

The kinematic calibration of industrial manipulators using Force/Torque sensor

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Abstract—This document is a model and instructions for \LaTeX . This and the `IEEEtran.cls` file define the components of your paper [title, text, heads, etc.]. *CRITICAL: Do Not Use Symbols, Special Characters, Footnotes, or Math in Paper Title or Abstract.

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I. INTRODUCTION

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II. MODEL AND PROBLEM FORMULATION

The only four unique DH parameters $\theta_i, d_i, a_i, \alpha_i \in \mathbb{R}$ for each i joint are commonly used to describe the serial chain manipulator kinematic [?]. The transform matrix T_{i-1}^i contains this parameters and describes transformation from the frame $i-1$ to i . The forward kinematic solution gives us the end-effector (frame n) transformation relative the base of manipulator frame 0, using multiplication of transform matrices $i = \overline{1, n}$ we get this solution

$$T_{i-1}^i = \begin{bmatrix} R_{i-1}^i & o_{i-1}^i \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$T_0^n = \prod_{i=1}^n T_{i-1}^i, \quad (1)$$

where $c(\cdot) = \cos(\cdot)$ and $s(\cdot) = \sin(\cdot)$, see Fig. II.

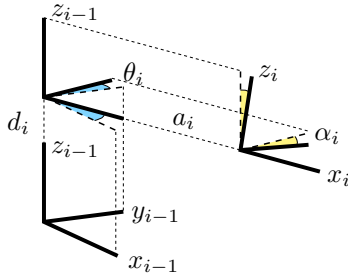


Fig. 1. DH convention visualization

Let us consider the revolute joint serial manipulator with Force/Torque sensor (Fig. II). Relation between force and joint torques

$$\tau = J^T \mathcal{F}, \quad \mathcal{F} = \begin{bmatrix} F_e \\ \tau_e \end{bmatrix}, \quad (2)$$

where $\tau_e, F_e \in \mathbb{R}^3$ is the torque and force applied to end-effector that combined in the generalized force vector \mathcal{F} , $\tau \in \mathbb{R}^n$ in the joint torque vector and $J \in \mathbb{R}^{6 \times 6}$ is manipulator Jacobian.

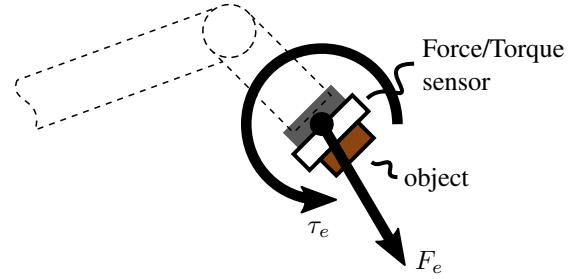


Fig. 2. End-effector scheme

In this work we solve the **kinematic model DH parameters estimation problem**. Consider the serial manipulator with revolute joint, the forward kinematic solution (1) and the force - torque relation (2). Define the unknown parameters vector p_i for each joint $i = \overline{1, n}$ that combined in the vector P

$$p_i = \begin{bmatrix} d_i \\ a_i \end{bmatrix}, \quad P = \begin{bmatrix} p_0 \\ p_1 \\ \vdots \\ p_n \end{bmatrix}, \quad i = \overline{1, n}. \quad (3)$$

Design the estimator

$$\hat{P} = f(\mathcal{F}, \tau, \theta, \alpha) \quad (4)$$

such that

$$\lim_{t \rightarrow \infty} P - \hat{P} = 0 \quad (5)$$

As usual to design the estimator we need the following assumptions

Assumption 1: The only measurable signals are \mathcal{F} , τ , θ , the α parameter is known

****Problem of the section above**

Say that we estimate only d_i and a_i

Define the vectors $\theta = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_n \end{bmatrix}$, $\alpha = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_n \end{bmatrix}$

III. KINEMATIC PARAMETERS ESTIMATION

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IV. SIMULATION AND EXPERIMENTAL RESULTS

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V. CONCLUSION AND FUTURE WORK

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