# EXPERIMENTS WITH POSITION AND INTERACTION CONTROL FOR A ROBOT WITH ONE FLEXIBLE LINK

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Abstract: One of the major drawbacks of flexible-link robot applications is its low tip precision, which is an essential characteristic for applications with position and interaction control with a contact surface. In this paper, position and interaction control strategies considering a rigid contact surface are applied to a flexible-link manipulator. The applied strategies are based on the closed-loop inverse kinematics algorithm (CLIK) to obtain the desired angular references to the joint position controller. The control schemes were previously tested by simulation and further implemented on a two degrees of mobility flexible-link planar robot. The obtained experimental results exhibit a good position and force tracking performance. The overall results reveal the successful implementation of the control architectures for a robot with one flexible link. 

Keywords: Flexible-link manipulator, closed loop inverse kinematics, tip position control, interaction control, real-time control

## 1. INTRODUCTION

The study of flexible-link robot control has received a growing attention by a lot of researchers during the last decades. In fact, there are some potential advantages for the application of this type of robots: they allow fast movements with lower energy consumption and are built with less expensive mechanical structures. However, flexible-link manipulators exhibit an important drawback in comparison with rigid robots, due to the difficulty in control of its end-point or tip position. The flexibility rises the dynamic coupling, the non-linearities, and gives to the robot infinite degrees of freedom derived from the vibration modes of the flexible elements. Due to these vibrations, the system becomes a non-minimum phase system (Talebi *et al.*, 1998). The zeros in the right semi-plan, due to the non minimum phase lead to an unstable system, when the tip position is directly controlled through feedback.

To avoid these drawbacks, several techniques to efficiently control flexible-link robots have been studied. The control of a flexible manipulator at joint level has been established by a lot of authors like Khorrami and Jain (1994) for the tracking problem and Vandegrift *et al.* (1994) for the regulation problem, among others. One of the proposed strategies to solve the inverse kinematics problem for flexible arms, was derived from the closed loop inverse kinematics

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algorithm (CLIK) developed for rigid manipulators (Siciliano, 1990). The inverse kinematics formulation with feedback of joint coordinates and deflection variables was developed by Siciliano (1999) and Siciliano and Villani (2001) for constrained flexible manipulators. Finally, more complex algorithms for solving the inverse kinematics problem for high speed velocities with flexible manipulators have been proposed by Cheong *et al.* (2004).

The purpose of this work is to obtain experimental results with position and interaction control algorithms for a planar robot with two revolute joints and two links, where the second link is flexible. The control strategies were implemented considering the CLIK algorithm to obtain the desired angular references to the joint position controller. The interaction control algorithm was applied considering only a rigid contact surface.

The outline of the paper is as follows: Section 2 describes the inverse kinematics formalism related to flexible link robots considering the closed loop inverse kinematics algorithm (CLIK) and the joint position controller implemented in real-time. In Section 3 a brief overview of the CLIK-based interaction control for a rigid contact surface is described. Section 4 describes the robot's control hardware and software architectures. In Section 5 the planar manipulator used in this work and the obtained experimental results are presented. Finally, in Section 6 some conclusions are drawn.

## 2. FLEXIBLE LINK KINEMATICS

Let us consider the two degree of mobility robot schematic representation presented in figure 1, where the first link is rigid and the second link is flexible (Martins, 2000).

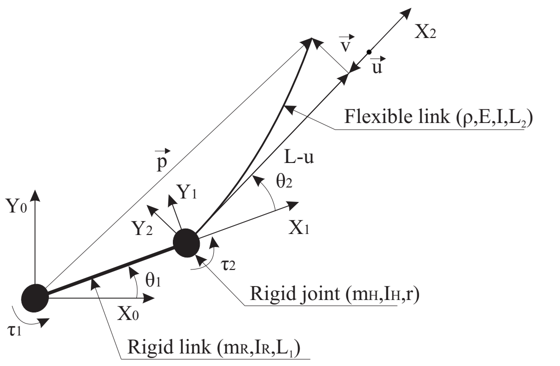


Figure 1. Planar flexible robot schematics.

Considering the length reduction approach due to deformation of the elastic link during trajectory evolution, the length reduction $u$ along the $x-$axis is given by:

$$u(x,t) = -\frac{1}{2}\int_r^x \left(\frac{dv}{d\xi}\right)^2 d\xi \qquad (1)$$

where $v$ is the lateral displacement. Considering only the two first vibration modes, $v$ is given by

$$v(x,t) = \sum_{k=1}^{2} \chi_i(x)\,\delta_i(t) \qquad (2)$$

where $\chi_i$ are the normalized mode shapes and $\delta_i$ are the generalized elastic coordinates. Vector $\boldsymbol{p}$ represented in figure 1 is the position on the link relative to reference frame $\{X_0,Y_0,Z_0\}$. This vector is represented by

$$\boldsymbol{p} = \boldsymbol{p_1} + R_0^2\,(\boldsymbol{p_2} - \boldsymbol{u} + \boldsymbol{v}) \qquad (3)$$

where $\boldsymbol{p_1}$ is the position of the tip of the first link relative to reference frame $\{X_0,Y_0,Z_0\}$ and $\boldsymbol{p_2}$ is the non-deformed second link end-effector position relative to reference frame $\{X_2,Y_2,Z_2\}$. The rotation matrix $R_0^2$ that describes the position relative to reference frame $\{X_0,Y_0,Z_0\}$ is represented by:

$$R_0^2 = \begin{bmatrix} cos(\theta_1+\theta_2) & -sin(\theta_1+\theta_2) \\ sin(\theta_1+\theta_2) & cos(\theta_1+\theta_2) \end{bmatrix} \qquad (4)$$

Considering the end-effector or tip position, $\boldsymbol{p}$ represents the forward kinematics of the flexible-link robot. Thus, the forward kinematic equations are given by:

$$\begin{aligned} p_x &= L_1\cos(\theta_1) + (L_2 - ||\boldsymbol{u}||)\cos(\theta_1+\theta_2) \\ &\quad -||\boldsymbol{v}||\sin(\theta_1+\theta_2) \\ p_y &= L_1\sin(\theta_1) + (L_2 - ||\boldsymbol{u}||)\sin(\theta_1+\theta_2) \\ &\quad +||\boldsymbol{v}||\cos(\theta_1+\theta_2) \end{aligned} \qquad (5)$$

where $||\boldsymbol{u}||$ and $||\boldsymbol{v}||$ are given by eq. (1) and eq. (2), respectively.

The inverse kinematics equations relate the cartesian position coordinates, given by eq. (5), and the joint $\theta$ and deflection $\delta$ coordinates. Replacing the equations (1)-(2) into (5), two equations and four unknown variables $(\theta_1, \theta_2, \delta_1, \delta_2)$ are obtained. Thus, the system is undetermined and other methods should be exploited to overcome this problem.

### *2.1 Closed Loop Inverse Kinematics*

To solve this problem, the well known Closed Loop Inverse Kinematics (CLIK) developed for rigid robots was adopted in this work, according to Siciliano (1999). This algorithm feeds back the joint angles $\theta$ calculated by the CLIK algorithm in a closed loop dynamic system in order to obtain the reference values to the joint position controller. In constrained motion, the deflection coordinates $\delta$ are also calculated by the CLIK algorithm. This algorithm is given by (Siciliano and Villani, 2001):

$$\dot{\theta}_d = J_p^T(\theta) K_P (p_d - p) \qquad (6)$$

where:

- $\dot{\theta}_d$ are the desired joint velocities,
- $J_p = J_\theta$ i.e., the rigid part of the Jacobian matrix,
- $p_d$ is the desired tip position,