CONTROL OF WALKING ROBOT LEG IN FAULT CONDITIONS

Resceanu Cristina Floriana
University of Craiova, Faculty of Automation, Computers and Electronics,
Decebal Blvd., no.107, Craiova, Dolj, Romania
e-mail: cristina@robotics.ucv.ro

Abstract: Fault tolerance is increasingly important for robots, especially those in remote or hazardous environments. Robots need the ability to effectively detect and tolerate internal failures in order to continue performing their locomotion without the need for immediate human intervention. The control of walking robot locomotion on difficult terrain demands the development of efficient and reliable algorithms to coordinate the movement of multiple legs according to a diversity of requirements. This paper presents a control algorithm for robot leg in fault conditions. The failure considered in this paper is a locked joint failure.

Keywords: leg, fault, robot, walking, control

1. Introduction

Using a suitable control of leg movements, a walking robot can climb step, cross ditches, locomotion on extremely rough terrain on which, due to irregularities, the robots with wheels do not be used. An important disadvantage of legged locomotion, when compared with wheeled locomotion, is the complexity of its control, even on completely flat ground.

Due to the large number of degrees of freedom of a walking robot and complexity of legged locomotion, human real-time control, individually, on joint or leg movements is almost impossible in practice. According with this, a walking machine, even if it is driven by a human, must have an autonomous behaviour at least at the joint actuation and leg coordination levels, given automatically a good terrain adaptation and body stability.

The basic control problems that all the walking vehicles confront are:

- How to generate the trajectory and the average speed?
- How to determine the best sequence for liftoff and placing the feet?
- What is the suitable distance that each leg should transfer in order to maintain a prescribed statically stability?
- How to control the body's inclination and height?
- How to develop a measurement system and information processing method to support the motion planning?

The problem of choosing the best sequence for liftoff and placing the feet of a walking vehicle is the gait selection problem.

Another 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. These 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 [3].

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 kinematics constraints of the failed leg in fault-tolerant gaits for a locked joint failure and, also, on the dynamic control of the robot's leg in fault condition.

2. Walking robot model

Kinematics Consideration

We consider a quadruped robot whose two-dimensional model is shown in Fig. 1 [4].

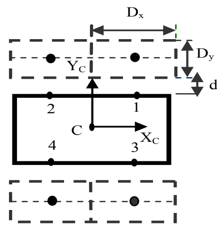

Fig. 1. Bidimensional model of quadruped robot.

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 an active revolute joint which is parallel with the body's longitudinal axis.

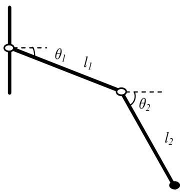

Fig. 2. Generalized coordination of quadruped leg

Dynamic model of leg

Dynamic equations of robot's leg are the following [1]:

$$\tau_1 = M_{11}\ddot{\theta}_1 + M_{12}\ddot{\theta}_2 - c\dot{\theta}_2^2 - 2c\dot{\theta}_1\dot{\theta}_2 + G_1 + F_{ex1} \quad (1)$$

$$\tau_2 = M_{12}\ddot{\theta}_1 + M_{22}\ddot{\theta}_2 + c\dot{\theta}_1^2 + G_2 + F_{ex2} \quad (2)$$

where

$$M_{11} = m_1 l_{c1}^2 + I_1 + m_2\left(l_1^2 + l_{c2}^2 + 2l_1 l_{c2}\cos\theta_2\right) + I_2$$

$$M_{22} = m_2 l_{c2}^2 + I_2$$

$$M_{12} = M_{21} = m_2 l_{c2}^2 + m_2 l_1 l_{c2}\cos\theta_2 + I_2$$

$$c = m_2 l_1 l_{c2}\sin\theta_2 \quad (3)$$

$$G_1 = -g\left(m_1 l_{c1}\cos\theta_1 + m_2\left[l_{c2}\cos(\theta_1+\theta_2) + l_1\cos\theta_1\right]\right)$$

$$G_2 = -g m_2 l_{c2}\cos(\theta_1+\theta_2)$$

$$F_{ex1} = -F_z\left[l_1\cos\theta_1 + l_2\cos(\theta_1+\theta_2)\right] + F_x\left[l_1\sin\theta_1 + l_2\sin(\theta_1+\theta_2)\right]$$

$$F_{ex2} = -F_y l_2\cos(\theta_1+\theta_2) + F_x l_2\sin(\theta_1+\theta_2)$$

G_1 and G_2 are gravitational moments due to mass m_1 and m_2, F_{ex1} and F_{ex2} environmental interaction of the foot with the ground. During stepping, when foot is in transfer phase, F_z the foot weight and $F_x = 0$. When the foot is in contact phase with the ground and the robot is a quadruped, then $F_z = 1/4$ of the whole weight of the robot. In this case $F_x = fF_z$, where f the coefficient of friction. In following simulations we will consider that $m_1 = m_2 = m$, $l_1 = l_2 = l$ and $l_{c1} = l_{c2} = l/2$.

