Compensation of thermal effects and cutting-forces acting on ultra high-precision robots

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Abstract:
While dealing with sub-micrometric precision robots, all the events that can deform the robot structure or change its physics proprieties cause a loss of accuracy. In this paper we will focus on two significant issues: the first is the thermal changes acting on the robot and its environment, the second is the deformations caused by the cutting-forces generated during the robot usage. We describe a strategy to measure the deformations caused by those two effects and we propose a calibration procedure to compensate them in real-time.

Keywords: Robotics, calibration, parallel robot, delta kinematic, identification, cutting-forces, compensation, unsteady environment, thermal effects, high-precision measurements, EDM process.

Introduction

Robot calibration is a process that allows increasing robot accuracy. It consists in modeling and compensating the sources of inaccuracy that affect robot positioning [1]. In this article we will focus on the calibration of sub-micrometric precision robots: as they are more precise, those robots are more sensitive to environmental thermal changes and manufacturing process cutting-forces [2]. Therefore, we will propose a strategy to compensate the deformations due to those two effects at the same time.

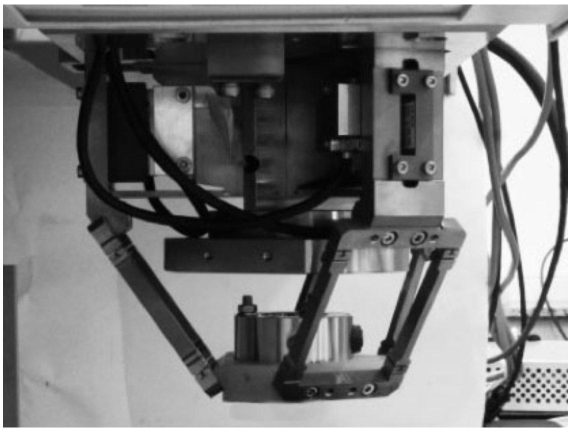

Fig. 1: *The robot Agietron micro-nano*

Our goal is to develop a calibration procedure that will maintain the robot accuracy even while the temperatures are changing and even while the robot is in use. As a case study, we have considered the robot Agietron Micro-Nano (Fig. 1 and 2), a robot designed for micro electrical discharge machining (μ-EDM). It has a resolution of 10 nm, a working volume of ~1 cm^3 and a size of ~20x20x25cm. The Agietron Micro-Nano is a parallel robot based on the professor Clavel's Delta kinematic [3][4]. To achieve high-precision, high-rigidity and no friction, it has been built in titanium, while all the joints are flexure hinges. The features of this robot have been drawn on to build a new modular concept of design that will bring more flexibility in robot industrial applications [5].

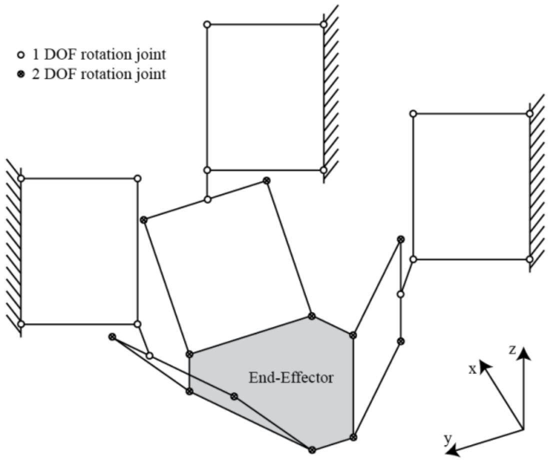

Fig. 2: *Kinematic chain of the robot*

The micro-EDM process is used for cutting complex shapes and thin walled configurations without distortion. It is recommended for hard materials or for materials typically machined by grinding [6]. The process is suited for applications characterized by extremely exacting tolerances (accuracy ~1 μm). Since it is a contactless process, it is also well suited for making fragile parts that cannot take the stress of a normal machining process. To perform it, an electrode or a wire is mounted on the robot end-effector. A controlled electrical spark is used to erode away from the manufactured object any material that can conduct electricity. A series of discharges takes places between the electrode and the conductor while the robot is moving along the desired trajectory.

The measuring system and the force simulator

To measure the deformations, we have developed a 6 DOF (degrees-of-freedom) measuring system (Fig. 3).

