Abstract: - Fault-tolerant gaits in robot’s locomotion are defined as gaits with which legged robot can continue their walking after a failure event occurs to a leg of the robot. 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 an occurrence of a failure, maintaining static stability. The considered failure is a locked joint failure which prevents a joint of a leg from moving and makes it locked in a known place. This paper presents a strategy for generating fault tolerant locomotion of a quadruped robot. The failure considered in this paper is a locked joint failure. The kinematic condition of fault tolerant locomotion is derived for straight line walking of quadruped robot on even terrain. An algorithm for fault tolerant locomotion in straight line is described.

Key-Words: - robot, quadruped, fault-tolerant, gait, locked joint, stability

1 Introduction
Autonomous mobile robots are finding applications in areas, such as cleaning, running errands, and assisting handicapped or elderly. Mobile robots are also being developed to be used in areas that are inaccessible for humans, for instance in hazardous environments, military, and exploration of volcanoes and space.

Walking robots are being developed to provide autonomous mobile robots the ability to traverse certain types of terrain (like, flat terrain or mountain, or other rocky terrain, in indoor environments with steps, stairways) in a more efficient and stable manner than more conventional robots, using wheels or tracks.

Another significant advantage of legged robots is their robustness to damages to legs (in specially, in static walking). Legged robots are able to continue to walk against a fault in a leg. They may maintain static stability even if a leg is broken so that is cannot support the robot body. Adaptation to a leg failure is one of the most important requirements for robust walking of legged robots, because the repair of the failed leg is almost impossible after legged robots have been launched in most applications. From their characteristics of having multi-legs, walking robots have inherent fault tolerance capability against a leg failure since a failed leg for itself may not cause catastrophic failure or instability in static walking. Among various leg failures, a locked joint failure is one of common failures that can be frequently observed in dynamics of robot manipulators [1].

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

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

2 Quadruped robot model
A two-dimensional model of a quadruped robot is shown in Fig. 1 [2]. The four legs are placed symmetrically about the longitudinal axis and have rectangular working areas with the length \(D_x\) and the width \(D_y\). \(C_i\) is the centre point of leg \(i\) working area. The robot body is also in the shape of a rectangle with \(2U\) width and distant from working areas by \(d\). \(C\) is the centre of gravity of the body and the origin of the robot coordinate system \(X–Y\).
A leg attached to the quadruped robot has the
geometry of the articulated arm as showed in Fig. 2. This model has two rigid links and three revolute joints; the lower link is connected to the upper link via an active revolute joint and the upper link is connected to the body via two active revolute joints, one parallel with the knee joint and the other parallel with the body’s longitudinal axis.

![Fig. 1 - Bidimensional model of quadruped robot](image)

![Fig. 2 - Generalized coordination of quadruped leg](image)

3 Kinematic Constraint

When the robot body translates in legged locomotion, the configurations of all the supporting legs should be simultaneously changed to maintain the current foothold position. If a locked failure occurs to a joint of a leg, however, the rank of Jacobean of the failed leg is reduced by one [4] 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. Furthermore, the forward movement of a leg with respect to the robot body is in executable 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. On the other hand, if joint two or three is locked from failure, the accessible area where the failed leg may place its foot is reduced to only a partial region of the working area, which forbids normal walking with continuous leg swing. Therefore, it is prescribed that the failed leg is moved only passively by the translation of the body.

We propose the following principles for the fault-tolerant gait planning:

1) 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.

2) 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.

In the following subsection we develop algorithms for fault-tolerant periodic gait for a quadruped robot when a locked failure occurs to first joint of leg 1. The gait sequence for failure events in other legs will be easily derived by symmetry.

4 Fault-tolerant gait planning

4.1 Failure of Joint One

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

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

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

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

**Step 1:** Check if $\dot{\theta}_1$ is locked

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

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

**Step 3:** Check if fault leg is in the support state
• if NOT then place the failed leg and jump at Step 5
• if YES then jump at Step 4

Step 4: Check if any leg is in the transfer state
• if NOT then jump at Step 5
• if YES then transfer forward and place the leg

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

Step 6: Check if selected leg is the failed one
• if NOT then swing the selected leg and jump at Step 5
• if YES then lift off the leg, move the robot body and jump at Step 5.