3. Kinematics constraints

In this section, we show that there exists a range of kinematic constraints which the configuration of the failed leg should satisfy for guaranteeing the existence of the previous fault-tolerant gait. We assume that a locked joint failure occurs to any joint of leg 1.

Case 1: Failure of Joint One

When joint one of leg is locked because failure, the leg can swing only the second link by the knee joint in the lateral direction. The resulting reachable region is thus of an arc shape as is shown in Fig. 3.

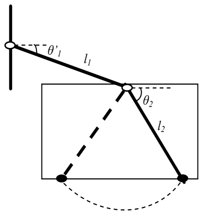

Fig. 3. Locked failure at joint one in straight-line walking (lateral view)

Depending on the features of its lateral motion, the leg can be placed on the inner foothold position P' of the outer position P, as show in Fig. 4, or cannot be placed on the ground in the worst case.

The kinematic constraint for guaranteeing such foothold positions can be described as

$$\left(D_y/2\right) + d \le r \le \bar{r} \quad (4)$$

where r is the radius of the arc and $\bar{r}$ is the distance between the leg attachment point and the front (or rear) boundary of the foot trajectory 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.

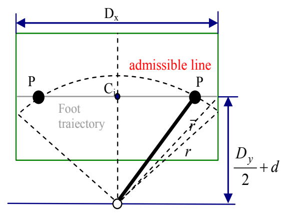

Fig. 4. Kinematics constraint of the quadruped leg

For describing (4) in terms of joint angles and robot parameters, let us rewrite $\bar{r}$ and r as

$$\bar{r} = \frac{1}{2}\sqrt{D_x^2 + \left(D_y + 2d\right)^2} \quad (5)$$

$$r = l_1 \cos \hat{\theta}_1 + l_2 \cos \theta_2 \ (6)$$

where $\hat{\theta}_1$ is the locked angle of joint one. 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_2 should also remain the same in the support phase. Substituting (5) and (6) into (4) leads to

$$(D_y/2) + d \le l_1 \cos \hat{\theta}_1 + l_2 \cos \theta_2 \le \frac{1}{2}\sqrt{D_x^2 + (D_y + 2d)^2} \ (7)$$

The above result prescribes the kinematic constraint of locked angle $\hat{\theta}_1$ which guarantees the existence of the fault-tolerant gait for straight-line walking proposed in [5].

Case 2: Failure of Joint Two

The motion of leg in the case of a locked failure at joint two is almost similarly as that of a locked failure of joint one. If joint two, or the knee joint, is locked because failure, the leg is reduced to a manipulator with one link and one revolute joint. The reduced reachable region in the working area is an arc as in Fig. 5.

The lateral motion of the failed leg is similar with that from figure 4, in which the leg is moved only by joint one and the second link is passively lifted associated with the lift-off of the first link.

The kinematics constraint for the existence of the fault-tolerant gait is the same as the case of joint one:

$$\frac{D_y}{2} + d \le l_1 \cos \theta_1 + l_2 \cos \hat{\theta}_2 \le \frac{1}{2}\sqrt{D_x^2 + (D_y + 2d)^2} \ (8)$$

where $\hat{\theta}_2$ is the locked angle of joint two.

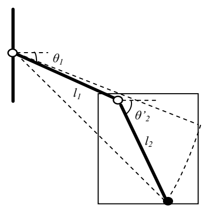

Fig. 5. Locked failure at joint two in straight-line walking (lateral view)

4. Algorithms control for leg positions

A. Control in normal conditions

We propose a closed loop control system to achieve a desired position using the mathematical model of the leg as shown below [2]:

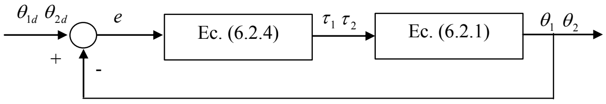

Fig. 6. Closed-loop control system to achieve a desired position of the foot

Error of the control system will be defined by:

$$e_i = q_i - q_{id}, \ i \in [1,2] \ (9)$$

We proposes a control law of the next form:

$$\tau_i = k_q^1 e_i + k_q^2 \dot{e}_i \ (10)$$

where k_q^1, k_q^2 are positive factors.

