Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 41 (2019) 249–256

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

8th Manufacturing Engineering Society International Conference

Positioning uncertainty of the control system for the planar motion of a nanopositioning platform

Lucía Díaz-Pérez *,[a] , Marta Torralba [b], José Antonio Albajez [a], José A. Yagüe-Fabra [a]

[a]I3A – Universidad de Zaragoza, C/ María de Luna, 3, 50018, Zaragoza, Spain.
[b]Centro Universitario de la Defensa Zaragoza, Ctra. Huesca s/n, 50090 Zaragoza, Spain.

Abstract

The novel nanopositioning platform (NanoPla) that is in development at the University of Zaragoza has been designed to achieve nanometre resolution in a large working range of 50 mm × 50 mm. The 2D movement is performed by four custom-made Halbach linear motors and a 2D laser system provides positioning feedback, while the moving part of the platform is levitating and unguided. As control hardware, this work proposes the use of a commercial solution, in contrast to other systems, where the control hardware and software were specifically designed for the purpose. In a previous work of this research, the control system of one linear motor implemented in the selected commercial hardware was presented. In this study, the developed control system is extended to the four motors of the nanopositioning platform to generate a 2D planar movement in the whole working range of the nanopositioning platform. In addition, the positioning uncertainty of the control system is assessed. The obtained results satisfy the working requirements of the NanoPla, achieving a positioning uncertainty of ±0.5 μm along the whole working range.

© 2019 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer-review under responsibility of the scientific committee of the 8th Manufacturing Engineering Society International Conference

Keywords: 2D positioning control; nanopositioning; Halbach linear motors; positioning uncertainty.

---

1. Introduction

In recent years, nanotechnology and nanoscience have increased their applications, demanding high accuracy positioning systems capable of working in large ranges at a nanometre scale. These positioning stages can be used for

---

* Corresponding author. Tel.: +34 976762561
E-mail address: lcdiaz@unizar.es

© 2019 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer-review under responsibility of the scientific committee of the 8th Manufacturing Engineering Society International Conference.

measuring or nanomanufacturing applications by integrating different devices [1]. The performance of these processes is directly related to the accuracy of the positioning systems and their working range. Therefore, accurate positioning control in a large working range is one of the main necessities of nanotechnology applications [2].

At the University of Zaragoza, a novel 2D nanopositioning platform (NanoPla) is in development. The design of the NanoPla has been optimized to achieve nanometre resolution in a large working range of 50 mm × 50 mm [3,4]. The motion of the moving part of the NanoPla is performed by four custom-made Halbach linear motors. These motors directly transform electrical energy into linear motion. In addition, the motion is performed without any mechanical guidance between the stator and the permanent magnet array, allowing planar motion [5]. A commercial control solution for these custom-made linear motors is not available. In other works [6,7], a control hardware and software were specifically designed and built for control issues. In contrast, in this project, the use of a commercial control hardware for generic motors has been proposed as a novel solution to perform their control and drive. The purpose of this is to facilitate a future replicability of the system.

In a previous research [8], a positioning control strategy was designed and implemented in the selected commercial control hardware for one linear motor performing a 1D movement on a linear guide. The right performance of this control system, according to the established design requirements, was experimentally verified. In this work, the control strategy is optimized for the 2D movement and implemented in the NanoPla to control and drive the planar motion of a nanopositioning platform in a range of 50 mm × 50 mm. The positioning feedback is provided by a 2D laser system, which presents high accuracy in large working ranges and direct traceability. Subsequently, the positioning uncertainty of the proposed control system is analysed. A preliminary modelling of the 2D control positioning control was presented in [9]. Nevertheless, this previous work is prior to the implementation of the commercial hardware and considers that the phase currents are controlled independently, which is not possible with the commercial control hardware solution proposed.

This article is divided as follows; Firstly, an overview of the NanoPla is presented, and the Halbach linear motors, the positioning sensor and the hardware of the control system are described. Then, a positioning 2D control system is proposed and experimentally validated. The positioning uncertainty of the 2D positioning control system is assessed. Finally, conclusions are withdrawn.

