Modeling and analysis of fault tolerant gait of a multi-legged robot moving on an inclined plane

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Abstract

This paper proposes the fault tolerant gait to be used in locomotion of hexapod robot on inclined plane. Comparison between various possible gaits has been made. Out of these, the described gait is selected for slow walking of hexapod. A general fault tolerant algorithm is developed depending on the leg failed. In case there occurs a sudden fault event in one of the legs, turning motion is used to rotate the robot body to desired position to avoid permanent damage of failed leg. The condition under which turning motion takes place is analyzed theoretically.

Keywords: Modeling; multi-legged robot; inclined plane; fault tolerant gait; turning gait

1. Introduction

Hexapod robots have been researched more keenly in recent years, reason being its advantages over wheeled robots as described in [1]. Key advantages of the hexapod are its versatility, stability and ability to move even in case of failure of a leg. Besides, one or two legs of the hexapod can be used to perform operations as desired while maintaining its stability with help of other legs. Here in this paper we have discussed about quadruped gait pattern for the movement of the hexapod. In this gait, at least four legs are always in support phase. This results in better stability without sacrificing much mobility and speed. This gait can be used for motion on inclined plane as
discussed later in paper. Next sections of this paper discuss about the hexapod model used and kinematic constraints for enabling fault tolerant gait. Subsequent sections study the motion of hexapod on an inclined plane.

### Nomenclature

| Symbol | Description                |
|--------|----------------------------|
| $\beta$ | duty factor               |
| $\theta$ | joint angle               |
| $\theta'$ | inclination angle       |
| $\phi$ | turning angle              |
| $g$ | acceleration due to gravity |
| $h$ | height of the robot body from the inclined surface |
| $L$ | link length               |
| $m$ | mass of the robot         |
| $N$ | normal force              |
| $R_x$ | length of the working area |
| $R_y$ | width of the working area  |
| $s$ | stability margin          |
| $U$ | width of the robot body   |
| $W$ | distance between working area and robot body |

### 2. Modeling

This paper studies a simple hexapod shown in fig. 1. $O$ is the centre of gravity of the robot and the origin of the co-ordinate system X-Y. $X$ is the longitudinal axis about which six legs of the hexapod are symmetrically attached. Dashed rectangles represent the working areas of the feet where they can be placed during the current position of the body. The actual reachable workspace of each leg is a sector of an annulus which also overlaps with the adjacent area as per the kinematic property of a multi legged robot. A rectangular region is chosen for every leg from the annulus area to avoid the interference. Reachability is compromised in such case. The stroke pitch is assumed to be the same as the length of a working area, $R_x$ . That is, and as shown in the fig. 1 working areas of the legs are adjacent to one another.

The leg model used in the hexapod as shown in the fig. 2 is composed of three rigid links. The body and the three links are connected to one another by help of active revolute joints. The joint at the main actuator is $\text{joint one}$, the joint at lifting actuator is $\text{joint two}$, and the joint at knee actuator is $\text{joint three}$. First joint axis is perpendicular to the plane of the body and the other two are parallel to the longitudinal direction. Hence the robot has three degrees of freedom and walking can take place in any direction. $\theta_1$, $\theta_2$ and $\theta_3$ are the respective joint angles. Following assumptions on kinematics and dynamics of the hexapod are made for the simplicity of analysis - i) Point contact between the foot and the ground, ii) Slipping between the foot and the ground is absent, iii) All the mass of the six legs is lumped into the body, and the centre of gravity is assumed to be at the centroid of the body, iv) The speed of the hexapod body when it moves and the average speed of each leg during transfer phase are constant and considered equal, v) Ground is flat over the region affecting the robot workspace.
3. Failure configuration

This paper considers failure mode due to locked joint failure i.e. joint of a leg locked at a known position. This may be due to actuator losing power, brakes applied by implemented failure detection software or the direct failure of the joint. Number of degrees of freedom reduces by one if a single joint fails. As the leg is considered to have three degrees of freedom in normal state, a locked joint failure results in two degrees of freedom i.e. two dimensional motion. This constrains the workspace of the leg and there is specific range of kinematic constraints which the configuration of the failed leg must satisfy to guarantee a fault-tolerant gait. [2, 3]

