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Performance analysis of laser measuring system for an ultra-precision 2D-stage

Lucía Díaz-Pérez [1], Marta Torralba [2], José A. Albajez [1], José A. Yagüe-Fabra [1]

[1] I3A, Universidad de Zaragoza, Zaragoza, Spain
[2] Centro Universitario de la Defensa, Zaragoza, Spain

jyague@unizar.es

Abstract

This work is focused on a 2D-stage (NanoPla) on development to obtain an effective metrological positioning with nanometre resolution and long working range (50 x 50 mm). After the manufacturing and assembly phases, the experimental characterization is now focused on the drive, control and measurement issues. In this phase, an analysis of the measuring system is needed to provide information to the control. To measure the displacements and rotation in the horizontal plane (XYRz), three plane mirror laser interferometers are used as feedback. Performance of this laser system integrated in the NanoPla is analysed and presented.

Nanopositioning; 2D-stage; Plane mirror laser interferometer; Resolution; Stability

1. Introduction

This work is part of a bigger project that is on development, a novel 2D nanopositioning platform stage (NanoPla) able to reach submicrometre accuracy along a large working range (50 mm x 50 mm). The motion of the NanoPla is performed by four custom-made linear motors. Plane mirror laser interferometers work as positioning sensors. The control loop for the 1D- and 2D-schemes was presented in a previous work [1], where the variable to be controlled is the XY-position of the platform. The closed-loop digital control feedback and analogue integration is achieved by a commercial solution of Texas Instruments: Digital Motor Control Kit (DMC). Three plane mirror laser interferometers that measure the displacements and rotation in the horizontal plane (XYRz) are used as feedback sensors.
A previous work dealt with the measurement accuracy analysis during the design phase of the NanoPla [2] and a self-calibration procedure for the laser-system was defined and validated, in order to obtain a better accuracy of this positioning stage [3]. In this work, the performance of the laser system is analysed, in order to verify its suitability as feedback positioning sensors.

2. Description of the laser system

The 2D-laser system belongs to the Renishaw RLE10 laser interferometer family. It consists of a RLE system that comprises two laser units (RLU), three detector heads (RLD), one per axis and one more in Y-axis to measure the rotation around Z-axis (Rz), two plane mirrors, and an environmental control unit (RCU), which compensates the effect of the environmental conditions in the refractive index and thermal expansion. In addition, one external interpolator (REE) is connected to each detector head, and reduces the expected resolution of the system from 9.88 nm to 1.58 nm.

The NanoPla design consists of three stages [4]; the inferior and the superior base, that are fixed, and the moving platform (Figure 1). The detector heads are placed on the inferior base, and the mirrors are attached to the moving platform. Three air-bearings provide relative non-contact motion to the moving platform between parts. Additionally, the NanoPla has three capacitive sensors for the measurement of deviations or out-of-plane motions: Z, Rx, Ry. Nevertheless, these sensors have no direct effect on the control loop. In turn, the NanoPla rests on a vibration isolation table inside a laboratory with controlled environmental conditions.

Although, the metrology frame of the final NanoPla is expected to be manufactured in Zerodur, due to its low thermal expansion coefficient, this first prototype has been manufactured in Aluminium.

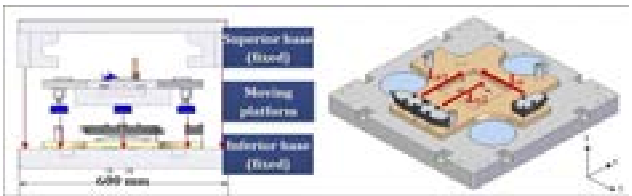

Figure 1. NanoPla exploded view (left) and laser heads detail (right)

The control loop has been developed using Matlab®, therefore, the feedback sensor needs to be able to work in the same environment. For this reason, a program that allows taking measurements in real time for the performance study was developed also using Matlab®.

3. Laser system performance

The performance study has been carried out before calibrating the 2D-system. Therefore, this work deals with the performance and stability of the laser system but not with its accuracy. Besides the readouts of the three detector heads, the system also provides the readouts of the RCU sensors: air temperature, material temperature and air pressure. The measurement of each signal takes approximately 0.04 seconds, thus, the maximum speed at which it is possible to record the six measurements is every 0.25 seconds. It is worth noting that even if the measurements are not recorded simultaneously, they are all taken in this interval of 0.25 seconds, what is enough for this application because the NanoPla maximum precision is required at a stationary position, having the air bearings shut-off. For this reason, this performance study has been done under those conditions. Besides, the reading data rate is limited by the specifications of the manufacturer.

Following, the resolution of the positioning of the NanoPla provided by the laser system is verified. Then, its short- and long-term stability are analysed. Not only the laser system is under study, but also the whole assembly of the NanoPla where it is integrated, including the vibration isolation table.