2. Method and materials

In this section, firstly, the NanoPla design and application is described. Then, the control system hardware is defined, as well as the actuators, the positioning sensor and the connections between them.

2.1. 2D Nano-positioning platform (NanoPla)

The NanoPla design was presented in [3]. An exploded view of the NanoPla can be seen in Fig. 1. It has a three-layered structure that consists of fixed inferior and superior bases and a moving platform that is placed between them. The moving platform is levitated by three air bearings while four Halbach linear motors perform its motion. A Halbach linear motor has two parts, a permanent magnet array and the stator that consists of three-phase ironless coils. In the NanoPla, the magnet arrays of the four linear motors are fixed to the moving platform and the stators are assembled to the superior base, which minimizes the weight of the moving part and makes it wireless. A 2D laser interferometer system works as positioning sensor. The laser heads are positioned in the inferior base and the positioning mirrors are fixed to the moving platform. The aim is to embed an atomic force microscope (AFM) in the NanoPla. The AFM will be fixed to the moving platform that will position it in the XY-plane, above certain area of the sample to be measured, allowing the characterization of a large area of the sample (50 mm × 50 mm). Once the AFM is positioned, the moving platform will remain static (air-bearings off) in order to carry out the scanning task.

The NanoPla presents a two-stage scheme, that is, the XY-long range positioning of the moving platform is complemented by an additional piezo-nanopositioning stage that is fixed to the metrology frame of the inferior base. This second stage is a commercial piezo-nanopositioning device (part of the AFM system) with a working range of 100 μm × 100 μm × 10 μm, which will perform the motion of the sample during the scanning operation. Therefore, it has been decided that the position control system accuracy should have a positioning error at least one order of magnitude smaller than the maximum XY range of the commercial piezo-nanopositioning stage, i.e., 10 µm. So that, this error could be corrected by the fine motion of the piezo stage.

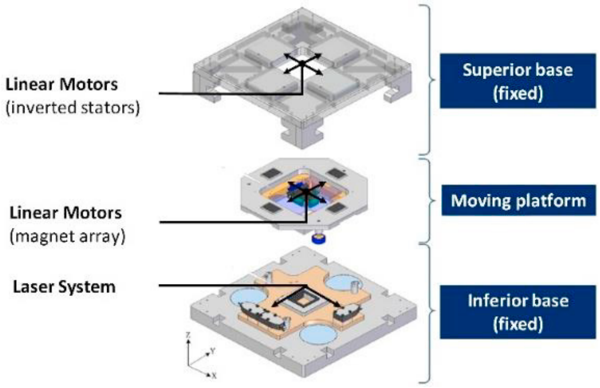

Fig. 1. Exploded view of the NanoPla

2.2. Components of the control system

Halbach linear motors have been selected as actuators in the NanoPla because of their many advantages in precision engineering due to the absence of mechanical transmission elements, like avoiding backlash. Similarly, the contactless unguided motion, prevents friction and allows planar motion. The Halbach linear motors used in the NanoPla were developed by Trumper et al. [5] and they are not commercialized. Therefore, they have been custom-made at the University of North Carolina at Charlotte, and the size of its winding area is large enough to allow planar movement in the 2D working range of the NanoPla. When DC current flows through the three-phase coils of a Halbach linear motor, the electric field interacts with the magnetic field of the magnet array, resulting in two orthogonal forces, one horizontal and the other vertical. The relation between the phase currents and the generated forces is defined by the motor law presented in [8]. The vertical forces of the four motors help to the moving platform levitation, while the horizontal forces perform the movement of the moving platform in the XY-plane.

A generic commercial control system for custom-made Halbach linear motors is not currently available. As a solution, other projects [6, 7] designed and built their own control hardware capable of acting directly on the phase currents. This project proposes to facilitate the 2D positioning control of the NanoPla by implementing a commercial control hardware. In contrast to the aforementioned custom-made control systems, generic motor control hardware acts on the phase voltages instead of acting directly on the phase currents. The selected device is the DRV8302- HC-C2-KIT Digital Motor Control (DMC) kit of Texas Instrument that is designed to operate with generic rotatory permanent magnet synchronous motors. It includes a 32-bit C2000 microcontroller unit (MCU). In addition, it has a power stage capable of controlling and generating three phase voltages by pulse width modulation (PWM). Thus, a DMC kit is required for the phase voltage generation of each linear motor of the NanoPla.

