Turning a machine vision camera into a high precision position and angle encoder: nanoGPS-OxyO®

Olivier Acher*, Thanh-Liem Nguyen
HORIBA France SAS, Passage Jobin Yvon, 15 Avenue Thomas Gobert, 91120 Palaiseau, France

ABSTRACT

Position determination is key in many aspects of automation, production technologies, and QA/QC. Optical technologies are used in several position sensing technologies, such as single-axis incremental encoders based on grating scales and interferometers. A lesser known approach for position sensing is based on imaging systems, where the position scale is based on semi-regular patterns read by a camera equipped with suitable optics. Specific algorithms extract the in-plane coordinates of the patterns that are conjugated with the center of the read head, along with the angle that corresponds to the orientation of the patterns. Consequently, it is possible to turn a machine vision camera into an encoder with 3 degrees of freedom: in-plane position x, y, and in-plane orientation φ_z.

Through a proper design of the 2-dimension scales, proprietary decoding software, and adequate implementation, we have been able to design and demonstrate absolute position determination with the nanoGPS Oxyo® technology, with nm resolution on x, y, and accuracy better than 100nm over 80mm. The resolution on the orientation has been found to be better than 10µrad on φ_z.

As an example, we have shown that this system can be extremely efficient for the performance assessment of a microscopy stage. The nanoGPS Oxyo® technology can be used to turn any camera into an absolute position encoder. This can be useful for a variety of purposes, such as checking trajectories, or checking the repositioning capabilities, or checking cameras axis alignment are with machine movement axis, etc. These tasks can be performed either on a QA/QC basis (in this case the scale is placed during the QC operation, and removed after), or on a permanent basis (in this case the scale should be integrated to the machine).

Keywords: optical encoder, absolute position, superresolution

1. INTRODUCTION

Position determination is key in many aspects of automation, production technologies, and QA/QC. Optical technologies are used in several position sensing technologies, such as single-axis incremental encoders based on grating scales and interferometers. A lesser known approach for position sensing is based on imaging systems, where the position scale is based on semi-regular patterns read by a camera equipped with suitable optics [1-3]. Specific algorithms extract the in-plane coordinates of the patterns that are conjugated with the center of the camera, along with the angle that corresponds to the orientation of the patterns. Consequently, it is possible build an encoder based on such patterned plate, a camera with suitable illumination and optics to image the scale, and appropriate software to decode the image into in-plane position x, y, and in plane orientation φ_z. The performance of such encoders, in terms of precision and accuracy will be presented below. Such encoders can be useful for a variety of applications.

2. EXPERIMENTAL DETAILS

The principle of nanoGPS OxyO® encoder plates [3-5] are presented on Fig. 1. In this example, the encoded plate is aimed at investigating the performance of the moving stage of a microscope (reproducibility, accuracy). The encoded plate has the form of a conventional microscopy slide, and its surface shows engineered patterns. The image of the patterns as recorded by the camera using a 10x objective are also represented on Fig. 1. The resolution of the image is no better than some microns, as the result of both pixel size and Abbe's law.

* olivier.acher@horiba.com

A dedicated software has been developed, in order to decode the engineered patterns into position, and orientation, as presented on Fig. 2. It also indicates the standard deviation on the last 30 measurement, which is useful to determine the precision of the technique.

This system can be used to investigate the performances of a moving stage, as represented on Fig. 3. In this example, the microscope records images of the patterned slide at video rate, and the images are interpreted in real time to extract position coordinates. In this way, the actual movement of the stage can be recorded, and compared to the instructions given to the stage.

The coordinate range of the stage that can be assessed in one experiment depend on the size of the patterned plate. Plates with a variety of dimensions can be made, as presented on Fig. 4, depending on the travel range to be characterized in a single operation. The plates can also be adapted to a variety of imaging systems, by scaling the size of the patterns so that the image contains a sufficient number of patterns to provide adequate position reading [6]. While patterned plates suitable for microscopy operation have patterns that cannot be seen with the naked eye, patterned plates suitable for reading at distances of 10cm to 1m for example, have patterns that can be distinguished at the naked eye (see Fig. 4).

While imaging systems such as microscopes and machine vision systems are fully suitable to read the patterned plates, and therefore to be turned into encoders, in some case it is desirable to design dedicated read heads to achieve maximum stability and precision on the position determination. Examples of such dedicated read heads are presented on Fi. 5, one with a read distance comprised between 3 and 5 mm, and the other one with a read distance comprised between 35mm and 350mm.