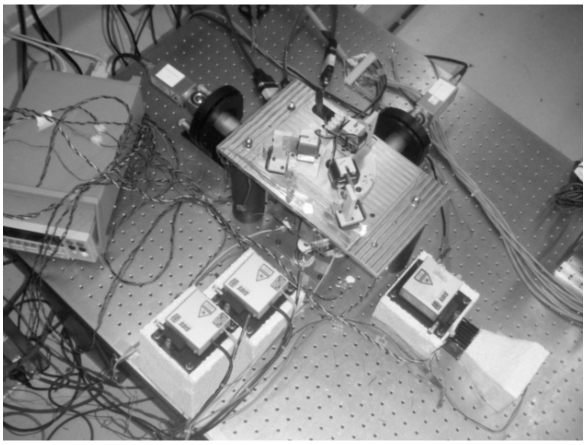

Fig. 3: *A picture of the system*

Translations are measured using 3 laser interferometers (SIOS SP-2000, resolution of ~1.24 nm, wavelength of ~633 nm, stroke of ~2 m) arranged orthogonally. However the three interferometers are mounted horizontally. While the interferometers measuring the horizontal axes have direct access to the cube facets (fig. 4), the vertical axis is measured using a 45° mirror (fig. 5).

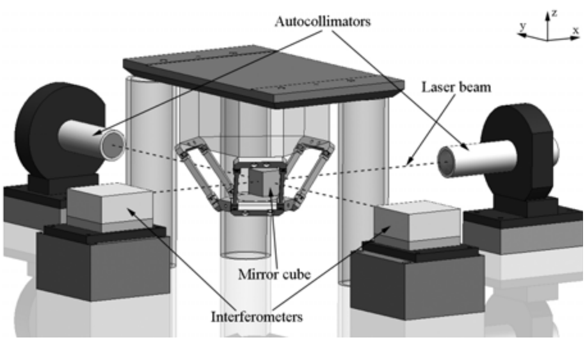

Fig. 4: *The instruments measuring horizontal translations and all rotations*

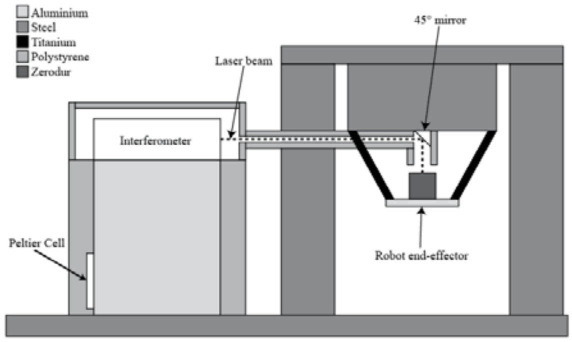

Fig. 5: *Scheme of vertical axis measurement*

Rotations are measured using 2 autocollimators (Newport LDS-1000 Autocollimator, resolution of 0.02 arcsec, stroke of ±400 arcsec, around the two axes perpendicular to the measuring beam), capable of measuring in total 4 DOF (the vertical axis measure is redundant). The principal aim of the rotation measurement is to compensate the end-effector parasitic rotations. In fact, those rotations affect the interferometer reading, adding the so called cosine error [7]. Errors dues to parasitic rotations are corrected in real-time. To avoid measuring the drift of the measuring system, we stabilize the instruments supports, with a maximum error of ±0.01 °C. The temperature control is done using a Peltier cell glued on each interferometer support.

A mirrored cube is glued on the end-effector of the robot. It will be use to reflect the beams of the measuring instruments. Furthermore, it defines the origin and the frame of the system. The cube is built in Zerodur®, a material with an extremely low thermal expansion coefficient (~0.02 x 10-6/K at 0-50°C). The surface roughness of the mirrored facets is 30 nm.

Temperatures measurements are acquired using a total of 11 platinum resistance thermometers: 3 sensors measure the air temperature near the interferometers beams and 8 sensors are glued on the system, along the measuring loop and on the robot. The thermal measurements are acquired using a high-precision multi-channel A/D converter (Keithley 2700).

To simulate the μ-EDM efforts we have built a device that generates definite contactless forces on the robot end-effector (Fig. 6).

