Dynamic Algorithm Control of Robot Manipulator Operating in Fault Conditions

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Abstract: The problems of control of robot manipulators in fault conditions are addressed in this paper. A fault tolerant control method is proposed for robot manipulators to maintain the required performance in the presence of actuation failures. The proposed approach integrates control law and actuator fault tolerance. Theoretical analysis and simulation results have confirmed the effectiveness of the proposed method.

Keywords: fault, dynamics, control, robot, manipulator.

1. INTRODUCTION

Robotic manipulators are designed to execute tasks that are either difficult for human beings, too time consuming or too much repetitive. Even though failures in robotic manipulators are to be anticipated, unfortunately the probability of joint failures increases when operating in remote and hazardous environments. In these situations, even if there are joint failures, it is important that the robot finishes its critical task because to perform maintenance operations in such environments can be impossible. Under such conditions, operational reliability of the robotic system is very important. This motivates the problem of analyzing and designing optimally fault tolerant control algorithms.

In general, the robot manipulators have more degrees of freedom than necessary to position and/or orient the end-effector so that there is generally a continuous family of joint configurations corresponding to an interior point of the workspace. This flexibility in choosing a suitable joint configuration for a kinematically redundant manipulator increases the likelihood that the robot can achieve a desired end-effector position/orientation if a failure should occur.

Robot fault detection recently attracted significant research interests. There are many researchers that have investigated the properties of the locked-joint failures and its effects of reduced manipulability and suggested methods of incorporating fault tolerance for this failure.

Caccavale and Walker (1997) used observers to developed fault detection. Residuals are generated by comparing measured system outputs and those predicted by the observers. However, in the observer-based methods, the estimation or measurement of joint acceleration is required.

Shin and Lee (1999) are proposed the position and velocity tracking errors method to detect joint failures. A robot joint is detected failed if a selected combination of the position error and velocity error is larger than a predefined threshold. There is possible to define such a threshold for a specific trajectory after some online tuning, but, in general, is difficult to define a globally efficient error threshold because the robot tracking error depends on the control law types, the position and orientation of the robot manipulator, etc. The cause for larger tracking errors might not be a joint failure.

Dixon et al. (2000) formulated an actuator fault detection method using full manipulator dynamics. The torque estimate is filtered in order to eliminate the need for joint acceleration measurement. Adaptive and robust techniques are then applied to deal with model uncertainties.
Among various manipulator failures, a locked joint failure is one of common failures that can be frequently observed in dynamics of robot manipulators, Lewis and Maciejewski (1997). They define a global measure of fault tolerance for locked-joint failures based on self-motion manifolds. Also, they use this measure to determine the necessary constraints on the joints of the manipulator that would guarantee the reachability of the task points after a joint failure.

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.

If a task can be completed after a joint failure, depends not only on the structure of the manipulator, but also on the specific joint angle at which the failure occurred. In general, failures at a fully extended or folded back position of a joint are most detrimental to the remaining capabilities of the manipulator.

In this paper, we propose a fault tolerant control method using a PD controller. The paper is organized as follows: Section 2 presents the proposed dynamic model formulation. Kinematic constraints of robot manipulator in fault conditions are discussed in Section 3. In Section 4, a fault tolerant control scheme is derived based on the dynamic model formulation. A design example and simulation studies are also presented in this section. Section 5 provides some concluding remarks.

2. DYNAMIC MODEL FORMULATION

We consider a robot manipulator whose two-dimensional model is (Fig. 1, Fig. 2):

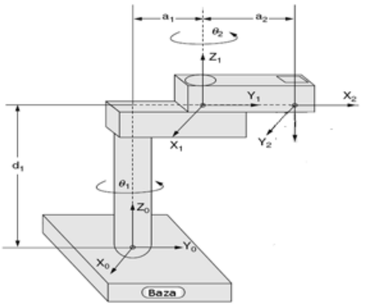

Fig. 1. Robot manipulator with two rotational joints.

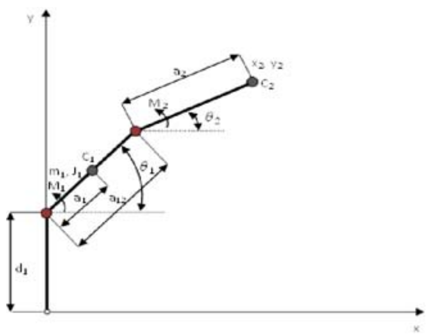

Fig. 2. Bidimensional model of robot manipulator.

