Comparative evaluation of three image analysis methods for angular displacement measurement in a MEMS microgripper prototype: a preliminary study

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ABSTRACT
The functional characterization of MEMS devices is relevant today since it aims at verifying the behavior of these devices, as well as improving their design. In this regard, this study focused on the functional characterization of a MEMS microgripper prototype suitable in biomedical applications: the measurement of the angular displacement of the microgripper comb-drive is carried out by means of two novel automatic procedures, based on an image analysis method, SURF-based (Angular Displacement Measurement based on Speeded Up Robust Features, ADMsurf) and FFT-based (Angular Displacement Measurement based on Fast Fourier Transform, ADMFFT) method, respectively. Moreover, the measurement results are compared with a Semi-Automatic Method (SAM), to evaluate which of them is the most suitable for the functional characterization of the device. The curve fitting of the outcomes from SAM and ADMsurf, showed a quadratic trend in agreement with the analytical model. Moreover, the ADMsurf measurements below 1° are affected by an uncertainty of about 0.08° for voltages less than 14 V, confirming its suitability for microgripper characterization. It was also evaluated that the ADMFFT is more suitable for measurement of rotations greater than 1° (up to 30°), with a measurement uncertainty of 0.02°, at 95% of confidence level.

1. 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 methods implemented ad hoc in Matlab environment: the Semi-Automatic (SAM), the SURF-based (Angular Displacement Measurement based on Speeded Up Robust Features, ADMsurf) and the FFT-based (Angular Displacement Measurement based on Fast Fourier Transform, ADMFFT). A comparison among the abovementioned methods has been made to estimate the angular displacement of a MEMS microgripper prototype comb-drive for biomedical applications. Semi-Automatic Method (SAM) 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 high computational costs and the operator dependence.
The above issues have been deepened in this work, starting from the previous study presented in [10]. In Section 2, the materials and methods are described, with particular reference to the experimental setup and the measurement protocol used for the digital image acquisition. Due to the limitation encountered in SAM previously proposed [7]-[9], in Subsection 2.1, the authors propose a new version of the SAM, in which novel tests have been implemented to quantify the uncertainty contribution introduced by the operator in the angular displacement measurement of a microgripper comb-drive prototype; in Subsections 2.2 and 2.3 the authors described two novel and automatic methods and their application for the measurement of the comb-drive angular displacement: the ADM\textsubscript{SURF}, based on the SURF algorithm [11], and the ADM\textsubscript{FFT}, that is an application of 2D Fast Fourier Transform (FFT) to digital images [12]-[16]. In Section 3, the procedure for estimating the sources of uncertainty of the three measurement methods is described and a comparison and the evaluation of the outcomes obtained through the three abovementioned methods have been carried out and discussed to identify which of the three implemented methods is the best suitable for the characterization of the MEMS device. Finally, in Section 4 and 5, the results of our study are illustrated, and the conclusions presented.

2. MATERIALS AND METHODS

In this section the main components of the experimental setup have been described together with a detailed overview of the three implemented methods; in particular, the SURF-based and the FFT-method have been proposed as alternative methods to the Semi-Automatic one for the measurement of the angular displacement of the comb-drive.

The device under examination is a microgripper prototype (Figure 1), which is part of a project concerning the metrological and performance characterization of a new class of MEMS devices for biomedical applications [17]-[21]. These devices mainly consist of capacitive electrostatic actuators (i.e., the comb-drives shown in Figure 2) and particular hinges called Conjugate Surfaces Flexural Hinges (CSFH) [22], 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. The device has been positioned on an instrumented stage with micrometric screws and powered through a HP E3631A power supply. The latter is electronically connected to the device by means of a 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 micropositioners 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 2 V step (i.e., 0 V, 2 V, 4 V, ... 24 V).

