6-DoF Accuracy Evaluation of a Precision Hexapod Using Digital Holography

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***Abstract*— Digital holography microscopy (DHM) is used to follow the 6 degrees of freedom (DoF) motions of a micro-structured pattern with nanometer accuracy. Out-of-plane DoF are addressed thanks to the interferometric character of DHM whereas complementary in-plane DoF are retrieved through photogrammetry processing of the micro-structured pattern features. The digital focusing principle of DHM extends the depth of focus of the microscope lenses used by one order of magnitude or more. The method performances are given and demonstrated through the characterization of the 6-DoF motion of a precision hexapod.**

I. INTRODUCTION

The measurement of 6-DoF motions in confined spaces with an accuracy suited to today's nano-actuation capabilities remains a poorly answered need. We address this issue by combining the well-known out-of-plane performances of interferometry with photogrammetry applied to complementary in-plane position measurements. In this aim, we apply DHM to track the motion of a flat surface patterned with a microstructure specifically designed to allow accurate in-plane positioning. The paper presents the method, summarizes the performances achieved, and reports on the 6-DoF characterization of a 3D motion performed by a precision hexapod.

II. METHOD

DHM is an interferometric method in which the camera records the coherent combination of the light beam issued from the object of interest with a known reference beam. The knowledge of the reference light wave allows the retrieval of the phase and amplitude of the object beam from the intensity recorded by the image sensor. This phase data, not accessible in conventional imaging, encodes the crossed path lengths modulo 2π under the well-known relation $\phi = 2\pi\, n\, d/\lambda$, where ϕ is the detected phase, n is the index of refraction, d is the distance crossed and λ is the light wavelength. In a reflective microscope configuration, the distance d varies as twice the elevation z of the object of interest. The detected phase is thus representative of out-of-plane information with very high sensitivity due to the sub-micrometer size of the light wavelength.

DHM records out-of-focus images, named holograms, and in-focus images are retrieved digitally through light propagation computations performed numerically [1]. This numerical compensation of the diffraction phenomenon avoids undetermined points where the recorded intensity is equal to zero. Furthermore, the numerical adjustment of the object reconstruction distance extends the depth of focus of the lenses used by one order of magnitude or more. Additionally and contrarily to phase shifting methods, DHM needs a single hologram to reconstruct the object and is thus compatible with the video rate processing of mobile targets. We use an off-axis DHM (R2100, Lyncee Tec SA, Switzerland) in which a fringe carrier is present in every recorded hologram.

In our 6-DoF motion tracking application, we combine DHM with photogrammetry applied to a micro-structured pattern specifically designed to allow the measurement of the three complementary in-plane DoF with high accuracy on large ranges. The method uses a pseudo-periodic pattern and, as detailed elsewhere, it achieves a resolution of about 1 nm in position and $4 \cdot 10^{-6}$ rad. for in-plane rotation [2], [3], [4]. The pattern used is a plane surface. Therefore, its out-of-plane position can be defined by its elevation at one point plus the roll and pitch angles. These out-of-plane parameters are retrieved directly from the hologram fringe carrier without the requirement for further object reconstruction at this stage.

The different steps of image processing are depicted in Fig. 1. Because of the defocus, the hologram looks like a blurred-quality image. In the zoom, however, the fringe carrier produced by interference appears clearly. It allows out-of-plane position detection. In-plane position requires digital object reconstruction at the right focus distance. This provides intensity and phase images of the microstructure that are processed further to localize very accurately the current zone observed within the complete encoded pattern.

III. PERFORMANCES AND APPLICATION

The method was validated and its out-of-plane performances, complementary to the in-plane ones discussed above, were characterized using a high-accuracy 3-DoF piezoelectric actuator (P-528.TCD, Physik Instrumente). Table 1 presents the results obtained for the method resolution, linearity, repeatability, range, and ambiguity. We see that the resolution achieves 1 nm in elevation and $0.1\,\mu$rad. in roll and pitch angles β and γ. The allowed ranges are limited by the hardware used; i.e. the light source coherence length in z, and the numerical aperture of the lens used for β, γ angles. Some degree of adjustment is possible with different