In a previous work [8], an experimental setup, external to the NanoPla, was assembled for the development and experimental validation of the control system of one Halbach linear motor in 1D. In that setup, the magnet array of the motor was fixed and the stator of the motor was the moving part, attached to a pneumatic linear guide. The control strategy was implemented in the DMC kit and a 1D interferometer laser system was used as positioning sensor. After that first validation, for the project presented in this paper, the four linear motors have been installed in the NanoPla and each of them connected to one DMC Kit. In turn, all the DMC kits are connected to the host PC that performs the coordination of the four motors. The movement is achieved while the moving platform is levitated by three air-bearings.

As mentioned, in the NanoPla, a 2D laser system is used as positioning sensor for the control system feedback. The laser system components belong to the Renishaw RLE10 laser interferometer family. It consists of a laser unit (RLU), three sensor heads (RLD), two plane mirrors (one per axis), and an environmental control unit (RCU). In addition, an external interpolator is used to reduce the expected resolution of the system from 9.88 nm to 1.58 nm. Besides the readouts of the three laser encoders, 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.

Fig. 2a represents a scheme of the connections between the host PC, the positioning sensors, the control hardware and the linear motors. The input is the target position in X, Y coordinates, which is entered by the user in the host PC. The control strategy is computed in the PC that receives the position feedback from the laser system. Then, the PC computes the phase voltages that must be generated at the control hardware to drive the linear motors that produce the movement. The plane mirrors are the moving target of the 2D laser system, and the magnet arrays are the part of the linear motors that perform the relative movement respect to the stator that is fixed. The plane mirrors as well as the magnet arrays belong to the moving platform.

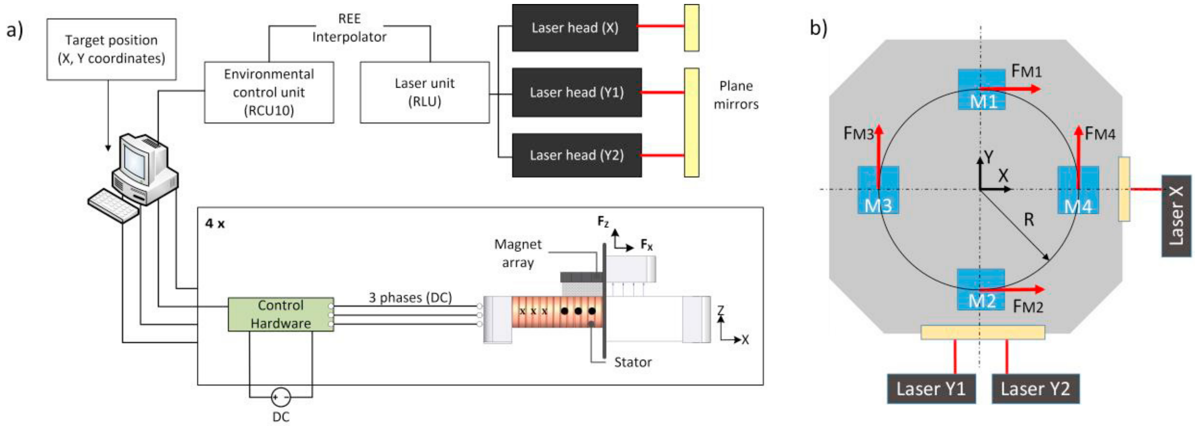

Fig. 2. a) Scheme of the connections between the host PC, control hardware and positioning sensor. b) Scheme of the forces that act on the moving platform

3. 2D positioning control

In this section, the 2D positioning control strategy for the NanoPla is presented and then, its performance is experimentally validated.

