Error budgeting as a tool for the design of a 2D moving platform with nanometer resolution

M. Torralba[1], M. Valenzuela[2], R. Acero[1], J.A. Yagüe-Fabra[2], J.A. Albajez[2], J.J. Aguilar[2], R.J. Hocken[3]

[1]*Centro Universitario de la Defensa, Zaragoza, Spain*
[2] *University of Zaragoza, Spain*
[3] *University of North Carolina at Charlotte, United States of America*
jyague@unizar.es

Abstract

Some of the new nanotechnology applications are strongly dependent on the development of also new high accuracy measuring and positioning devices. It is in this context that a novel two-dimensional moving platform is being designed. With nanometer resolution and submicrometer accuracy, the particular requirement is the large range of travel 50x50 mm, in order to increment the displacement of an integrated Atomic Force Microscope (AFM). To predict the final errors of the first obtained prototype a design methodology based on an error budgeting is presented. The evaluation is done by the combination of a mathematical machine model and the estimation of the geometrical errors related to the platform motion.

1 Introduction

The 2D moving platform under development allows X and Y planar movement which will be measured by a Renishaw RLE fiber optic laser encoder system comprising a RLU laser unit, three RLD laser detector heads (two for Y axis and one for X axes) and RCU compensation units of environmental conditions (temperature, humidity, pressure). The RLD detector heads constitute the core of the optical measuring system containing double pass interferometric optics, so that, with the use of two flat mirrors, allow the determination of the relative displacement between an optical reference (housed within each of the RLD10) and the respective plane mirror positioned on the axis of measurement. The configuration used provides a theoretical resolution of 10 nm. The possible spurious translation errors in Z, as well as the roll and pitch errors, will be measured by means of three capacitive sensors (Lion Precision probe C5-E Elite driver).

2 Machine model

To evaluate the performance of the initial design, a geometrical model of the machine was defined based on the relationships between two different coordinate systems: the fixed stage $\{O_0\}$, and the moving platform $\{O_1\}$. The first one is located in the center of the metrology frame, where the three laser encoder heads are integrated. The y-axis interferometers, as a reference, are assumed to be parallel to the coordinate system (Y_0). Hence, $\{O_0\}$ is the main reference and the global system. The second one is placed in the center of the second metrology frame. (X_1) and (Y_1) are aligned with the plane mirrors surface normal vector, and (Z_1) with the capacitance sensors target surface normal vector. Therefore, this is the local system. The two system origins are coincident when the displacement is zero. This is illustrated in the Figure 1 (left).

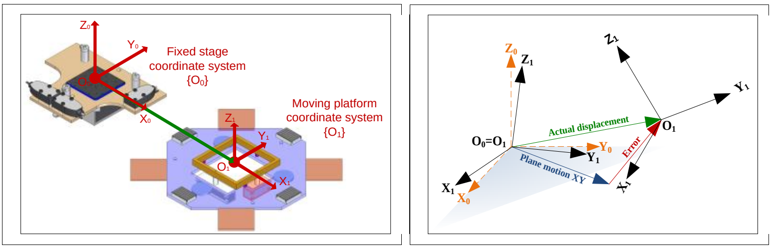

Figure 1: 2D moving platform (left) and machine coordinate systems (right)

Also in Figure 1 (right), the difference between the actual displacement and the plane motion XY is shown, function of the translational, rotational and squareness errors. In order to keep a machine model as simple as possible the rigid-body behaviour is assumed. Likewise, in spite of the XY plane positioning, it is also assumed that systematic errors in each axis are only dependent on the displacement along that axis. The mathematical model with these considerations can be written as in (1):

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 1 & -\varepsilon_z & \varepsilon_y \\ \varepsilon_z & 1 & -\varepsilon_x \\ -\varepsilon_y & \varepsilon_x & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} + \begin{bmatrix} \delta_x(x)+\delta_x(y)-\alpha_{xy}\,y \\ \delta_y(x)+\delta_y(y) \\ \delta_z(x)+\delta_z(y)-\alpha_{xz}\,x-\alpha_{yz}\,y \end{bmatrix} \tag{1}$$

where ε_u represents an angular error motion around the u axis, $\delta_u(v)$ is the linear error motion in u direction under nominal v motion, and α_{uw} is the squareness error between u and w axis; u and w can be x, y or z, and v axis only x or y. Due to the different influences, these component contribution errors are calculated as a quadratic sum.

