Sensor for Picometer-Scale Positioning in Vacuum

Demonstration of an IDS3010-Based Ultra-Precise Closed-loop Linear Drive System

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As technology reaches the atomic and quantum scale, sub-nanometer motion control is no longer optional - it is a necessity. From wafer positioning and EUV lithography in semiconductor fabs to quantum device assembly and high-precision optical alignment, industries require unmatched positioning accuracy and reliability, often in vacuum environments where even the smallest disturbances are effectively suppressed. Laser interferometers are at the forefront of sensor technologies enabling this, and attocube's IDS3010 is the industrial-grade solution of choice. This TechNote demonstrates the integration of the IDS3010 into a state-of-the-art closed-loop linear drive system by IMMS in vacuum to perform ultra-precise, repeatable positioning at the sub-nanometer scale in vacuum.

Objective

Within this work, attocube partnered with the Institut für Mikroelektronik- und Mechatronik-Systeme gemeinnützige GmbH (IMMS GmbH) in Ilmenau, a research and transfer institute of the German Federal State Thüringen and an affiliated institute of TU Ilmenau that develops advanced microelectronic and mechatronic systems for industrial applications. One of IMMS's core competencies lies in advancing ultra-precise magnetic drive systems through sophisticated control approaches. Within their publication "Picometer-Scale Positioning of a Linear Drive System via Feedforward-Feedback Control" [1] they presented an advanced control approach for a closed-loop voice coil actuator system, enabling positioning performance well into the sub-nanometer range at ambient condition. The goal for this work was to use the vacuum-compatible attocube laser interferometer IDS3010 [2] as the sensor feedback for the closed-loop system to first demonstrate the capability of achieving comparable results even in a vacuum environment.

Setup and Integration

Sensor System

Even though the control approach used by IMMS enables a positioning performance that effectively exceeds the classical limitations of the sensor noise within the closed loop, the sensor noise was found to still be the limiting factor within the setup. Therefore, the newest generation of attocube's laser interferometer IDS3010 (indicated by serial numbers containing the hardware version A03 – within this work: SN "IDS3010-A03-0547") was used because of its improved noise performance.

Furthermore, a vacuum-compatible differential sensor head was developed to satisfy the requirement of a differential sensor signal to further minimize the measurement noise by compensating for any drifts in position and refractive index in the optical path between sensor and target. The sensor head design (see Figure 1) incorporates an integrated tip-tilt stage, enabling straightforward optical alignment of the reference and measurement beams. The overall design was optimized for compactness: excluding the base plate and space required for routing the optical fiber, it occupies only about 60 × 40 × 30 mm³. Sufficient clearance needs to be provided to allow both fiber routing and screw adjustment during operation. The differential sensor head requires only one of the three measurement ports of the IDS3010. To transfer the optical signal from the IDS3010 to the sensor head, a standard ambient fiber patch cord, a KF40 vacuum feedthrough, and a vacuum-compatible optical fiber patch cord with a stainless-steel tubing were used.

Figure 1: Vacuum-compatible differential sensor head

Drive and Closed Loop Control System

The closed-loop linear drive system was implemented by integrating the IDS3010 with a voice coil actuator and advanced control algorithm developed by IMMS [1]. Two mirrors—one static and one actuated—serve as the differential target for obtaining the interferometric sensor signal, see Figure 2. The control loop is executed on a dSPACE MicroLabBox, which serves as a data acquisition card and computation platform for executing the MATLAB/Simulink-based control logic in real-time. A low-noise linear amplifier developed by IMMS serves as a power supply for the voice coil actuator.

