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A comparison among three different image analysis methods for the displacement measurement in a novel MEMS device

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Abstract **–** The functional characterization of MEMS devices is of great importance today, since it has the purpose both of verifying the behavior of these devices and of improving their future design. In this regard, the main topic of this study is the functional characterization of a microgripper prototype, a MEMS suitable in biomedical applications: to this aim, the measurement of the angular displacement of its comb-drive (capacitive electrostatic actuator that allows its movement) is provided by means of two novel automatic procedures, based on an image analysis software, the SURF-based (Speeded Up Robust Features) and the FFT-based (Fast Fourier Transform) method respectively. A preliminary comparison has been made, also with a previous semiautomatic method, to evaluate which of them is the best suitable for the functional characterization of the microgripper, highlighting their main advantages and limitations. The results obtained from the SURF-based method are promising; the curve obtained from the data showed a quadratic trend in agreement with both the analytical model and with the results obtained through the semi-automatic method. Moreover, the measurement obtained by the SURF-based method are affected by less than 0.2° uncertainty, that is less than one half of the measurement uncertainty due to the FFT-based algorithm.

I. INTRODUCTION

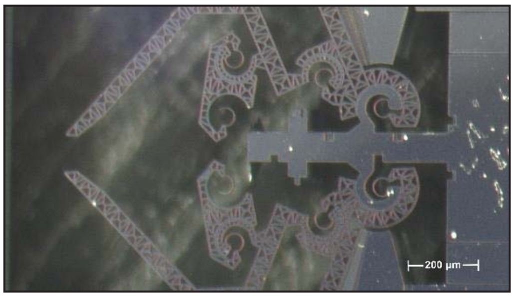
MEMS devices (Micro-electro-mechanical systems) represent a category of sensors and actuators widely used in the most varied fields of technology, from automotive, to micro assembly for photonics and RF application, microphones, microfluidic device, gyroscopes, chemical sensors for microfluidics systems, lab-on-chip systems and complex actuation systems [1]. One of the most promising fields of application is undoubtedly the biomedical one, such as biology [2-3] and microsurgery [4-6]. Microgrippers are a particular class of MEMS devices, able to handle objects, including cells and molecules that have micrometric dimensions. Nowadays, there are few works concerning the characterization of devices such as microgrippers, even if the study of the metrological and performance characteristics would be of great help for the optimization of the prototypes and the improvement of their performances. In this study, a set of images have been acquired by means of a trinocular optical microscope and processed by means of three different software implemented ad hoc in Matlab environment: the semi-automatic, the SURF-based (Speeded Up Robust Features) and the FFT-based (Fast Fourier Transform). A comparison between the three implemented software has been made to estimate the angular displacement of a microgripper prototype comb-drive for biomedical applications. Semi-automatic software already widely described by the authors in [7-9], is based on template-matching, and it is able to evaluate the rotation and both the gripper and the angular displacement of a microgripper. Its main limitations are the operator dependence and the high computational costs. For this reason, the authors have proposed two novel and automatic methods: the first one named SURF [10], (Speeded Up Robust Features) and the second one based on the application of Fast Fourier Transform to digital images [11-15].

II. MATERIALS AND METHODS

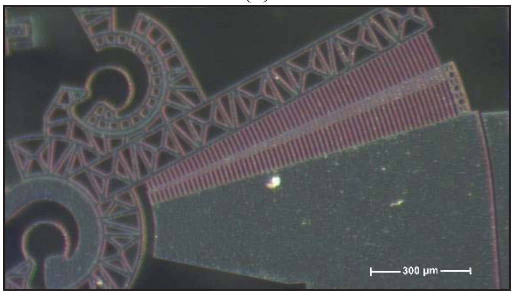
In this section the main components of the experimental setup have been described together with a detailed overview of the SURF-based and the FFT-software proposed as alternative methods to the semi-automatic one for the measurement of the angular displacement of the comb-drive.