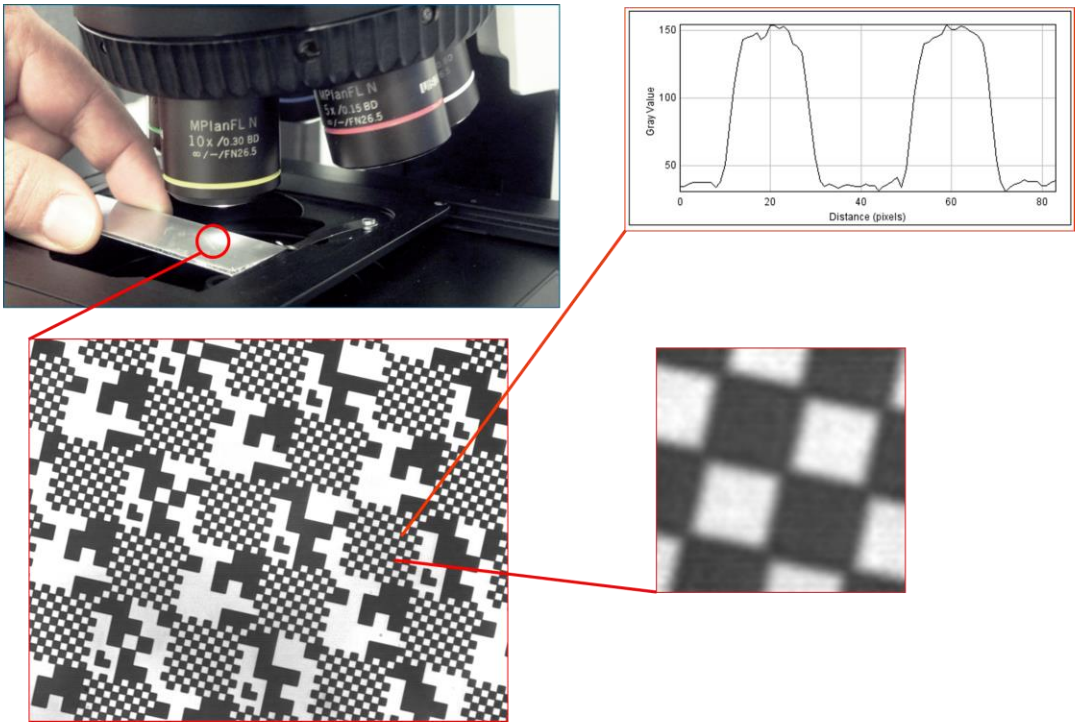

Figure 1. nanoGPS Oxyo® patterned slide used for checking microscope stability and stage performance, and image of the slide through a 10x objective, with detail of the image and profile along a line. The size of small squares is 10µm in the object plane, and 20 pixels in the image plane in this example.

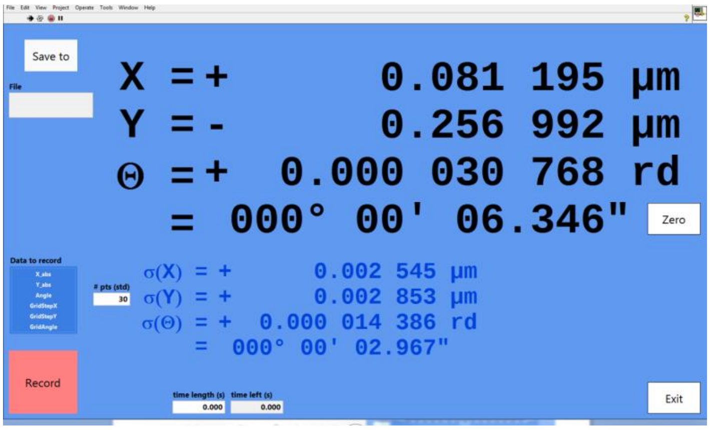

Figure 2. Software interface of the nanoGPS OxyO encoder, providing real-time position and orientation of the patterned plate in the camera coordinate system, along with standard deviation on these quantities.