3.1. Resolution

According to Renishaw documents, the analogue output signal period of a plane mirror system is 158 nm, a quarter of the laser wavelength, and the minimum output resolution that the RCU is able to achieve is 9.88 nm. Nevertheless, the system under study includes interpolators with an interpolation factor of 100 over the analogue output resolution. Thus, the final resolution of the laser system is 1.58 nm. In order to verify the resolution, only the data of one detector head has been recorded at a speed of one measurement per 0.04 seconds. The measurements recorded during one second are represented in Figure 2. It can be observed that they oscillate between two levels, 0 and 1.58 nm, which is the resolution limit.

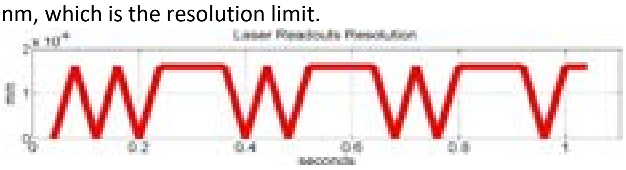

Figure 2. Laser system resolution

3.2 Short-term and long-term stability

In order to study the behaviour of the laser system, measurements have been recorded every 2 seconds during one hour, at a constant temperature (ΔT < 0.01 ºC), at the reference position with a dead path of 39 mm for the X-axis and 49 mm for the Y-axis. In Figure 3, the measurements of one of the two laser detectors of Y-axis has been represented. It can be observed that the magnitude of the noise is constant and the difference between measurements at the same position is smaller than 20 nm. Similar results have been obtained by the other two laser detectors.

Figure 3. Measurements at a constant temperature for 1 hour

Having 30 measurements per minute, in Figure 4, the averages of the readouts every minute, for 60 minutes, have been represented for every laser detector. It can be seen that, by averaging, the magnitude of the noise has been reduced down to 10 nm. The standard deviations of the measurements taken during 60 minutes are 5.4 nm for X- axis and 4.13 nm and 4.2 nm for the two laser detectors of Y-axis, respectively. These values are considered acceptable for the right performance of the NanoPla, taking into account that the uncertainty (k=2) of the laser system after being calibrated is 200 nm.

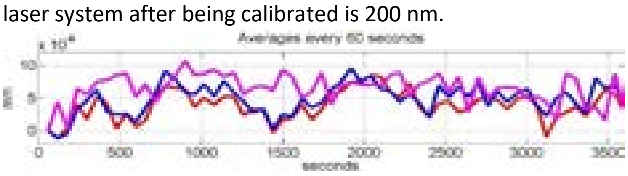

Figure 4. Averages of the previous measurements

With the aim of studying the behaviour of the laser system, for different positions of the moving platform, the measurements of the X-axis laser detector at the reference position (red line in Figure 5) are compared to the X-axis measurements at another position 28 mm apart from the reference position (blue line in Figure 5). As in the previous case, the measurements have been recorded every 2 seconds for 1 hour, at constant temperature. In Figure 5, the standard deviations of the readouts per minute are represented. It can be observed that far from the reference position the noise is higher and the standard deviations have a maximum value of 16 nm, when at the reference position the maximum value is 6 nm. This is due to the proportional error terms that increase with the measured distance, such us laser wavelength stability and accuracy. Nevertheless, it is still considered acceptable for the right performance of the control loop of the NanoPla, considering that the NanoPla is moving on a range of ±25 mm and, thus, these values will not increase.

Figure 5. Standard deviation of the X-axis readouts at two different positions

The long-term performance of the laser system has also been studied. Figure 6 represents the measurements recorded for more than 14 hours of the two laser detectors for the Y- and X-axis. In each graph, the thermal expansion of the metrology frame (Aluminium) due to the temperature variation has been represented in green. It can be observed that the readouts of both laser detectors of the Y-axis are coincident, and that the variation recorded by the laser system corresponds to the expected thermal expansion, for both axes. It should be noted that X- and Y-axes have the same response to thermal variation and that, in the final prototype, the metrology frame will be manufactured in Zerodur, with a lower thermal expansion coefficient.

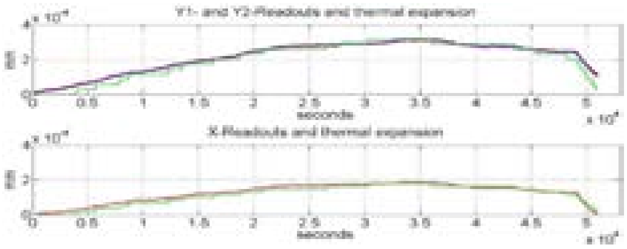

Figure 6. Measurements compared to thermal expansion: (up) Y-axis readouts; (down) X-axis readouts

5. Conclusion

The target of this study was to verify the right performance of the laser system integrated in the NanoPla and to confirm its suitability to be implemented in the control loop of a 2D-long range system. For this purpose, the lasers resolution and stability have been studied and the results meet the requirements, obtaining stable measurements. In future works, it will be necessary to calibrate the laser system, following the self-calibration procedure defined in [3], and then, implement the laser system in the positioning control loop.

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