- *Experimental Setup*

The device under examination is a microgripper prototype (Figure 1a), which is part of a project concerning the metrological and performance characterization of a new class of MEMS devices for biomedical applications [16-20]. These devices mainly consist of capacitive electrostatic actuators (i.e. the comb-drives shown in Figure 1b) and particular hinges called CSFH (Conjugate Surfaces Flexural Hinges) [21], which allow the mechanical movement of the tips located on the end of the device. The images have been acquired through a NB50TS trinocular light microscope equipped with a 6MP camera.



(a)



(b)

Fig. 1. Microgripper prototype (a) and the comb-drive (b)

The device has been positioned on an instrumented stage with micrometric screws and powered through a HP E3631A power supply. The latter is electrically connected to the device by means of coaxial cable and tungsten needles put in contact with the electrical connections of the device. The voltage has been brought to the electrical connections by means of two micro-positioners that allow the tungsten needle movement along the three axes, x, y and z. A set of 30 images has been collected for each applied voltage with a 2V step (i.e. 0V, 2V, 4V, ... 24V).

A. *Semi-automatic based software*

The first software used in this study, has been the semi-automatic one, widely described in [7-8] and used in [9]. As illustrated in [7-9], the software introduces a measurement uncertainty contribution which corresponds to 0.02 °, at 95% confidence level, and has been evaluated by means of Monte Carlo simulation. The main disadvantage in using this semi-automatic method is that the measurement results are highly operator dependent.

B. *SURF-based software*

An automatic software based on Speeded Up Robust Features (SURF) has been implemented to measure the angular displacement of the comb-drive, as already described in [22]. It is an interest point detector and descriptor, used in many applications including image registration, object recognition and 3D reconstruction [23]. The main advantage of this software is mainly the computational cost reduction; in fact, as illustrated in [10] by the authors, a significant reduction in image processing time has been observed thanks to the reduction of the complexity of the descriptor, without altering the performance in terms of repeatability, noise robustness, detection errors, geometric and photometric deformation. The in-house software consists of three main steps:

1) *finding interest points on the image*; in particular, a ROI_{0V} (Region of Interest) is selected on the first image Img_0, that corresponds to 0V power supply, and it is important that this selected area is chosen by the operator in an image area where the movement of the comb-drive is visible; the coordinates of the selected ROI are saved and used to select the ROIs (i.e. $ROI_{2V}, ROI_{4V}, ROI_{6V}, \ldots ROI_{24V}$) of all the subsequent images $Img_{2V}, Img_{4V}, Img_{6V}, \ldots Img_{24V}$. After that the algorithm finds the interest points on each selected ROI.

2) *building a descriptor for the representation of the interest points*; for example, in this case they are the red circles for the first image and the green crosses for all the others (Figure 2).

3) *matching the various descriptors found on the images*; by using a geometric transform, the object position on the images can be obtained and therefore it has been possible go back to its relative rotation referred to each applied voltage.

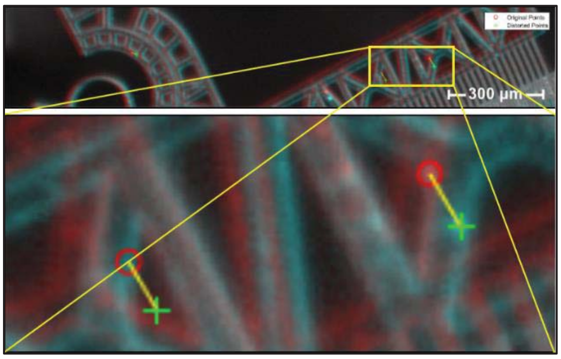


Fig. 2. Interest points descriptor of the first image (red circles) and of other images (green cross)

C. *FFT-based software*

This software is based on the application of the Fourier transform to digital images. As shown in Figure 3, the comb-drives of the microgripper have a particular periodic pattern; also, if an image consists of an array of uniformly spaced parallel straight lines, the Fourier transform of the combination will be the convolution of their respective Fourier transform. The result will be a string of impulses (see Figure 4), with a separation equal to the reciprocal of the spacing of the lines and in a direction perpendicular to these parallel lines [11-12]. This last feature has been used to estimate the angular aperture of the comb-drive: in fact, for each angular opening, the corresponding pattern of the comb-drive will take a different direction and consequently, also the positions of the impulses will change and assume a different direction each time. Therefore, for each angular opening, and for each image, there will be a series of points in different directions; subsequently a least squares approximation has been used to find the linear polynomial function that best approximates these points from which the angular coefficient of the straight line is obtained and therefore the opening angle of the comb-drive.