The simulation results are suggestive illustrated in Fig. 7, which can track initial positions, final and intermediate positions. Mechanical parameters of the system are m = 1400g, length of each link is the total length of the leg is L = 0.8m. We consider the initial position of the foot is lifted to its position [2].

$$e(t) = q(t) - q_d(t) \ (11)$$

$$\dot{e}(t) = \frac{\partial q(t)}{\partial t} \ (12)$$

For a quantitative understanding of system evolution, as represented in Fig.8, phase portrait of the movement is represented, where we considered the overall error of control system defined by [2].

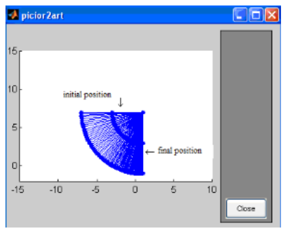

Fig. 7. Evolution of foot to the desired position

Evolution of error and its derivative, represented in phase plane, it can see the following figure:

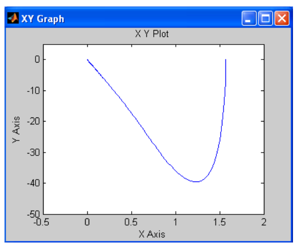

Fig. 8. Phase portrait

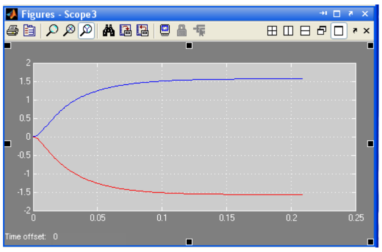

Fig. 9. Evolution of generalized internal coordinates q

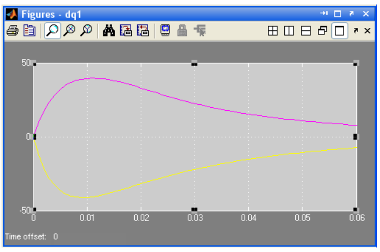

Fig. 10. Evolution of derivatives dq / dt

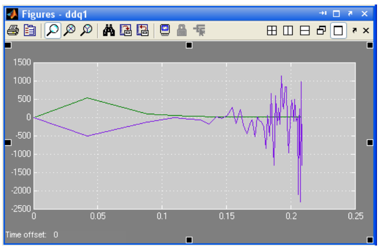

Fig. 11. Evolution of angular acceleration d2q/dt2

B. Control in Fault Conditions

We propose a closed loop control system to achieve a desired position of leg with a blocked joint, as shown following:

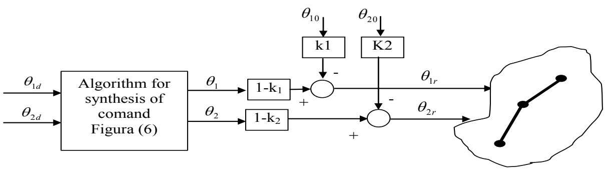

Fig. 12. Control system to achieve a desired position of the foot when blocking a joint

According to the figure, commands were sent to foot the expression:

$$\theta_{ir} = (1-k_i)\theta_i + k_i\theta_{i0}\text{, i=1,2,3} \quad (13)$$

where:

k_i =0, when joint actuator is in good condition;

k_i =1, when joint actuator is locked in an arbitrary angle θ_{i0} .

The vector of commands has the following expression:

$$\Theta_r = \begin{bmatrix}\theta_{1r}\\ \theta_{2r}\end{bmatrix} = (I-K_D)\begin{bmatrix}\theta_1\\ \theta_2\end{bmatrix} + K_D\begin{bmatrix}\theta_{10}\\ \theta_{20}\end{bmatrix} \quad (14)$$

where:

$$K_D = \begin{bmatrix}k_1 & 0\\ 0 & k_2\end{bmatrix} \quad (15)$$

is matrix of fault. When $K_D \equiv 0$, it can make the claim that the system works correctly.

The vector $[\Theta_0]^T = [\theta_{10} \quad \theta_{20}]$ represent values of blocking angles. Respect to Fig. 12 and relations (14) (15), we study the behavior of leg by the choosing particular structures for matrix of fault.

Case 1: Failure of Joint One

The simulation results are suggestive illustrated in Fig. 13, which can track initial positions, final and intermediate positions. Mechanical parameters of the system are m = 1400g, length of each link is the total length of the leg is L = 0.8m. We consider the initial position of the foot is lifted to its position and the first joint is blocked at angle $\theta_{10} = -\pi/4$ [2].