3.1. 2D Control strategy

In the NanoPla, the motors are placed in parallel pairs (Fig. 2b), thus, two motors, motor 1 and motor 2 (represented as M1 and M2 in Fig. 2b), generate forces in X-axis (F_{M1} and F_{M2}) that move the platform in X direction. Similarly, the other two parallel motors, motor 3 and 4 (M3 and M4) generate forces in Y-axis (F_{M3} and F_{M4}) that move the platform in Y direction. In addition, the four motors are placed at a distance R from the center of the platform and, thus, their forces generate a torque at the center of the moving platform, around Z-axis. The movement of the platform in X and Y-axes, X_s and Y_s, and the rotation around Z-axis, θ_{zs}, is monitored by the 2D laser interferometer system (Laser Y1, Y2 and X). The total forces in X and Y-axes and the torque around Z-axis (T_z) can be calculated as follows:

$$F_x = F_{M1} + F_{M2} \tag{1}$$

$$F_y = F_{M3} + F_{M4} \tag{2}$$

$$T_z = -F_{M1} \cdot R + F_{M2} \cdot R - F_{M3} \cdot R + F_{M4} \cdot R \tag{3}$$

Fig. 3a represents the scheme of the control system that has been implemented in this project. The input of the control system is the target position (X_{ref}, Y_{ref}) of the moving platform that is entered in the graphic user interface. In addition, for the laser system to read, the plane mirrors attached to the moving platform must remain perpendicular to the laser beams projected by the laser heads. Therefore, the rotation around the Z-axis should be kept minimal ($\theta_{zref}=0$). The control strategy is computed in Simulink®, in the host PC (Fig. 3b). Three independent PID controllers have as reference input X_{ref}, Y_{ref} and θ_{zref}, while the feedback input is the actual position of the moving platform, recorded by the laser system (X_s, Y_s, and θ_{zs}). The control strategy calculates the forces F_x and F_y needed to move the platform to the target position as well as the torque T_z, that is required to correct the platform misalignment. Then, considering symmetry of the moving platform, the horizontal forces that each of the linear motor needs to generate are computed. The phase currents that each linear motor requires to generate those forces are calculated according to the motor law. The output of the control strategy are the corresponding phase voltages that the control hardware must generate for each motor. These phase voltages are generated at the power stage of each DMC kit. Then, the interaction of the phase currents flowing through the stator coils with the magnetic field of the magnet arrays of the moving platform generate the horizontal forces that move the platform. This movement is recorded by the laser system and fed back to the control strategy.

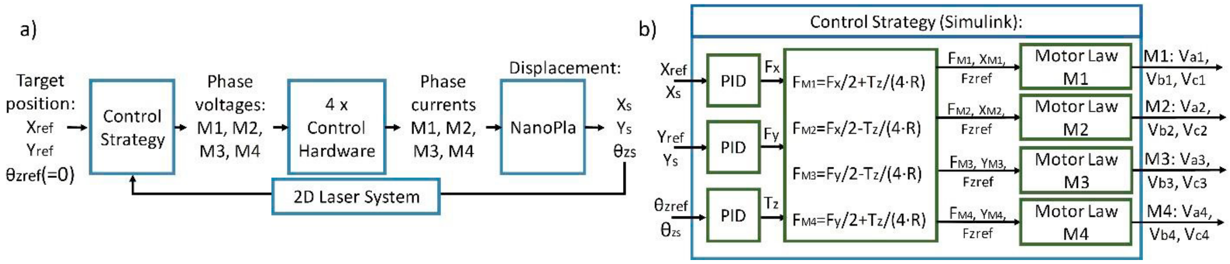

Fig. 3. a) Diagram of the control system. b) Detail of the control strategy.

3.2. Experimental results

The proposed control system has been implemented in the NanoPla and its correct performance has been experimentally verified. For these experiments, the vertical force generated by each motor has been defined to be 2 N, which limits the phase currents working range to ±0.83 A.