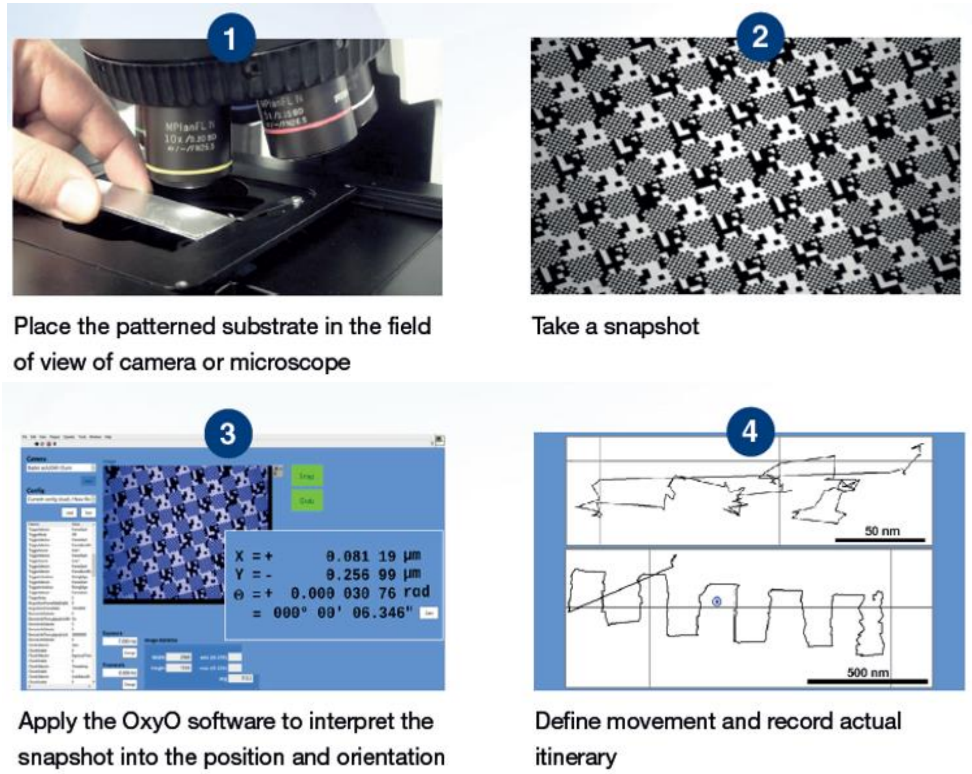

Figure 3. Example of operation of a nanoGPS OxyO calibration plate on a microscope, and its use to check the performance of a moving stage.

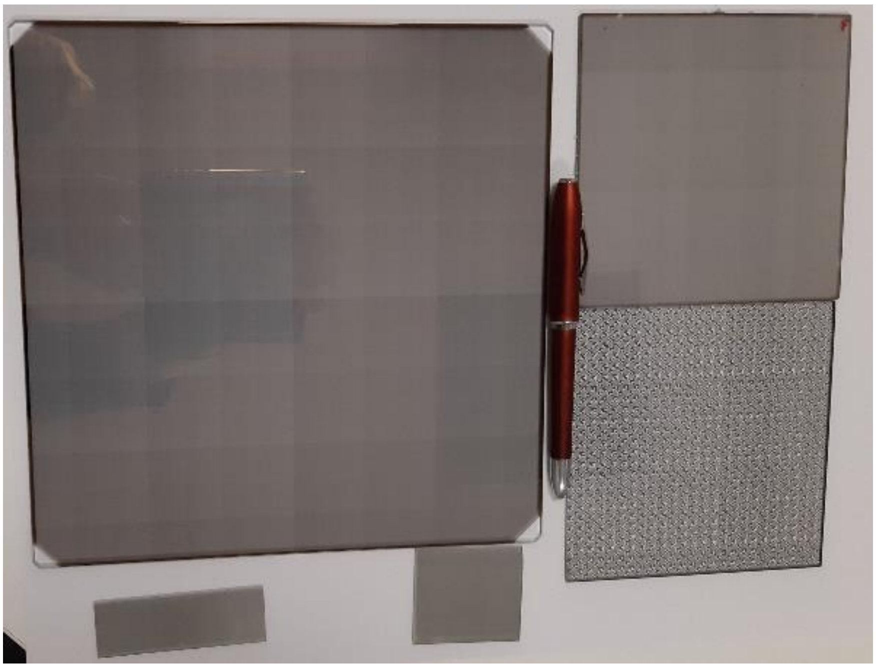

Figure 4. NanoGPS OxyO patterned plates with different patterned characteristic dimensions for different reading optics focal distances, and different sizes and shapes of encoded zone.

