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Performance improvement of optical mouse sensors for position measurement

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Abstract
Optical mouse sensors constitute a cost-effective alternative for position measurement systems requiring micrometre accuracy. Nevertheless, heavy signal processing taking place inside the mouse sensor chip severely constrains the overall system's control bandwidth and endangers its stability. In this work, a predictor-like state estimator is used to compensate the dynamics caused by these filters in order to increase the control bandwidth of a cost-effective positioning stage.

Keywords: Optical mouse sensor, precision planar stage, state estimator.

1. Introduction

The cost of sensors, actuators, and fine mechanics are the main drivers behind the cost of closed-loop precision stages. In [1], a cost-effective (~€200,-) positioning stage for microscopy applications has been designed and built. In this work, we explain the use of a standard optical mouse sensor as a position sensor in this planar stage. One of the major drawbacks of this approach is that the measurements taken by the mouse sensor chip are affected by dynamic effects due to digital filters implemented in the chip itself. We propose and validate a method to compensate these dynamics based on the use of a predictor-like state estimator to obtain position and velocity measurements without the dynamical effects of the digital filters. These estimates are then used to drive the motion controllers of the stage.

In Section 2, the use of an optical mouse sensor as a position sensor is explained. The undesired sensor dynamics due to the digital filters in the sensor are characterized in Section 3. The state estimator used to predict the position and velocity measurements is presented in Section 4, together with an overview of the motion controller design. Experimental results are presented in Section 5 and conclusions given in Section 6.

2. Optical mouse sensor as position sensor

In an optical mouse sensor, a light source (usually a LED) illuminates a surface. The light emitted by the source reflects diffusively on the surface and part of it goes through a lens. The lens projects this light onto a photodiode array (PDA) and, since the photodiodes generate a current proportional to the received irradiance, a (pixelated) image of the surface is created. Using Digital Image Correlation (DIC), the patterns in different frames are compared in order to determine how much the object (e.g. the mouse) has moved. Since mouse sensors measure the displacement between two consecutive image frames, a position measurement can be obtained by integrating the displacement over the time interval between frames. In the measurement system of the positioning stage designed in [1], an optical mouse sensor "looks" at the bottom of the stage to measure its in-plane displacements.

3. Sensor dynamics

Initial attempts to close the control loop of the positioning stage result in unstable behaviour and hint at a very low control bandwidth of the system. A frequency analysis via an open-loop sine sweep is carried out to further investigate this. The displacement measured by the mouse sensor is compared to the "real" displacement measured by an external, more accurate, reference sensor. The resulting Bode plots are shown in Fig. 1. The magnitude plot shows some "bouncing" behaviour on the mouse sensor not present in the reference sensor. These bounces are found in finite impulse response (FIR) filters common in digital data processing applications. Because of these, the phase of the optical mouse sensor rolls over to -180 degrees at around 1.5[Hz], effectively limiting the bandwidth of the system.

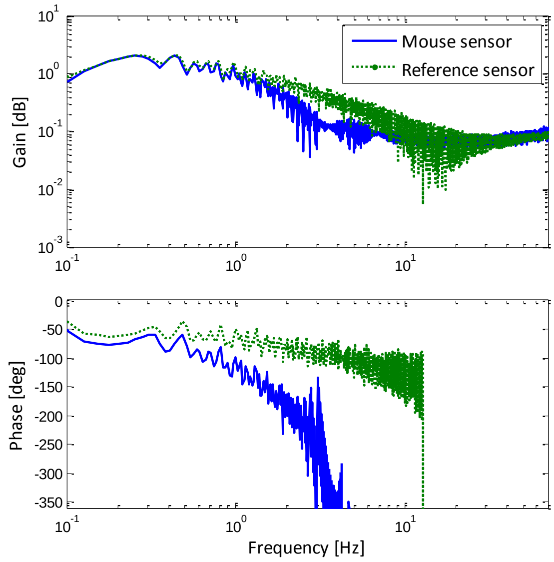

Figure 1. Frequency domain comparison between the measurements of the reference sensor and the mouse sensor.

To verify if a digital filter in the optical mouse sensor chip is indeed causing the undesired dynamic behaviour, an arbitrary step is made with the stage and measured with both sensors (mouse and reference). A moving average filter with a cut-off frequency of 3.5 [Hz] is used to filter the signal from the reference measurement as well. The result, depicted in Fig. 2, shows that the measurement of the mouse sensor overlays the filtered reference signal, thereby confirming that a heavy digital filter is integrated in the optical mouse sensor.

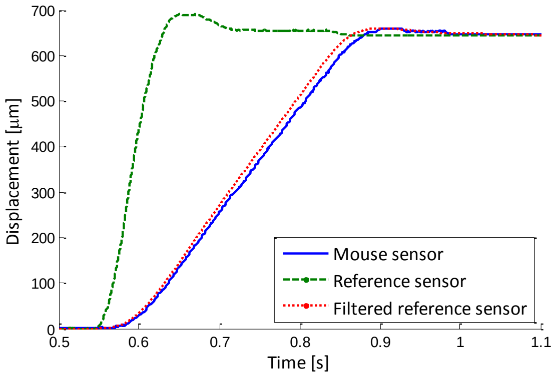

Figure 2. Emulation of the sensor dynamics on a step response. The measurement of the reference sensor differs from the measurement of the mouse sensor due to on-chip filtering. This is verified by filtering the reference measurement.