As it was mentioned, the NanoPla has a two-stage scheme. The moving platform performs the coarse movement in the large working range of 50 mm × 50 mm, once the moving platform has arrived to the target position, it will stay static (air bearings off) and a piezo-nanopositioning stage place on the inferior base will perform the fine displacement, required for the scanning task, in a range of 100 µm × 100 µm. Therefore, the performance of the control system has been tested when performing a displacement to a target position. Fig. 4a shows the response to a 100 µm displacement in X-axis, while Y-axis is kept static. When the platform reaches the target position at stationary state the positioning error is 0.038 µm and the root mean square (RMS) deviation positioning error is 0.11 µm. In addition, the proposed control system is capable of moving the platform in X and Y-axes simultaneously without losing the alignment of the laser beams and the plane mirrors, that is, keeping the rotation around Z-axis, θ_{zs}, minimal. In Fig. 4b, a displacement describing a 4-mm diameter circumference, moving simultaneously in the two axes, has been represented.

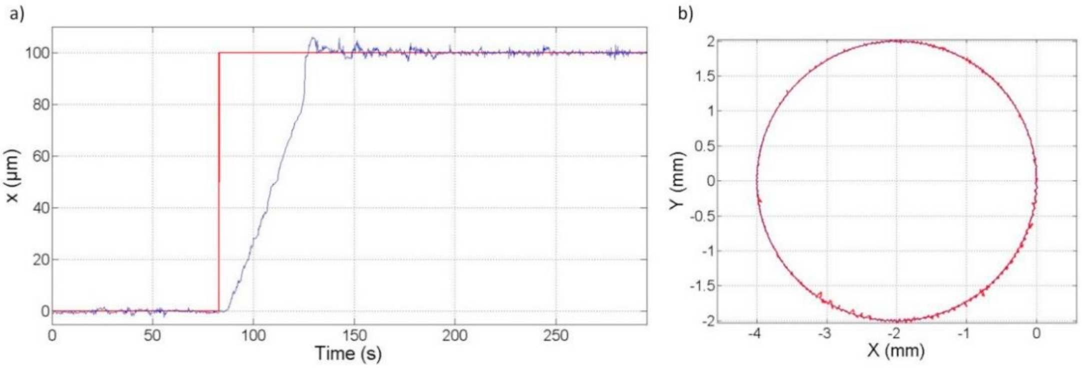

Fig. 4. a) 100 µm displacement in X-axis, while Y-axis is kept static. b) Simultaneous displacement in X and Y-axes describing a circumference.

4. Positioning uncertainty of the control system

The control system of the NanoPla has been optimized to reduce the positioning errors. Nevertheless, the computing operation in the control hardware is performed with finite numbers, which implies a rounding operation resulting in a truncation error that depending on its magnitude may not be negligible. In addition, the errors due to electronic devices noise cannot be completely eliminated and they result in a positioning noise. Thus, the positioning uncertainty of the control system is assessed and analyzed in this section.

In Fig. 5, the control system dataflow has been represented in a block diagram. The data type of the transmitted information is shown in colored arrows. The control strategy is computed in Simulink® (MATLAB®). X_{ref} and Y_{ref} are the desired positions in X and Y-axes. The real position of the NanoPla is measured by a 2D laser system and extracted by MATLAB into the Simulink program. The control strategy computed in the PC by Simulink uses a 64-bit double-precision floating point format (blue arrows) and, in this case, the rounding operation has no significant influence on the calculated results. The control strategy outputs are the required phase voltages, contained in a range of ± 6 V, and they are sent to the control hardware by a Serial Communication Interface (SCI) (green arrows). The MCU of the control hardware works with 32-bit data types, and the voltage values are transmitted as 32-bit fixed point with a 25-bit fraction length (red arrow). The resolution derived from the data type used for the voltages values is 0.0298 nV. These phase voltages are generated in the power stage of the control hardware by PWM. The DMC kit includes a High Resolution PWM (HRPWM) module that is capable of extending the time resolution capabilities of the PWM function. Thus, the resolution of the voltage generation is defined by the time resolution of the HRPWM module and is 26.1 μV. This resolution is sufficient to perform a minimum incremental motion of approximately 700 nm in open-loop. Therefore, the hardware is not able to generate the exact combination of phase currents for every target position. Nevertheless, when working in closed-loop, the positioning controller is capable of partially correcting this error by switching between combinations of phase currents [10].

