Calibration and measurement reconstruction of a precision positioning stage

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Abstract

The paper presents a metrology laboratory experiment for the accurate positioning of an xy table using sensors collocated with the actuators. Positioning accuracy is achieved thanks to a calibration and a measurement reconstruction based on a least-square optimization of data from a temporary measurement of the table position. A rapid control prototyping system is used to run the experiment both in simulation and on the real plant.

1 Introduction

In various precision applications the calibration of a mechanical structure, i.e. the characterization of its behaviour, is often necessary because accurate measurements of the quantity of interest are not available. Based on the calibration results, other related measurements are used to calculate an estimate of the quantity of interest. In practice, the quantity of interest can be accurately measured with a laboratory grade measurement system (typically an interferometer) and the relation between this quantity and other related quantities are determined.

A laboratory experiment offered to senior bachelor students in mechanical engineering at SUPSI aims at accurately positioning an xy table using sensors collocated with the actuators but without direct measurement of the table position.

2 The XY Table

The mechanical system used is shown in Fig. 1. The xy table can be positioned on a plane with a stroke of 10mm along both axes with the help of voice-coil motors and position sensors which lie underneath the two axes (not visible on the picture).

Positioning is achieved with a repeatability in the order of a few tenths of micrometers. Because of unmodeled geometric behavior, the positioning of the table is far from accurate with positioning errors exceeding 50 micrometers.

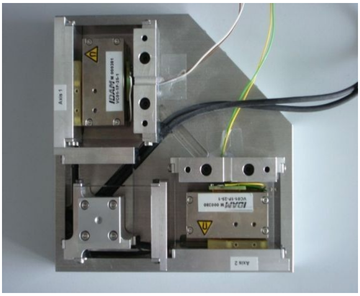

Figure 1: 2-DOF structure with flexible joints. The table to be positioned accurately is shown in the bottom-left corner.

3 The control and measurement environment

The control and measurement platform [1] is composed of a standard PC and of a commercial Compact-PCI system. Three Compact-PCI boards developed at SUPSI measure the axis sensor and interferometer signals and drive the voice-coil motors.

The platform exploits the results of the RTAI project (www.rtai.org), which offers a real-time extension of the Linux operating system and interfaces with various CACSD tools (Matlab/Simulink, Scilab/Scicos or EicasLab are supported).

The calibration and reconstruction can be first performed and evaluated in simulation on the PC, and then, through minor modifications, repeated on the real system with the help of the Compact-PCI system.

4 The measurement reconstruction

The system can be simulated thanks to a Simulink file (see Fig. 2) containing the dynamic model of the 2 DOF structure (see block “2dof flexure model”) and the geometric model of the table position (x_o, y_o) as a function of the axes position (x, y) (see block “interferometer model”). A controller processes the measurements of (x, y) and moves the axes to the position (x_{ref}, y_{ref}). The simulation shows that the table position (x_o, y_o) remains far from (x_{ref}, y_{ref}).

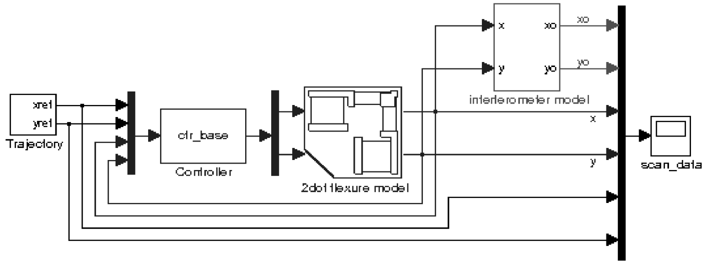

Figure 2: Simulink model of the system for simulation.

The functions $x=f_x(x_o,y_o)$ and $y=f_y(x_o,y_o)$, if known, could be used to determine the value of (x, y) which is necessary to take the table position (x_o, y_o) to the desired value (x_{ref}, y_{ref}). Unfortunately, the exact form of these functions is unknown. However, a polynomial approximation of the form

$$x=f_x(x_o,y_o) \sim \theta^x_1+\theta^x_2\cdot x_o+\theta^x_3\cdot y_o+\theta^x_4\cdot x_o\cdot y_o+\theta^x_5\cdot x_o^2+\theta^x_6\cdot y_o^2=\mathrm{x}_{\mathrm{rec}} \quad (1)$$

$$y=f_y(x_o,y_o) \sim \theta^y_1+\theta^y_2\cdot x_o+\theta^y_3\cdot y_o+\theta^y_4\cdot x_o\cdot y_o+\theta^y_5\cdot x_o^2+\theta^y_6\cdot y_o^2=\mathrm{y}_{\mathrm{rec}} \quad (2)$$

can be used (here a second order one). The variables x_{rec} and y_{rec} are the reconstructed measurements (i.e. the estimate of (x, y) which corresponds to a desired value of (x_o, y_o)). The unknown parameters θ^x_i and θ^y_i can be obtained from a set of measurements indicated by the vectors of variables $\boldsymbol{x}$, $\boldsymbol{y}$, $\boldsymbol{x}_o$ and $\boldsymbol{y}_o$. Equation (1) expands accordingly to the vector equation