4. Predictor-like state estimator and controller design

A predictor-like state estimator is designed to compensate for the sensor dynamics and increase the system's control bandwidth (see Fig. 3). The idea is to construct a model of the system (like in an observer) and to append to this model a correcting term which drives the states of the system and the estimator together (also like in an observer). The difference with a common observer is that, since only the output of the plant after it has been affected by undesired dynamics is accessible, the output of the estimator goes through a model of the undesired dynamics in order to carry out a relevant comparison in the correcting term [2]. The controller is not driven by the (affected) output of the plant, but rather by the unaffected output of the estimator. The sensor dynamics required to implement the state estimator are modelled as the FIR filter used in Section 3 in order to obtain matching measurements between the mouse and reference sensor.

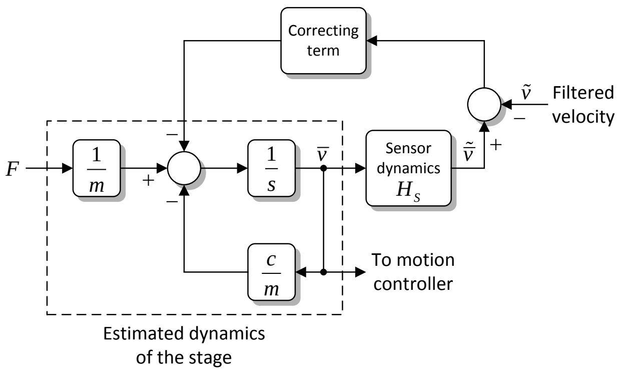

Figure 3. Block diagram representation of the state estimator used to compensate the sensor dynamics.

Since the maximum velocity and acceleration of the stage is limited, a cascaded position-velocity controller with velocity saturation is designed to control the stage's position. An outer position control loop (PID) provides a target velocity for an inner velocity control loop (PI). Two state estimators are used to estimate the position and velocity of the stage. These estimates are used to drive the controllers instead of the filtered signals coming from the measurement system.

5. Experimental results

In the first experiment, shown in Fig. 4, a 1[mm] closed-loop step response results in a 95% settling time of 0.98[s]. The settling time is affected by a standstill due to the estimator overshooting its target. This means that a better tuned controller and observer could significantly reduce the response time of the system, effectively increasing its control bandwidth.

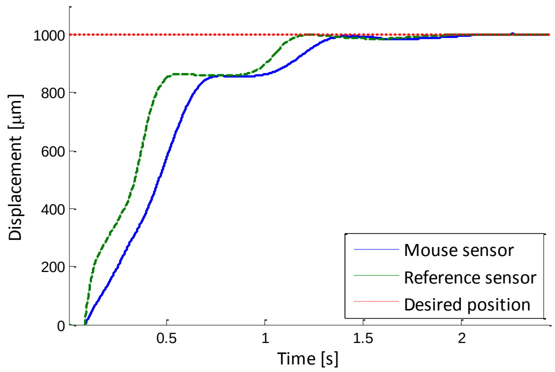

Figure 4. Measured closed-loop step response showing the feasibility of attaining a higher control bandwidth.

In the second experiment, shown in Fig. 5, the precision of the measurement system is determined by comparing the displacements measured by the mouse sensor and the reference sensor. The mean measurement error for 100 trials is 0.5[µm], whereas the 3σ positioning error is 9.7[µm].

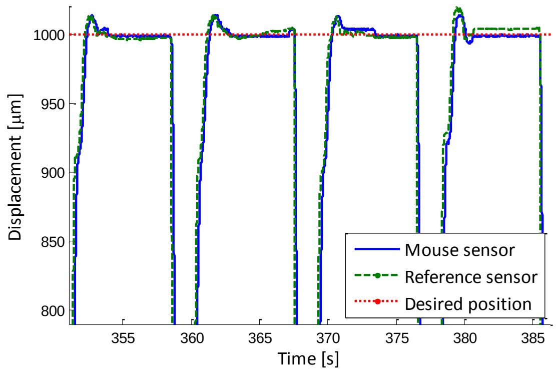

Figure 5. Successive 1[mm] step response measurements used to determine the stage's positioning accuracy and precision.

6. Conclusions

The position measurement system of a cost-effective planar precision stage is presented. This measurement system is based on a commercially available optical mouse sensor chip. Our focus has been on improving the servo performance of the stage by compensating the dynamics introduced by digital filters already present in the mouse sensor chip. In order to do so, a predictor-like estimator is designed to estimate the state of the stage. This estimator uses information about the model of the system, sensor dynamics, system inputs, and sensor output so that, instead of controlling the stage with delayed information from the sensor system, the predicted state of the stage is used to drive the controller. By doing so, it becomes feasible to increase the control bandwidth of the system.

References

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[2] Alvarez-Aguirre A, van de Wouw N, Nijmeijer H. and Oguchi T 2014 Predictor-based remote tracking control of a mobile robot *IEEE Transactions on Control Systems Technology* 2087–2102