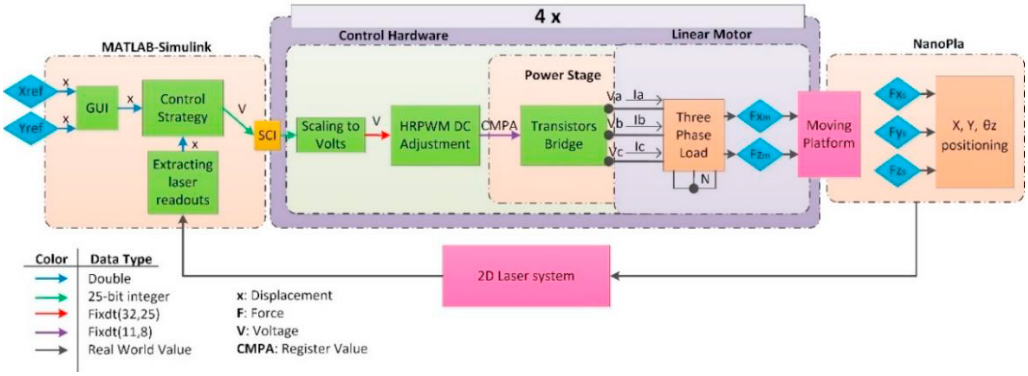

Fig. 5. Block diagram of the data flow in the control system of the NanoPla

In Fig. 5, the real world values are represented with black arrows. These values are the generated phase voltages, the derived currents and resultant forces. In addition, the 2D laser interferometer system measures the moving platform displacement The uncertainty of the laser system measurement also affects the positioning uncertainty of the control system.

It must also be taken into account that the PWM controlled phase voltages lead to a ripple in the phase currents. The current ripple is directly related to the inductance of the stator coils. The resistance and inductance of the coils have been experimentally measured and are 0.88 Ω and 0.24 mH in each phase coil. The electric circuit has been simulated in order to calculate the current ripple derived from the PWM generated phase voltages. The current ripple has a sawtooth waveform with a frequency of 29.28 kHz, which is the double of the PWM frequency. Moreover, the current ripple peak to peak value is dependent on the duty cycle (DC) of the PWM voltages, in this case of study the currents working range is ±0.83 A, which corresponds to a DC between 43.08% and 56.92%. For these values, the peak to peak value of the current ripple has a maximum magnitude of 0.09 A. The actual phase currents have been experimentally measured using a data acquisition system (DAQ) of National Instruments. This DAQ is able to record the measurements at a frequency of 500 kHz and with a resolution of approximately 2 mA. In Fig. 6a, an experimentally measured phase current is compared to the simulated one and, as shown, the current ripple in both cases is almost coincident. Nevertheless, the experimentally measured phase current includes an additional noise, that can be seen in Fig. 6b, where the difference between the measured and the simulated phase currents have been represented. This deviation has different sources, including the DAQ own noise. One of the contributors is the noise of the DC power supply that feeds the power stage of the control hardware. The noise of the DC power supply is imprinted in the PWM phase voltages and, thus, is transmitted to the phase currents. To minimize this contributor, a low noise power supply, with a peak to peak noise of 10 mV has been used.

