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Procedia Engineering 132 (2015) 824 – 831

Procedia Engineering

www.elsevier.com/locate/procedia

The Manufacturing Engineering Society International Conference, MESIC 2015

Preliminary modelling and implementation of the 2D-control for a nanopositioning long range stage

M.Torralba[a,*], J.A. Albajez[b], J.A. Yagüe[b], J.A. Aguilar[b]

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

Abstract

Different systems are recently developed to obtain effective positioning at nanometer scale with increased working ranges. For this purpose, a two-dimensional nanopositioning platform (NanoPla) has been design and manufactured. To assure the demanding metrological performance the drive and control system is being defined and validated. Based on four home-made linear motors as actuators, this work is focused on the study of the control-loop for 1D- and 2D-cases with the aim of the preliminary modelling and posterior implementation. The different required blocks are presented and an initial controller solution is proposed to achieve the established positioning requests.

Peer-review under responsibility of the Scientific Committee of MESIC 2015

Keywords: Linear motors; nanopositioning; control implementation; long range; 2D-stage

1. Introduction

Positioning stages act as a supplementary unit to measure and manipulate samples. New trends in metrology are focused on the development of long range systems for nanotechnology applications, e.g. computer hard disk development, layer deposition operations and integrated circuits manufacturing. For this reason, a 2D-long range nanopositioning stage has been designed and manufactured [1]. Its range is established in 50 mm x 50 mm and the first integrated probe is an atomic force microscope (AFM). The obtained prototype is shown in Figure 1. The

* Corresponding author. Tel.: +34-976-739-831; fax: +34-976-739-824.
E-mail address: martatg@unizar.es

1877-7058
Peer-review under responsibility of the Scientific Committee of MESIC 2015
doi:10.1016/j.proeng.2015.12.566

moving platform is installed between two fixed bases and displaced by four home-made linear motors (stator and Halbach magnet array). To assure the demanding metrological performance during positioning, the drive and control system is being defined and validated. These actuators have been successfully integrated in similar stages [2, 3]. High resolution sensors provide the location of the moving platform in 6-DoF: plane mirror laser interferometers and capacitive sensors. Therefore, this work presents the study and experimental characterization of the control loop for one of this motors installed in a 1D-linear stage, as a first approximation for the global scheme. Simulations are carried out, the tuning of a controller is justified and the different required blocks are analyzed also for the 2D-scheme.

2. One-dimensional long range control

Previously to the study of the global control for the 2D-long range positioning, it seems necessary to start with the simpler case of one linear motor. This is justified in the initial strategy proposed for the planar motion. The system is displaced purely in X- or Y-direction. Thus, an experimental set up similar to the NanoPla design has been used to characterize the 1D-liner stage.

The considered scheme for the control of one linear motor is shown in Figure 2. In a feedback loop, the controller acts after comparison between the reference and the measured position. According to the calculated error, this controller establishes the value of the required forces (force assignment). In particular, the action proposed by the controller affects to the horizontal force (F_x), while the vertical actuation is kept constant. Once known the required forces, commutation law allows to determinate the corresponding phase currents of the motor. Next block of the diagram is the plant. There, the input currents are converted in forces by the motor law and the linear motion stage is displaced to a new position.

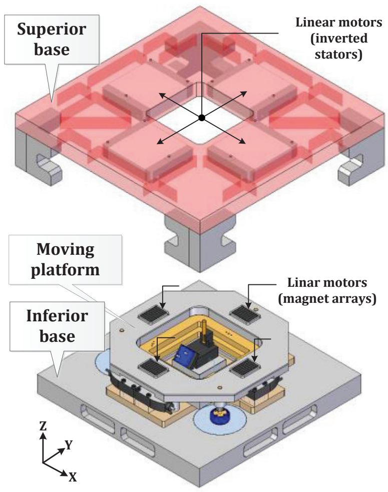

Fig. 1. NanoPla prototype overview.