Final error motion is calculated then as in (2), and the final value should be less than the initial accuracy specifications (40, 40, 5) nm expected in this first design step:

$$error = \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{global} - \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{local} - \begin{bmatrix} X \\ Y \\ 0 \end{bmatrix} \tag{2}$$

3 Considered errors

The sensors used for determining the displacement in all three directions are the three laser interferometer encoders and the three capacitance probes. The XY measurement system should consider various instrumental influences in the $\delta_x(X)$ and $\delta_y(Y)$ geometric errors. The wavelength stability, according to the manufacturer specifications and the ±25 mm desired displacement, contribute to the uncertainty with ±1.25 nm. Resolution error is equal to 10 nm and beam mixing or spurious beams lead to a non-linearity error of 2 nm. Due to the interferometer architecture there is no dead-path error. In reference to the capacitance probes, the predicted accuracy is equal to 5 nm, that means a result of ±2.5 nm for $\delta_z(X)$, and a rotational error, ε_x and ε_y, of 23.4 nrad, considering the distance between the three symmetrical probes.

The laser beam and the plane mirror misalignment are caused by two aspects: lack of parallelism between the travel axis and the laser beam and inclination between the travel axis and the plane mirrors surface normal vector. Assuming that and the previously controlled correction of the yaw rotation, according to the presented work by Holmes in [1], the significant errors are $\delta_x(X)$ and $\delta_y(Y)$ and equals to 0.56 nm. Squareness error, α_{yx}, between the surfaces of the x and y plane mirrors is limited by the aligning system, an autocollimator, likewise between the mirrors and the capacitance probes: α_{zx} and α_{zy}. These angles are around 1,5 and 5 arcsec respectively. The difficult characterization of parallelism between the sensor and the capacitive target is taken into account with a $\delta_z(X)$ value of 25 nm.

As a result of the plane mirror non-uniform surface, form errors should be considered. A mirror flatness tolerance of 63 nm ($\lambda/10$) has been considered for the

geometric parameters $\delta_x(X)$, $\delta_y(Y)$. Yaw error, ε_z, depends on the distance between the y-interferometers and the previous value, with a result of 1.145 μrad.
Environmental changes produce variations in the refractive index of air and thermal expansion effects in components, holders and sensors. In order to apply real time compensation a unit with calibrated sensors is used. For a ±0.1ºC variation and ±25 mm displacement the accuracy of the system is ±2.5 nm. Analyzing the possible thermal expansion of located components in the metrological frames, and because of the symmetrical and particular mounting design, the only considered error is $\delta_z(X)$ with an estimated value around 25 nm, due to the capacitance probes thermal growth.

4 Error budget

The error budget is calculated substituting the combined errors shown in Table 1 into the error model and equations (1) and (2). The absolute offset (ΔX, ΔY, ΔZ) obtained in the external point of the nanopositioning AFM stage is (66, 64, 29) nm, still far from the initial requirements of (40, 40, 5) nm. The ideas proposed to minimize these final-point error would include the characterization of the mirror flatness (the main error contribution) and the study of the alignment system for the capacitance probes. The reset error of the under development homing sensors will also be considered for future estimations of repeatability.

Table 1: Combined geometric errors computed in the budget

$\delta_x(X) = 63.9$ nm	$\delta_x(Y) = 0$ nm	$\varepsilon_x = 2.3\cdot10^{-8}$ rad	$\alpha_{xy} = 5.2\cdot10^{-6}$ rad
$\delta_y(X) = 0$ nm	$\delta_y(Y) = 63.9$ nm	$\varepsilon_y = 2.3\cdot10^{-8}$ rad	$\alpha_{zx} = 2.4\cdot10^{-5}$ rad
$\delta_z(X) = 29.0$ nm	$\delta_z(Y) = 0$ nm	$\varepsilon_z = 1.1\cdot10^{-6}$ rad	$\alpha_{zy} = 2.4\cdot10^{-5}$ rad

5 Conclusions

This paper has described the error budget of an initial 2D nanopositioning platform design. With a mathematical model and the study of the geometric error influences, the estimation has concluded with the improvement ideas in the design process. Self-calibration techniques will be applied in order to obtain the required accuracy.

Reference:

[1] Holmes M, Hocken R, Trumper D. The long-range scanning stage: A novel platform for scanned-probe microscopy, Precision Engineering 24 (2000) 191-209.