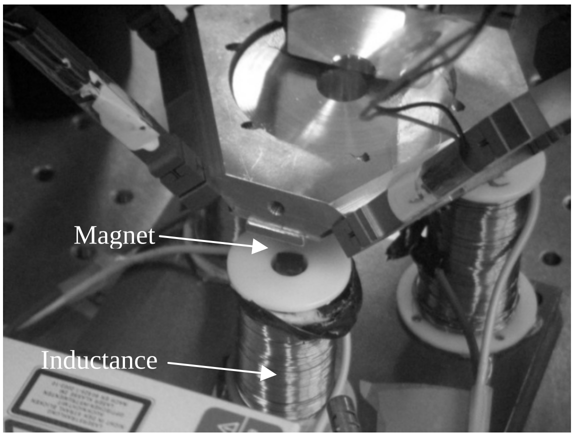

***Fig. 6:** The force simulator system mounted under the robot end-effector*

Three inductances have been mounted right under the robot end-effector, while three magnets have been fixed on the end-effector, in axis with the inductances. By applying a current to the inductances, we can generate repulsive forces and momentums on the end-effector. Those forces are dimensioned to be similar to the ones generated during the μ-EDM process (around 1-2 N [8]). Further details about this device can be found in [9].

Measures

To study the thermal behavior of the robot, we have measured the robot position while the environmental temperatures were changing. We used the air conditioning (AC) to simulate the free oscillation of an industrial environment in the following way: before starting the measuring session, the AC consign has been putted to 20 °C. When the lower temperature has been reached, we turned off the AC and we started acquiring the measurements. Therefore, the measurements have been collected while the temperatures were varying. In a period of 5 hours, the air temperature has varied of ~3°C (Fig. 7 – Notice the difference between the air temperature and the robot temperature. This is due to the fact that during the measures the robot was in use. The heat produced by the motors has augmented the robot structure temperature).

To collect the deformations measurements, the robot has been displaced in 216 positions, a motor coordinates grid of 6x6x6 positions. In each of them a set of forces has been imposed to the end-effector (0, 0.5, 1, 1.5 and 2 N), and a measure for each force has been taken. In total 1080 measures have been acquired. This set of data will be used only for calibration. This set of measure has been repeated two times in order to measure the force deformations also while the environmental temperature is changing. Totally 2160 measures have been acquired. A second set of data has also been taken. This time the set is composed by 125 positions (a grid of 5x5x5 position). Notice that those points are not coincident with the one of the first set. Also in this case several forces have been imposed to the end-effector (0, 0.5, 1, 1.5 and 2 N), obtain in total 625 points. This data set will be used only for the validation of the model.

For each point, a set of four measures is acquired. The standard deviation of those four points is calculated. This value is never superior to 30 nm. This control is done to assure the quality of the measures.

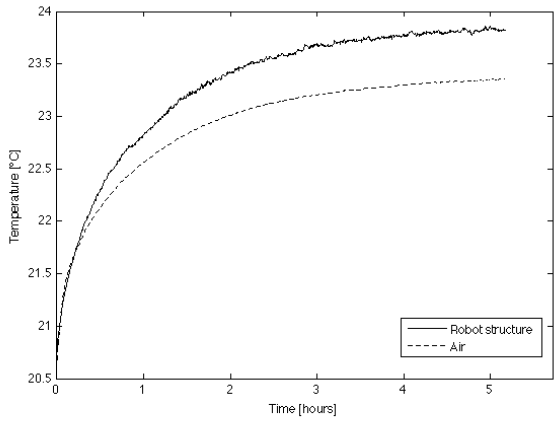

***Fig. 7:** Temperatures during the measures*

Data processing and calibration

Following the calibration procedure described in [10], the next step is to use the collected measurements to build a calibrated model of the robot. This model will have as input the desired end-effector position (X, Y, Z), the value of the force applied on the end-effector and the temperatures. As output, it will return the motor coordinates (q_1, q_2, q_3) corresponding to the desired position. In robotics, this is called “inverse geometric model” (eq. 1), IGM.