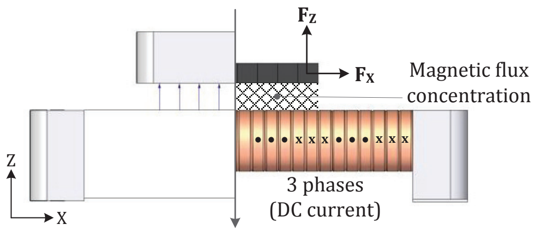

Fig. 3. NanoPla linear motor: created dual forces.

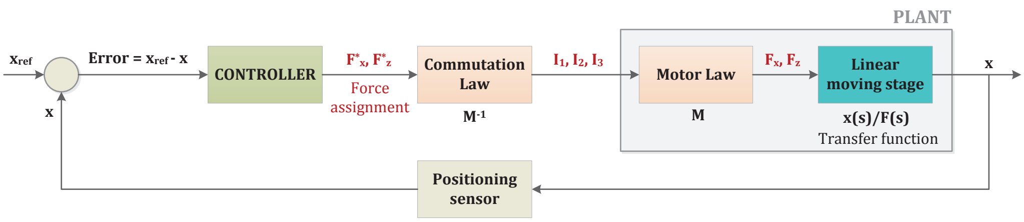

Fig. 2. Control closed-loop for the 1D-linear stage.

2.1. Motor law

The used actuators in the NanoPla system are linear motors, developed by Trumper et al. [4]. The working principle is based on the electromagnetically interaction between the magnetic field of the Halbach array (that concentrates the flux) and the currents driven through the coils. This interaction concludes in orthogonal dual forces F_x or F_y and F_z (see Figure 3), which direction and amplitude depend on the relative positions between the stator and the magnet array.

The characterization tests are presented in [5]. Two similar set ups have been used to determine the parameters of the motors, using a constant input current per phase, a force gauge and a positioning measurement system. The results are the mathematical relationship between forces and input currents, which is denote as M matrix below:

$$\begin{bmatrix} F_x \\ F_z \end{bmatrix} = M \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \tag{1}$$

$$M = \begin{bmatrix} a_{x,1} \cdot \sin\left(k_{x,1} \cdot x + \phi_{x,1}\right) & a_{x,2} \cdot \sin\left(k_{x,2} \cdot x + \phi_{x,2}\right) & a_{x,3} \cdot \sin\left(k_{x,3} \cdot x + \phi_{x,3}\right) \\ a_{z,1} \cdot \sin\left(k_{z,1} \cdot x + \phi_{z,1}\right) & a_{z,2} \cdot \sin\left(k_{z,2} \cdot x + \phi_{z,2}\right) & a_{z,3} \cdot \sin\left(k_{z,3} \cdot x + \phi_{z,3}\right) \end{bmatrix} \tag{2}$$

where $a_{x,i}$, $k_{x,i}$, $\phi_{x,i}$, $a_{z,i}$, $k_{z,i}$ and $\phi_{z,i}$ are fitted parameters for i phase ($i = 1,2,3$) of x- and z-force, respectively.

2.2. Commutation law

The commutation law is the inverse of the motor law and it is needed to calculate the required phase currents:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = M^{-1} \begin{bmatrix} F_x^* \\ F_z^* \end{bmatrix} \tag{3}$$

In this block, the input data are the assigned forces to achieve the new position and the actual x , because $M^{-1} = f(x)$. If the fitted terms are simplified as in eq. (4) and considering eq. (5),

$$c_{f,i}(x) = a_{f,i} \cdot \sin\left(k_{f,i} x + \phi_{f,i}\right) \tag{4}$$

$$\begin{bmatrix} F_x \\ F_z \end{bmatrix} = \begin{bmatrix} c_{x,1} & c_{x,2} & c_{x,3} \\ c_{z,1} & c_{z,2} & c_{z,3} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \tag{5}$$

it is possible to obtain two expressions for I_1 and I_2 conditioned by I_3 :

$$I_1 = \frac{c_{x,2} F_z - c_{z,2} F_x + \left[c_{z,2} c_{x,3} - c_{x,2} c_{z,3}\right] I_3}{c_{z,1} c_{x,2} - c_{x,1} c_{z,2}} \tag{6}$$

$$I_2 = \frac{c_{z,1} F_x - c_{x,1} F_z + \left[c_{x,1} c_{z,3} - c_{z,1} c_{x,3}\right] I_3}{c_{z,1} c_{x,2} - c_{x,1} c_{z,2}} \tag{7}$$

