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THERMAL BEHAVIOR OF AN ULTRA HIGH-PRECISION LINEAR AXIS OPERATING IN INDUSTRIAL ENVIRONMENT

Emanuele Lubrano, Prof. Reymond Clavel

EPFL, LSRO, Lausanne, Switzerland

Abstract: Thermal expansion is the major source of inaccuracy for ultra high-precision robots. In this paper we propose a strategy to model and compensate this effect. The experiment is run using a 1 DOF (degree-of-freedom) parallel robot equipped with ten temperature sensors; the displacements of the end-effector are measured using an interferometer. After a session of measurements the data collected has been processed using the stepwise regression algorithm. A model of the thermal robot behavior has been found and implemented in the robot controller. In this way it has been possible to compensate all the thermal effects, reaching an absolute accuracy of 10 nanometers.

Key words: Calibration, Robotics, Parallel Robots, High-precision measures, Interferometer, Thermal stabilization, Thermal drift.

I INTRODUCTION

Calibration is the art of improving accuracy [1]. In robotics, it consists in modeling and compensating the sources of inaccuracy that affect robot positioning [2]. These are considered according to the robot application and according to the desired level of accuracy [3] [4]. Since this work considers a flexure hinges based 1 DOF parallel robot designed for sub-micrometer applications, it is not sufficient to consider only the robot geometric errors: temperature variations have a significant influence on the robot precision, deforming the robot parts.

In a previous work [5] a thermal stabilization of the robot and of the measuring devices has been done before proceeding with the calibration. Even if this approach gave good results (accuracy after calibration below ±100 [nm]), it is not possible to use it in an industrial context: a thermal stabilization of 8-10 hours must be done before the normal use of the robot. Therefore, the aim of this article is to propose a strategy to keep the robot calibrated while the environmental characteristics are changing, compensating the thermal drift in a closed-loop way. Moreover, we analyze how temperature variations act on robot geometry and on the measuring loop. The experience gained on the 1 DOF case will be finally used to study more complex cases such as a 3 or a 6 DOFs robots.

II THE MEASURING SYSTEM

Since we are interested in measuring the displacements of the end-effector and the thermal behavior of all the robot parts, a convenient measuring system has been built (Fig. 1).

Robot displacements are measured using a laser interferometer (SIOS SP-2000, resolution of ~1 nm). Ten temperatures sensors (platinum resistance thermometers – pt1000) have been mounted on the entire measuring loop (refer to Fig. 1 for the sensors position). The thermal measurements are acquired by a computer using a multi-channel A/D converter (Keithley 2700).

The linear axis has a stroke of 10 mm and it is moved by a voice-coil motor. Its position is read by a Heidenhain® rule with a resolution of 10 nm. The system is controlled in real-time by a computer.

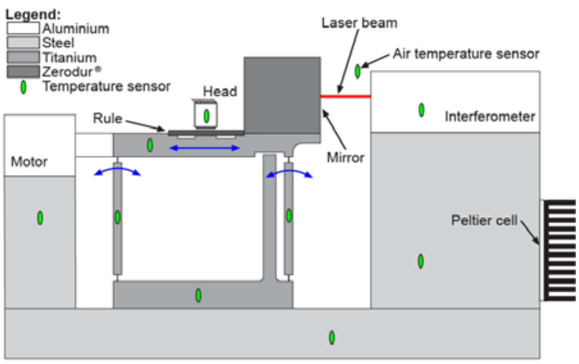

Figure 1: The robot and the measuring system

The problem in measuring at nanometer precision is that thermal expansion affects also the measuring device. The data collected neglecting the interferometer drift is basically wrong, because it does not represent the behavior of the robot, but the behavior of the system "robot + measuring device". Even if it is possible to find a model that fits the data, it will be false as well: in fact, manufacturing a piece with such a wrong model will not have the accuracy expected.