4. Normal walking gait for inclined plane

When a robot body has to climb upon inclined plane as shown in fig.4, it will be susceptible to toppling and sliding and more instability as compared to plane terrain motion. In such a condition, it is needed to select a particular gait pattern which will be fast and will have good stability margin, s. Now, as discussed in [1, 2, 3], we have different gaits available to choose from. Tripod gait has duty factor of 1/2 and is the fastest amongst all gaits. But stability margin $s < 0$ [1] and also it is statically unstable and possible only when the body is moving. Quadruped gait has stability margin $s \leq 0$ and hence we have to select either quadruped or pentaped gait. In case of quadruped gait with duty factor $\beta = 2/3$, the support pattern formed at any point of cycle is unsymmetrical quadrilateral and may make $s < 0$ [1]. As a result duty factor of 3/4 shown in fig.3 is chosen. If leg 1 and 6 are swung and the body is on support of other four legs, then $s < 0$ and even if the body moves it doesn't improve
appreciably. So we go for Follow The Leader [1] principle as shown in fig.5. We first swing rear pair of legs, leg 5 and 6 and put them at foothold position of legs ahead of it. Then, pair of leg 3 and 4 is swung and put at foothold position of leg 1 and 2. Leg 1 and 2 are swung with same stride length and then the body moves by the stride length and hence is stroke of the robot body. If the time of swing of the leg and that of the motion of the body are considered equal, we obtain duty factor of 3/4. This gait gives the best stability margin and is fast. In case of motion on inclined plane, the stability margin is given as $s_i \cos \theta$, where $s_i$ is the stability margin in normal even terrain.

5. Fault tolerant gait on inclined plane

The case of locked joint failure has been considered in this paper. In such a case, the failed leg can't have an active swing if joint 1 is locked. If joint 2 or 3 are locked, then the reachable workspace reduces. In all cases, the leg loses one degree of freedom. So failed leg is used during support phase only and moved by the motion of the body. The duty cycle is kept same for the fault tolerant motion.
The same sequence of motion of legs is followed as in normal gait. First, leg 5 and 6 are lifted off and swung. Then subsequently leg 3 and 4 are lifted and swung when previous pair was put at its front foothold position. Finally, one of the fault ridden legs of front pair is swung forward and placed as shown. The body is moved and we get the initial configuration of the placement of legs again. In this fault tolerant gait the duty factor is \( \frac{3}{4} \) as shown in fig.7 and stride length and stroke of the body are same as in normal case even though its stability margin has reduced. As can be seen from fig. 6 (e), the hexapod is having zero stability margin but it will continue to move being in dynamic state.

Fig. 6: (a), (b), (c), (d) and (e) represent the sequence of leg motion in fault tolerant gait

Fig. 7: Gait diagram for fault tolerant motion
Let us consider a hexapod going up an incline at a moment when the rearmost pair of legs is in swing. Let the
legs as shown in fig. 8 have same normal force acting on them and same friction force due to symmetry of their
position.

Then we get the normal forces as

\[ N_1 = \frac{mg \left( \frac{R}{2} + h \tan \theta \right) \cos \theta}{2R_x} \quad \text{and} \quad N_2 = \frac{mg \left( \frac{R}{2} - h \tan \theta \right) \cos \theta}{2R_x} \]

It can be seen that \( N_1 > N_2 \) and hence the maximum friction force acting on that leg is more than the other. As a result the reaction force acting on the rear leg is more. Hence more actuator torque is required for that leg. Now, for a leg with locked joint, it is better to be subjected to lesser load when the actuator is not fully functional. Hence, it is beneficial to have the locked joint failure at the front legs. If failure occurs in one of the rear legs, we propose that the body is rotated by 180° so that it experiences the minimum force and further damage can be avoided.

Fig. 9 shows the spinning gait that has to be followed. Initially all the legs are placed at their rearmost foothold position. Now, after rotating by any angle, the legs 2 and 5 are unable to reach the rear foothold position of the new workspace of the hexapod. Hence, to enable the legs to reach a state similar to previous state before rotation, the body is rotated and adjusted as shown. Here, the legs at a, b, c, d, e and f are placed at a′, b′, c′, d′, e′ and f′ respectively such that the final foothold position are at a distance ‘S’ from the rearmost foothold position of the new workspace. Now, from the constraints on the motion of leg 2 and 5 it can be seen that \( S \leq R_x/2 \). Thereafter, the body can follow spinning gait using the same sequence as in fault tolerant longitudinal gait and the body is rotated by 180° to bring the failed leg at the front end of the hexapod and then continue the fault tolerant longitudinal motion. The above mentioned strategy is followed when one of the legs in the rear end of the body fails. Otherwise, the longitudinal fault tolerant gait is followed to move up the incline.

6. Conclusions

In this paper, the motion of hexapod over inclined plane is considered. It is seen how the gait described is better than other hexapod gaits. And it has been shown what to do depending on the failure of the leg and which leg has been affected. Further studies need to be done to ascertain other aspects like the inclination angle to which the body
will be able to move without toppling. Also, here the legs have been considered massless but the masses of the legs will also enter into the governing dynamic equations and determine the fate of hexapod in its motion. Similarly, this concept may be utilised in obstacle avoidance. In cases where the robot body is moving on a plane terrain and is encountered by the obstacles of different altitudes and slopes, the robot has to choose one to move across and there it needs to determine which. So gait planning for inclined motion is an important study and much work needs to be done.

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