However, with only two equations (one for each force), the three unknown terms of the phase currents cannot be determined. Another condition should be considered. According to [6], one proposed constraint could be based on the power minimization. Due to the Joule effect, the loss of energy is proportional to the conductor resistance, to the time during charges circulation and to the square of the current. For this particular problem:

$$f = I_1^2 + I_2^2 + I_3^2 \tag{8}$$

Then, the last condition to solve the system is eq. (9), and the final expression for I_3 is eq. (10):

$$\frac{\partial f}{\partial I_3} = 0 \tag{9}$$

$$I_3 = \frac{\left[c_{x,3}\left(c_{z,1}^2 + c_{z,2}^2\right) - c_{z,3}\left(c_{x,1}c_{z,1} + c_{x,2}c_{z,2}\right)\right]F_x + \left[c_{z,3}\left(c_{x,1}^2 + c_{x,2}^2\right) - c_{x,3}\left(c_{x,1}c_{z,1} + c_{x,2}c_{z,2}\right)\right]F_z}{c_{x,1}^2\left(c_{z,2}^2 + c_{z,3}^2\right) + c_{x,2}^2\left(c_{z,1}^2 + c_{z,3}^2\right) + c_{x,3}^2\left(c_{z,1}^2 + c_{z,2}^2\right) - 2\left[c_{x,1}c_{x,2}c_{z,1}c_{z,2} + c_{x,1}c_{x,3}c_{z,1}c_{z,3} + c_{x,2}c_{x,3}c_{z,2}c_{z,3}\right]} \tag{10}$$

Therefore, the three expressions for the commutation law are the equations (6), (7) and (10), which relate each current of the three phases to the input dual forces, position and fitting parameters of the linear motors performance.

2.3. Transfer function

The plant for the case of controlling the 1D-system (one linear motor) is also characterized by the linear moving stage. Its transfer function relates the produced motor force and the obtained position achieved by the stage due to the applied force: $x(s)/F(s)$. Hence, it is necessary to determinate experimentally the transfer function, in view of a specific dynamic behavior model of the characteristic studied plant.

The moving platform, as the linear motion stage, is described by a mass-spring-damper system. That supposes to consider three elements in the balance force: inertial, elastic and frictional, respectively. If the parameter m is the mass of the moving platform, b the damping coefficient, k the spring constant and x position during motion for the force F, the resultant second-order differential equation is:

$$F = m\frac{d^2x}{dt} + b\frac{dx}{dt} + k \cdot x \tag{11}$$

Considering next terms of characteristic frequency of the system and damping relation, respectively

$$\omega_n^2 = \frac{k}{m} \tag{12}$$

$$2\xi\omega_n = \frac{b}{m} \tag{13}$$

the transfer function in the Laplace domain is represented in eq. (14):

$$G_P(s) = \frac{x(s)}{F(s)} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n + \omega_n^2} \tag{14}$$

The matter of the analyzed problem is the achievement of these terms with a similar set up that imitates the final application of the NanoPla (considering its dynamic behavior). However, it is important to point out a special issue of the controlled system. As it is known, the force of the motors depends on the relative position between parts and the input current. That means that the determined transfer function will be valid for one value of input current (the one used during the experimentation). That complicates the control task, which is more difficult to design than in a stationary system. The control implementation in variable plants with traditional controllers results on worse response when more pronounced variations characterize the transfer function. For this reason, it has been decided to calculate the transfer function for 1 A and 3 A of input current per phase. This initial approximation of the system response similar to the final application should be optimized. Thus, a posterior study and final implementation will conclude with the adequate tuning controller for the 1D-stage.

