot, thereby guaranteeing positive gait stability. This hardware scheme is required for the quadruped robot to walk over uneven terrain, especially slopes and rough terrain where the projection of the body cg on the ground may be displaced due to gravity and other influences. A 3D simulation result validates the applicability of the proposed gait planning. Applying the proposed gait planning to a real quadruped robot is under way.

ACKNOWLEDGMENT

The work of J.–M. Yang and S. W. Kwak was supported by the National Research Foundation of Korea grant funded by the Korea government (MEST) (No. NRF–2011–0027705). The work of P. M. Pathak, M. M. Gor, and A. K. Samantaray has been funded by DST, India and NRF South Korea under Indo–Korea Joint Research In Science and Technology vide Grant No. INT/Korea/P–13.

REFERENCES

[1] C. H. Cho, B. C. Min, and D. H. Kim, “A gait generation for an unlocked joint failure of the quadruped robot with balance weight,” Lecture Notes in Computer Science, vol. 5744, pp. 251-261, 2009.

[2] S. K. K. Chu and G. K. H. Pang, “Comparison between different model of hexapod robot in fault tolerant gait,” IEEE Transactions on Systems, Man, and Cybernetics–Part A, vol. 32, no. 6, pp. 752-756, 2002.

[3] J. D. English and A. A. Maciejewski, “Fault tolerance for kinematically redundant manipulators: anticipating free-swinging joint failures,” IEEE Transactions on Robotics and Automation, vol. 14, no. 4, pp. 566-575, 1998.

[4] M. Goel, A. A. Maciejewski, and V. Balakrishnan, “Analyzing unidentified locked-joint failures in kinematically redundant manipulators,” Journal of Robotic Systems, vol. 22, no. 1, pp. 15-29, 2005.

[5] R. Jacobs, “Biologically inspired legged robots for space operations,” NIAC phase I report, 1999.

[6] B. W. Johnson, “Fault-tolerant microprocessor-based systems,” IEEE Micro, vol. 4, no. 6, pp. 6-21, 1984.

[7] V. L. Krishnan, P. M. Pathak, S. C. Jain, and A. K. Samantaray, “Reconfiguration of four legged walking robot for actuator faults,” Proceedings of IMechE Part I: Journal of Systems and Control Engineering, vol. 226, no. 1, pp. 11-26, 2012.

[8] G. A. Pratt, “Legged robots at MIT: what's new since Raibert?” IEEE Robotics and Automation Magazine, vol. 7, no. 3, pp. 15-19, 2000.

[9] C. F. Resceanu, “Control algorithms for multi-legged robots in fault conditions using fuzzy logic,” In: Proceedings of 15th International Conference on System Theory, Control, and Computing (ICSTCC), Oct., pp. 1-5, 2011.

[10] S. M. Song and K. J. Waldron, Machines That Walk: The Adaptive Suspension Vehicle, MIT Press, 1989.

[11] J.-M. Yang, “Fault-tolerant gaits of quadruped robots for locked joint failures,” IEEE Transactions on Systems, Man, and Cybernetics–Part C, vol. 32, no. 4, pp. 507-516, 2002.

[12] J.-M. Yang, “Crab walking of quadruped robots with a locked joint failure,” Advanced Robotics, vol. 17, no. 9, pp. 863-878, 2003.

[13] J.-M. Yang, “Fault-tolerant crab gaits and turning gaits for a hexapod robot,” Robotica, vol. 24, no. 2, pp. 269-270, 2006.

[14] J.-M. Yang, “Two-phase discontinuous gaits for quadruped walking machines with a failed leg,” Robotics and Autonomous Systems, vol. 56, no. 9, pp. 728-737, 2008.

[15] J.-M. Yang and J.-H. Kim, “Fault-tolerant locomotion of the hexapod robot,” IEEE Transactions on Systems, Man, and Cybernetics–Part B, vol. 28, no. 1, pp. 109-116, 1998.

[16] J.-M. Yang, S. W. Kwak, P. M. Pathak, and A. K. Samantaray, “Enhancing stability of fault-tolerant gaits of a quadruped robot using moving appendage,” In: Proceedings of the 3rd International Conference on Circuits, Systems, Control, Signals (CSCS’12), Oct., pp. 47-52, 2012.