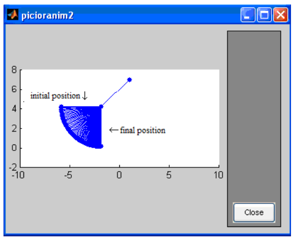

Fig. 13. Evolution of foot to the desired position

Evolution of error and its derivative, represented in phase plane, it can see the following figure:

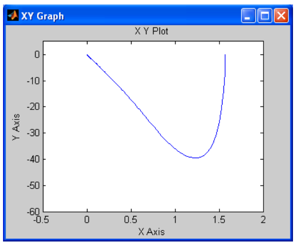

Fig. 14. Evolution of foot to the desired position

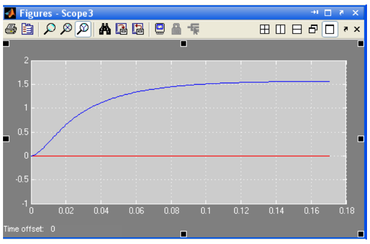

Fig. 15. Evolution of generalized internal coordinates q

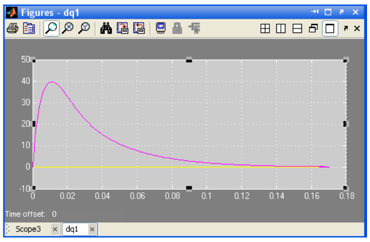

Fig. 16. Evolution of derivatives dq / dt

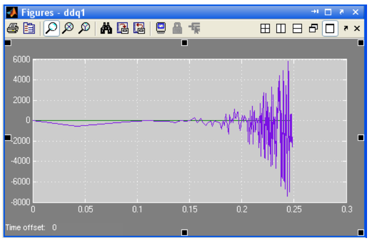

Fig. 17. Evolution of angular acceleration d2q/dt2

Case 2: Failure of Joint Two

We consider the initial position of the foot is lifted to its position and the first joint is blocked at angle $\theta_{20} = \pi/2$ [2]. The simulation results are suggestive illustrated in Fig. 12, which can track initial positions, final and intermediate positions.

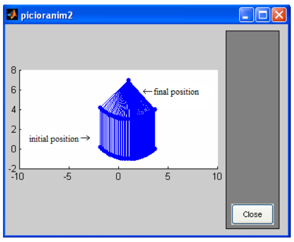

Fig. 18. Evolution of foot to the desired position

Evolution of error and its derivative, represented in phase plane, it can see the following figure:

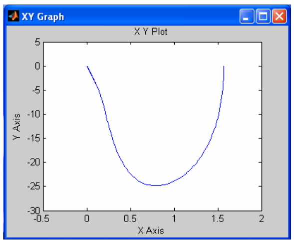

Fig. 19. Evolution of foot to the desired position

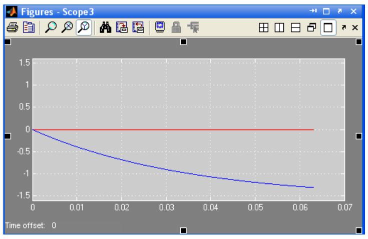

Fig. 20. Evolution of generalized internal coordinates q

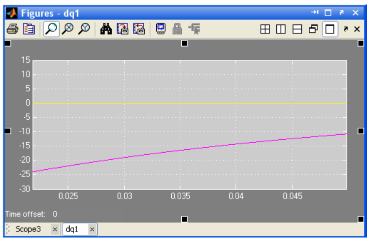

Fig. 21. Evolution of derivatives dq / dt

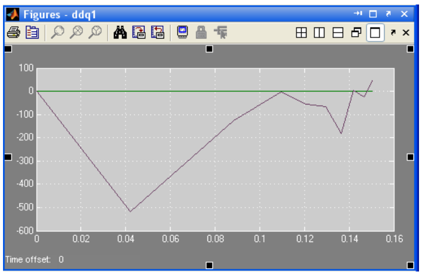

Fig. 22. Evolution of angular acceleration d2q/dt2

5. Conclusions

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

6. References

[1] Pana C., Stoian V.l, "A Fault-Tolerant Control System for a Hexapod Robot", 4th Conference Mechatronic System and Materials 2008, MSM 2008 Bialystok, Poland , July 14-17 2008;

[2] Pana C., "Control algorithms for legged robots in fault conditions," Ph.D. dissertation, Dept. Mechatronics., University of Craiova., 2009;

[3] Lewis C.L, Maciejewski A.A., "Fault tolerant operation of kinematically redundant manipulators for locked joint failures" IEEE Trans. Robot. Autom., Vol.13, No.4, pp. 622–629, 1997;

[4] Chen F.T., Lee H.L., Orin D.E., "Increasing the locomotive stability margin of multilegged vehicles" Proc. IEEE Int. Conf. Robot. Automat., pp. 1708–1714, 1999;

[5] Hirose S., "A study of design and control of a quadruped walking vehicle," *Int. J. Robotics Res.,* vol. 3, no. 2, pp. 113-133, 1984.

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