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Positioning uncertainty assessment of a large-range nanopositioning platform

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Abstract
This work assesses the actual positioning uncertainty of a Nanopositioning Platform, referred as NanoPla, which is capable of achieving submicrometre resolution along its large working range of 50 mm × 50 mm. The uncertainty sources that affect the positioning process of the NanoPla were theoretically analysed during the design phase using the error budget methodology. After manufacturing and assembly phases, its performance as a positioning system has been validated. Once the system is operating, the main uncertainty contributors have been identified, and experimental data have been recorded to perform the uncertainty assessment based on Monte Carlo method of propagation of distributions. The target is to characterize the errors that affect the NanoPla, and, thus,find the most effective way to reduce the positioning uncertainty, which implies minimum changes in its design.

Positioning uncertainty, nanopositioning, Monte Carlo simulation, uncertainty budget.

1. Introduction

Precision design has been subject of study for several decades now, precision principles and techniques have been outlined, reviewed and updated by many authors. One of these principles is uncertainty budgeting, also known as error budgeting, which helps predict the repetable and not repeatable errors of a machine [1]. The uncertainty budget of a precision system identifies all relevant error influences and calculates the total uncertainty of the system. This tool can be used during the early stages of the design phase, when changes in the design are still feasible. However, uncertainty budgeting can also be performed on a functional system in order to estimate the limits of the system performance or minimize the main error sources, when possible.

The subject of this work is a precision large-range nanopositioning system called NanoPla, it has a working range of 50 mm × 50 mm. The NanoPla has been designed, manufactured and built at the University of Zaragoza [2]. During its design phase, the NanoPla was optimized using the uncertainty budget methodology in order to improve its measurement accuracy [3]. At present, the NanoPla is already a functional system, and, thus, this work focuses on the assessment of the NanoPla positioning uncertainty by performing an uncertainty budget which is based, when possible, on experimentally obtained data. A Monte Carlo simulation is performed in order to quantify the propagation of all the uncertainties and their effect in the final positioning uncertainty.

2. NanoPla overview

The NanoPla design and implementation has been the subject of previous works [2]: It consists of three stages, the inferior and the superior base that are fixed and a moving platform that is placed in the middle. The moving platform is levitated by three vacuum-preloaded airbearings and it is actuated by four Halbach linear motors which are unguided. This allows the moving platform to perform a planar displacement in X and Y-axes. A 2D plane-mirror laser interferometer system from Renishaw is used as a positioning sensor in the XY-plane. Commercial capacitive sensors are used to measure parasitic out-of-plane motions (Lion Precision, model C5-E). The capacitive sensor probes are attached to the metrology frame of the inferior base, while the target surfaces are placed at the bottom of the moving platform.

The NanoPla is intended for metrological applications, specifically for the characterisation of large surfaces at a submicrometre scale. In these applications, a measuring instrument is fixed to the center of the metrological frame of the moving platform which performs the coarse motion, whereas during the scanning task, the fine positioning of the sample is performed by a commercial piezostage that is integrated in the metrological frame of the inferior base. In this work, only the uncertainties of the NanoPla itself are taken into account, without considering the measuring instrument, nor the piezostage attached to it, since they are interchangeable.

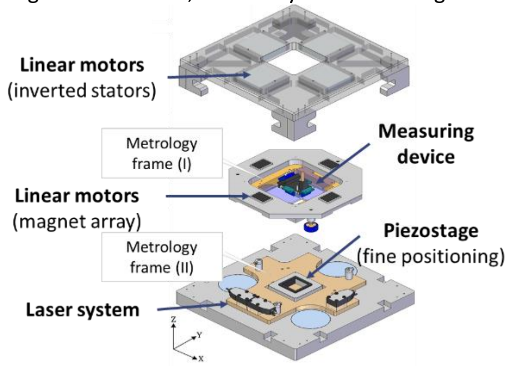

Figure 1. Exploded view of the NanoPla.

3. Uncertainty Budget

The uncertainty budget methodology consists in identifying, classifying and, then, quantifying the influence of the uncertainty contributors in the final output of the system. In this case, the final output is the position of the measuring instrument which is fixed to the moving platform of the NanoPla.

In this section, firstly, the mathematical model of the NanoPla is obtained, then, the errors are identified and classified and, the total uncertainty of the system is assessed.

3.1. NanoPla mathematical error model

During the design phase of the NanoPla, its mathematical error model was analysed [3]. This equation has been reviewed assuming that the rotational errors are negligible. This is justified by the fact that for the laser system to read, the angular deviations between moving platform (mirrors) and the inferior base (laser sources) must be smaller than 1.2×10^{-4} rad [4]. The deviations taken into account are motion errors along the three axes ($\delta_x, \delta_y, \delta_z$) and orthogonality errors ($\alpha_{xy}, \alpha_{yz}, \alpha_{zx}$).

$$\Delta P = \begin{pmatrix} \Delta P_x \\ \Delta P_y \\ \Delta P_z \end{pmatrix} = \begin{pmatrix} \delta_x \\ \delta_y - \alpha_{xy} L_x \\ \delta_z - \alpha_{yz} L_y + \alpha_{zx} L_x \end{pmatrix} \quad (1)$$

Where ΔP represents the error vector or difference between the measuring instrument real position and its measured position.

