Precision positioning system with high-speed FPGA-based closed loop control

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Abstract

High resolutions and positioning accuracies are often required in precision engineering and microsystems' technologies. An experimental ultra-precision mechatronics system with long travel ranges is conceived in this work. The mechanical design of the system is optimized in order to achieve ultra-precision displacements. The control system of the device is integrated into a high-speed FPGA-based module as a virtual instrument (VI), where closed loop feedback is obtained by employing microstepping control. User controls are programmed as an independent Host VI. A linear incremental encoder with a sinusoidal output signal, which is interpolated and converted into a TTL signal, is employed for position feedback. Experimental validation of the achieved results is conducted by using laser interferometry. A set of short and long step point-to-point positioning experiments are performed and true sub-micron positioning repeatability and accuracy are obtained.

1. Introduction

Precision positioning systems are widely used in AFM and STM microscopy, machine tools, robots, semiconductor manufacturing, etc. Linear displacements are often achieved by using mechanisms driven by rotary motors and ball screws [1]. To achieve high resolutions and positioning accuracies, the mechanical components of the system have to be optimized and suitable control typologies have to be adopted [2]. In this work a Field Programmable Gate Array (FPGA) module is used for implementing micropositioning control. When compared with conventional stepper motor controls, where step resolution is fixed and determined by the employed stepper motor, microstepping control allows generating a very large number of micro steps for each step of the motor, which allows also smooth operation.

2. Experimental Set-Up

The experiments are conducted on the vertical axis of a multi-axes experimental system which is composed of a stepper motor, a feedback sensor, mechanical elements and the control system (Fig. 1). In order to validate positioning accuracy and repeatability, a Michelson-type laser Doppler interferometer is used.

The main mechanical elements of the system are SKF-type SH miniature ball screw and ball bearings, a Misumi miniature Al coupling and Schneeberger MINIRAIL guideways [3]. The mechatronics system is driven by a PM55L-048 stepper motor with 48 steps per revolution. Microstepping control uses analog *sin* and *cos* voltage levels for driving the stepper actuator, where each actuator's step is divided into 1024 sub-steps so that approximately 50'000 micro steps per revolution are obtained. The used feedback sensor is an RSF Elektronik MS 30.03 linear incremental encoder with sinusoidal 20 μm period and 1 V_{PP} output signals. The signal is interpolated and converted to a TTL signal by using a Heidenhain APE 371 interpolation unit with an adjustable interpolation resolution. The maximum interpolation rate (100 x) is used, allowing a resolution of 50 nm to be obtained.

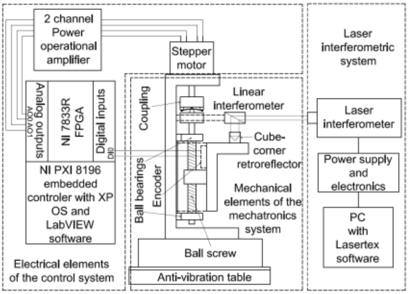

Figure 1: Experimental set-up

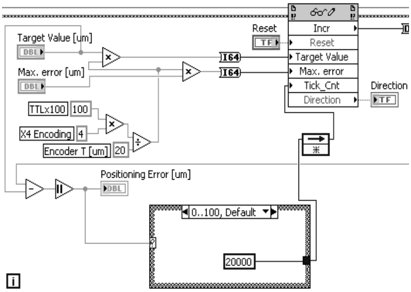

Figure 2: HOST VI block diagram

3. Control algorithms

The control algorithm is composed of LabVIEW® virtual instruments (VIs), where each VI consists of a front panel with user controls, indicators and graphs and a block diagram with graphically coded parts. The proposed solution consists of two main VIs. The FPGA VI is written to the Real-Time (RT) target that represents an interface between the encoder and the actuator. It is also used for implementing the control algorithm. The Host VI (Fig. 2) enables the conversion of the digital representation of the variables to engineering units and, by converting users’ inputs to FPGA VI digital values, it is also used to communicate with the VI running on the RT target.