III. UNCERTAINTY ANALYSIS

In order to make a comparison between the three different image analysis methods, it is necessary to estimate the main sources of uncertainty introduced by the measurement systems. It is important to underline that the experimental setup is the same, except for the three different software. Following the procedure adopted in [7], Type A and Type B uncertainties will be combined [24], as follows:

$$\delta_T = \sqrt{\delta_A^{\,2} + \delta_B^{\,2}} \tag{1}$$

In particular, Type A uncertainty, δ_A, has been calculated directly from the standard deviation of the experimental data, while Type B uncertainty, δ_B, has been obtained considering the uncertainties due to the power supply (evaluated from the datasheet), the optical system [7-9], the angle measurement, which uncertainty contribution has been assessed by means of a Monte Carlo simulation [25-28] in order to estimate the uncertainty related to the two implemented software.

Once uncertainties have been evaluated, a comparison between three different set of results will be made, following the procedure adopted in [8] and reported in [29].

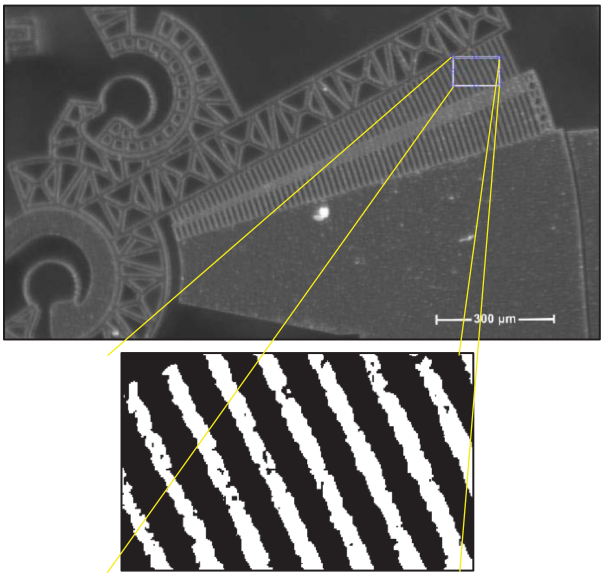


Fig. 3. Comb-drive pattern

Fig. 4. Example of Fourier transform of images properly filtered, constituted by a string of impulses

In practice, the different software algorithms are able to measure the angular displacement of the comb-drive without significant differences if the following condition is verified:

$$\left|\bar{M}_1 - \bar{M}_2\right| \le \left(\delta_{T_1} + \delta_{T_2}\right) \tag{2}$$

where $\bar{M}_1$ and $\bar{M}_2$ are the mean values of the measurement results, while δ_{T_1} and δ_{T_2} are the total uncertainty estimate. In particular, if the difference $|\overline{M_1} - \overline{M_2}|$ has the same order of magnitude as, or even less than, the sum $\left(\delta_{T_1} + \delta_{T_2}\right)$, then measurements can be considered consistent, within the interval of the experimental uncertainties.

