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Influence of linear stage technologies for a high speed optical sensor

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Abstract

Surface characterization provides crucial indicators in many quality control processes, as surface parameters give information about the properties of the item inspected. The most used technologies for surface characterization in the micro- and nano level are Coherence Scanning Interferometry (CSI), Imaging Confocal Microscopy (ICM) and Focus Variation (FV). These technologies are based on optical principles, causing no damage to the sample while being inspected and obtaining nanometer resolution. Nevertheless, they suffer from having to perform a mechanical scan of the whole sensor, causing the acquisition time to be increased.

To evolve towards industry 4.0, closed loop manufacturing is essential to reach the automatization of the different steps of the manufacturing processes. In this context, industry is demanding higher speeds and smaller sensors to reduce the quality inspection costs, especially in in-line processes where it is usually required to inspect the sample in less than 1 s. To achieve this requirement using optical profilers the camera frame rate must be increased while reducing the sensor's size and mass as to improve the dynamics of the mechanical scan.

In this paper we analyze the performance characteristics of a linear stage with a linear brushless motor in terms of travel range, accuracy and repeatability compared to a linear stage driven by a stepper motor. The linear stage with brushless motor moves only the objective instead of the whole sensor, enhancing the acceleration dynamics. Additionally, we propose applying different movement profiles to the motor. These new profiles aim to minimize the system's downtime caused by the acceleration and deceleration of the motor, as all the aforementioned metrology technologies require a very stable constant speed when scanning continuously. The downtime reduction leads to a faster acquisition rate, allowing for real-time 3D topographies to be obtained.

Keywords: Confocal, Metrology, Microscope, Surface

1. Introduction

In recent times, there is the demand of more complex, precise, and digitized manufacturing processes. Quality control is compulsory in most of them and can seriously affect throughput, thus there is the need for more advanced, application-specific metrology techniques that can provide more accurate results in less time.

There is also the direction towards integrating in-line sensors to provide feedback for close-loop manufacturing in surface engineering. This trend is demanding constricted form factors and weights, and faster sensors.

The most common surface characterization techniques are Imaging Confocal Microscopy (ICM), Coherence Scanning Interferomety (CSI) and Focus Variation (FV). Depending on the surface, the most appropriate technology can be chosen, being confocal the most versatile of them as it allows measuring from optically smooth to rough surfaces.

However, all of these three metrology approaches rely in scanning the sample along the optical axis, meaning that the mechanical displacement is limiting the measurement speed when a high framerate is achieved.

In order to improve mechanical dynamics, we have evaluated the use of a linear stage with a brushless linear motor scanning only the objective lens compared to a linar stage with ballscrew and linear motor moving all the sensor head.

Finally, we have studied how a sinusoidal movement profile affects the 3D measurement on large movement ranges, instead of focusing on small ranges, which has been already studied.

2. Methodology

Most optical profilometers require a precision Z stage for the correct measurement of the sample's surface. In this paper we analyzed three linear Z stages based on different technologies: a linear brushless motor, an ultrasonic piezoelectric and a stepper motor with leadscrew. The first technology has very low friction and almost no retention capacity when powered off, therefore when placed vertically uses a magnetic counterbalance system to compensate the action of gravity.

While in our setup the stepper motor moves the whole sensor in the axial direction, the linear brushless motor and the ultrasonic piezoelectric only move the focusing lens, therefore carrying a much lower weight.

The non-linearities of the Z stage are the main source of accuracy error in optical profilometers, as the error of positioning of the stage will directly translate into an error in the height measurement [1]. Therefore it is critical to minimize this error or to characterize it in order to compensate it if it is systematic.

The most common way to measure a sample is starting the movement when the sensor is focused onto its surface, move downwards half of the travel range, start the acquisition upwards and finally return to the original position. To minimize the measurement downtime these positioning movements are done rapidly, which increases the whole measurement speed of the system.

We characterized these two perfomance characteristics in each Z stage by means of an interferometric displacement sensor. The positioning error is obtained by moving continuously the sensor at a constant speed and subtract the linear component on the movement profile. The stabilization time is obtained by observing on a step movement when the movement profile is steady.

Additionally, we also simulated the metrological effects when using a sinusoidal movement profile [2,3], instead of a continuous linear profile. This sinusoidal profile will extend the stage lifetime by avoiding sudden acceleration changes. It is interesting for quality control applications where each sample is located at the same axial position and a very fast acquisition rate is demanded. We analyzed the error on a theoretical CSI scanning assuming camera noise and positioning error of the stage during the vertical scan.

3. Results

The three Z stages metioned in the former section were moved 3 mm travel at a constant speed of 400 µm/s and their position was recorded with a laser interferometric displacement sensor (Attocube IDS3010, Munich). In Figure 1 we show the non-linearities when moving the Z stage at constant speed.

