

DESIGN OF A PRECISION SCRIBING SYSTEM

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INTRODUCTION & OVERALL GOAL

This report presents the mechanical design and control strategy for a precision scribing system. The goal is to integrate this scribing system with an XY scanning platform to produce grating masters at groove densities of over 50 lines/mm. In 2020, the positioning mechanism in the z-axis of the scribing system is mechanically developed and verified by replacing the grating substrate with a shear force sensor.

The precision of the scribing system requires not only a stable mechanical structure but also a robust control strategy that deals with various accidental issues in practical fabrication for grating masters. Our scribing system design shows extraordinary performance through preliminary tests. And it is fully prepared with an advanced controller for the coming grating ruling challenge in 2021.

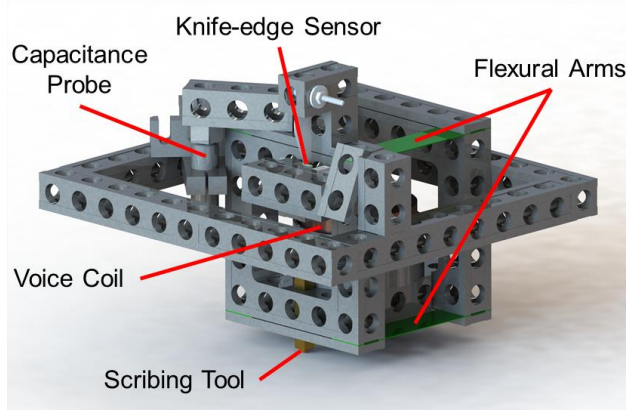
MECHANICAL DESIGN

The scribing system design is based on a 4-bar accurate flexural positioner, where the activating force is applied on the centerline between the two platforms and reeds both vertically and horizontally. [1] A Demetric view of our design is illustrated in Fig. 1 (A), where the 4-bar compliant

system builds up a linear actuator in the z-axis. The scribing system is mounted on an XY stage adapter in a rectangular shape as shown in Fig. 1 (B). The adapter serves as a stable base for the z-actuator, and it also provides fixtures for the capacitance probe and the knife-edge sensor. Due to limited space beneath the stage platform, the sensors and the corresponding components, e.g., the knife, are placed above the stage platform. With every component fixed, the overall scribing system can be reinstalled onto different platforms without the need for recalibration. The scribing tool is pushed and locked by a screw to the interior walls of a mech block, with its height adjustable by loosening the locking screw.

When a positive voltage (current) is applied to the voice coil, the scribing tool will be actuated towards the substrate by magnetic force, as illustrated in Fig. 2. By applying a finely tuned PID controller with feedbacks from the position sensors, the scribing tip can be positioned precisely beneath the upper surface of the substrate. A micro-groove can then be formed along the x-y plane via a relative motion between the scribing tool and the substrate.

(A)



(B)

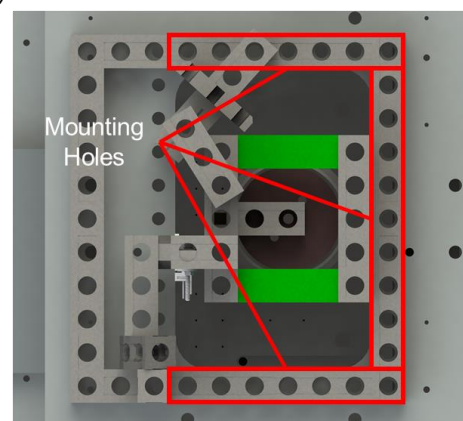


Figure 1 (A) Mechanical design of the 4-bar flexural scribing system; (B) Top view of scribing system mounted on the XY stage, where the mounting holes on the stage adapter are marked with red boxes.