IV. RESULTS

In this section the preliminary data obtained by means of the three different software are reported and commented. The graphs in Figure 5 and 6, show the results related to the comb-drive angular displacement, expressed as mean value, corresponding to the semi-automatic based system and SURF-based system (Figure 5) and FFT-based system (Figure 6) respectively. A preliminary analysis of the data showed that both semi-automatic and SURF-based methods follow a quadratic trend, which appears to be in good agreement with the results obtained through the analysis of the analytical model [30]. As can be seen in the graph shown in Figure 5, in correspondence with the applied voltages greater than 18 V, the results obtained with the two different image analysis methods seem not to be compatible. However, as reported in, [29] if the difference $|\bar{M}_1 - \bar{M}_2|$ has the same order of magnitude as, or even less than, the sum $\left(\delta_{T_1} + \delta_{T_2}\right)$, then measurements can be considered consistent, within the interval of the experimental uncertainties. From the data shown in Figure 5, for voltages greater than 18 V, the differences between the mean values have the same order of magnitude with respect to the sum of the correspondent total uncertainties, so the measurements can be considered compatible. For this reason, it can be said that the new developed software SURF, is able to measure the angular displacement of the comb-drive of the prototype of microgripper under examination. Instead, as regards the data obtained with the FFT software, it emerged that the results do not follow a trend that can be closely related to the angular displacement of the comb-drive. From a first analysis, it can be deduced that, the FFT-based method cannot be considered suitable for the measurement of MEMS devices, since there is no possibility of appreciating displacements around the tenth of a degree.

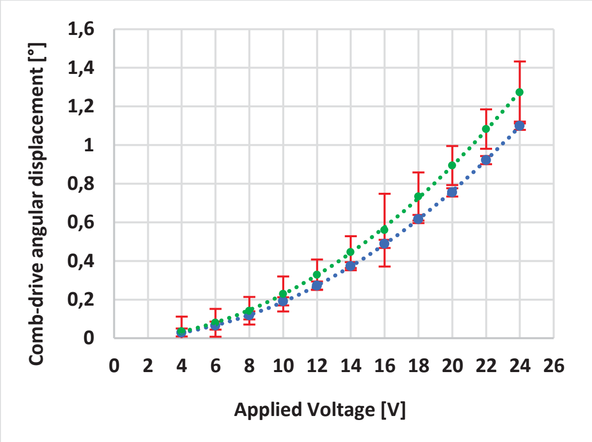


Fig. 5. Relationship between angular displacement and applied voltage considering semi-automatic software (blue dot line) and SURF-based software (green dot line)

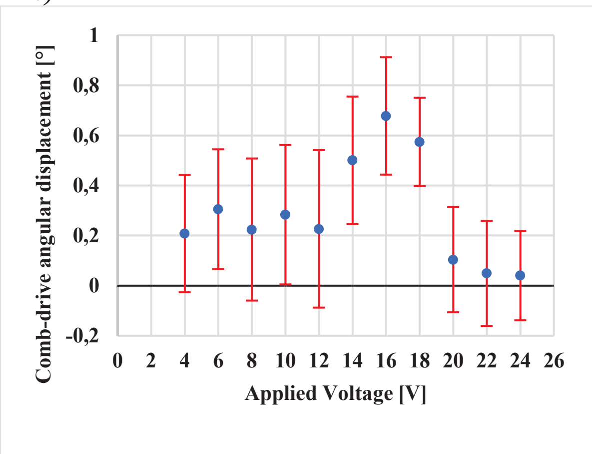


Fig. 6. Relationship between angular displacement and applied voltage considering FFT-based software

V. CONCLUSIONS

This preliminary study has the purpose of comparing the measurements performed by different methods for the angular displacement of a comb-drive of a microgripper prototype for biomedical applications. In particular, three in-house software have been implemented in Matlab environment: semi-automatic, SURF-based and FFT-based software. After the description of the fundamental steps of each implemented software, the main advantages and limitations have been highlighted; from the first experimental results obtained, it has been found that the semi-automatic software and the SURF are able to measure the angular displacement of the comb-drive of the microgripper, showing quadratic curves, consistent with the results obtained with the analytic model [30]. Instead, from the results retrieved by means of FFT-based software, it has been found no good correlation between angular displacement and applied voltage that describe the real behavior of the device, and the data are not consistent with both the data obtained through the analytical method and with the two software mentioned above. For this reason, a comparison based on the method suggested in [29], between the semi-automatic and SURF method, will be carry out in the near future. For this purpose, it will be necessary to perform a detailed uncertainty analysis of the measurements, highlighting the main sources of error and establishing which of the two implemented software is the best suitable for performance characterization of a MEMS device like microgripper for biomedical applications.

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