Robotics and Computer–Integrated Manufacturing 49 (2018) 204–214

Contents lists available at ScienceDirect

Robotics and Computer–Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Geometrical calibration and uncertainty estimation methodology for a novel self-propelled miniature robotic machine tool

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ARTICLE INFO

Keywords:
Kinematical calibration
Uncertainty
Observability index
Parallel kinematic machine
Hexapod
Parameter identification

ABSTRACT

This paper reports on a novel calibration method which enables completely automatic identification of the kinematics of a walking hexapod robotic machine tool. The method uses three on-board cameras and relies on a coupled model that combines kinematics and photogrammetry. Both the mathematical modelling and the actual implementation are detailed.

Besides the calibration method, the paper proposes an analytical methodology to estimate the uncertainties of the identified kinematical parameters. The methodology is validated against both experimental results and against previously reported observability indexes. This methodology enables moving from qualitative indexes, observability indexes, to quantitative estimations.

The methodology is applied to guaranty a calibration configuration that allows estimating the robot parameters with an uncertainty of 0.1 mm due to non-repeatability of the measurements.

1. Introduction

Critical installations such us offshore equipment, power plants and large science facilities require a step forward on technologies that enable in-situ repair and maintenance in order to reduce the down times and overall cost of the operations [1]. A shift on technology is happening with the introduction of multipurpose machines that carry out tasks that previously required a set of tailored tools [2]. Technological advances and smart use of joints, drives, controllers and feedback systems [3] as well as proper design methodologies [4] enable the miniaturization of fully featured machine tools providing enough portability to use them in-situ, i.e. out of the workshops. In [5] one of such machines is introduced, FreeHex, a 6 degrees of freedom Parallel Kinematic Machine, PKM, essentially a Stewart–Gough platform [6,7] without any base, so each foot can be freely located according to the characteristics of the part/installation under repair manually by the operator. The parallel kinematic architecture boosts its stiffness and dynamic capabilities compared serial architectures of similar size and weight [8]. Recently, a step-advanced second prototype of this kind of robotic machine has been developed [9], WalkingHex, which has the ability to walk several meters by its own, thus improving the ability to reach intricate spaces where a human operator could not place the machine.

However, in order to take advantage of the capability of this type of bespoke robotic machine tools, calibration procedures must be developed in order that the kinematics are appropriately identified every time the WalkingHex is used without user intervention, autonomously and quickly. In fact, this is a general requirement for PKM of all kinds but especially to robotic systems that are intended to be used as machine tools, because there are no shop-floor oriented calibration and machine geometric accuracy solutions that aid users of PKMs [8,10]. Moreover, the kinematical design of the robots with the ability to move by itself [11,12], even if the purpose of the robot is to carry out repair and maintenance tasks, has been optimized to provide good propulsion performance sacrificing the simplicity and introducing many joints that eventually prevent the robot from achieving high stiffness and accuracy.

Previous work on parallel kinematics calibration has relied mainly on external means to carry out the measurements that feed the calibration procedure, using for example Ball Bars [13,14] like in the case of the FreeHex machine [15], comparator indicators [16], large artefacts [17–19], Laser Trackers [20,21], Coordinate Measuring Machines [22] and articulated measuring arms [23], cameras [24–27], autocollimators and laser interferometers [28,29] or tailored measuring devices [30,31]. Only few works consider providing the machine with the required metrology means to carry out the calibration measurements with internal means. This consists on monitoring passive joints or mobile platform with redundant sensors. In the case of mechanisms with lower mobility joints (planar kinematics) it can be straightforward to use rotary encoders on passive joints [32]. However, truly 3D mecha-

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http://dx.doi.org/10.1016/j.rcim.2017.06.011
Received 9 January 2017; Received in revised form 29 June 2017; Accepted 30 June 2017
Available online 8 July 2017
0736-5845/