2.1. Semi-Automatic based method (SAM)

The first method used in this study, has been the Semi-Automatic one, which for clarity we will call S-AM\textsubscript{e} widely described in [7],[8] and used in [9]. As illustrated in [7]-[9], the method introduces a measurement uncertainty contribution which corresponds to 0.02 °, at 95% confidence level, evaluated by means of Monte Carlo simulation. Moreover, the software requires high computational costs and the uncertainty analysis of the preliminary results obtained with the S-AM\textsubscript{e} was previously carried out partially [7]-[10], assuming the uncertainty component introduced by the operator’s subjectivity; for this reason, in this study further tests were carried out to better evaluate the above contribution. The test on the S-AM\textsubscript{e}, in fact, consists, in its first part, of a selection by the operator of four points and of a Region of Interest (ROI) on the image; to evaluate the dispersion in the selection of these points, in the new version of Semi-Automatic method, called S-AM\textsubscript{a}, ten different observers were asked to identify both the four points and the ROI in an image of the comb-drive, for a number of times equal to 30. In particular, for the four points, the x and y coordinates on the image were considered and for the ROI, the coordinates of the top left vertex (x and y), its length and width (each of them expressed in pixels), as can be seen in Figure 3.

2.2. Speeded Up Robust Features based method (SURF)

An automatic method based on Speeded Up Robust Features (SURF) has been implemented to measure the angular displacement of the comb-drive (ADM\textsubscript{SURF}), as already described in [23]. It is an interest point detector and descriptor, used in

Figure 1. Microgripper prototype.

Figure 2. The comb-drive.

Figure 3. Four points (red cross) and ROI (yellow square) selection on the comb-drive image.
As previously noted in [10], the major limitation associated with this procedure is due to the inability of the ADMFFT to measure angular displacements less than a tenth of a degree, typical of MEMS devices for biomedical applications such as microgrippers. However, some microgrippers actuated by rotary comb-drive, as those studied in this work, are powered with voltages much higher than 30 V [25,26] and therefore it was considered relevant to define whether this method could be used for the characterization of other MEMS devices. In order to evaluate the limit of applicability of the ADMFFT, we proceeded in this way: once an image that presented a pattern like the one shown in Figure 5 was identified, it was rotated of a quantity reported in Table 1, where SET1 and SET2 correspond to two set of rotation, the first consisting of rotations less than one degree, the second higher than one degree; in particular, the rotation values of the first set correspond to the measurements obtained from the images acquired during the experimental campaign, using the SAM.

### 3. Uncertainty Analysis

In order to make a comparison among the three different image analysis methods, it is necessary to estimate the main uncertainty sources introduced by the measurement systems. It is important to underline that the experimental setup is the same, except for the three different methods. Following the procedure adopted in [7], Type A and Type B uncertainties will be combined [27], as follows (1):

\[
\delta_T = \sqrt{\delta_A^2 + \delta_B^2},
\]

where

- **δT** is the total uncertainty,
- **δA** is the Type A uncertainty,
- **δB** is the Type B uncertainty.
where Type A uncertainty, $\delta_a$, has been calculated directly from the standard deviation of the experimental data, while Type B uncertainty, $\delta_b$, 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 [28]-[29] in order to estimate the uncertainty related to the three implemented methods.

Considering the SAM, in order to simulate the uncertainty of the operator’s point selection and therefore evaluate the algorithm uncertainty, a Monte Carlo simulation with $10^6$ iterations has been performed. In Table 2, the variables $x, y$ and ROI with their assigned distributions and their standard deviations have been reported, in order to estimate the uncertainty introduced by the method. This contribution has been evaluated for each angular displacement of the comb-drive (i.e., $\delta_1, \delta_2, \delta_3, \delta_4, \delta_5$, and combined with the Type A uncertainty, following the equation (1). On the other hand, to evaluate the uncertainty introduced by the FFT based method in the measurement of the angular displacement of the comb-drive, the image in Figure 5 has been subjected to different rotations. The contribution of the systematic uncertainty, considered in this procedure, has been evaluated by building a particular 4K (3840 px x 2160 px) image (Figure 7), rotated by the same quantities reported in Table 1. This contribution is mainly due to the uncertainty with which the software implements the rotation of the image and therefore into the error that it makes in measuring the angle $\alpha$. Considering that at angles up to $15^\circ$ the sine is only about 1% different and the tangent about 2% different from the measurement of the angle in radians [30], the following approximation can be used (2):

$$\tan \alpha \cong \alpha = \frac{a}{b},$$

where $a$ and $b$ are the measurements of the segment reported in Figure 7, therefore, for angles less than $15^\circ$, the angle measurement relative uncertainty $\delta_a$ has been evaluated by the following equation (3):

$$\delta_a = \frac{\delta_a}{a} = \sqrt{\frac{\delta_a^2}{a} + \frac{\delta_b^2}{b}}.$$