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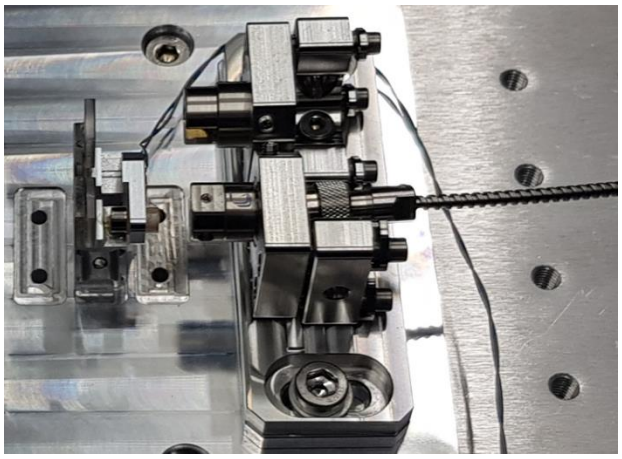

Figure 2: Setup including the IMMS voice coil actuator and the attocube differential sensor head

Vacuum System

The measurements were conducted in a vacuum chamber at IMMS reaching pressures during these experiments at about 4.5×10^{-6} mbar. Figure 3 shows how the closed loop drive system was installed within the chamber. During the measurements the turbo pump was switched off to minimize mechanical noise within the environment.

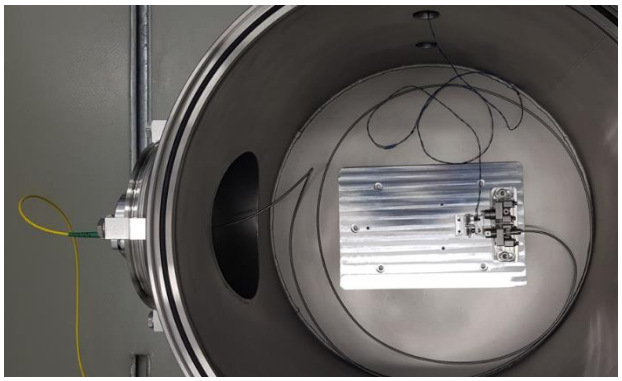

Figure 3: Mechanical closed-loop drive setup inside the opened vacuum chamber

Integration

The sensor system was installed at an absolute distance of approximately 20 mm from the measurement point on the differential target mirrors. Optical alignment was performed using the provided tip-tilt stages. To enable real-time communication with the control system, the unfiltered IDS3010 sensor signal was transmitted via the digital AquadB real-time interface (resolution: 1 pm, clock rate: 80 ns) and fed into the dSPACE MicroLabBox, which sampled the input at 10 kHz. To ensure stable control behavior, the control parameters were adjusted to match the characteristics of the modified setup. The functionality of the setup was first demonstrated under ambient conditions before being transferred to vacuum.

Vacuum Measurements

Open Loop

Before operating the drive system in closed loop, the IDS3010 sensor signal was measured to analyze noise and stability. Figure 4 shows three measurements in open loop, each recorded over a duration of 30 seconds. No significant drift was observed, and the noise standard deviation (1σ) remained below 70 pm.

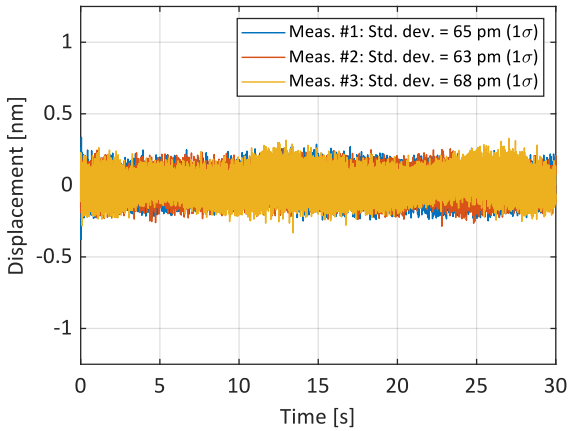

Figure 4: Open loop measurement of the IDS 3010 sensor signal

Closed Loop

In the next step, the drive system was operated in closed loop, and five increments of different sizes were commanded in both forward and backward directions, resulting in a pyramid-shaped time trace. This was used to assess whether the system could execute these increments reliably and repeatably.

Figure 5 shows the unfiltered measurement result when commanding increments in the size of a single nanometer. The system can reliably follow the setpoints without visible deviations.