The whole system has been conceived in order to let drift only the robot. The most expensive solution to obtain this is to use a dual beam interferometer: one beam is used to measure the displacement, while the second one is used to map and compensate the interferometer drift. In this paper we propose another reliable way that uses a one-beam interferometer.

Firstly, we use the air temperature compensation feature built in the interferometer. This feature will automatically compensate the drift due to the internal interferometer parts drift and the drift due to the air temperature changes.

Secondarily, we stabilize the support where the interferometer is mounted. A Peltier cell has been mounted on the interferometer base in order to compensate the heat produced by the interferometer head and to stabilize it. A PID controller logic is used to command the Peltier cell, and the interferometer base is kept to the temperature of 23 °C, with a maximum error of ±0.01 °C (see Fig. 2). To reach this level of stabilization only half an hour is needed.

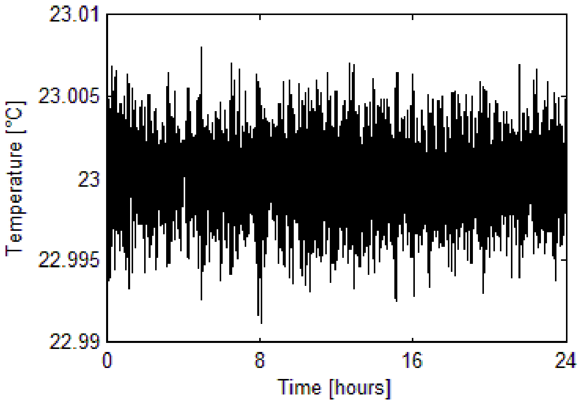

Figure 2: The temperature of the interferometer base during the entire measurement session

The mirror cube used to reflect the interferometer beam is built in Zerodur®, a material with an extremely low thermal expansion coefficient (~0.02 x 10^{-6}/K at 0-50°C).

In Fig. 3 is shown the measurement loop and the parts that are thermally insulated, compensated or limitedly affected by thermal drift.

Notice also that all the system is mounted over a Newport vibration insulating table. The stabilization done on the interferometer base doesn't affect the temperature of the table because of its wideness. The table and the robot follow the evolution of the temperature air. At last, the motor and its support are not considerate in the stabilization because they are outside the measurement loop.

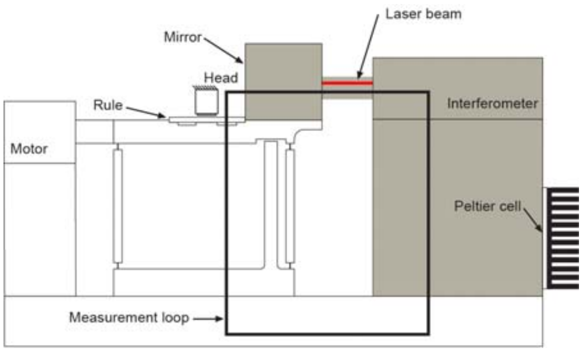

Figure 3: The measuring loop and the parts that are not affected by thermal drift (in gray).

III MEASURE AND DATA PROCESSING

A. Measuring strategy

The measurements have been done for 1 day, while the room temperature was changing (from 20.5 °C to 21.5 °C. We used the air conditioning 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 the minimum temperature level possible (~20 °C). We started the measurements when the room reached the lowest temperature. After that, a higher consign has been imposed to the AC device (~22 °C). Therefore, the measurements have been collected during this air temperature change.

The data has been acquired during the weekend and all the equipment were controlled remotely. In this way the temperature drift due to operators entering in the robot's room has been minimized.

The robot workspace is a line of 10 mm length. Measurements have been taken to the following motor coordinates: 0.0 -4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 [mm] (18 points – the origin is placed in the center of the rule). For each of those points the interferometer acquired 4 separate measurements. Each single measurement in actually an average of 2048 measurements, but the interferometer controller communicates only the average to the computer. The purpose of measuring 4 times the same point is the quality control of the measures. We can detect if something went wrong in the measurement by calculating the standard deviation of those 4 measurements. If the value of it is superior to 5 [nm] the whole four points will be rejected (see Fig. 4 for the plot of the standard deviations). Otherwise they will be averaged and kept for the next phases of the experiment.