In the absence of joint friction, the dynamic model of robot manipulators is written as follow:

$$J_1'\ddot{\theta}_1 + J^* \cos(\theta_1 - \theta_2)\ddot{\theta}_2 + J^* \sin(\theta_1 - \theta_2)\dot{\theta}_2^2 + + M_1' \cos\theta_1 = M_1 \tag{1}$$

$$J_2'\ddot{\theta}_2 + J^* \cos(\theta_1 - \theta_2)\ddot{\theta}_1 - J^* \sin(\theta_1 - \theta_2)\dot{\theta}_1^2 + + M_2' \cos\theta_2 = M_2 \tag{2}$$

where:

θ_1, θ_2 - the two revolute joints

$J_1' = J_1 + m_1 a_1^2 + m_2 a_{12}^2$

$J_2' = J_2 + m_2 a_2^2$

$J^* = m_2 a_{12} a_2$

$M_1' = g(m_1 a_1 + m_2 a_{12})$

$M_2' = g m_2 a_2$

a_{12}, a_2 - length of links arm

J_1, J_2 - Jacobian

m_1, m_2 - mass of each link

M_1, M_2 - inertial moments

3. KINEMATIC CONSTRAINT

In this section, we show that there exists a range of kinematic constraints which the configuration of the robot manipulator should satisfy for finishing its critical task. We assume that a locked joint failure occurs to any joint of robot manipulator.

3.1 Failure of Joint One

We consider the case where joint one is locked from failure. In this case, the robot manipulator can move only the third link by the second joint (Fig. 3).

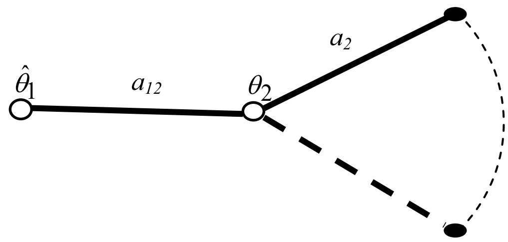

Fig. 3. Locked failure at joint one of robot manipulator (upper view), where $\hat{\theta}_1$ is the locked angle.

The resulting reachable region of robot manipulator is thus of an arc shape (Fig. 4). In this case, the robot manipulator can be move from the inner position A to the outer position B.

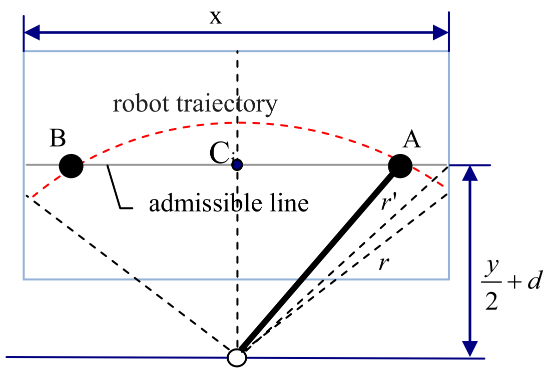

Fig. 4. Kinematic constraint of the robot manipulator, where r is the radius of the arc and $\bar{r}$ is the distance between the arm attachment point and the front (or rear) boundary of the arm trajectory projected onto the X–Y plane.

The kinematic constraint for guaranteeing these positions can be described as

$$(y/2) + d \le r \le \bar{r} \tag{3}$$

where:

$$\bar{r} = \frac{1}{2}\sqrt{x^2 + (y + 2d)^2} \tag{4}$$

$$r = a_{12}\cos\hat{\theta}_1 + a_2\cos\theta_2 \tag{5}$$

Introducing (4) and (5) in (3), we obtain the kinematic constrain in case of blocked first joint:

$$(y/2) + d \le a_{12}\cos\hat{\theta}_1 + a_2\cos\theta_2 \le$$

$$\le \frac{1}{2}\sqrt{x^2 + (y+2d)^2} \tag{6}$$

3.2 *Failure of Joint Two*

If joint two is locked because failure, the arm of robot manipulator is reduced to a manipulator with one link and one rotational joint. The reduced reachable region in the working area is an arc (Fig. 5).

