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Vision-based kinematic calibration of a small-scale spherical parallel kinematic machine

G. Palmieri*, M.-C. Palpacelli, L. Carbonari, M. Callegari

Department of Industrial Engineering and Mathematical Sciences, Polytechnic University of Marche, Ancona (AN), Italy

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ABSTRACT

The paper deals with the kinematic calibration of a mini pointing device with a two degrees of freedom spherical motion. Given an error kinematic model, based on a first order approximation approach, a global calibration method that includes the hand-eye pose estimation is proposed. The calibration method is based on an iterative procedure of refinement, whose convergence is proved. Data for calibration are obtained from a vision system in eye-to-hand configuration. A series of tests were carried out in order to find the best experimental setup and to assess the accuracy of the measurement system. Finally, the results of the calibration procedure are discussed.

1. Introduction

Kinematic calibration is always required in order to improve the accuracy of a mechanical device before its installation and operation. Errors due to imperfect geometrical dimensions of design parameters and to the intrinsic accuracy of the sensing system needed to have a feedback by the actuated joints cause a small, but often significant, change in the pose of the manipulator end-effector. This effect is even more important when mini or micro scale devices are used, namely when high precision is required to manipulate or assemble micrometric objects.

Parallel manipulators are often mentioned for their position accuracy when compared to serial robots, mainly due to the assumption that errors are averaged instead of added cumulatively. However, calibration of parallel robots is generally more complex because not all joint variables are sensorized and they have to be derived from closure equations as a function of actuated variables. A detailed survey about the major approaches toward kinematic calibration is proposed in [1]. Many methods can be practiced to calibrate a manipulator [2], from the use of mechanical constraints that locate the end-effector in a known position [3], to the use of exteroceptive sensors like cameras [4,5] or even more peculiar methods [6–8].

A further problem in kinematic calibration of robots is the hand-eye pose estimation, i.e. the estimation of the relative pose between the end effector of a manipulator and the tool fixed to its end effector, which can be an exteroceptive sensor, as well as a measurement target, used to execute the calibration procedure. Being a classical problem in robotics, several approaches can be found in literature [9–14].

In this paper it is presented the calibration of a mini spherical robot by means of a vision system for experimental measurements and an iterative model-based algorithm used for the estimation of geometrical errors.

The strength of the proposed calibration method is the combined approach aimed at performing simultaneously the hand-eye calibration and the identification of the error kinematic model. Furthermore, experimental data required for calibration have been obtained from a simple and reliable vision system, whose accuracy has been proved to be adequate to precision tasks, such as the calibration of a mini robotic device.

The manipulator is a parallel kinematic machine designed to have two rotational degrees of freedom (DoF). Its kinematics derives from a 2-DoF version of the Agile Eye [15], which demonstrated to be a stiff, fast and versatile device. Several studies were developed by the authors dealing with position and velocity kinematics, design and experimental tests and effect of joint and link compliance [16,17]. A prototype of the pointing device (Fig. 1) was built by the authors and some preliminary tests were made to analyze its behavior.

Dealing with the experimental approach, a vision-based system was adopted. Vision measurement, in fact, is largely used in robotics for calibration or control. Several examples of kinematic calibration techniques based on artificial vision can be found in the literature: in [18] a single camera is used to perform a 3D pose estimation solving the Radial Alignment Constraint (RAC) problem; an eye-to-hand approach is used in [19] to calibrate a Gough-Stewart platform using the interval method; in [20] the accuracy of the vision system is assessed by comparison with laser interferometry, and then used to calibrate the H4 parallel kinematic machine; a Modified Complete and Parametrically Continuous (MCPC) model for the serial robot PUMA is identified by vision in

* Corresponding author.
E-mail address: g.palmieri@univpm.it (G. Palmieri).

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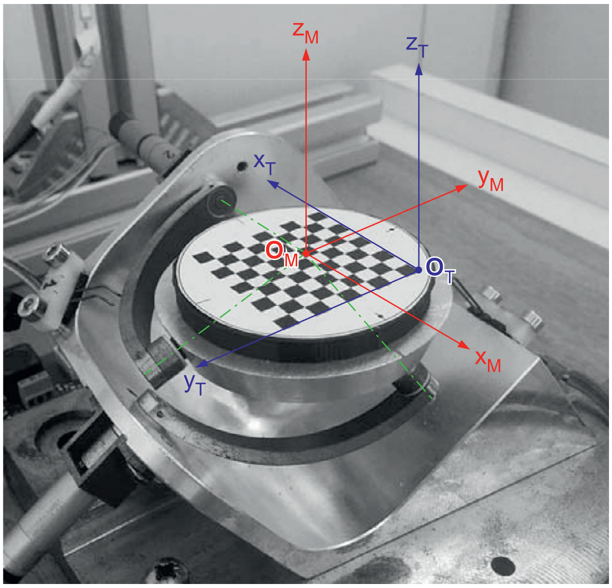

Fig. 1. Mini pointing device with the optical target; mobile $\{M\}$ and tool $\{T\}$ frames are plotted.

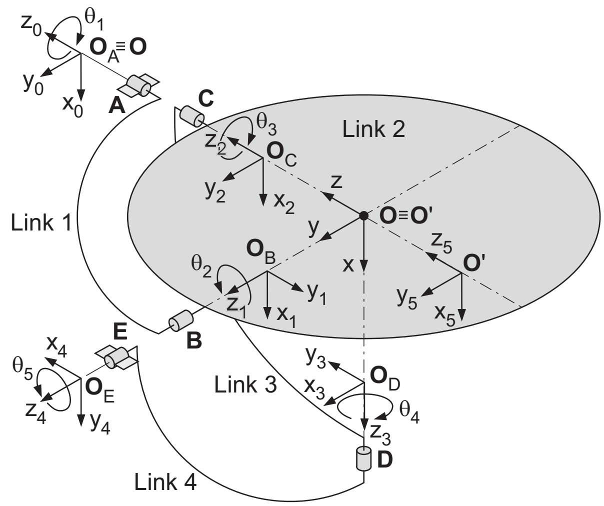

Fig. 2. Reference systems in the home configuration.