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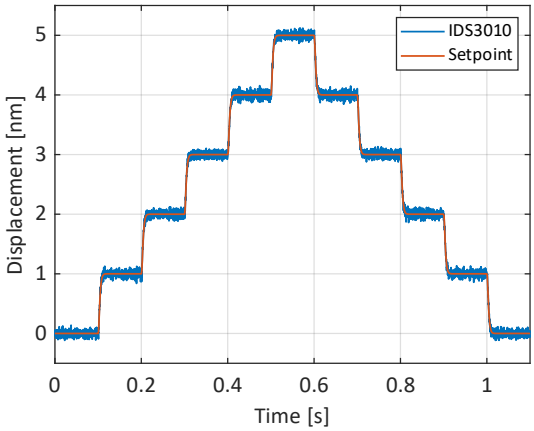

Figure 5: Closed loop movements with 1 nm increments

Figure 6 shows the measurement result when commanding increments in the size of a 100 picometers. This is close to the standard deviation (1σ) of the sensor noise and therefore the raw signal only allows a rough estimate of the resulted movement. But analyzing the filtered data that is available within the control logic, one can see that the control loop and the drive system can generate a movement in accordance with the commanded setpoints.

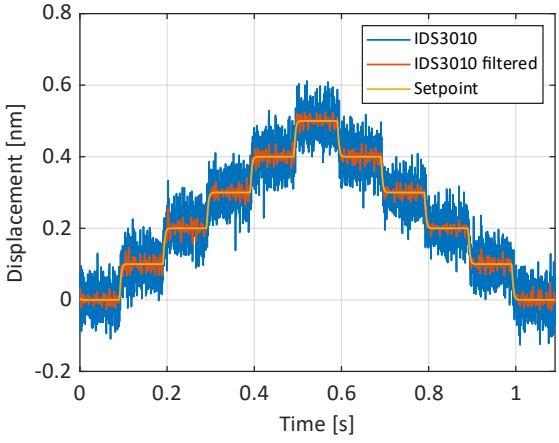

Figure 6: Closed loop movements with 100 pm increments

Figure 7 shows the measurement result when commanding increments in the size of a 20 picometers. This clearly exceeds the sensor noise and therefore results in only a vague trajectory when looking at the raw sensor signal. But if again the filtered signal is assessed, one can see that the drive system can follow the setpoints, which underlines the effectiveness of the control methodology developed by the IMMS.

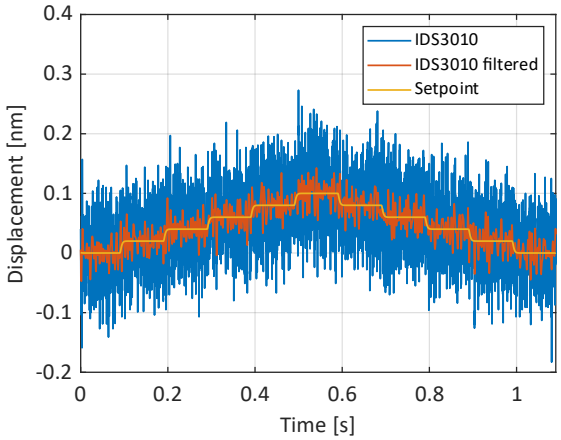

Figure 7: Closed loop movements with 20 pm increments

Conclusion

It was demonstrated that the IDS3010, combined with a differential sensor head operating in vacuum, exhibits a sensor noise of <100 pm (1σ) at a sampling rate of 10 kHz. By integrating this sensor signal with the drive and control system methodology proposed by IMMS [1], repeatable closed-loop positioning at 1 nm, 100 pm, and — with certain limitations — even 20 pm was achieved. The results confirm that the attocube IDS3010 enables state-of-the-art closed-loop positioning performance in the sub-nanometer scale in vacuum. The demonstrated setup highlights the system's capability for high-precision and stable operation under demanding environmental conditions. attocube would like to thank IMMS for the fruitful collaboration, their valuable expertise, and for conducting the measurements.

References

[1] Huaman, Alex S., et al. "Picometer-Scale Positioning of a Linear Drive System via Feedforward-Feedback Control." 2021 IEEE International Conference on Mechatronics (ICM). IEEE, 2021.

[2] attocube IDS3010 Displacement Laser Interferometer Displacement Measuring Interferometer