$$q_1, q_2, q_3 = f(X, Y, Z, F, T_1, \dots, T_{11}) \qquad (1)$$

The model built in such way will keep in account the geometric features of the robot, the deformations caused by the cutting-forces and the thermal effects. This model will be done multiplying the variables seen before (the measures and the forces), and finding the good coefficients to fit the relation. To perform the coefficients research, we will use the “stepwise regression” algorithm (Matlab®, Statistics Toolbox™). This algorithm has the capability of adding or removing terms from a multi-linear model. This is done comparing the statistical significance of the terms in a regression. The algorithm starts with an initial model that is compared with larger or smaller models. At each step, a coefficient is added to the model, thus, it is compared the final error with or without this last coefficient. If there is an improvement in the prediction, the coefficient is kept. Otherwise the coefficient is discarded. For the coefficients that are already in the model it happens the same: if the influence of any coefficient is under a certain threshold, the coefficient is rejected.

Depending on the terms included in the initial model and the order in which terms are moved in and out, the method may build different solutions from the same set of terms. The method terminates when any single step improves the model prediction capability. There is no guarantee that a different initial model or a different sequence of steps will not lead to a better fit. In this sense, stepwise models are locally optimal, but may not be globally optimal.

The stepwise regression algorithm has been chosen for two reasons: firstly it automatically deletes useless parameters, keeping the robot model computationally fast. Secondly, the algorithm converges and gives a solution in some seconds. On the contrary, algorithms tested in previous works (neural networks, gradient descent based parameters research, genetic algorithms and splines optimization) take some hours to give a solution [7].

Generating the data for the calibration

The first step that we do is separate the relation (1) in three different one. In this way the problem will be less complex. Basically, what we do here is to calibrate each motor separately (eq. 2):

$$\begin{cases} q_1 = f(X,Y,Z,F,T_1,\dots,T_{11}) \\ q_2 = f(X,Y,Z,F,T_1,\dots,T_{11}) \\ q_3 = f(X,Y,Z,F,T_1,\dots,T_{11}) \end{cases} \qquad (2)$$

For each equation of the system we will consequentially find different coefficients.

We will now focus on how we calibrated one single axis; the procedure is the same for the remaining two.

What we want is a model that, given the desired end-effector coordinate, the force acting on the end-effector in that moment and the temperatures, it returns the motor coordinate for the motor q_1. For the moment we have only 15 variables, so we will use them to generate new ones: this is done by multiplying them together, in order to see if the model fits the correlation of more complex variables.

From three interferometer readings (1st order) we generate terms of the 2nd and 3rd order:

1st order: X, Y, Z

2nd order: $X^2, Y^2, Z^2, XY, YZ, XZ$

3rd order: $X^3, Y^3, Z^3, XYZ, X^2\,Y, X^2\,Z,$
$Y^2 X, Y^2 Z, Z^2\,X, Z^2\,Y$

From the departing 3 readings, we have generated 16 new correlation variables. In total, we have 19 pure geometrical variables.

Doing the square and the cube of the force, we obtain three new variables: F, F^2, F^3.

Multiplying the 19 geometrical variables with the force ones, we obtained 57 new variables.

Adding all the variables together and including the 11 temperature readings gives a final number of 90 variables. The calibration of one axis can be seen as the research of the coefficients $a_1,\dots,a_n$ that satisfy the following relationship (eq. 3):

$$\begin{bmatrix} q_1 \\ \cdots \\ q_m \end{bmatrix} = A \begin{bmatrix} a_1 \\ \cdots \\ a_n \end{bmatrix} + b \qquad (3),$$

$$\mathrm{A} = \begin{bmatrix} X_{1,1} & \dots & F_{1,1} & \dots & T_{1,1} & \dots \\ \dots & & \dots & & \dots & \\ X_{1,m} & \dots & F_{1,m} & \dots & T_{1,m} & \dots \end{bmatrix} \qquad (4)$$

where $[q_1 \quad \cdots \quad q_m]^T$ is the vector of the motor coordinates q_1, A is an *m x n* matrix containing the values of the all interferometers readings, force values plus all the built coefficients corresponding to the motor coordinate plus all the correlated coefficients we want to fit, $[a_1 \quad \cdots \quad a_m]^T$ is a vector containing the parameters that “stepwise regression” has to fit to make the (3) true and b is an offset (the last coefficient to be found). In this case m = 2160, the total number of measures used for the calibration.