The set up for the control of only one motor reproduces the behavior of a moving part in the same conditions than in the 2D-moving platform. All the required instrumentation is shown in Figure 4. Due to the necessity of reproducing the frictionless displacements of the moving platform (levitation by air bearings), the actuator is installed in the pneumatic linear guide used in the previous characterization tests. The CMM acts here only as a support structure to install de magnetic array. The laser interferometer and optics are used to determinate continuously the position of the linear motor moving part (stator) relative to the fixed element.

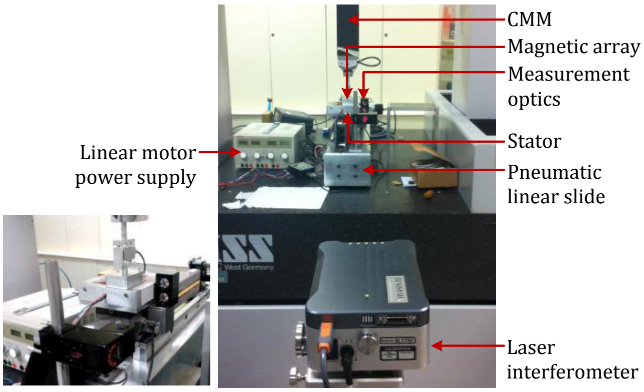

Fig. 4. Transfer function characterization for the linear motion stage.

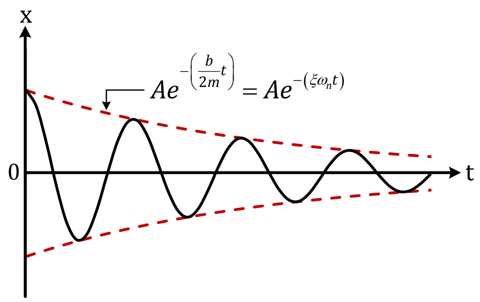

Fig. 5. Positioning vs. time after unbalance the motor.

With the presented scheme of Figure 4, it has been possible to monitor the stator position along the time, after forcing it to oscillate in a free mode until the state of equilibrium. The use of the interferometer is justified, because of the necessity of continuous measurement. After lightly pushing of the stator, the obtained response position vs. time is illustrated in Figure 5. The obtained curve turns out a dynamic underdamped behavior. In other words, the system oscillates around the equilibrium position with a characteristic frequency and gradually decreasing amplitude.

Two are the terms that determinate the dynamic of the response. The frequency term can be calculated from the study of the relationship position-time by analyzing the maximum amplitude points in each oscillation. The factor that includes the damping ratio can be estimated by adjusting the exponential curve that relates the considered points of maximum amplitude in each oscillation. The final results after the data treatment conclude in the next transfer functions of eq. (14) and (15). These $x(s)/F(s)$ relations are then used to carry out the tuning of the controller (next subsection); in particular, the defined $G_P(s)$ for 1 A of input current per phase.

$$G_{P,1A}(s) = \frac{1.263}{s^2 + 2\cdot 0.395\cdot s + 1.263} \tag{15}$$

$$G_{P,3A}(s) = \frac{3.194}{s^2 + 2\cdot 0.525\cdot s + 3.194} \tag{16}$$

2.4. Controller

The controller could be analyzed by simplification of the control loop. This is possible according to the relation between the two motor and commutation law blocks. Both required algorithms are inverse functions (see Figure 2). Thus, the scheme considered in this point only includes the subsystems: controller, $G_C(s)$; and transfer function, $G_P(s)$. It is assumed that the input current would have a value around 1 A. After simulations and final implementation, it could be possible to establish conclusions about the applicability of this assumption.

First of all, it is necessary to establish the requirements of the control. In nanopositioning this could be summarized as accuracy, stability and fast response for the required speed of operation. In particular, for the NanoPla system, the linear motors are in charge of the moving platform displacement, where the AFM will be installed. The initial design displaces the microscope along the working area of 50 mm x 50 mm. However, during the scanning task a commercial nanopositioning stage moves the sample in the 100x100x10 μm^3 volume. Hence, they are characteristics of the XY-control:

- The largest position change is the displacement of 50 mm (all the long travel range).
- The positioning error in this initial approach for controlling should be less than 100 μm (XY-range of the nanostage).
- Initial settling time is established in around 50 s. Nevertheless, this parameter is not critical in the control task. The process could be dragged out if it is required for the improvement in the accuracy and stability of the positioning.