The FPGA VI (Fig. 3) consists of a 2-frame stacked sequence structure that returns data only when the last frame is executed. Frame 0 is used for initializing the variables, while frame 1 is composed of three control algorithm’s while loops. The left while loop is used for reading the interpolated TTL encoder signals and incrementing or decrementing the *incr* variable depending on the direction of motion. Every transition from logic “0” to “1” and vice versa is counted for both encoder channels, since X4 encoding is used. The *while loop* in the upper right corner is part of actuator’s driving signal. It consists of *case structures* (*if* statements) of which the most important ones are: *type* used for generating the motion type (pause or continuous), *sin* and *cos* for reading the value of the signal from the memory block, *scale* for scaling the voltage levels and *AO* for generating the analog output. The third loop in the lower right corner of Fig. 3 is used to compare the actual and the reference position, define the maximum allowable error and alter the direction of motion. Micro steps are generated (motion type *continuous*) until the system reaches its final position. When the error is lower than the allowable one, motion type *pause* is activated but the motor coils are still powered to preserve the reached position.

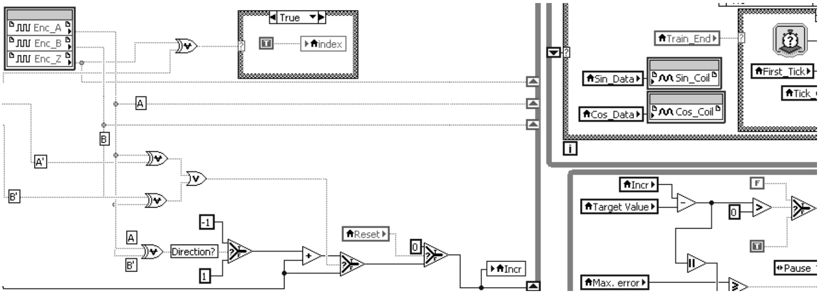

Figure 3: FPGA VI block diagram

An important part of the Host VI (Fig. 2) is a case structure that, depending on the position interval, is used to define the time between micro steps that directly affects the velocity of the actuator. The structure has three cases: positioning intervals from 0 to 100 μm, from 101 to 500 μm and > 500 μm. In the other words, in order to reduce overshoot, the velocity of the motor is reduced as the system approaches reference position. However, some overshoot is still present for shorter steps (see Fig. 4).

4. Results

Experimental validation of the positioning repeatability and accuracy is performed by using a Michelson-type laser Doppler interferometric system. Experimental results for a set of short (5 μm) and long (1 mm) point-to-point positioning steps are given in Table 1, while Fig. 4 shows system's dynamic response.

Table 1: Errors in [μm] for point-to-point positioning experiments

Point # Step size	1	2	3	4	5
5 μm	0.17	0.01	-0.37	-0.22	0.3
1 mm	2.11	0.33	-0.93	0.33	-0.06

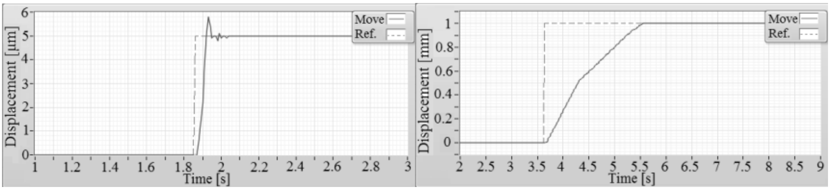

Figure 4: Dynamic response of the system for 5μm step (left) and 1mm step (right)

5. Conclusions

A micropositioning mechatronics system, where closed loop feedback is obtained by using microstepping control, is convinced in this work. Experimental validation is performed via a set of point-to-point positioning steps. It is hence determined that, for short range (5 μm) steps, positioning accuracy and repeatability are, respectively, 0.02 and 0.28 μm. When longer steps (1 mm) are used, these values are, respectively, 0.36 and 1.1 μm. In future work the final configuration of the system, with 4 axes (6 DOFs) aimed at micromanipulation, will be designed and tested.

References:

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