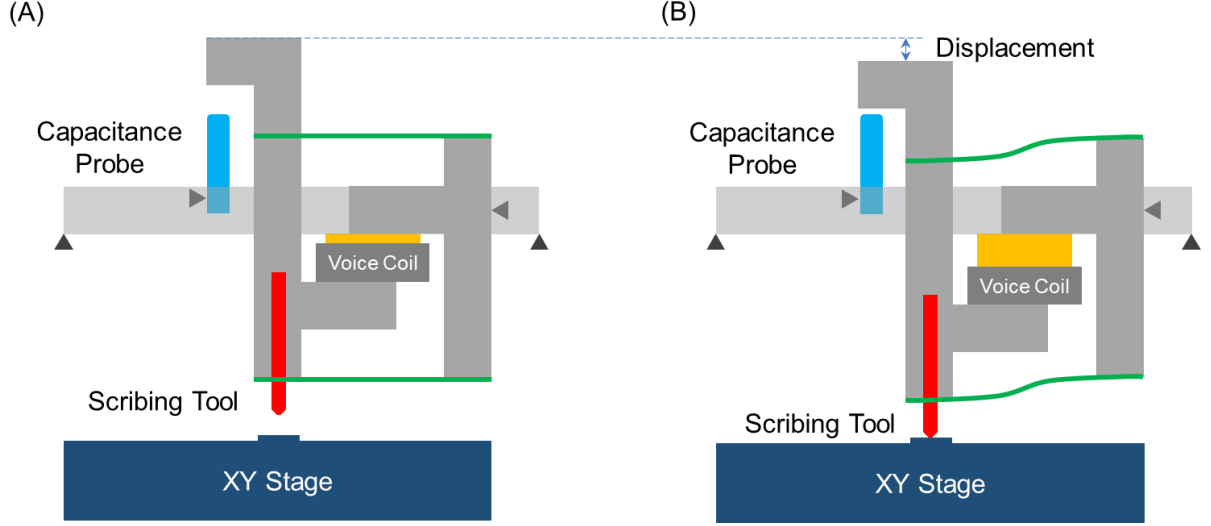


Figure 2 (A) and (B) are two states of the scribing tool. Displacement is generated corresponding to the voltage applied to the voice coil. Black triangles refer to fixtures

WORKFLOW & CONTROL STRATEGY

To fabricate a grating, the overall workflow for our design is illustrated in Fig. 4 (A). The main steps are listed as follows.

Substrate Characterization

First, an assumption should be made that the upper surface of the grating substrate is flat, but it is tilt to the stage motion plane (x-y plane) with angles of (α, β) . Fig. 3 (A) illustrates the tilt angle α to the direction of scribing, which causes variation in the depth of a single groove. Fig. 3 (B) shows that tilt angle β in another direction varies scribing depth among grooves. To ensure uniformity of depth within a single groove and among different grooves, we propose a pre-characterization of the substrate.

A 3-point surface detection is performed at the beginning of each fabrication for gratings, after which the tilt angles and the overall surface

profile are measured. As illustrated in Fig 3. (C), point a , b , and c are the 3 points whose positions are recorded to obtain the surface profile, which can be represented as:

$$\begin{vmatrix} x - x_1 & y - y_1 & z - z_1 \\ x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\ x_3 - x_1 & y_3 - y_1 & z_3 - z_1 \end{vmatrix} = 0 \quad (1)$$

The detailed procedure for surface detection will be discussed in the next section.

For each groove to be scribed, the tilt angle along the scribing motion will be compensated with a measured surface profile to ensure a uniform depth. At the beginning of scribing each groove, an independent surface detection will be performed to compensate for the possible drift of the capacitance probe. The scribing process will abort if the detected surface position is too far away from the measured surface profile.

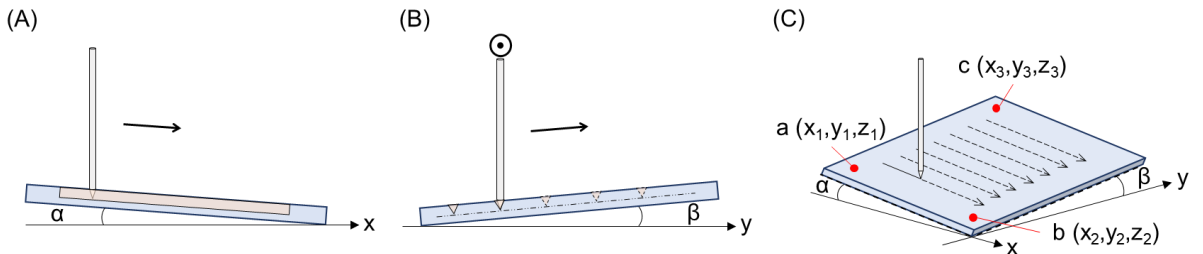


Figure 3 (A) Tilt to the direction of scribing, i.e., x-axis; The scribing depth of single groove will vary without compensation; (B) Tilt to the direction perpendicular to scribing, i.e., y-axis. The depths of grooves will vary progressively along the y-axis; (C) Demetric view of the substrate; Positions of points a , b , and c are measured by surface detection procedure. The surface profile can be calculated with the 3 points.