3.2. Error identification and estimation

The NanoPla control system performs the positioning of the moving platform in the XY-plane. Once the platform is positioned, the measuring instrument, fixed to it, performs the measurement in Z-axis. The deviations in Z-axis position of the measuring instrument are caused by spurious motions, and they are not controlled, only monitored, so that they can be corrected in the measuring process. In this first approach, thermal expansions are considered not to be compensated. In this work, the uncertainties are divided in two main groups depending on whether they affect the positioning process of the platform, that is, uncertainties in the XY-plane; or whether they affect the measuring process, that is, the position in Z-axis. Inside these two main groups, the uncertainty sources have been divided in three subgroups depending on their cause: system components inaccuracies, misalignments and environmental sources.

- Uncertainty sources in the positioning process (XY-plane): They include positioning uncertainties in X and Y-axes (δ_x, δ_y) and orthogonality between X and Y-axes (α_{xy}). Due to the fact that the moving platform performs a frictionless unguided plane motion, one of the main uncertainty sources are the positioning sensor (laser system) inaccuracies and misalignments. The environmental variations affect the refractive index of the laser system and they cause the thermal expansion of the metrology frame. The most significant errors are summarized in Table 1:

Table 1. Main positioning process errors: δ_x, δ_y, α_{xy}

Uncertainty Type	Uncertainty Source	Value [nm]
System inaccuracies	Laser system wave length instability	$\delta_x=\delta_y=\pm1.25$
	Laser sensor resolution [4]	$\delta_x=\delta_y=1.58$
	Laser beam mixing	$\delta_x=\delta_y=<\pm2$
	RMSD of the laser system [4]	$\delta_x=\delta_y=\pm5.4$
System misalignemnts	Misalignment errors of the laser system assembly (Std value)	$\delta_x=\pm25$ $\delta_y=\pm25$ $\alpha_{xy}=\pm1.09\times10^{-6}$ rad
	Plane mirror form errors	$\delta_x=\delta_y=\pm15.75$
Thermal errors ($\Delta T = \pm1$ °C)	Laser system refractive index environmental compensation	$\delta_x=\delta_y=\pm2.5$
	Metrology frame expansion (aluminium)	$\delta_x=\pm1284.1$ $\delta_y=\pm2282.8$

RMSD: Root Mean Square Deviation

- Uncertainty sources in the measuring process (Z-axis): They include positioning uncertainties in Z-axis (δ_z), and orthogonality between Z-axis and X and Y-axes (α_{yz}, α_{zx}). The spurious motions in Z-axis are measured by the capacitive sensors, and, then, corrected from the measurement. Thus, one of the main uncertainty sources are the capacitive sensors inaccuracies and misalignments. Thermal variations also affect the capacitive sensors measurement and cause the thermal expansion of the airbearings which support the moving platform in Z-axis. In addition, during the manufacture and assembly of the NanoPla, misalignments between parts were minimized but could not be completely avoided. The most significant errors are summarized in Table 2:

Table 2. Main measuring process errors: δ_z, α_{zx}, α_{yz}

Uncertainty Type	Uncertainty Source	Value [nm]
System inaccuracies	Capacitive sensors RMSD* [5]	$\delta_z=\pm34.18$
	Capacitive sensors positioning error *	$\delta_z=\pm60.7$
System misalignments	Misalignments between moving platform and fixed base	$\alpha_{zx}=\pm1.35\times10^{-4}$ rad $\alpha_{yz}=\pm1.34\times10^{-4}$ rad
Thermal errors ($\Delta T = \pm1$ °C)	Thermal expansion of capacitive probes (aluminium)	$\delta_z= \pm941.64$
	Thermal expansion of capacitive targets (steel)	$\delta_z= \pm63.24$
	Thermal expansion of air bearings (brass and aluminium)	$\delta_z=\pm569.21$

*Effective value at the center of the moving platform

3.3. Uncertainty quantification using Monte Carlo simulation

The contributions of each uncertainty source have been experimentally measured when possible. The ones that cannot be measured, have been evaluated by other means, such as the calibration certificate of the manufacturer. Their values are represented in Table 1 and 2, additionally, their probability functions have also been identified. Monte Carlo method is used to calculate the propagation of distributions and their effect in the final uncertainty of the system (100,000 iterations). The final positioning error in X and Y-axes is position dependant. At one of the edges of the working range (L_x=25 mm, L_y=25 mm), ΔP_x and ΔP_y are 1.5±1.3 µm and 2.7±2.3 µm, respectively. The highest contribution in these axes is the thermal expansion of the metrology frame made of aluminium. In Z-axis, the final positioning error ΔP_z is 1.2±4.8 µm. In this case, the higher contributors are the orthogonality errors.

4. Conclusions

The position uncertainty of the NanoPla has been assessed. As shown, the main contributor to X and Y-axis deviations is the thermal expansion of the metrology frame, made of aluminium in this first prototype. Thermal errors could be monitorized and compensated. In addition, if it was made of Zerodur, as intended in the final design, the error could be reduced by two orders of magnitude. Similarly, the capacitive sensors housing could be made of Invar, to reduce their thermal expansion in Z-axis. The main contributors to Z-axis deviations are the orthogonality errors caused by the NanoPla assembly misalignments. Future work should focus in reducing and compensating these errors.

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