Table 2. Variables settings in MCS to estimate the uncertainty introduced by the operator’s subjectivity.

| Parameter               | Distribution | Standard Deviation in px |
|-------------------------|--------------|--------------------------|
| P1 Coordinate x         | Gaussian     | 8                        |
| P2 Coordinate x         |              | 10                       |
| P3 Coordinate x         |              | 8                        |
| P4 Coordinate x         |              | 9                        |
| P1 Coordinate y         |              | 6                        |
| P2 Coordinate y         |              | 7                        |
| P3 Coordinate y         |              | 6                        |
| P4 Coordinate y         |              | 7                        |
| ROI Coordinate x        |              | 15                       |
| ROI Coordinate y        | Gaussian     | 14                       |
| ROI width               |              | 20                       |
| ROI height              |              | 18                       |

Table 1. Rotation values.

| SET1 in ° | 0.007 | 0.032 | 0.070 | 0.120 | 0.194 | 0.277 | 0.379 | 0.497 | 0.631 | 0.777 | 0.939 | 1.118 |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1         | 2     | 3     | 4     | 5     | 7     | 10    | 13    | 16    | 20    | 25    | 30    |       |

where $\delta_a$ and $\delta_b$ are the measurement uncertainty of segments $a$ and $b$, respectively, which are considered $\pm 1$ px, and on the other hand, if $\alpha$ is greater than $15^\circ$, it can be determined as follows (4):

$$\alpha = \arctg\left(\frac{a}{b}\right).$$

and its uncertainty $\delta_\alpha$ can be evaluated by equation (5), as

$$\delta_\alpha = \frac{d[\arctg(\epsilon)]}{dc} \cdot \delta_c,$$

where $\epsilon$ is the ratio between the segments $a$ and $b$, while $\delta_c$ is the corresponding uncertainty. Once this uncertainty contribution has been evaluated, for each angular displacement, it is then combined following the equation (1).

Once uncertainties have been evaluated, a comparison among the three different set of results will be made, following the procedure adopted in [8] and reported in [31]. In practice, the different methods are able to measure the angular displacement of the comb-drive without significant differences if the following condition is verified (6):

$$|\bar{M}_1 - \bar{M}_2| \leq (\delta_T_1 + \delta_T_2),$$

where $\bar{M}_1$ and $\bar{M}_2$ are the mean values of the measurement results, while $\delta_T_1$ and $\delta_T_2$ are the total uncertainty estimate. In particular, if the difference $|\bar{M}_1 - \bar{M}_2|$ has the same order of magnitude, or even less than, the sum $(\delta_T_1 + \delta_T_2)$, then measurements can be considered consistent, within the interval of the experimental uncertainties.

4. RESULTS AND DISCUSSION

In this section the outcomes from SAM, ADM_SURF and ADM_FFT are reported and commented. The graphs in Figure 8 and in Figure 9, show the results related to the comb-drive angular displacement, expressed as mean value, corresponding to SAM, ADM_SURF and ADM_FFT respectively.

Table 4 shows the measurement results expressed as the mean

![Figure 7. 4K image, rotated of 20° for the estimation of angular rotation uncertainty in FFT-based method.](image-url)
value and the corresponding measurement uncertainties at 95% of confidence level. In particular, the SAM introduces a measurement uncertainty contribution which corresponds to 0.8°, at 95% confidence level, and has been retrieved from 2.5 and 97.5 Monte Carlo distribution percentiles.

The analysis of the data showed that both the SAM and the ADMsURF follow a quadratic trend, that is in good agreement with the results obtained through the analysis of the analytical model [32]. As reported in [31], if the difference \( |\bar{M}_1 - \bar{M}_2| \) has the same order of magnitude as, or even less than, the sum \( (\delta_R + \delta_P) \), then measurements can be considered consistent, within the interval of the experimental uncertainties. From the data reported in Table 4, the differences between the mean values are less with respect to the sum of the correspondent total uncertainties, therefore the measurements can be considered compatible, confirming that the ADMsURF is suitable for the measurement of the angular displacement of the comb-drive of the MEMS microgripper under test. Moreover, it is important to underline that the computational complexity has been considerably reduced by using the ADMsURF: to process 390 images, as in our case, the SAM requires about 2 hours, instead the ADMsURF about 4-5 minutes only.