Fabrication Loop

Surface Detection

By applying a linearly incremental voltage (current) to the voice coil, the scribing tool will be actuated and move towards the substrate. However, the motion profile of the scribing tool will have a drastic change before and after contact with the substrate, i.e., the gradient of position increment will significantly decrease after contact when the same voltage increment is added to the voice coil actuator. By detecting the change point of the motion profile, the contact position can be measured precisely with repeatability under 100 nm.

Control Loop

The control loop contains 2 sets of PID controller, one is for positioning before contact, which has smaller PID parameters, and the other one is applied after contact, whose PID parameters are

tuned larger for more sensitive and rapid feedbacks. It should be noted that the PID controller after contact is not tuned to the fastest in order to avoid overshoot, which can completely damage the optical quality of the grating. During the scribing of a single groove, the desired position will vary corresponding to the measured surface profile. The position will mainly be measured by the capacitance probe for its larger measuring range and better resolution. However, it might have drifting problems. So, a knife-edge sensor is applied to monitor the drifting from time to time.

Next Groove

When one groove has been successfully scribed, the scribing tool will be lifted. After that, the XY stage moves the substrate to the starting point of the next groove, followed by surface detection and scribing.

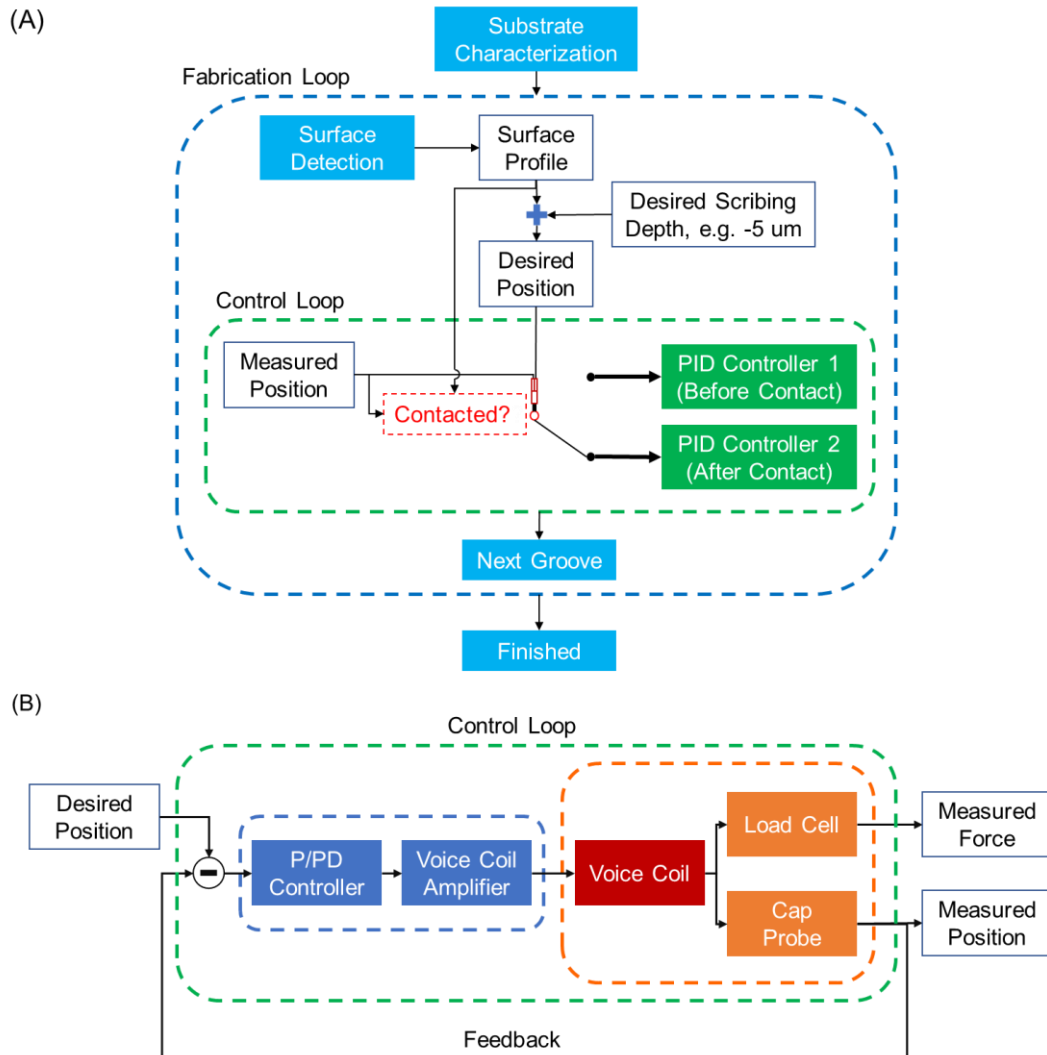


Figure 4 (A) Workflow of the scribing process; Light blue boxes refer to certain processes; White boxes with blue edges refer to physical values; Green boxes refer to controllers; The PID switch is triggered by the comparison of current measured position with surface position in the z-axis (B) Illustration of control strategy corresponding to the green PID controller boxes in (A)

SYSTEM CHARACTERIZATION

Performance of Surface Detection

Surface detection is performed at (1) 3-point substrate characterization and (2) the beginning of scribing each groove. Thus, the precision and repeatability of surface detection directly determine the quality of the grating fabrication.