Additional considerations affect to the transient behavior. It is preferable that this period do not have oscillations. An over-damped response would be better, in order to not exceed the established position reference. This turns important considering collisions between physical elements and regarding metrology. No oscillations around the reference suppose a positioning measurement in the same sense during motion. Backlash errors and hysteresis are also avoided.

For the initial control strategy, it has selected for basic action a series compensation of a simple process. As it is presented in [7], traditional proportional-integral-derivative feedback controllers are an adequate possibility for nanopositioning and popular in SPM applications. Then, the first approach feedback option is a PID, implemented in parallel form (no ideal):

$$G_c(s) = K_P + K_I \frac{1}{s} + K_D \left(\frac{N}{1 + N\frac{1}{s}} \right) \tag{17}$$

where K_P, K_I and K_D are proportional, integral, and derivative gains, respectively. N is the used constant by the software for the first-order derivative filter. The proportional action is upgraded with the integral and derivative options. The integral action improves the stationary period, eliminating the residual steady-state error consequence of the pure proportional controller. The derivative action improves the transient response at some level (relative stability). The PID tuning has been made according to the root locus method as initial approximation. A future experimental adjustment will be necessary, because of the variable transfer function (dependent of the input currents), discrepancies during its experimental evaluation, etc. Nevertheless, it turns necessary to apply a valid methodology. The iterative process has been base on the defined requirements of operation and it is summarized as following: i) tuning of the PD action to attain the specifications of the transient period; ii) parameters adjustment of the PI action to eliminate the offset without modifying the transient response (pole at the origin and closer zero); iii) determination of the controller gain (dominant poles of the closed-loop as close to the resultants of the PD action). The obtained results after applying the algorithm concluded in the information of Table 1. These parameters of the controller are the ones used in the simulation of the global control loop. The step response with the selected parameters results in an inexistent overshoot over the set point value of 0.05 m.

Table 1. PID tuning for the 1D-linear motion stage.

	Parameter	Value	Comments
Input parameters	Transfer function	-	1 A (see eq. 15)
	Step change	50 mm	Largest NanoPla displacement
	Limit error	10 µm	One order of magnitude less than the nanostage working range
	Desired time of response	2 s	To achieve the 98% of the set point value
Output parameters	K_P	4.28	Controller parameters (see eq. 17)
	K_I	1.24	
	K_D	3.15	
	N	100	
	Time of response	32.7 s	To achieve the established limit error

The tuning of the PID controller has only considered the transfer function of the simplified plant: $x(s)\,/\,F(s)$ of the linear moving stage. If the motor and commutation laws are included in the control loop, it is possible to check the maximum achieved values of the related parameters: forces, input currents per phase and speed of motion. The evaluation has been carried out with MATLAB/Simulink® software. The defined model includes the PID controller, the commutation law and the plant with the motor law and transfer function (see Figure 2). The action of the controller provides F_x. The vertical force has established as a constant value of 0.625 N of attraction between actuator parts. This is consequence of the global vertical equilibrium of forces and weights and the equivalent distribution of the load in the four actuators. The significant results conclude in peaks of current less than 0.7 A, so that the assumption of using $G_{P,1A}(s)$ instead of $G_{P,3A}(s)$ is reasonable for this first approximation.

2.5. Implementation

The immediate work to carry out after simulation is the hardware implementation. The used device is the DRV8302-HC-C2-KIT of Texas Instruments (Digital Motor Control Kit to operate with brushless motors). The kit contains a specific control card (F28035) and the DRV8302 board to install it. It provides the closed-loop digital control feedback, the current sense amplifiers and the required inverter stage for commutation. Besides the kit has a three-phase power stage, a separated power supply is installed. The software for the linear motion control is based on the Target Support Package for Embedded Code. That integrates MATLAB® and Simulink® with Texas Instrument tools and C2000 processors, to generate, compile, implement and optimize the control code after experimentation. Thus, the simulated algorithm should be traduced by using the block libraries for on-chip and on-board peripherals.