As regards the data obtained with the ADMsFFT (Figure 9), 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 ADMsFFT cannot be considered suitable for the measurement of MEMS grippers whose angular displacement is below 1°, as there is no possibility of appreciating displacements around the tenth of a degree. Anyway, since some prototype of microgrippers, built with rotary comb-drives, are powered with voltages higher than 30 V and can be moved with angular displacements above 1°, the ADMsFFT is evaluated also for an object that rigidly rotates around its axis by quantities greater than 1°. Table 3, shows the measurement of rotation, MoR1, calculated applying ADMsFFT to an image (see Figure 5), rotated of a quantity equal to SET1; and the measurement of rotation, MoR2, calculated applying the ADMsFFT to the same image, rotated of a quantity equal to SET2, together with the angle measurement uncertainty \( \delta_M \), estimated from (3), considering \( \alpha < 15° \) and from (5), considering \( \alpha > 15° \). Test results confirm that angular displacements up to 30° can be measured with an angle measurement uncertainty \( \delta_M \) lower than 0.02°, as can be seen in Table 3. The different behavior of the

| SET1 in ° | MoR1 in ° | \( \delta_M \) | SET2 in ° | MoR2 in ° | \( \delta_M \) |
|----------|----------|-------------|----------|----------|-------------|
| 0.007    | 0        | 0.03        | 1        | 1.193    | 0.015       |
| 0.032    | 0        | 0.015       | 2        | 2.767    | 0.015       |
| 0.070    | 0        | 0.016       | 3        | 3.918    | 0.015       |
| 0.120    | 0        | 0.015       | 4        | 4.029    | 0.015       |
| 0.194    | 0        | 0.016       | 5        | 4.963    | 0.015       |
| 0.277    | 0        | 0.015       | 7        | 5.078    | 0.015       |
| 0.379    | 0        | 0.015       | 10       | 8.857    | 0.015       |
| 0.497    | 0        | 0.015       | 13       | 8.127    | 0.016       |
| 0.631    | 0.735    | 0.015       | 16       | 14.697   | 0.015       |
| 0.777    | -0.262   | 0.015       | 20       | 16.571   | 0.015       |
| 0.939    | 1.193    | 0.015       | 25       | 19.759   | 0.015       |
| 1.118    | 1.193    | 0.015       | 30       | 29.237   | 0.015       |
ADM<sub>FFT</sub> depending on the angular range can be deduced from results of the two rotation sets (Table 1) in Figure 10: for rotations below 1°, the least squares regression line has shown a $R^2 = 0.54$, while $R^2 = 0.97$ for angles between 1° and 30°. In conclusion, it is possible to confirm that the ADM<sub>FFT</sub> is not suitable for the measurement of rotations below 1°, but for greater rotations (higher than 1°), it has an almost linear behavior.

5. 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 MEMS gripper prototype for biomedical applications. In particular, three in-house methods have been implemented in Matlab environment: the SAM, the ADM<sub>SURF</sub> and the ADM<sub>FFT</sub>. Considering the SAM, the contribution of uncertainty related to the subjectivity of the operator has been estimated, which has found to be 0.8° at 95% of confidence level, as previously indicated. From the experimental results obtained, it has been found that the SAM and ADM<sub>SURF</sub> are suitable to measure the small angular displacement of the comb-drive of the microgripper, showing quadratic curves, consistent with the results obtained with the analytic model. Conversely, from the results retrieved by means of the ADM<sub>FFT</sub>, it has been found no good correlation between small 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 abovementioned methods.

Anyway, it was also assessed that this method was suitable for measuring rotations from 1° to 30°, and a good correlation is observed between the ADM<sub>FFT</sub> outcomes and the rotations applied by the operator, with an uncertainty of about 0.02°. A comparison between the SAM and the ADM<sub>SURF</sub> has been proposed: the measurements can be considered compatible, confirming that the ADM<sub>SURF</sub> is suitable for the measurement of the angular displacement of the comb-drive of the MEMS microgripper under test can be considered compatible. In particular the ADM<sub>SURF</sub> measurements of the comb-drive angular displacement are affected by an uncertainty lower than 8% for voltages less than 14 V, as well as smaller than SAM. In conclusion, it can be confirmed that the ADM<sub>SURF</sub> is the most suitable method among the three proposed for the characterization of the angular displacement of MEMS devices such as microgrippers, both for the results obtained and the significant reduction of the computational costs.

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