Fig. 5 shows a single round of surface detection. We apply a linear increment (10 mV/s) on the voltage applied to the voice coil actuator, while the capacitance probe detects the displacement, respectively. It can be concluded that the gradient of displacement variation changes significantly at the contact point of the scribing tool and the surface of the substrate. The measured contact points of the scribing tool approaching and leaving the substrate have a stable difference of ~500 nm. During a multiple-round test, the repeatability of the contact point measurement is under 100 nm, which meets the standard of grating fabrication. It should be noted that we use a load cell to simulate the substrate. In the practical fabrication of a grating, the surface detection process will be more precise due to the enhanced stiffness of the substrate.

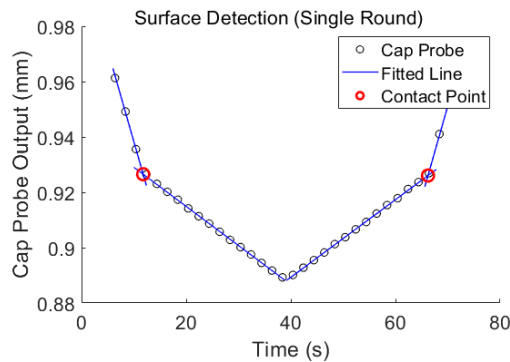


Figure 5. Surface detection in a single round. The red circle indicates the contact point of the scribing tool and the surface of the substrate

Then, the performance of the scribing system under our PID controller is characterized. Mainly, we characterize the step response and frequency response of the scribing system before and after contact with the load cell.

Fig. 6 is the time-domain response of the scribing system. Before contact, the performance of the scribing system is only indicated by the capacitance probe. We can see that the rise time is around 120 ms with no load, as shown in Fig. 6 (A). After contact, the force is also measured by the load cell. If PID parameters remain small as the no-load condition, the system would have a much worse performance of time-domain response. On the other hand, overshoot could damage the groove being scribed, for which it

should be prevented, and the PID parameters should not be pushed to its limit. We finely tuned the PID parameters under this condition and the rise time is optimized to 650 ms, as shown in Fig. 6 (B). From the after-contact step response, it can be seen that the slow readout rate (10 Hz) of the load cell causes a significant time delay of around 300 ms.

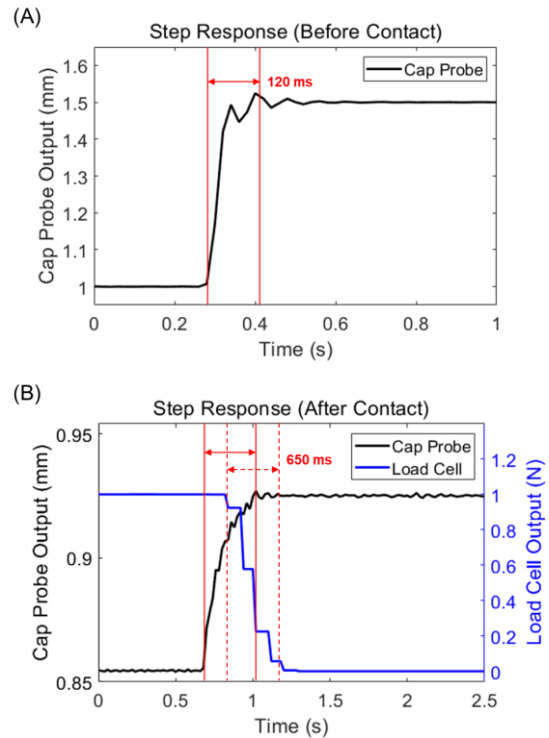


Figure 6. Step response in the time domain: (A) Before the contact of the scribing tool and the load cell; (B) After the contact of the scribing tool and the load cell.