Stepwise regression algorithm has been launched to solve this problem and only 33 parameters have been kept. The measurements in the calibration set have been fitted with an error of ±59 nm in the 90% of the points (1.645σ). Regarding the q_2 and the q_3 motor coordinates, we had respectively a model composed by 35 and 39 parameters, with an error in predicting the calibration set of ±67 and ±77 nm (fig. 8).

Calibration results

The parameters found before are finally used with the validation set. As seen before, this data has not been used to calibrate the robot, so it will be the final demonstration of its calibration.

Using the validation error we have a final error of ±95 nm along the q_1 axis, ±77 nm along the q_2 axis and ±76 nm along the q_3 axis, considering an interval of confidence of 90 % (1.645σ) (fig. 9).

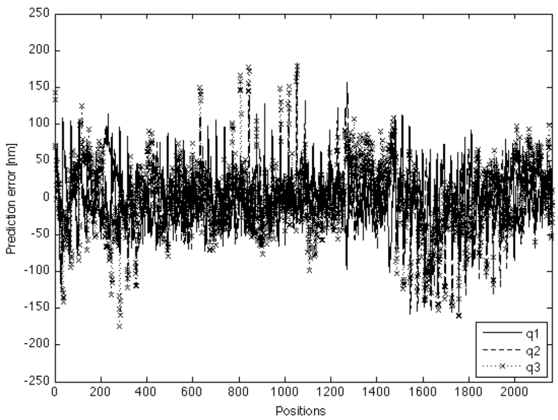

Fig. 8: *Error prediction after calibration in the data set used for calibration*

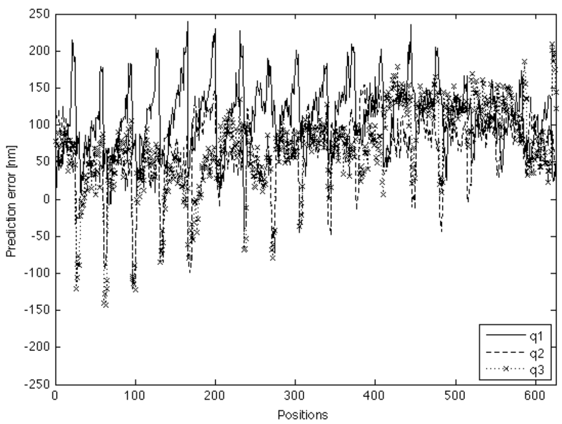

Fig. 9: *Error prediction after calibration in a data set not used for calibration*

To prove that that force and temperature have both to be considered to have a good calibration, we have tried to test different models (see Table 1). With a model that keeps in account only the geometric parameters (first column of the table) we obtained an absolute accuracy in the best case of ±1.5 μm. The results are similar if we introduce the force calibration (second column). When adding the parameters related to the temperature (third column) we obtain an absolute accuracy of ±97 nm in the best case. Nevertheless we observe that for the coordinates q_2 and q_3 the results are still improvable. This happens because the force generated by the force simulator is almost completely discharged on q_2 and q_3 axes. To improve the accuracy of the two axes, we have to consider also the force in the calibration process (fourth column).

	G	G+F	G+T	G+T+F
q_1	±1.5 μm	±1.5 μm	±97 nm	±95 nm
$param_{q_1}$	14	14	28	33
q_2	±2.1 μm	±2.1 μm	±184 nm	±77 nm
$param_{q_2}$	15	15	23	35
q_3	±2.6 μm	±2.6 μm	±270 nm	±76 nm
$param_{q_3}$	17	18	27	39

Table 1: *Absolute accuracy obtained on each motor axis, using a pure geometric model (G), a geometric model + force model (G+F), a geometric + thermal model (G+T) and a complete model (G+T+F). The number of parameters used to obtain this result for each axis is also indicated.*

Conclusion and future work

We have demonstrated that to reach a level of accuracy inferior to ±100 nm we have to keep in account thermal effects and the cutting-forces acting on the robot end-effector.
Furthermore, we have seen that thermal effects are more significant than cutting-forces effects.
In the future we will work on the calibration of a two robots system. We will study how two robot can interact together at high-precision, while thermal effects and cutting-forces are acting on them.
The original contribution of this work is the calibration of a 3 DOF ultra high-precision robot while environmental effects and cutting-forces are acting on the robot.
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