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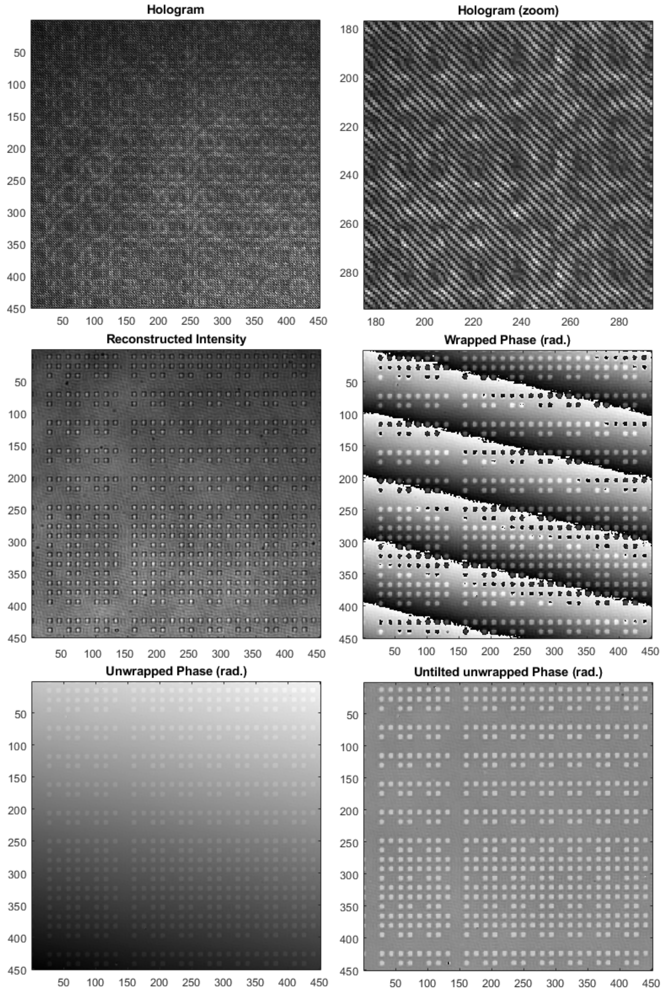

Fig. 1. Steps for 6-DoF motion tracking by DHM. The fringe carrier (zoom) can be noticed as well as the micro-structured pattern designed for in-plane position referencing.

TABLE I

EVALUATED OUT-OF-PLANE PERFORMANCES

	z	β	γ
Resolution	1 nm	0.1 µrad	0.1 µrad
Linearity	0.03 %	1 %	0.51 %
Repeatability	0.12 nm	0.03 µrad	0.04 µrad
Range	0.2 mm	0.21 rad	0.21 rad
Ambiguity	337.5 nm	n/a	n/a

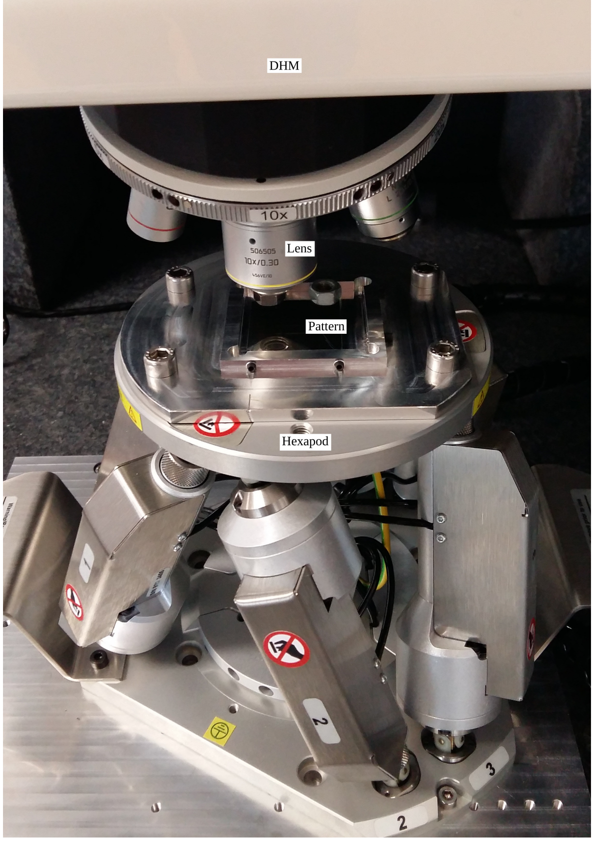

Fig. 2. Experimental setup.

hardware choices. For the elevation z, the phase computation method used returns data modulo 2π. Therefore, the elevation is subject to 2π ambiguities as many interferometric devices. To avoid z errors equal to an entire number of the half-wavelength, the target motion must be sufficiently slow to ensure that changes in z remain smaller than $\lambda/4$ between two recorded frames. A well-known means to extend this ambiguity range, and thus to allow faster z motion, is to work with two or more wavelengths [5].

To demonstrate the method's capabilities to reconstruct 3D trajectories with nanometer resolution, the pattern was fixed onto a precision hexapod (HXP50-MECA, Newport). The whole setup is depicted in Fig. 2. The driven motion applied corresponds to linear displacements along z and α, thus inducing X, Y displacements, whereas β and γ angles remain unchanged. Fig. 3 presents the reconstructed out-of-plane variations whereas in-plane ones are presented in Fig. 4. An unexpected disturbance is observed around the middle of the travel with a half micron impact on the elevation z and clearly visible impacts on X, Y trajectories. We suspect an external disturbance to be responsible for this jitter. However, we have no certainty on the source of this behavior and further experiments will be carried out to explore the hexapod behavior more precisely.