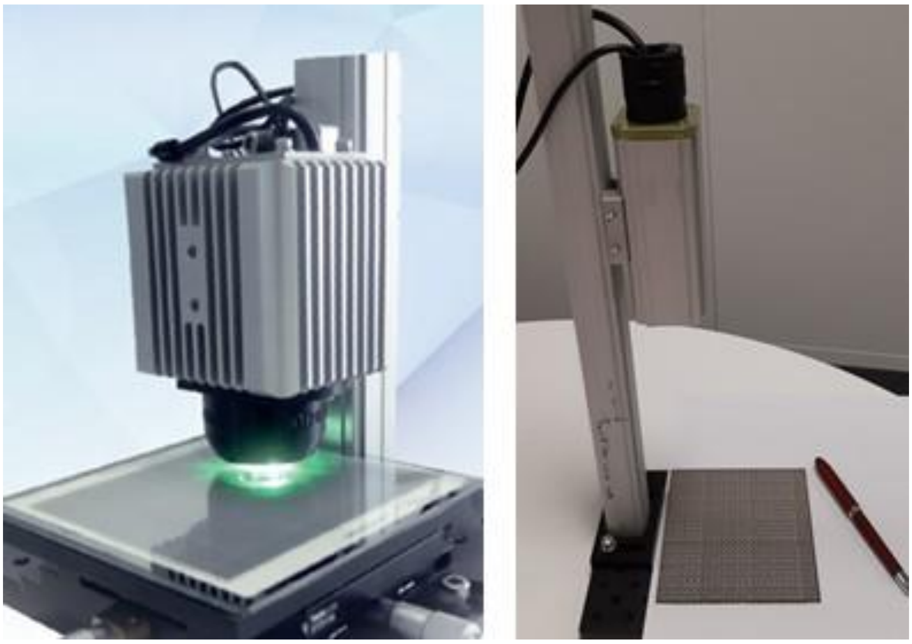

Figure 5. Read head with short working distance (left); read head with longer working distance (right)

3. EXPERIMENTAL RESULTS

The accuracy and precision of the position reading using nanGOSP OxyO systems depend on the property of the imaging system. We report below precision and accuracy obtained with a dedicated read head with a read distance that can be adjusted in the 3,5mm to 7mm range (pictured on Fig. 5, left). The model of patterned plate was the one presented on Fig. 1.

3.1 Precision

The precision on the measurement have been assessed by recording position for a system without intentional movement, in a quiet environment. Typical experimental results are represented on Fig. 6, for a system without movement. The standard deviation on the X coordinate is 0,9nm, and the standard deviation for the Y is 1.1nm. The standard deviation on the orientation is 9µrad. It indicates that the relocalization accuracy much exceeds the optical resolution of the raw image, that is in the µm range as reported on Fig. 1. The underlying physics that makes it possible to determine the position of an object with an accuracy that much exceeds the resolution of its image, is known under the designation "localization microscopy" [7].

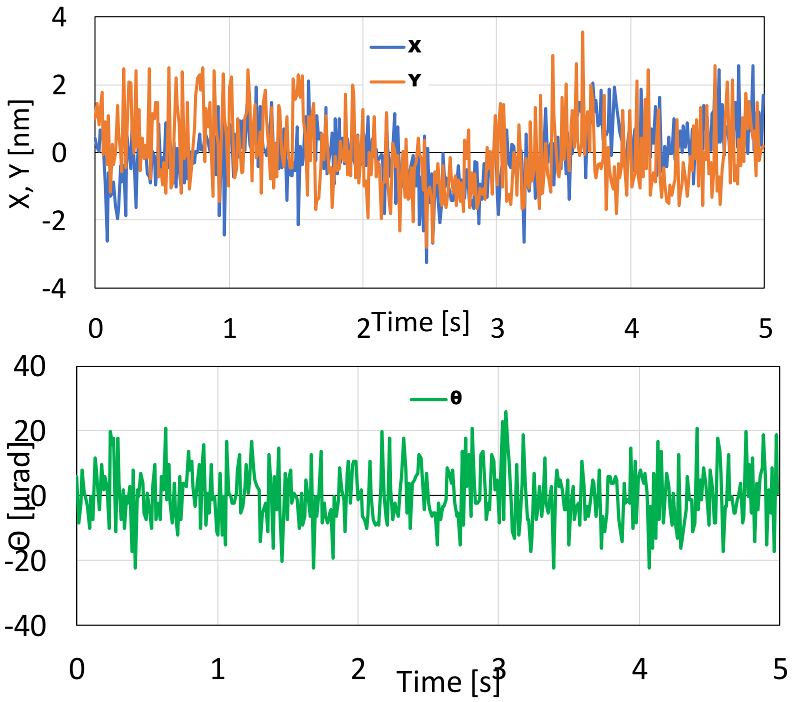

Figure 6. Noise on the x,y and φ_z coordinates measured in a stable environment.

