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

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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. **??**.

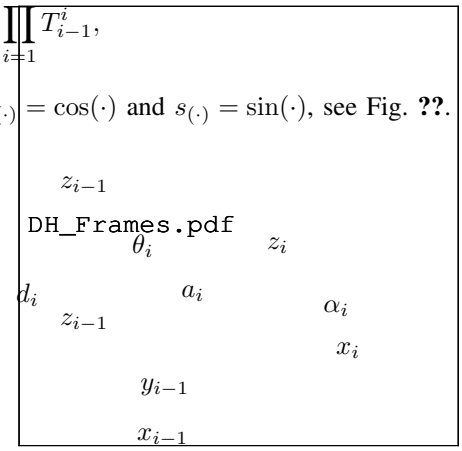

Fig. 1. DH convention visualization

Let us consider the revolute joint serial manipulator with Force/Torque sensor (Fig. **??**). 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.

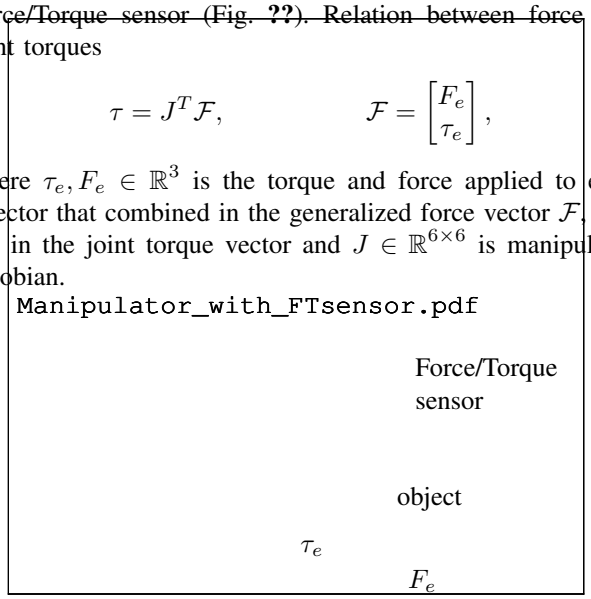

Fig. 2. End-effector scheme

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

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

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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