Fig. 7 is the frequency response of the scribing system, acquired by applying sinusoidal input at different frequencies to the system. The frequency response is of great importance as it shows the maximum speed that the system can achieve. From the performance of the frequency response, we can directly get knowledge of the fastest scribing speed towards the desired surface roughness. The amplitude response is good enough, i.e., ~1, when the frequency is under 1 Hz, meanwhile, the phase delay can be kept under 0.05 rad before and after contact with the load cell. The phase delay measured by the load cell is much worse due to the slow readout rate, similar to the situation in the time-domain response. From both time-domain response and frequency response, we can conclude that although the capacitance probe and load cell measure the same dynamic process, we should only use the capacitance probe for reliable feedback.

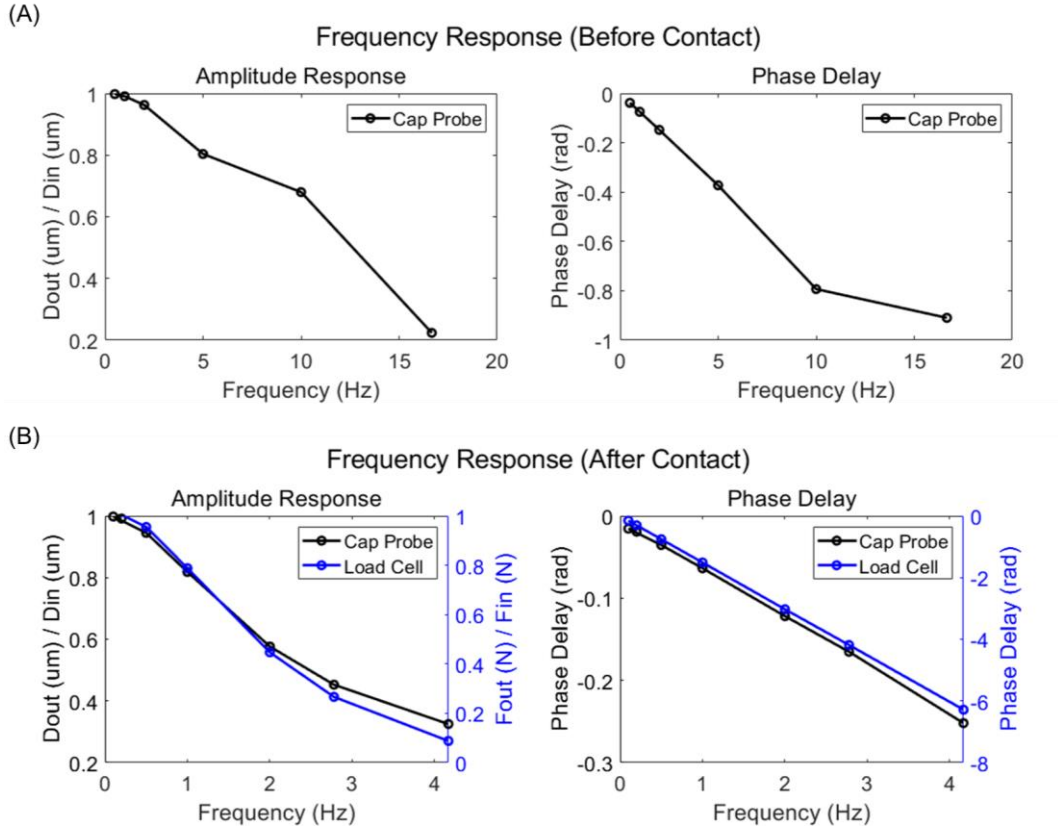


Figure 7. The frequency response of the scribing system. (A) Before the contact of the scribing tool and the load cell; (B) After the contact of the scribing tool and the load cell.

ERROR BUDGET

In this section, the error sources are analyzed to estimate the precision of the scribing system.