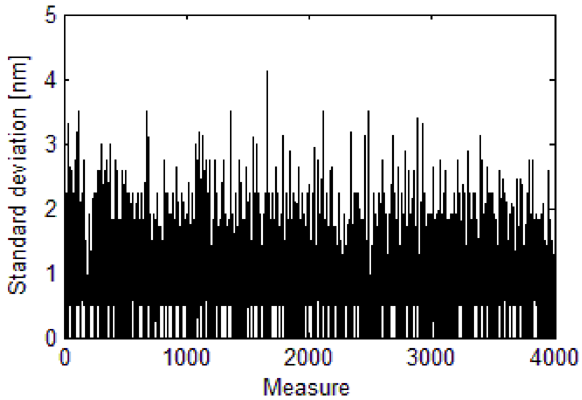

Figure 4: Standard deviations of the measurements

During 24 hours, a total of 15844 measures have been taken (3961 groups of 4 measures). Since any group of 4 has a standard deviation superior to 5 [nm], all the points have been considered. For the next phase, only the data collected in the first four hours of the experiment has been considered, because the temperature variation occurs in this period. The graph in fig. 5 shows the evolution of the air temperature during the first 4 hours of measurements.

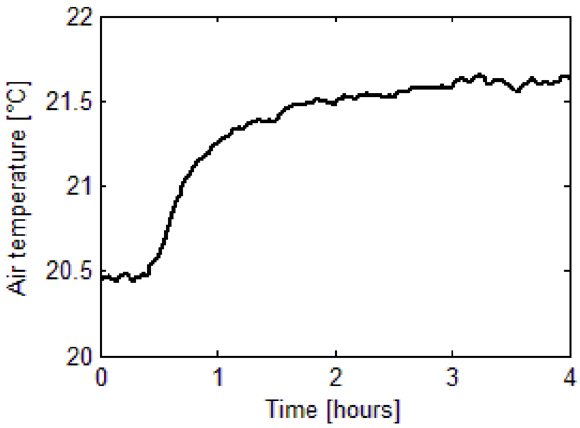

Figure 5: Air temperature during the measures

4032 measures have been considered, and after merging each group of 4 measurements together, only 1008 points remains.

This data set has then been divided in two different sets, the first composed of 840 points (that we will call the "input" set), the second of 168 (the "validation" set). The input set will be used to find the model parameters, while the second one will be used for validation and to calculate the error after calibration.

B. Data processing

At this point of the work, it was possible to choose between model based approaches (e.g. parameters research) and model-free ones (e.g. neural networks). The choice has been oriented towards model based approaches because in industrial context, they are well understood and are more reliable than the model-free ones [5].

Between all the different model based approaches the "stepwise regression" algorithm (Matlab®, Statistics Toolbox™) has been chosen. In fact, this algorithm is one of the fastest in finding the coefficient values. Thus, it is capable to delete useless coefficients and finally, the solution proposed by the algorithm is at least locally optimal [10].

This method 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 – over a certain tolerance – in the prediction, the coefficient is kept. Otherwise the coefficient is putted to zero (discarded). For the coefficients that are already in the model it happens the same: if the influence of the old 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.

C. The parametric model

The parametric model that has been used during the experiment is the following:

$$y = \alpha x^2 + \beta x + \gamma + a_1 t_1 + \ldots + a_{10} t_{10} \qquad (1)$$

In this equation, x is the position measured with the interferometer; y is the position measured on the robot rule and $t_1,\ldots,t_{10}$ are the readings of the 10 temperatures sensors.

This model could be divided in two parts: the coefficients α and β are dependent by the robot geometry, while the coefficients $a_1,\ldots,a_{10}$ depend from the temperatures. In short, the model is composed by 13 parameters, 2 purely geometrical, 10 depending from thermal behavior and an offset.