[21]; in [22] it is presented an automatic self-calibration procedure for robots with an eye-in-hand configuration; a single camera vision system is used in [23] to calibrate a 2-DoF spherical manipulator.

The calibration method proposed in this paper exploits a kinematic error model developed by the same authors in [24]; such model, based on a formulation inspired to Denavit–Hartenberg (D-H) [25] and on a first order approximation, is briefly recalled in Section 2. Section 3, divided in two parts, firstly introduces the algorithm used to estimate the parameters of the error model and of the hand-eye pose; finally, details on the vision system and its measurement accuracy are given. Results of the calibration procedure are presented in Section 4, where the effectiveness of the error model in fitting experimental data is proved. A brief discussion on advantageous aspects, critical points and future developments of this work is finally given in Section 5.

2. Error kinematic model

The pointing device shown in Fig. 1 inherits its kinematics from a conventional spatial five-bar linkage, whose basic scheme is shown in Fig. 2 where the reference systems of each link are defined on the basis of the D-H convention. In the ideal case, the axes of all the revolute joints intersect at a common point which remains fixed during platform's motion, i.e. the spherical center **O**; thus, the relative pose of the mobile platform with respect to the fixed frame can be simply expressed by a rotation matrix, obtained as a concatenation of relative rotations between the links. However, the kinematic model changes if errors are considered in the mechanics of the device. It is well known that a spherical five-bar linkage (conceived as a closed kinematic chain composed by five links and five revolute joints) results to be overconstrained. To make the structure non-overconstrained, avoiding internal stress and undesired deformations of the links, it is necessary to replace three revolute pairs with cylindrical ones. According to the mechanical design of the mini pointing device, the three internal revolute joints can be actually thought of as cylindrical joints, leaving unchanged the two actuated revolute joints connected to the fixed frame. An ideal motion of pure rotation of the platform would produce only the rotations of such cylindrical joints (θ_2, θ_3, θ_4), whereas the real kinematics affected by errors will introduce also a slide on each joint (d_2, d_3, d_4), leading to a complex motion of rotation and translation of the mobile platform. Table 1 summarizes the constant and variable nominal D-H parameters of the kinematic model. A minimum set of parameters can be identified,

Table 1
Nominal D-H parameters of the kinematic model ($d_2 = d_3 = d_4 = 0$ in the case of ideal kinematics).

Link i	α_i	a_i	θ_i	d_i
1	$-\pi/2$	0	θ_1	0
2	$\pi/2$	0	θ_2	d_2
3	$\pi/2$	0	θ_3	d_3
4	$\pi/2$	0	θ_4	d_4
5	$\pi/2$	0	θ_5	0

Table 2
External parameters of the kinematic model to be defined by calibration.

Parameters	Description
θ_i	i^{th} actuated variable (R-joints, $i = 1, 5$)
a_i, α_i, d_i	i^{th} D-H constant geometric parameters (R-joints, $i = 1, 5$)
a_j, α_j	j^{th} D-H constant geometric parameters (C-joint, $j = 2, 3, 4$)

namely the external parameters (Table 2), whose actual value must be experimentally identified by calibration in order to obtain a kinematic model that describes the real mobility of the machine.

Parameters of Table 2 will be treated in the article by considering their deviation from nominal values; they can be collected in a 14×1 vector, that represents the vector of the design parameters errors:

$$\delta\lambda = \left[\delta\theta_1\ \delta d_1\ \delta\alpha_1\ \delta a_1\ \delta\alpha_2\ \delta a_2\ \delta\alpha_3\ \delta a_3\ \delta\alpha_4\ \delta a_4\ \delta\theta_5\ \delta d_5\ \delta\alpha_5\ \delta a_5\right]^T \tag{1}$$

The error vector in the end-effector pose can be expressed in a linear form as follows:

$$\delta\mathbf{e} = \mathbf{J}(\mathbf{Q}, \lambda)\,\delta\lambda \tag{2}$$

The Jacobian $\mathbf{J}(\mathbf{Q}, \lambda)$ is a 6×14 sensitivity matrix, function of the actuated variables vector **Q** and of the geometrical parameters vector λ. Error vector $\delta\mathbf{e}$ in Eq. (2) is a 6×1 vector defined as $\delta\mathbf{e} = \left[\delta\mathbf{p}\ \delta\boldsymbol{\phi}\right]^T = \left[\delta x\ \delta y\ \delta z\ \delta\phi_x\ \delta\phi_y\ \delta\phi_z\right]^T$; it represents the pose error of the end-effector with respect to the absolute reference system. Rotations are in this case expressed as infinitesimal angles: given the mobile platform angular velocity $\boldsymbol{\omega} = \left[\omega_x\ \omega_y\ \omega_z\right]^T$, it is $\delta\phi_x = \omega_x\,\mathrm{d}t$ (and similarly for the other components). Details on the mathematics required to calculate the sensitivity matrix **J** are fully described in [24]; basically, starting from the closed loop equation $\mathbf{H}_1\,\mathbf{H}_2\,\mathbf{H}_3\,\mathbf{H}_4\,\mathbf{H}_5 = \mathbf{I}_{4\times4}$, where $\mathbf{H}_i$ is the homogeneous transformation giving the pose of frame i with respect to frame