3.2 Accuracy

The accuracy was investigated using a Newport XM350 ultraprecision linear stage, and a nanoGPS OxyO encoder with 5mm read distance head and a 125mmx125mm quartz scale [6]. In order to detect and mitigate any systematic error in the scale, 4 experiments were performed, with a $\pi/2$ rotation of the OxyO scale between each experiment. Fig. 7 shows that the on-axis residual error is less than 0.4µm over the 80mm travel distance. This error is much less than the guaranteed On-axis accuracy stated in the XM table documentation, +/- 0,75µm. The dashed line represents the effect of a 0.3°C temperature difference between calibration temperature of the aluminum stage and experiment temperature. If this linear error attributed to temperature effect is removed, the experiment suggests that the difference between stage encoder and nanoGPS OxyO encoder is less than 0.2µm, which suggests that both encoders have excellent accuracy characteristics, much below 1µm. The sum of stage non-reproducibility and OxyO error is less than +/-100nm. As the guaranteed bidirectional repeatability of the XM 350 stage is +/-40nm, this would suggest that the maximum OxyO error is comprised between 60nm and 100nm.

Cross-axis measurements show that the sum of OxyO error and stage non-reproducibility is less than 150nm. Stage straightness is found to be better than +/-150nm, which is fully consistent with the guaranteed straightness of +/-0,75µm.

This further confirms that the OxyO error is very small compared to this value, which is consistent with the finding that the maximum error lies below 100nm on this 80mm travel range.

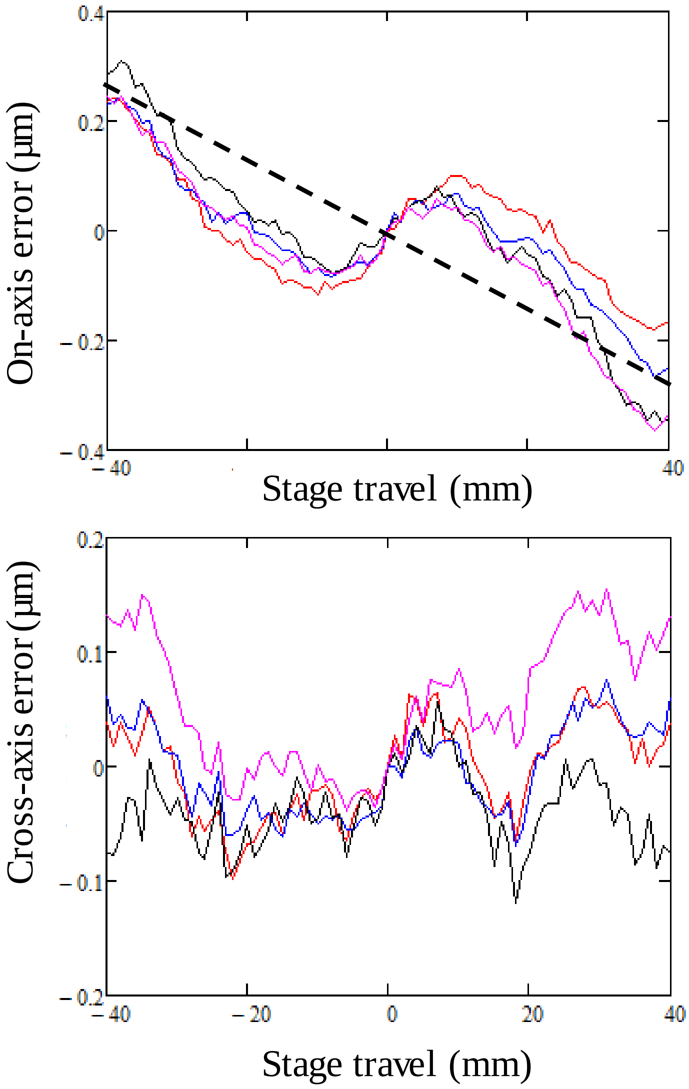

Figure 7. Accuracy experiments performed on a Newport XM350 ultra precision linear motorized stage and a short reading distance nanoGPS OxyO read head, performed with 4 different orientation of the OxyO scale: a) difference in travel distance between stage reading and OxyO reading; b) residual displacement normal to the travel axis.

Investigation of the resolution and accuracy of the in-plane angle measurement have been performed and reported elsewhere [8]. Accuracuy has been investigated using laser interferometry, but because of the low angular acceptance of the interferometers these investigation were restricted to a small angle range of 2mrad. Errors have been found to be less than 15µrad in this regime.