Nomenclature

i, j, k	Index for leg (i = 1…6), camera (c = 1…3) and target (k = 1…6)
l_i	Length of leg i
$Offset_i$	Length offset of leg i
$Actuator_i$	Leg i actuator position
$\{x \quad y \quad z\}^T$	Machine end-effector or Tool Center Point position
(α, β, γ)	Machine end-effector or Tool Center Point attitude (Euler angles)
$\{xf_i \quad yf_i \quad zf_i\}^T$	Position of the fixed joint of leg i
$\{xm_i \quad ym_i \quad zm_i\}^T$	Position of the moving joint of leg i
$\{xc_j \quad yc_j \quad zc_j\}^T$	Position of the projection center of camera j
$\{xt_k \quad yt_k \quad zt_k\}^T$	Position of target k
$\{um_i \quad vm_i \quad wm_i\}^T$	Position of the moving joint of leg i in the moving reference frame
$\{uc_j \quad vc_j \quad wc_j\}^T$	Position of the projection center of camera j in the moving reference frame
$R(\alpha, \beta, \gamma)$	Rotation matrix defined by Euler angles (α,β,γ)
Rc_j	Orientation of camera j in the moving reference frame defined by a rotation matrix
N_j	Orientation of camera j defined by a rotation matrix
$m^j_{\alpha\beta}$	Elements of matrix N_j
NT_j	Translation and orientation of camera j defined as an affine transformation matrix
$(c^j_k \quad r^j_k)$	Estimated position of target k imaged at camera j
$(c^j_{ppal} \quad r^j_{ppal})$	Principal point of camera j
f^j	Focal distance of camera j
$(\delta c \quad \delta r)$	Optical distortion
s^j_k	Denominator of collinearity equations associated with the projection of target k in camera j
$\left(\begin{matrix} c_{meas}{}^j_k \\ r_{meas}{}^j_k \end{matrix}\right)_{pose}$	Measured position of target k imaged at camera j
J_{pose}	Jacobian of calibration equation in one pose
J	Aggregated Jacobians in every pose considered in the calibration
$\Delta param$	Estimation of the required increment of the identified parameters
O_1 to O_5	Observability index 1 to 5
$\sigma_1, \sigma_2, \sigma_m$	Singular values (1 to m) of the aggregated Jacobian matrix
m	Number of singular values
C_m	Covariance matrix of the measurements
C_p	Estimated covariance matrix of the identified parameters
U_{param_i}	Estimated uncertainty of parameter i
UPF_{param_i}	Uncertainty Propagation Factor of parameter i

nisms do not allow the integration of sensors so easily, even if some authors have shown theoretical performance of the calibration approach [33,34]. From the implementation point of view, there are no accurate encoders which are suitable to measure the position of spherical joints as those used in the WalkingHex.

Another calibration methodology consists on reducing the mobility of the robot [35], likely by mechanical means. In this way, the mechanism becomes a redundantly actuated one so that internal measurements of the actuators of the robot provide redundant measurements. Mobility constraint can be obtained by different ways, for example Nahvi and co-workers [35–38] describe a mechanical locking of joints. It should be noted that locking of actual joints is not the only possibility to implement this approach, but virtual degrees of freedoms can be constraint. For example in [39,40] orientation constraint of the mobile platform is implemented with the aid of biaxial inclinometers. Several authors have reported the implementation of this method by constraining the displacement of the Tool Centre Point [16,41]. Finally, in the special case of redundantly actuated parallel kinematics this approach can be adopted without extra sensing devices [42].

It can be concluded that there are no previous calibration solutions suitable to be applied to the WalkingHex machine concept so that the kinematics are appropriately identified every time the WalkingHex is used without user intervention, autonomously and quickly.

Moreover, the development of calibration solutions lacks powerful tools to evaluate the appropriateness of proposed configurations during design phase. A number of observability indexes have been proposed [43–48] with this aim, however, there is still discussion about which is better suited for a given scenario [25,49] although practical outcomes have been obtained to determine what parameters are identifiable and what are not [50]. Another approach to estimate the observability and the uncertainties of identified parameters relies on Monte Carlo simulations [51,52], although it requires extensive computing power and time to perform the simulations. In practice, only few work has been reported related to uncertainty estimation on the calibration of robots [53].

This paper aims to address two main research gaps in the field of robotics. On the one hand, the paper reports on a novel calibration solution that is appropriate for a self-propelled robotic machine tool, which consists of a mathematical modelling framework that supports it and the actual implementation on a novel robotic system, i.e. WalkingHex. On the other hand, the paper reports on a methodology to analytically evaluate a calibration configuration (robot poses and calibration hardware) from the design phase that provides a better insight on the identified parameter uncertainties than previous approaches based on observability indexes.

The proposed methodology is validated against both experimental results and against previously reported observability indexes. This methodology is applied to identify the calibration solution for a novel self-propelled robotic system, i.e. WalkingHex, in order to justify the selected configuration. This methodology enables moving from qualitative indexes, observability indexes, to quantitative estimations.

2. Proposed autocalibration solution for a walking hexapod machine tool

The geometrical calibration of a mechanism consists in obtaining a model that relates the actuator positions and end-effector position and attitude with the aim of enhancing the positioning accuracy. In practice, the actual parameters of the assembled machines cannot be measured directly with enough accuracy, but need to be estimated from indirect measurements following an inverse problem approach.

The WalkingHex robotic machine tool is built around a Stewart–Gough [6], or more commonly known hexapod, topology. However, the base platform that links the static joints has been removed, Fig 1, and the top spherical joints have been provided with actuators to enable walking to the place of intervention [9]. The calibration solution is required in order to identify accurately, 0.2 mm, the location of the joints on the feet once the robot is in place, so it can provide accurate performance as it does a machine tool.

Table 1 compares some feasible approaches in terms of the metrics that are more relevant for the application. On the one hand, some solutions from previous literature are considered, on the other hand, the new coupled model approach is also presented.

Solutions based on mechanical locking are hardly applicable to the WalkingHex because the complexity of implementing a locking solution for the rotary joints and developing leg actuators that could be passively