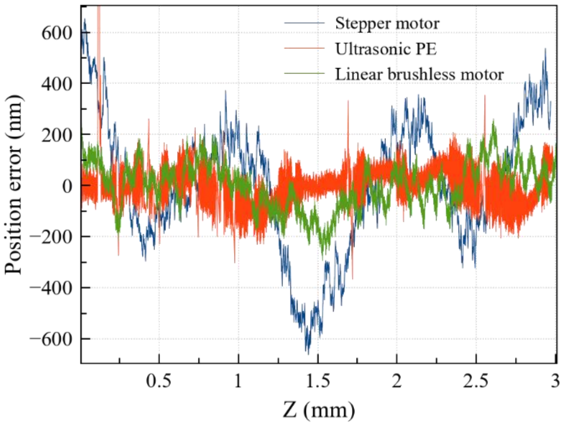

Figure 1. Positioning error of each linear stage in a 3 mm travel range with a 400 µm/s speed.

It can be observed that the stepper motor has a periodic non-linearity with a very determined frequency of 1 mm, corresponding to the leadscrew pitch. Both the ultrasonic piezoelectric and linear brushless motor have a position error predominantly within 400 nm peak to valley (0.01%, of the travel range). Nevertheless, the ultrasonic piezoelectric waist of noise is higher probably due to the position loop trying to compensate real-time the positioning error. These deviations from the commanded movement profile will translate into an error of the surface measurement.

In Figure 2 we show the positioning error of each motor after performing a 100 µm step downwards at maximum speed.

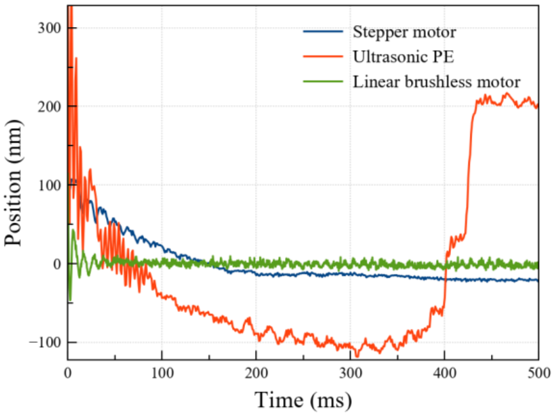

Figure 2. Stabilization time after a 100 µm step.

While the linear brushless motor needs only 50 ms to stabilize, the stepper motor and the ultrasonic piezoelectric require 150 ms and almost 450 ms, respectively. This long stabilization will increase the downtime as the system will need to wait for the stabilization time as in this region the measurement would not be reliable.

For the alternative movement profile we simulated a semi-sinusoidal movement profile of 2 s period with an amplitude of 500 µm, so we set a 1 mm travel range acquired in 1 s. For each theoretical position of the simulation we calculated the CSI signal of an interferometer with a broadband light source of 20 nm on a tilted mirror covering the 1 mm peak to valley. The CSI envelope signal is further recovered and the maximum position calculated to recover the profile of the tilted mirror. Figure 3 shows the metrological error corresponding to a tilted mirror and a sinusoidal scanning profile.

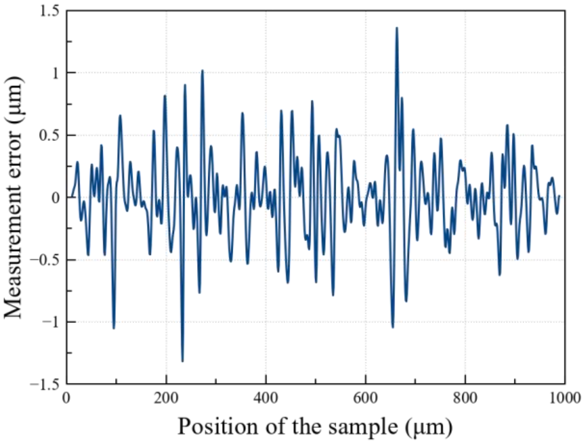

Figure 3. Simulated measurement error on different positions within a sinusoidal theoretical movement profile.

The results show a root mean square error of 0.32 µm on the full travel range at 1 mm. This is very suitable for many industrial applications which need micrometric resolution with high acquisition rate.

4. Conclusions

In this paper we have compared the performance of Z stages based on different technologies, being the most reliable for optical profilometers the linear brushless motor. We have also simulated a sinusoidal movement profile for extending the stage lifetime and have concluded that it is suitable for some industrial applications which require repetitive measurements with high acquisition rate and long travel ranges.

Future work will consist of implementing the sinusoidal movement profile in a real stage and analyze its metrological characteristics.

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