$$\boldsymbol{x}=\theta^x_1\cdot\mathbf{1}+\theta^x_2\cdot\boldsymbol{x}_o+\theta^x_3\cdot\boldsymbol{y}_o+\theta^x_4\cdot\boldsymbol{x}_o\cdot\boldsymbol{y}_o+\theta^x_5\cdot\boldsymbol{x}_o^2+\theta^x_6\cdot\boldsymbol{y}_o^2+\boldsymbol{e}_x$$

$$=[\mathbf{1}\ \boldsymbol{x}_o\ \boldsymbol{y}_o\ \boldsymbol{x}_o\cdot\boldsymbol{y}_o\ \boldsymbol{x}_o^2\ \boldsymbol{y}_o^2]\cdot[\theta^x_1\ \theta^x_2\ \theta^x_3\ \theta^x_4\ \theta^x_5\ \theta^x_6]^T+\boldsymbol{e}_x=\Phi\cdot\Theta_x+\boldsymbol{e}_x$$

The approximation error $\boldsymbol{e}_x = \boldsymbol{x} - \Phi \cdot \Theta_x$ can be minimized with the least square estimate $\Theta_{\boldsymbol{x}} = (\Phi^T \cdot \Phi)^{-1} \cdot \Phi^T \cdot \boldsymbol{x}$ yielding the parameters θ^x_i for the polynomial (1). The same procedure applies to the y axis.

The modified Simulink model with the variable reconstruction is shown in Fig. 3. In the block "reconstruction", the polynomials of equations (1) and (2) are implemented.

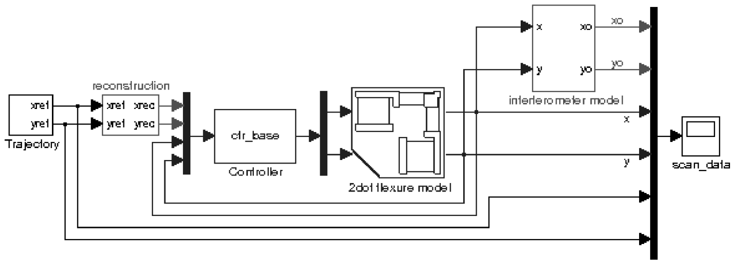

Figure 3: Simulink model with the reconstructed measurements.

5 The experiment

A Simulink model is used to perform measurements on the real hardware (see Fig. 4). The main difference with the model of Fig. 3 is that the block "2dof flexure" now contains the interfaces to the actuators and sensors. Also, the geometric model is replaced by the interfaces to the interferometer.

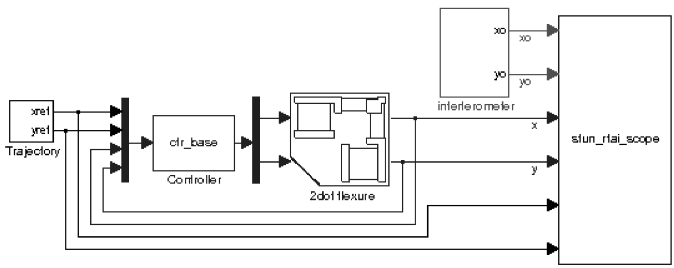

Figure 4: Simulink model with interfaces to the real system

The Simulink model can be compiled and transferred to the Compact-PCI system from where a sample trajectory can be run on the mechanical system. The axis sensors and interferometer measurements can be recorded and uploaded to the PC.

The steps simulated above can be repeated with the measured data. With the new reconstruction functions the Simulink model of Fig. 4 is modified similarly to the changes from Fig. 2 to Fig. 3.
With the modified model containing the on-line reconstruction of the table position it is possible to achieve accurate positioning of the xy table without any direct measurement. Fig. 5 shows the resulting improvement with the positioning error reduced from 100 μm to 0.5μm without the need of any explicit geometric model.

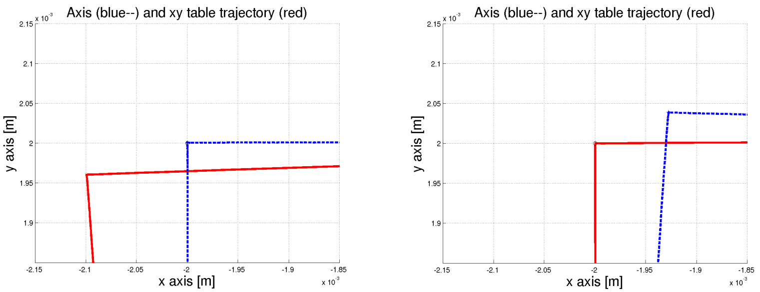

Figure 5: Original trajectories (left) and trajectories with data reconstruction using a 4th order polynomial approximation (right).

6 Conclusions

The presented experiment is very valuable to students, who are able to effectively learn how to characterize the behavior and then to improve the positioning accuracy of a precise system.
The documentation for the students is published on the web [3], while the solution and support for replicating the experiment are available on request from the author.

References:

[1] S. Balemi, Rapid Controller Prototyping Platform for Precision Applications, Proc. of 6th EUSPEN intern. Conf., Baden b. W., 2006
[2] R. Bucher and S. Balemi. Rapid controller prototyping with Matlab/Simulink and Linux. Control Eng. Practice, 14:2, Feb. 2006
[3] www.dti.supsi.ch/~smt/labo_metro.html: SUPSI Metrology Lab.