4. APPLICATIONS

The nanoGPS OxyO system has been used to investigate the accuracy of a microscope motorized stage, as shown on Fig. 1. The distance between absolute position read from the stage encoders, and the position read using the image of the patterned plate taken by the microscope, for a travel of 60mm, is pictured on Fig. 8. As we established that the accuracy of the nanoGPS OxyO technology is in the sub 100nm range, the differences in position which are of several µm can be clearly ascribed to the microscopy stage. A further proof for this has been obtained by using another slide, with a different code, and recording this same quantity during the same stage coordinates. Both results (shown in gold and blue curve on Fig. 8), show that the error is repeatable, clearly showing that the microscope stage has an accuracy in the 5µm range, but a repeatability that is one order of magnitude better. This experiment also rules out that the discrepancy between stage encoder and OxyO encoder come from some defect in the patterned plate coding or reading, as such defects would be different between 2 encoded plates with different codes, which is clearly not the case.

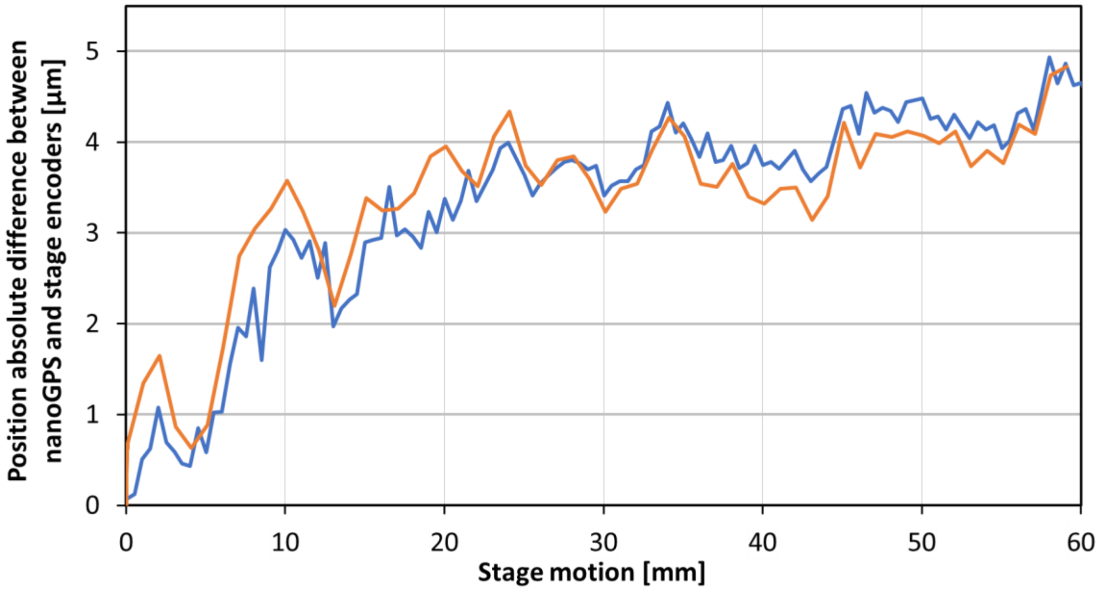

Figure 8. Distance between position determined by stage encoder and by nanoGPS OxyO, for a 60 mm trajectory of a microscope stage, This distance has been assessed with 2 nanoGPS OxyO slides with different position coding, in order to remove any systematic errors due to imperfection of the patterns, or residual error in the software interpretation of the patterns into a position.

5. CONCLUSION

We have shown that nanoGPS OxyO technology is a versatile and highly performant technology to determine position. By adjusting the scale and size of the patterned plates, it can be adapted to motion control missions on microscopes, or any system comprising machine vision cameras. It is a very efficient solution for QA, QC, and a variety of calibration tasks. A nanometric precision, and an absolute accuracy better than 100nm over 80mm travel, have been demonstrated on a system based on a microscope-type imaging system. In contrast with other position monitoring solutions based on fiducials, the precision and accuracy of the technology demonstrated here much exceeds the optical resolution, because it relies on the so-called “localization microscopy” principle, that is one path to achieve superresolution. It is also possible to use this technology to build encoders that are integrated into a system. Unlike incremental encoders, nanoGPS OxyO encoder are absolute encoders, and they provide precise measurements on both in-plane position, and orientation. In some configurations, they are much easier to install and implement, than laser interferometers.

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