3. Two-dimensional long range control

Once studied the 1D-motion system, it is time to focus on the NanoPla whole stage. The control-loop includes now the four linear motors, the integrated sensors and also the power electronics block (see Figure 6). The main differences in comparison to the previous analyzed case are the following. First, the 6-DoF to determine by the high resolution sensors (plane mirror laser interferometers and capacitive probes) are the displacements x, y, z and the rotations θ_x , θ_y and θ_z . The action to develop by the global control is also based on six parameters: three forces (F_x , F_y and F_z .) and three torques (T_{θ_x} , T_{θ_y} and T_{θ_z} .). Then, the tuning of different individual controllers will be required. Finally, the force assignment phase is here denominated as stage-motor transform. The output of this part of the loop is the value of the provided forces of each actuator. This part of the control scheme establishes the force assignment: the relationships between the input parameters of forces and torques and the output values of individual motor forces distribution.

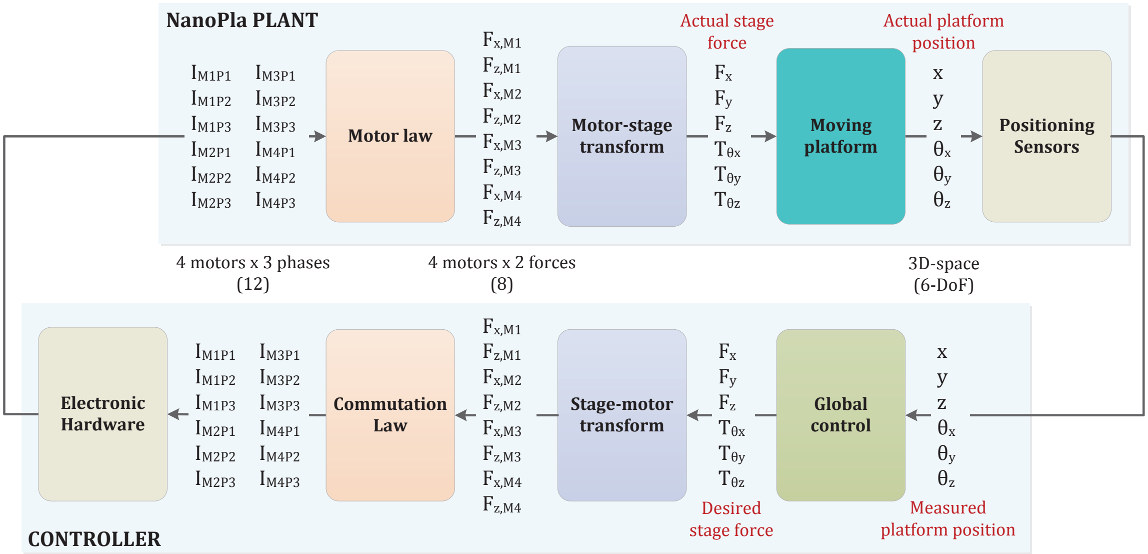

Fig. 6. Control closed-loop for the 2D-NanoPla positioning system.

4. Conclusions

The presented work shows the first approximation for the control task in a 2D-long range nanopositioning system. After experimental characterization of the used actuators, the initial study has been considered the 1D-case. The control loop has been defined, so that all the required algorithms are firstly determined (i.e. commutation laws and transfer functions). The tuning of the proposed PID controller has been also justified, to assure the requirements during the positioning operation. Future works include the implementation of the simulated loop on the specific hardware and optimization of the embedded code. Furthermore, modern feedback control technics will be studied to improve the performance while maintaining stability of the global system.

Acknowledgements

This work was funded by the Spanish government project DPI2010-21629-C02-01 "NanoPla" and DGA-FSE. Special thanks to the Center for Precision Metrology at the UNC Charlotte (USA) for its collaboration.

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