Models that imply interaction between geometric and thermal coefficients have been tested as well (consider the interaction between geometry and temperatures will generate other 20 coefficients), but all the mixed coefficients were rejected by the stepwise regression algorithm because they were insignificant.

IV RESULTS

The "stepwise regression" algorithm has been launched using the input data set and the model (1). The parameters founded have been used to calculate the position of the validation set. In this set, a final absolute error of ±10 nm for the 90% of the points has been obtained. In the input set the errors are of the same order of magnitude.

To demonstrate the importance of the temperature prediction it has been build a model that considers only the geometric error of the robot (model with 3 parameters). In this case we have an error of ±206 nm for the 90% of the points. In Fig. 6 it is possible to see a comparison of the two models in all the measures. It is interesting to compare how the geometric model error follows the plot of the air temperature of Fig. 5.

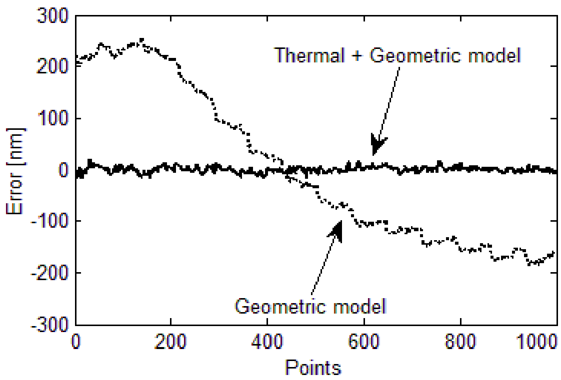

Figure 6: Comparison between error with pure geometric model and geometric + thermal model

It has also been tested what happened using a smaller data set for the parameter research. The input set has been cut in order to have only the first 300 points. The stepwise regression has converged, but this time the error in the validation set was ±40 [nm] for the 90% of the points.

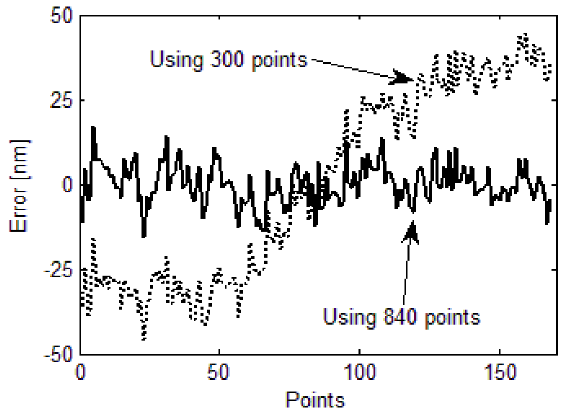

Figure 7: Comparison between errors with two models (in the validation set)

From the point of view of the robot final user, it is important to underline that the sensors and the thermal compensation must be active during the normal use of the robot. Temperature has to be read and used to compensate the drift. From the computational point of view, for a 1 DOF robot, this operation is not so demanding. But for a more complicate case (for example a 3 DOFs robot), it could be necessary to separate the geometric model parameters calculation from the thermal compensation one. The geometric model part can be solved in real-time, while the thermal compensation part has not this necessity: it could be calculated every 10 seconds, because the changes of the temperatures are very slow.

V CONCLUSIONS AND FUTURE WORK

As we have shown in this paper, it is fundamental to keep in account thermal variations while dealing with ultra high-precision levels of accuracy. During the normal use of the robot, temperatures must be read and used to compensate the thermal drift. Moreover, the concept of "thermal calibration" for ultra high-precision robots has been proved.

In comparison with previous works on this subject we have obtained the following improvements: firstly, there is no more need to stabilize the environment for 8-10 hours, for every use of the robot. Now only a stabilization of the interferometer it is needed and it takes half an hour. Secondly, we have reached a ten times better level of final accuracy.

The results extrapolated from this work will be used to perform the thermal calibration of a 3 DOFs robot.

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