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

Step 1: Check if \( \hat{\theta}_{i_2} \) is locked
• if NOT then continue the gait in normal condition (without fault)
• if YES then jump at Step 2

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

Step 3: Check if fault leg is in the support state
• if NOT jump at Subroutine: Placing the Failed Leg (PFL)
• if YES then jump at Step 4

Step 4: Check if any leg is in the transfer state
• if NOT then jump at Step 5
• if YES then transfer forward and place the leg and jump at Step 5

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

Step 6: Check if selected leg is the failed one
• if NOT then lift the selected leg without robot body movement and jump at Step 5
• if YES then jump at Subroutine: Lifting the Failed Leg (LFL)

Subroutine (PFL) : Check if the failed leg can be placed
• if NOT then eliminate this leg from the gait strategy
• if YES then place the failed leg by acting the joint three and adjusting the body amplitude and jump at Step 5

Subroutine (LFL) : Check if the failed leg can be lifted
• if NOT then drag the leg on the ground executing a discontinuous robot body movement in regard of this
• if YES then lift the failed leg by acting the joint three

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

Step 1: Check if \( \hat{\theta}_{i_3} \) is locked
• if NOT then continue the gait in normal condition (without fault)
• if YES then jump at Step 2

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

Step 3: Check if fault leg is in the support state
• if NOT jump at Subroutine: Placing the Failed Leg (PFL)
• if YES then jump at Step 4

Step 4: Check if any leg is in the transfer state
• if NOT then jump at Step 5
• if YES then transfer forward and place the leg and jump at Step 5

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

Step 6: Check if selected leg is the failed one
• if NOT then lift the selected leg without robot body movement and jump at Step 5
• if YES then jump at Subroutine: Lifting the Failed Leg (LFL)

Subroutine (PFL) : Check if the failed leg can be placed
• if NOT then eliminate this leg from the gait strategy
• if YES then place the failed leg by acting the joint two and adjusting the body amplitude and jump at Step 5

Subroutine (LFL) : Check if the failed leg can be lifted
• if NOT then drag the leg on the ground executing a discontinuous robot body movement in regard of this
• if YES then lift the failed leg by acting the joint two

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

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

These properties are of great advantage to mobility of the robot. The property a) guarantees a deadlock-free locomotion, and properties b) and c)

imply that the derived gait sequence is optimally drive in the sense that no backward swing of the leg is necessary and that the robot body has the maximum stride length in a locomotion cycle.

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

5 Straight-line gait of quadruped robot with failure of joint one

Let $x_i$ to be the $X$ coordinate of the foothold position of leg $i$ ($i=1,4$) in the body coordinate system at the initial state. Then

$$0 \leq x_1, x_3 \leq D_x$$
$$-D_x \leq x_2, x_4 \leq 0$$

where $D_x$ is the length of the working area. Note that $x_1$ is a constant value since joint one of leg 1 is locked from failure. The fault-tolerant periodic gait is defined as follow:

1) initial foothold position

1.1) $\frac{D_x}{2} \leq x_1 \leq D_x$
$$x_2 + x_3 = 2(D_x - x_1)$$
$$x_4 = -x_1$$

1.2) $0 \leq x_1 < \frac{D_x}{2}$
$$x_2 = 0$$
$$x_3 = D_x$$
$$x_4 = -x_1$$

2) stride length

$$\lambda = \begin{cases} 
\frac{D_x}{2}, & \text{if } 0 \leq x_1 < \frac{D_x}{2} \\
\frac{D_x}{2}, & \text{if } \frac{D_x}{2} \leq x_1 \leq D_x 
\end{cases}$$

3) gait sequence

lift and place leg 3 at distance $\lambda$ → lift and place leg 2 at distance $\lambda$ → lift leg 1 → move body with $\lambda$ → place leg 1 → lift and place leg 4 at distance $\lambda$

Fig. 3 illustrates an instance of the improved fault tolerant periodic crab gait in which the proposed adjustment procedure is embedded. We assume that a locked joint failure has occurred to joint one of leg 1 and the resulting kinematic constraint is beyond the reach of the present foot trajectory. Black circles denote foothold positions of supporting legs and white circles denote the previous locations of foothold positions. The dashed triangle is the support pattern in a state where a leg is in the transfer phase. Without loss of generality, all the four legs are supposed to be in the support phase in the beginning of the gait.

Fig. 4 - Gait diagram of the proposed fault-tolerant gait

In Fig. 4 is presented the gait diagram of the proposed fault-tolerant gait for both cases of gait: straight-line a gait on flat terrain.
6 Conclusion
In this paper, a locked joint failure event was defined, and the behavior of legged robots with a locked joint failure was examined. It was show that locked joint failure do not reduce stability of a gait but constrain the workspace of the failed leg. A fault-tolerant gait algorithms for locked joint failure (cases of one, two and three joint) was proposed in the straight-line walking of a quadruped robot over even terrain. In these algorithms, for avoiding defect caused by a locked joint failure, the robot has the discontinuous movement of the body with respect to leg swing and the failed leg is lifted and placed passively by translation of the quadruped body. The quadruped robot, with the proposed gait strategy, avoids any deadlock caused by the locked joint failure and has the maximum stride length in a cycle.

References: