Reference Position of a 2D Positioning Platform with Halbach Linear Motors

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1. Introduction

Nanotechnology has become essential in the world of Science and Technology. Nanopositioning platforms are crucial in applications such as metrology or micromanufacturing. Nanopositioning platforms that offer nanometric precision and a large working range [1, 2] are necessary for applications such as lithography and surface characterization using optical and scanning microscopes [3]. Therefore, the University of Zaragoza has developed a large range nanopositioning platform called NanoPla [4].

The NanoPla is a 2D nanopositioning platform with submicrometric precision and a large working range (50 mm × 50 mm). The structure of the NanoPla is divided into three levels: a fixed lower base, a fixed upper base, and a moving platform located between both bases. The application for which the NanoPla first prototype is intended is the metrological characterization of large samples at a submicrometre scale. In these applications, the metrological instrument will be attached to the metrology frame of the moving platform, while the sample to be measured is placed on the sample holder fixed to the metrology frame of the inferior base. The first metrological instrument that has been integrated in the NanoPla is a confocal sensor. Specifically, the confocal sensor is the model CL4 with the magnifier MG 35 and the controller CCS Optima Plus from Stil®. The confocal sensor performs a 1D measurement without contact with the target, in a range of 4000 µm. Figure 1a shows an exploded view of the NanoPla.

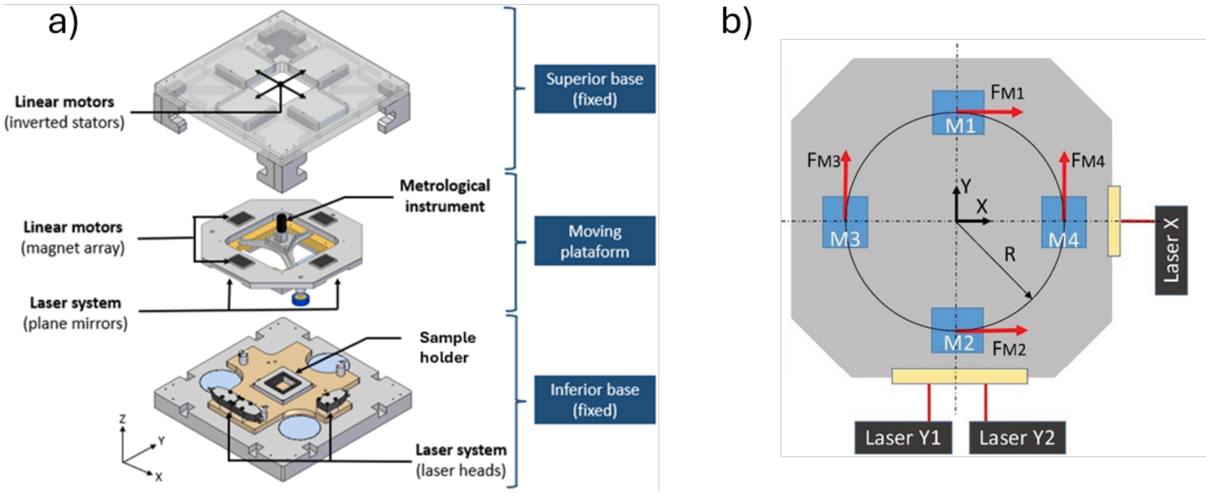

Figure 1: a) NanoPla Exploded view. b) Schematic top view of the moving platform and the laser heads

To perform the motion of the moving platform, three air bearings levitate the platform, and four Halbach linear motors work as actuators in X and Y-axis. The stators of these motors are fixed to the upper base, while the magnetic arrays are located on the moving platform. A 2D plane mirror laser interferometer system serves as the position sensor, providing high precision and direct traceability.

The four motors in the NanoPla are arranged in parallel pairs (Figure 1b); The thrust forces of the pair of motors M1 and M2 displace the platform along X-axis, while the thrust forces of the pair of motors M3 and M4 displace the platform along Y-axis. Additionally, the thrust forces of the four motors generate a torque around Z-axis at the central point of the moving platform.

The 2D laser system belongs to the Renishaw RLE10 laser interferometer family. It consists of a laser unit (RLU), two sensor heads (RLD), two plane mirrors (one per axis), and an environmental control unit (RCU). In addition, an external interpolator is used to reduce the expected resolution of the system from 10 nm to 1.58 nm. In the NanoPla, the three laser heads are positioned in the metrological frame of the lower base, two for Y-axes (Laser Y1 and Laser Y2 in Figure 1b), and one for X-axes (Laser X in Figure 1b). While the plane mirrors are fixed to the metrological frame of the moving platform. This setup allows measuring displacements in both X and Y directions, as well as rotation around the Z axis. Moreover, using flat mirrors as retroreflectors enables the measurement of coplanar displacement along two axes. As a drawback, the laser beams must be always kept perpendicular to the plane mirror, thus, the rotation around Z-axis of the moving platform is restricted to a very small angle. If the laser beams are misaligned with respect to the mirrors, the laser system stops reading and loses its reference.

In previous works [5], the position control system for the NanoPla has been developed to coordinate the operation of the four Halbach motors and integrate the two-dimensional laser system as a sensor for position feedback. The position control system design is the following: the user introduces the desired target position in XY coordinates, then, in the position control strategy, two PID controllers act on the total force in X and Y-axes to correct the positioning error in X and Y-axes, respectively. There is one additional PID controller that prevents the rotation of the moving platform around Z-axis, so that the laser system is not misaligned. Then, the required forces are distributed symmetrically in the four motors, and, according to the motor law of each motor, the phase voltages commands are sent to the control hardware that generates the voltages that produces the phase currents in the linear-motor stators. Finally, the generated thrust forces produce the motion of the moving platform. This displacement is recorded by the laser system and fed back to the PID controllers.

In metrological applications, the basic measurement procedure of the NanoPla is the following: while levitating thanks to the air-bearings, the moving platform displaces to the measuring point, and once it is there, the air-bearings are shut off and the moving platform lands, resting statically while the measurements in Z-axis are recorded by the confocal sensor. Once the measurements at that measuring point have been recorded, the air-bearings are turned on, and the moving platform displaces to the next measuring point, repeating the procedure. The results are discrete values for Z-axis at XY-coordinates that represent the surface that is being measured.

It is important to note that the laser interferometer system is a differential system, not an absolute one, so it is essential to define a reference position each time the position control system is turned on. In addition, it must be considered that the laser system can be misaligned while a measurement is being performed, thus, to continue with the measurement, the reference position must be reestablished. In case that happens, the repeatability of the procedure for defining the reference position is crucial for the final precision of the measurement. In this work, first, a procedure for establishing a reference position for the NanoPla positioning system is defined and its repeatability studied. Then, an optimization of the procedure is proposed to improve the repeatability. In addition, in both procedures, the target in both procedures is to use the components that are already integrated in the NanoPla.

2. Halbach linear motors as open loop servosystems

The aim to this section is to explain the working principle of the Halbach linear motors integrated into the NanoPla, which is essential to understand the referencing procedures proposed in this work. Each of these Halbach linear motors consists of a three-phase ironless stator and a Halbach permanent magnet array. As shown in Figure 2a, when the current flows through the three-phase coils, the electromagnetic interaction results in two orthogonal forces, a horizontal thrust force (F_x), and a vertical force (F_z), according to the motor law introduced in [6]. In the NanoPla, the horizontal forces from each pair of parallel motors provide motion in the X and Y axes, respectively. Although the vertical forces of the four motors could be used for levitation, the NanoPla uses air-bearings for levitation and to absorb the vertical forces of the motors due to their stiffness.

As shown in Figure 2b, for certain constant phase currents, the forces vary spatially in a sinusoidal way depending on the relative position between stator and magnet array (represented as “x” in Figure 2). There is a position of stable equilibrium between magnet array and stator where the motor remains motionless, which corresponds to $F_x = 0$ N and F_z is at its maximum positive value. If a disturbance slightly displaces the motor from this stable equilibrium position, the electromagnetic force will push it forward ($F_x > 0$) if the displacement is negative, or backward ($F_x < 0$) if the displacement is positive, always returning it to the stable equilibrium position ($F_x = 0$). It is important to note that there is also an unstable equilibrium position, occurring when $F_x = 0$ N and Fz is at its minimum negative value. At this point, if a disturbance slightly displaces the motor, the electromagnetic force will push it to the nearest stable equilibrium position.

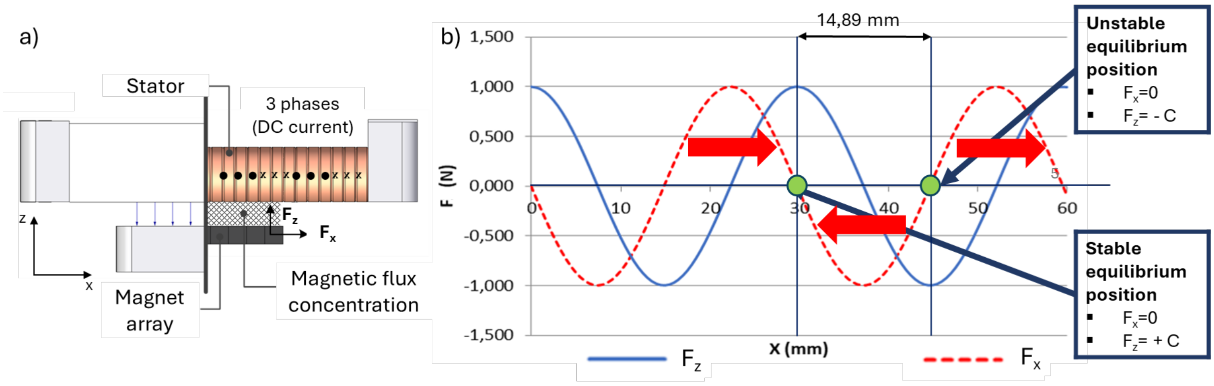

Figure 2. a) Graphical representation of the dual forces generated by the Halbach linear motor. b) Forces and equilibrium positions along the working range of the Halbach linear motor.

An open loop position control strategy can be developed by leveraging the properties of the stable equilibrium position: around the stable equilibrium position, the motor functions as an open loop servosystem using this equilibrium position as the reference position, this reference position can be defined and adjusted by controlling the phase currents [6]. The command of this open loop position control strategy is a desired position, “x”, for which the horizontal force is null ($F_x = 0$) and the vertical force (F_z) is positive and has a constant value, so that it results in a stable equilibrium position. The value of F_z is relevant because it affects the slope of F_x in the linear zone around the equilibrium position (Figure 2b). The higher the value of F_z at the stable equilibrium position, the greater the thrust forces that push and maintain the motor at this position. However, a higher value of F_z requires higher phase currents, which generate more heat in the motor coils.

3. Open loop position control strategy for referencing

The initial reference position of the position control system of the NanoPla needs to be defined by referencing or “zeroing” the laser system (setting X=0 and Y=0) when the moving platform is at that initial position, thus, it must be done by displacing the moving platform to that position without the feedback of the laser system. Therefore, in this work, we propose to use the open loop position control strategy for the referencing procedure: the reference position can be obtained by commanding each motor to maintain a stable equilibrium position at the center of the NanoPla working range, so that the four motors work as independent open loop servosystems. However, because the moving platform is a rigid body, it is unlikely that all four motors will reach their individual equilibrium positions simultaneously, hence, a "combined equilibrium position" is sought, which will serve as the initial reference to establish the (0,0) position. The individual initial equilibrium positions of the motors can be adjusted to find a combined equilibrium position that minimizes measurement error while maintaining alignment between the mirrors (fixed to the moving platform) and the laser heads (fixed to the NanoPla's lower base). This equilibrium position is chosen to center the moving platform within its working range and align the lasers.

Therefore, in the open loop position control strategy procedure, the reference position is obtained using equal but independent open loop position control strategies for each motor of the NanoPla. As mentioned, the reason for using open loop position control to establish the reference position is that the laser system is a differential measurement system and needs to be referenced every time it is turned on, or every time it is misaligned and loses its reference. Once the reference position of the laser system has been defined in open loop, a closed loop position control can be implemented, using the laser system as positioning sensor in a closed loop position control strategy. However, as mentioned earlier, each time the lasers are turned off or misaligned, a new reference must be established. For this reason, the repeatability and stability of the procedure for defining the reference position of the moving platform are important considerations. Following, a repeatability study of the referencing procedure is conducted.

The repeatability of the reference position defined with the open loop position control strategy has been tested as follows: The moving platform is static with the air-bearings off, and the laser system not referenced. The first step is to activate the open loop position control strategy. Then, when the air-bearings are turned on and the moving platform levitates, it displaces to the stable equilibrium position defined by the open loop position control strategy. At that position, that centers the moving platform in the NanoPla working range, the initial reference position is established, zeroing the laser system. Afterwards, the procedure is repeated 9 more times, turning off the air-bearings, and turning them on again, making the moving platform displace to the stable equilibrium position each time the moving platform starts levitating once again. After the first time, although the open loop strategy is maintained, the laser system is not zeroed anymore, instead, the position reached after turning on the air-bearings is recorded, to measure the deviation between the different stable equilibrium positions reached each time. Moreover, to obtain reliable results minimizing measurement errors, the laser system and motors must be turned on approximately 45 minutes before measurements are initialized. This helps to prevent errors due to expansions or heating of the devices. In addition, the NanoPla is placed in a metrology lab with a controlled temperature of 20 ± 1 °C. The experiment is repeated for three cases: F_z equal to 2 N, 4 N, and 6 N at the stable equilibrium position of each motor. Table 1 shows the maximum deviation in X and Y-axes for each value of F_z.

Fz/N	**Max. deviation in X-axis/µm**	**Max. deviation in Y-axis/µm**
2	-3.415	10.132
4	-3.177	0.655
6	1.409	0.388

Table 1. Maximum deviation of 10 repetitions defining the reference position using an open loop position control strategy, for different values of F_z.

In addition, Figure 3 shows the deviations of the stable equilibrium position obtained in X and Y-axis for the specific case of F_z = 6 N.

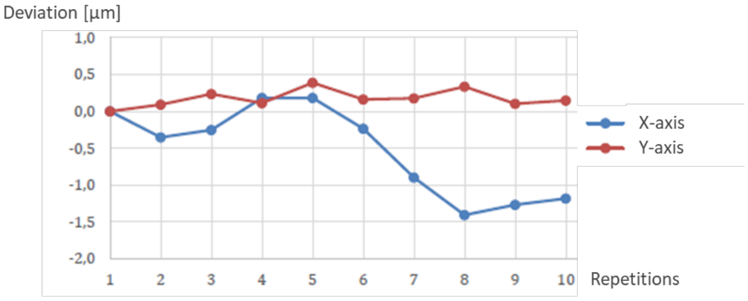

Figure 3. Deviations of the stable equilibrium position in X and Y-axes for F_z = 6 N.

It is observed that a higher F_z in the motor results in a smaller measurement error. In addition, for F_z equal to 6 N, errors exceeding 0.5 µm occur only on the X-axis and in the later repetitions (Figure 3). Furthermore, these errors are not relatively high compared to the closed loop NanoPla positioning error, 0.5 µm, which was assessed in a previous work [5].

Next, the stability of the equilibrium position is analyzed to study its displacement through time. In these new tests, the moving platform is levitated, the reference is established, and data are collected for approximately 30 minutes, while maintaining the (0,0) position in open loop. As in the previous case, three cases are studied: F_z equal to 2 N, 4 N, and 6 N. Table 2 shows the maximum displacement of the stable equilibrium position of X and Y-axes for each value of F_z.

Fz/N	Max. displacement in X-axis/µm	Max. displacement in Y-axis/µm
2	3.365	1.903
4	-0.972	3.450
6	0.550	-1.672

Table 2. Maximum displacement of the reference position for 30 minutes when using an open loop position control strategy, for different values of F_z.

In addition, Figure 4 shows the displacement of the stable equilibrium position of the NanoPla in open loop during the test (30 minutes) for F_z equal to 6 N. In the figure, it can be observed that the measurements in X-axis present a higher noise, this may be because there is only one laser head in X-axis, while in Y-axis there are two laser heads and the position is calculated as the mean of both measurements, reducing the noise of the readouts.

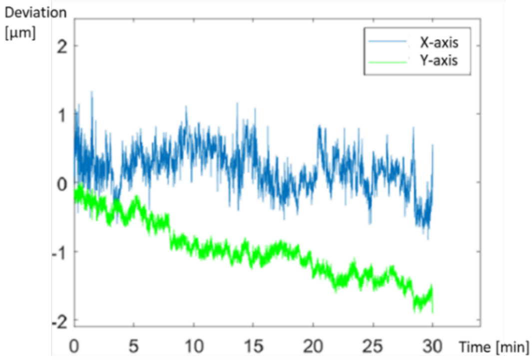

Figure 4. Displacement of the stable equilibrium position in X and Y-axes for F_z = 6 N.

In view of the results, it can be concluded that the F_z applied to the motor influences the results, but it is not a determining factor. That is, based on the general operation of the motors, it is estimated that the higher F_z is, the smaller the errors and standard deviations will be. However, this is not decisive since the errors in Y-axis in the case of F_z equal to 2 N are smaller than those in the case of 4 N, which could be due to external causes: less temperature variation, or less electrical noise. Additionally, to achieve a higher F_z, the motors require a higher current, which results in increased internal heating. In any case, as shown in Table 2, the maximum displacement of the stable equilibrium position is higher than 0.5 µm in both axis for every case.

4. Optimization of the referencing procedure

The experimental results show that the open loop position control referencing procedure has a limited repeatability and stability. Therefore, the aim is to optimize the procedure for referencing so that it achieves a higher level of repeatability in the X and Y-axes, hence, the (0,0) reference can be reestablished at the same point if the lasers are misaligned during a measurement. For this purpose, a referencing procedure that uses the metrological instrument integrated in the NanoPla, a confocal sensor, is proposed. The NanoPla confocal sensor has a minimum static noise higher of 99 nm, and a resolution of 122 nm. In this procedure, a specific point of a certain geometry will be used to reference each of the axis.

Initially, different geometric shapes have been considered. To select the most suitable geometry for the referencing procedure in the NanoPla, an initial approach was taken in a simpler setup, which consists of the confocal sensor in an external support with a commercial linear guide. For the experimental tests, the contour standard IF-VerificationTool from Alicona has been used. After analyzing the repeatability with which the confocal sensor detects the specific points of the geometric shapes of the contour, the 2000-µm step-height was selected for the NanoPla referencing procedure, as it presents the best repeatability. However, it must be considered that the edge of the step is an area that is complex to polish and may have defects.

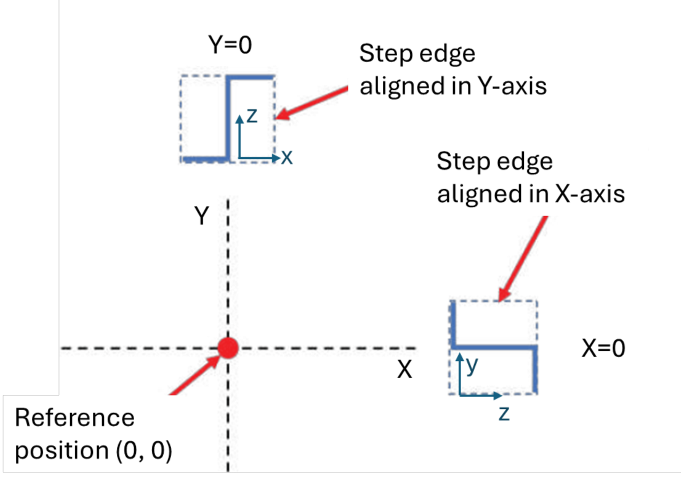

Figure 5. Step-height standards aligned with the X and Y NanoPla axes.

Once the geometric shape is determined, the referencing procedure of the NanoPla with the integrated confocal sensor is defined. The proposed procedure requires two step-height standards positioned in the sample holder as follows (Figure 5): The first step-height standard is fixed at the sample holder with the edge of the step aligned with Y-axis where the X-axis of the NanoPla is desired to be X=0. Similarly, the second standard (rotated 90°) is fixed at the sample holder with the edge of the step aligned to X-axis where the Y-axis of the NanoPla is desired to be Y=0. Then, the referencing procedure begins using the closed loop position control strategy, for which, before, it has been necessary to establish a provisional reference position in the laser system using the previously described open loop procedure. With the closed loop position control strategy and the moving platform levitating, the platform is moved along the Y-axis until the confocal sensor detects the edge of the step. At this point, the X-axis of the laser system is referenced (zeroed). Next, the moving platform is moved along X-axis until the confocal sensor beam detects the edge of the step aligned in X-axis. Once there, the Y-axis of the laser system is referenced.

An experimental validation has been conducted on the NanoPla for both the X and Y axes. For illustrative purposes, Figure 6 shows the results of three different measurements of the confocal sensor when detecting the edge of the step-height standard aligned with X-axis, with the NanoPla displacing along Y-axis. The results of the experimental validation show that the maximum deviation when determining the edge of the steps in both axes is lower than 0.400 µm, which is smaller than the deviations obtained for the open loop position control referencing procedure.

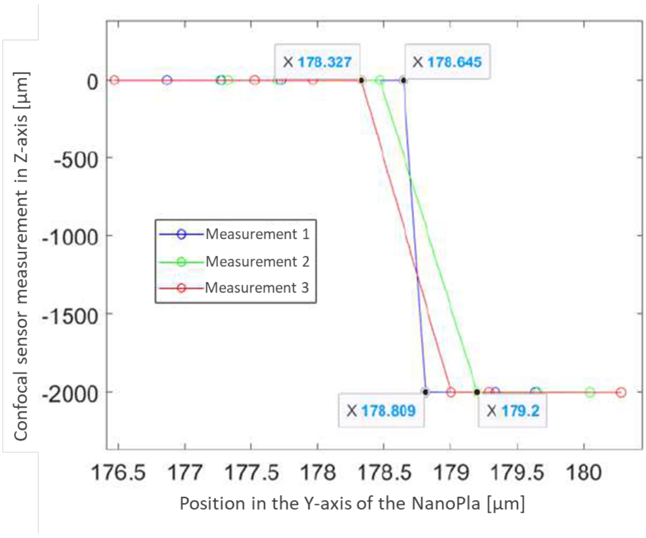

Figure 6. Confocal sensor readouts when detecting the edge of the 2000-µm step-height standard aligned with X-axis.

5. Conclusions

The NanoPla is a nanopositioning platform with a large working range of 50 mm × 50 mm in X and Y-axes that can be used for the metrological characterization of surfaces. For this purpose, a confocal sensor has been integrated in the NanoPla as a metrological instrument in Z-axis. The NanoPla closed loop position control system consists of four Halbach linear motors that work as actuators, and a 2D laser system as positioning sensor. However, the laser system is a differential measurement system that needs to be referenced every time it turns on, or after it is misaligned. In the normal operation of the NanoPla, it is only necessary to reference the laser system once, at the beginning of the measurement. However, in the specific case that the laser system becomes misaligned during a measurement, or when the reference position must be maintained through different measurements (carried out in different moments), the laser system would need to be re-referenced. In that case, the repeatability of the referencing procedure is crucial and can affect the final measurement. In this work, we propose two different referencing procedures for the laser system with the target of utilizing only the components and devices that are already integrated in the NanoPla.

The first procedure takes advantage of the property of the motors to operate as an open loop servo system. An independent open loop position control strategy is implemented in each motor, displacing the moving platform to a stable equilibrium position that is selected to be at the center of the working range of the NanoPla, and at that position, the laser system is referenced (0,0). However, the repeatability and stability studies that have been carried out, show that in some cases, the deviations between reference positions obtained by this procedure are higher than 0.5 µm. As mentioned, in the specific case that the laser-system needed to be re-referenced during a measurement, the deviation between reference positions can affect the final measurement accuracy. For this reason, a second referencing procedure is proposed.

The second referencing procedure consists of using the metrological instrument, a confocal sensor, attached to the NanoPla to establish the reference position. In this procedure, at the beginning, it is necessary to establish a provisional reference position using the first open loop procedure. Then, the moving platform, working already in closed loop, displaces in Y-axis until the confocal sensor detects a specific geometry aligned with the desired reference position X=0, and, similarly, it displaces in X-axis until the confocal sensor detects a specific geometry aligned with the desired reference position Y=0. The X and Y-axes of the laser system are referenced at these positions. The geometry that has been proposed in this work is the edge of a 2-mm step-height standard. With this procedure, the repeatability of the referencing procedure is improved, and experimental results show a deviation lower than 0.4 µm. However, it must be noted that the deviations are directly related to the lateral precision of the metrological instrument integrated in the NanoPla.

Both referencing procedures proposed in this work are valid, the first one is fast and efficient when the laser system has to be referenced only once at the beginning of the measurement. The second procedure, on the other hand, requires more time, but it is more repeatable in return, and thus, it is more suitable for measurements in which the laser system may need to be re-referenced.

In future works, a more precise referencing procedure can be proposed by integrating new components to the NanoPla, such as capacitive sensors aligned in X and Y-axes.

Acknowledgements

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