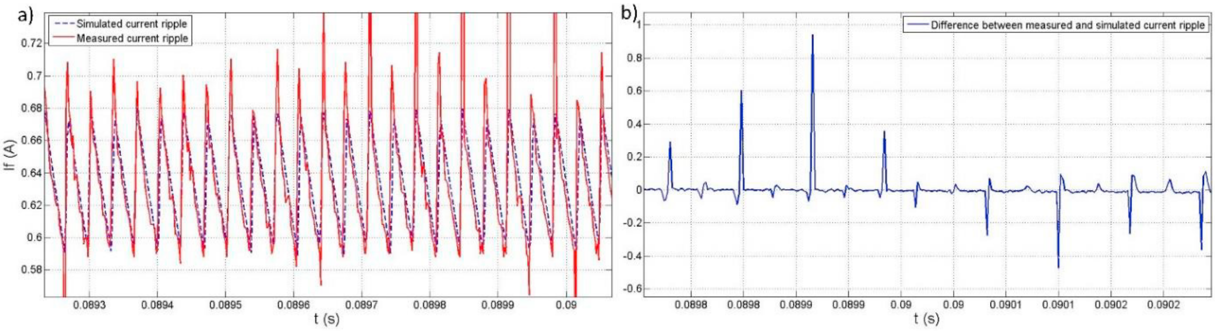

Fig. 6. a) Current ripple of the phase currents generated by PWM controlled phase voltage. b) Difference between the measured and the simulated phase currents.

In a previous work [11], a self-calibration procedure for the geometrical characterization of the 2D laser system of the NanoPla was proposed. The standard uncertainty of the calibrated laser system, after correcting the geometrical errors, was calculated to be 99 nm in X and Y-axes. The laser system resolution is 1.58 nm and the RMS deviation of the laser readouts of an axis is 6 nm. In addition, the stability of the 2D laser system integrated in the NanoPla was verified in [12].

In the control system of the NanoPla, the phase currents noise generates deviations in the forces that act on the moving platform, producing undesired vibrations of the platform. These vibrations are recorded by the laser system, added to the laser system own noise and fed back to the control strategy. This results in positioning noise of the moving platform that has been experimentally measured and computed as the RMS positioning error that is 0.11 µm in each axis. It has also been experimentally verified that the main contributor to the RMS positioning error is the phase currents noise.

In Table 1, the calculation of the positioning uncertainty according to [13] and its contributors has been represented. The resultant positioning uncertainty U_{XY} (k=2) in each axis and in all the working range of 50 mm x 50 mm is equal to 0.50 µm.

Table 1. NanoPla positioning uncertainty contributors and calculation

Source	Justification	Standard uncertainty	Relative contribution
Resolution at the HRPWM u_{HRPWM}	Resolution of 26.2 µV	0.7/√12 µm	65.1%
Laser system resolution u_{Lres}	Resolution of 1.58 nm	1.58/√12 nm	0.00%
Laser system calibration u_{Lcal}	Geometrical errors + measuring system calibration [12]	99 nm	15.6%
RMS positioning error u_{RMS}	Laser system noise + phase currents noise + NanoPla vibrations	0.11 µm	19.3%
Positioning uncertainty $U_{XY}(k{=}2)$	$U_{XY}(k{=}2)=k\sqrt{u^2_{HRPWM}+u^2_{Lcal}+u^2_{Lres}+u^2_{RMS}}$	0.50 µm	100%

In the Table, two types of contributors can be identified: the ones that add a constant positioning error (i.e. laser system resolution and calibration uncertainty) and the ones that contribute to the RMS positioning noise. The main contributor is the HRPWM module resolution and it contributes partially to both. That is, when the laser system detects this error, the controller acts on the horizontal force to correct it, resulting in oscillations. The phase currents noise is another main contributor to the positioning uncertainty. None of this errors can be corrected without additional electronics. Nevertheless, the resultant positioning uncertainty is much lower than the initial working requirements of the NanoPla, thus, the developed positioning control system is considered valid.

5. Conclusions

In this work, a positioning control system for a 2D nanopositioning stage has been designed and implemented in the NanoPla. The proposed control system drives four Halbach linear motors that allow planar motion while a 2D plane mirror laser interferometer system works as positioning sensor. The selected control hardware is a Digital Motor Control kit of Texas Instruments for generic rotative motors. The target is to obtain an accurate positioning control system that fulfils the NanoPla requirements by implementing the commercial hardware and without any additional electronics.