Misalignment of the Voice Coil

Given the mechanical error during the manufacturing and assembling, the voice coil's direction is always not parallel to the direction of actuation, as shown in Fig. 8 (A). With a misalignment angle $\Delta\theta$, the error of displacement of the voice coil can be expressed by Eq. (2):

$$\frac{\Delta x}{x} = \cos\Delta\theta - 1 \quad (2)$$

Misalignment of the Position Sensor

The capacitance probe faces misalignment issues as shown in Fig. 8 (B):

$$\frac{\Delta x}{x} = \frac{1}{\cos\Delta\gamma} - 1 \quad (5)$$

Similarly, the misalignment between the blade and optical sensor makes the position measurement inaccurate, as shown in Fig. 8 (C) (D). There will be two misalignment angles, $\Delta\alpha$ and $\Delta\beta$, representing the pitch and heading angles' misalignments and inducing the position measurement errors, expressed by Eq. (3-4):

$$\frac{\Delta x}{x} = \cos\Delta\alpha - 1 \quad (3)$$

$$\frac{\Delta x}{x} = \frac{1}{\cos\Delta\beta} - 1 \quad (4)$$

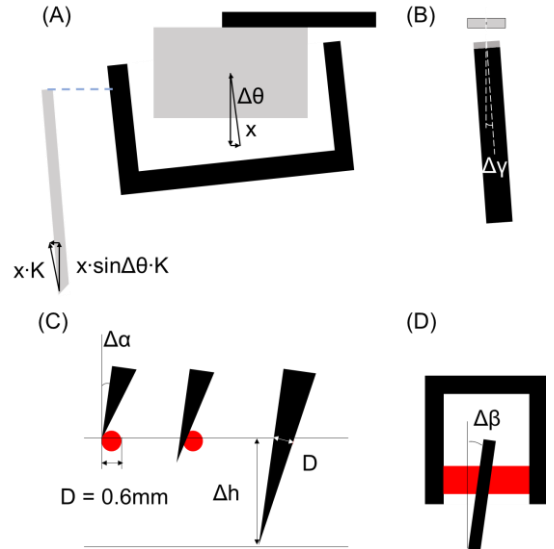


Figure 8. (A) Misalignment of the voice coil; (B-D) Misalignments of the position sensor.

Load Cell Error and Electrical Noises

When working for a long period, the load cell will have stability errors. We measured that the maximum error is about 0.0005N. The square variance is $3.6e^{-06} N^2$. Besides, the optical sensor has a 15mV electrical noise, which indicates a 1% amplitude of sensor noise.

Surface Detection Error

As stated in System Characterization Section, the scribing tool and substrate's contact point measurement has a repeatability under 100 nm. For the test with the load cell, it has a stroke of 0.2 mm. Thus, the displacement error is at the level of 0.05%.

Other Error Sources

Numerous factors degrade the system's precision, such as the data acquisition card's errors and the amplifier of the voice coil, the electromagnetic interference between the support, voice coil, and the environment, the vibration of the building, etc. However, these factors are not the critical problems of our system, according to the experiment requests.

Table 1. Error budget for the precision scribing system

Error source	Amplitude	Error
Misalignment of the Voice Coil	$\sim 1^\circ$	$\sim 0.02\%$
Misalignment of the Position Sensor	$\sim 1^\circ$	$\sim 0.02\%$
Surface Detection Error	100 nm	$\sim 0.05\%$
Load Cell Error	~ 700000	$\sim 0.1\%$
Electrical Noise	$\sim 0.015V$	$\sim 1\%$

CONCLUSION

In conclusion, we have designed a precision scribing system based on a 4-bar accurate compliant positioner, which is activated by a voice coil actuator. The system is equipped with advance controller and adaptive workflow for robust positioning in z-axis. Precision surface detection technique is applied to pre-characterize the upper surface of the substrate at the beginning of grating fabrication, which is followed by repeated detection before scribing each groove of the grating to avoid sensor drift and unevenness of the substrate. Thorough tests for the performance metrics are conducted to evaluate the mechanical design and the controller. In the end, we analyze the possible errors mechanically and electrically, and find the error budget is mainly from electrical noises. With all the errors taken into consideration, we believe our design is promising to fabricate a real grating in the 2021 challenge.

REFERENCE

- [1] Highly Accurate Flexural Systems:
<https://www.precisionballs.com/Flexures.php>
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