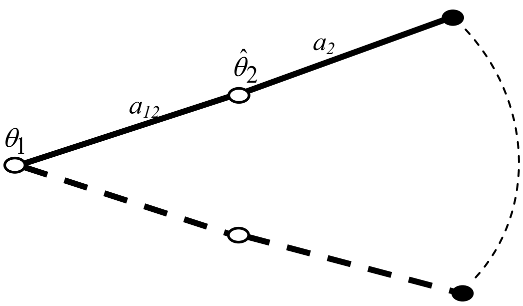

Fig. 5. Locked failure at joint two (upper view), where $\hat{\theta}_2$ is the locked angle.

The resulting reachable region of robot manipulator is similar with first case (Fig. 4). The kinematic constraint for guaranteeing these positions can be described as:

$$(y/2) + d \le a_{12}\cos\theta_1 + a_2\cos\hat{\theta}_2 \le$$

$$\le \frac{1}{2}\sqrt{x^2 + (y+2d)^2} \tag{7}$$

4. FAULT-TOLERANT CONTROL OF ROBOT MANIPULATOR

4.1 *Control in Normal Conditions*

We propose a closed loop control system to achieve a desired position using the mathematical model of the robot manipulator as shown in next figure (Fig. 6):

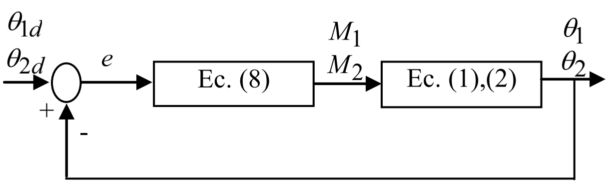

Fig. 6. Closed-loop control system to achieve a desired position of the robot manipulator.

Error of the control system will be defined by:

$$e_i(t) = \theta_i(t) - \theta_{id}(t), \qquad i \in [1,2] \tag{8}$$

We proposes a control law of the next form:

$$M_i = k_q^1 e_i + k_q^2 \dot{e}_i, \qquad i \in [1,2] \tag{9}$$

where k_q^1, k_q^2 are positive factors, and $\dot{e}_i$ is

$$\dot{e}(t) = \frac{\partial\theta(t)}{\partial t} \tag{10}$$

The simulation results are suggestive illustrated in (Fig. 7), which can track initial positions, final and intermediate positions. Mechanical parameters of the system are $m_1 = m_2 = 100$g, length of each link is $a_{12} = a_2 = 280$ mm.

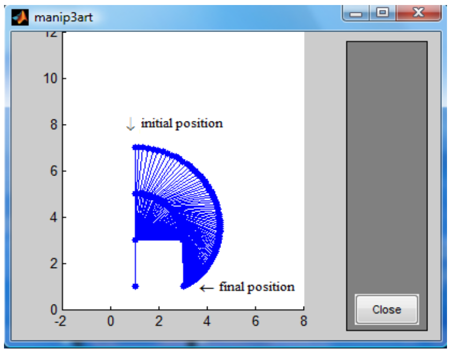

Fig. 7.Evolution of robot manipulator to the desired position.

For a quantitative understanding of system evolution, (Fig.8), phase portrait of the movement is represented, where we considered the overall error of control system.

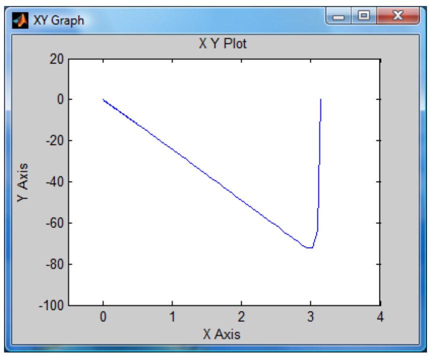

Fig. 8. Evolution of error and its derivative, represented in phase plane.

How you can see in above figure (Fig. 8), the error and its derivative go to zero, this means that the control algorithm is good and system is stable.

4.2 *Control in Fault Conditions*

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

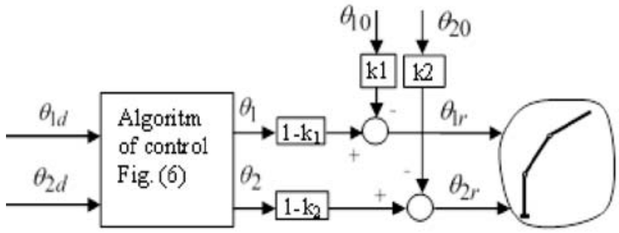

Fig. 9. Control system to achieve a desired position of the robot manipulator when blocking a joint.