The NanoPla presents a two-stage scheme, which complements the XY-long range positioning of the moving platform (50 mm × 50 mm) with an additional commercial piezo-nanopositioning stage that is fixed to the inferior base. This second stage works in a range of 100 μm × 100 μm. Due to this, the position control system accuracy requirement of the NanoPla in X and Y-axes has been decided to be 10 μm. In addition, the rotation around Z-axis must be kept minimal in order to avoid the laser system misalignment. The correct performance of the proposed control system has been experimentally verified in the NanoPla. In addition, the positioning uncertainty of the control system has been computed and its contributors analysed. The obtained positioning uncertainty $U_X = U_Y = U_{XY}$ (k=2) is equal to ±0.50 μm in each axis and in all the working range of the NanoPla. Therefore, the resultant positioning uncertainty of the control system implemented in a commercial generic hardware and without additional electronics is much lower than the NanoPla required accuracy, broadening the applicability scope of the designed positioning system. In future works, possible alternatives to improve global uncertainty with additional electronics will be studied.

References

[1] W. Gao, S. Kim, H. Bosse, H. Haitjema, Y. Chen, X. Lu, W. Knapp, A. Weckenmann, W. Estler and H. Kunzmann. Measurement technologies for precision positioning. CIRP Annals 64 (2015) 773-796

[2] E. Manske, G. Jäger, T. Hausotte and R. Füßl. Recent developments and challenges of nanopositioning and technology. Measuring Science Technology 23 (2012) 74001–74010

[3] M. Torralba, M. Valenzuela, J.A. Yagüe-Fabra, J.A. Albajez, J.J. Aguilar. Large range nanopositioning stage design: A three-layer and two-stage platform. Measurement 89 (2016) 55–71.

[4] M. Torralba, J. A. Yagüe-Fabra, J. A. Albajez and J. J. Aguilar. Design Optimization for the Measurement Accuracy Improvement of a Large Range Nanopositioning Stage. Sensors 16/84 (2016)

[5] D. Trumper, W. Kim, M. Williams. Design and analysis framework for linear permanent-magnet machines. IEEE Trans. Ind. Appl. 32 (1996) 371–379.

[6] S. Ruben. Modeling, control, and real-time optimization for a nano-precision system. Ph.D. Thesis, University of California, Los Angeles, CA, USA, 2010.

[7] H. Yu, Design and Control of a Compact 6-Degree-of-Freedom Precision Positioner with Linux-Based Real-Time Control. Ph.D. Thesis, Texas A&M University, College Station, TX, USA, 2009.

[8] L.C. Díaz-Pérez, M. Torralba, J.A. Albajez, J.A. Yagüe-Fabra. One dimensional control system for a linear motor of a two dimensional nanopositioning stage using a commercial control hardware. Micromachines, 9 (2018) 421.

[9] M. Torralba, J. A. Albajez, J. A. Yagüe-Fabra and J. J. Aguilar. Preliminary modelling and implementation of the 2D-control for a nanopositioning long range stage. Procedia Eng. 132 (2015) 824–831.

[10] L.C. Díaz-Pérez, J.A. Albajez, M. Torralba, J.A. Yagüe-Fabra.Vector control strategy for a Halbach linear motor implemented in a comercial control hardware. Electronics 7 (2018) 232.

[11] M. Torralba, L.C. Díaz-Pérez, M. Valenzuela, J.A. Albajez, J.A. Yagüe-Fabra. Geometrical Characterisation of a 2D Laser System and Calibration of a Cross-Grid Encoder by Means of a Self-Calibration Methodology, Sensors 17/9 (2017) 1992.

[12] L. Díaz-Pérez, M. Torralba, J. A. Albajez and J. A. Yagüe-Fabra. Performance analysis of laser measuring system for an ultra-precision 2D-stage. Euspen's 17th International Conference & Exhibition, Hannover, Germany, 2017.

[13] ISO/TR 230-9. Test Code for Machine Tools. Estimation of Measurement Uncertainty for Machine Tools Test according to Series ISO 230, Basic Equations; International Organization for Standardization: Geneva, Switzerland, 2005.

Acknowledgements: Funded by the Gobierno de Aragón (Reference Group T56_17R) and co-funded with Feder 2014-2020 "Construyendo Europa desde Aragón" and the Spanish government project DPI2015-69403-C3-1-R “MetroSurf” with the collaboration of the Diputación General de Aragón – Fondo Social Europeo.