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.**

***Index Terms*—component, formatting, style, styling, insert**

I. Introduction

The development of the industry does not stop for a day. And every year more and more different tasks are automatization and most of the operations in them need an accurate position control of the tool. Some of them require high accuracy. For example, use a manipulator for milling or drilling in production is very attractive due to its versatility, large work area, and relatively low cost, but it is not enough to use the kinematic parameters from the technical manual to obtain the required product quality.

The accuracy of the tool positioning is defined by the accuracy of the kinematical model parameters, which used in forward and inverse kinematics tasks. Inaccuracies in kinematic parameters may arise due to the impossibility of accurately producing manipulators part the defined size and due to assembly error in the assembly process.

A lot of models are available in the literature for kinematic modeling of robotic manipulators as Classic Denavit-Hartenberg model (DH) and modified DH model, a complete and parametrically continuous kinematic model, the product of exponential model, and S model.

II. Model and problem formulation

The only four unique DH parameters θ_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

$$T_{i-1}^i = \begin{bmatrix} R_{i-1}^i & o_{i_1}^i \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} c_{\theta_i} & -s_{\theta_i} c_{\alpha_i} & s_{\theta_i} s_{\alpha_i} & a_i c_{\theta_i} \\ s_{\theta_i} & c_{\theta_i} c_{\alpha_i} & -c_{\theta_i} s_{\alpha_i} & a_i s_{\theta_i} \\ 0 & s_{\alpha_i} & c_{\alpha_i} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$T_0^n = \prod_{i=1}^{n} T_{i-1}^i, \tag{1}$$

where $c_{(\cdot)} = \cos(\cdot)$ and $s_{(\cdot)} = \sin(\cdot)$, see Fig. II.

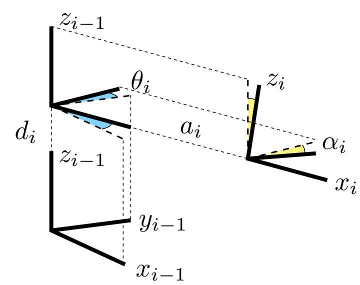

Fig. 1. DH convention visualization

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

$$\tau = J^T \mathcal{F}, \qquad \mathcal{F} = \begin{bmatrix} F_e \\ \tau_e \end{bmatrix}, \tag{2}$$

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.

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

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

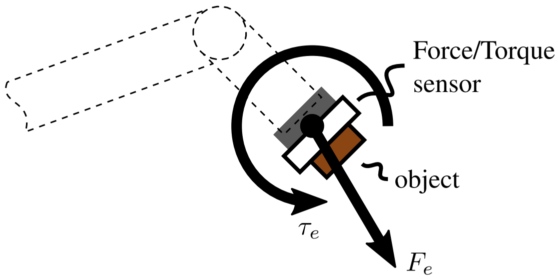

Fig. 2. End-effector scheme

Design the estimator

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

such that

$$\lim_{t \to \infty} P - \hat{P} = 0 \tag{5}$$

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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