IV. CONCLUSION

This paper presents how Digital Holography Microscopy can be used in combination with phase-based in-plane motion measurement to follow the 6-DoF trajectory of a precision robot. The eventual high accuracy achieved results from linear phase computations applied to both the interference signals and the pseudo-periodicity of a dedicated microstructured pattern. This method provides unique capabilities to track 6-DoF motion at the micrometer scale.

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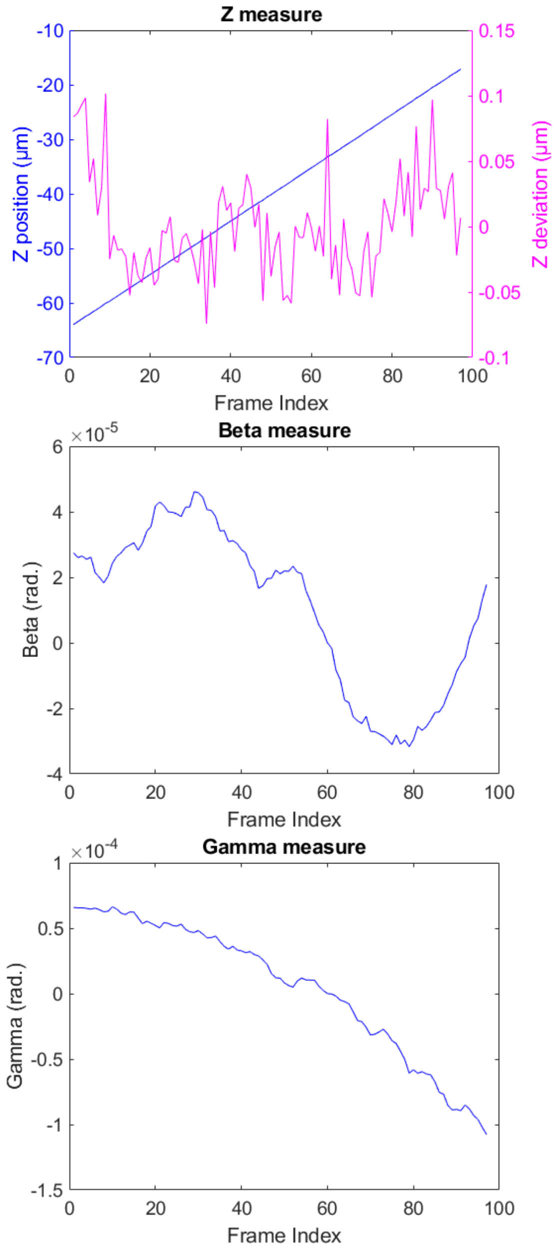

Fig. 3. Reconstructed out-of-plane hexapod motion.

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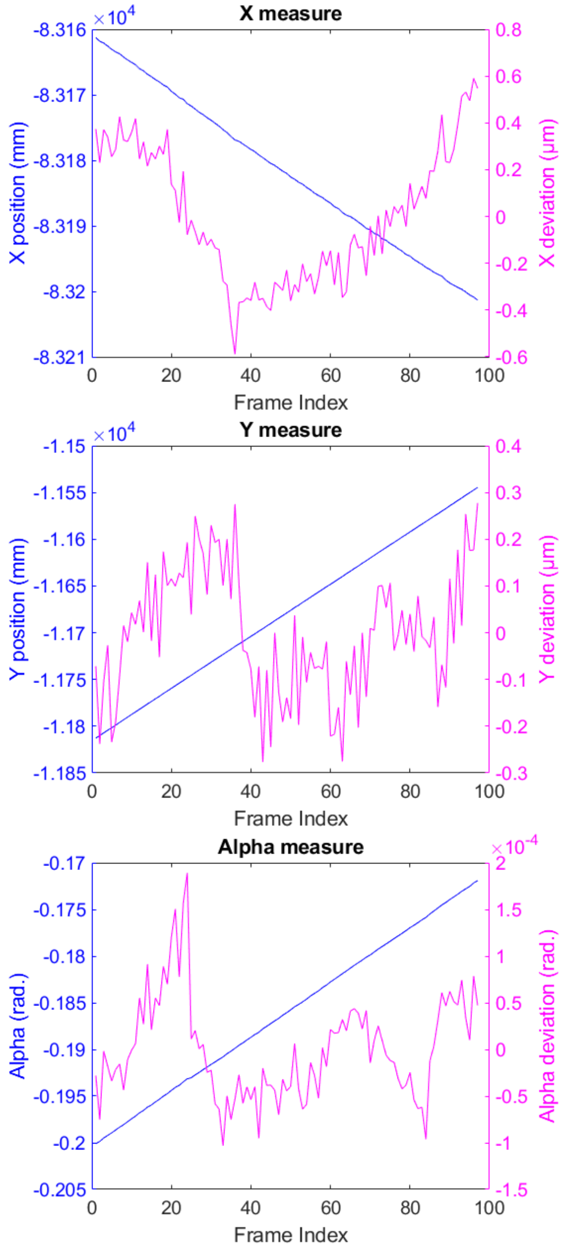

Fig. 4. Reconstructed in-plane hexapod motion.