Commands were sent to robot manipulator the expression:

$$\theta_{ir} = (1-k_i)\theta_i + k_i\theta_{i0}\,, \quad \text{i=1,2} \tag{11}$$

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:

$$\Theta_r = \begin{bmatrix} \theta_{1r} \\ \theta_{2r} \end{bmatrix} = (I - K_D)\begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} + K_D\begin{bmatrix} \theta_{10} \\ \theta_{20} \end{bmatrix} \tag{12}$$

where:

$$K_D = \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix} \tag{13}$$

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. 9 and relations (12) and (13), we study the behavior of robot manipulator by the choosing particular structures for matrix of fault.

Case I: Failure of Joint One

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_1 = m_2 = 100g, length of each link is a_{12} = a_2 = 280 mm. We consider that the first joint is blocked at angle $\theta_{10} = \pi/2$.

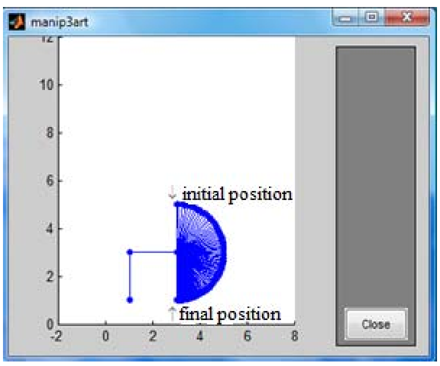

Fig. 10. Evolution of robot manipulator to the desired position.

The phase portrait of the error and its derivative is:

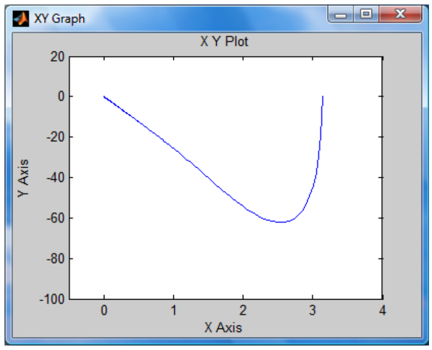

Fig. 11. Evolution of error and its derivative, represented in phase plane.

How you can see in above figure (Fig. 11), the error and its derivative go to zero, this means that the control algorithm is good and system is stable.

Case II: Failure of Joint Two

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_1 = m_2 = 100g, length of each link is a_{12} = a_2 = 280 mm. We consider that the first joint is blocked at angle $\theta_{20} = \pi$.

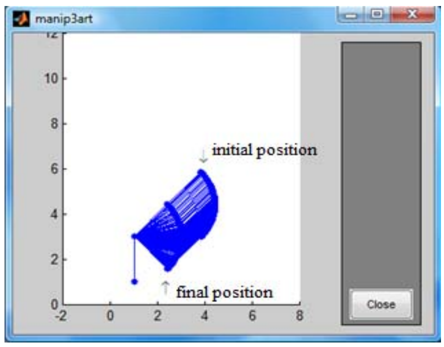

Fig. 12. Evolution of robot manipulator to the desired position.

The phase portrait of the error and its derivative is:

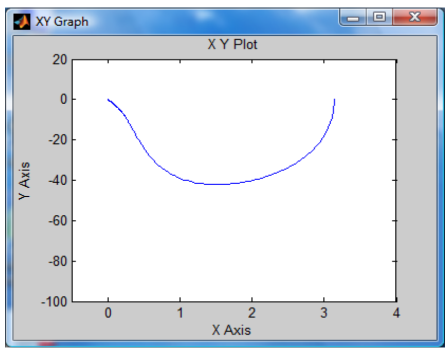

Fig. 13. Evolution of error and its derivative, represented in phase plane.

How you can see in above figure (Fig. 13), the error and its derivative go to zero, this means that the control algorithm is good and system is stable.

5. CONCLUSIONS

In this paper, a locked joint failure event was defined, and the behaviour of robot manipulator with a locked joint failure was examined. A fault tolerant control method was proposed for robot manipulators to maintain the required performance in the presence of actuation failures. Theoretical analysis and simulation results have confirmed the effectiveness of the proposed method. It was demonstrated that the system was stable in both conditions: normal functional and fault case, the error and its derivative go to zero.

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