High speed vision system for the dynamic characterization of 3D printed sensors

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Abstract. Additive manufacturing technologies allows to create a wide variety of geometries even for single prototypes, allowing to develop 3D printed sensors, optimizing the characteristics of the sensing device to the need of each specific application. The dynamic characterization of these sensors is a key point, in particular for the applications where internal deformation of the sensor is used to transduce the quantity of interest. In this work, a 3D measuring system based on a single high speed camera is developed to characterize the dynamic behaviour of 3D printed accelerometer prototypes. The proposed measuring technique is based on the pose estimation: a vision-based method that allows to recover the position and orientation of a target of known geometry, by means of its image acquired by a single camera. The dynamic response of the 3D printed prototypes is analysed with impulse, random and harmonic excitation. Experimental results proved that the developed measuring technique is suitable for the test of this type of sensors, since allows to measure the motion of the suspended mass and of the external frame, without any loading effect and considering the six degrees of freedom contemporarily.

1 Introduction

Micro Electro-Mechanical System (MEMS) devices are sensors characterized by an overall size in the scale of micrometers. MEMS technology can be considered one of the most revolutionary of the 21st century because it has changed dramatically the design strategy in the field of electro-mechanical sensing, control and actuation. The fabrication of MEMS started from the evolution of process technology in semiconductors; the basic techniques are deposition of material layers, photolithography and etching to produce the required characteristics. The principal materials used for their fabrication are silicon, polymers, metals and ceramics. Among the most common commercial application of MEMS we can list: accelerometers, gyroscopes, pressure sensors, optical switching devices, microphones, magnetometers and ultrasound transducers. Nowadays MEMS inertial sensors are very popular in a number of application fields, including automotive, smartphones and consumer electronics in general, because of their continuous improvement in terms of miniaturization, reliability and power consumption.
Additive Manufacturing (AM) technologies allow to obtain 3D shapes with a very high flexibility on the obtained geometry. Moreover, in recent years, AM techniques are applied also for metal alloys: this development pushed the research on the development of MEMS-inspired 3D printed sensors.

This work is a feasibility study, to check the possibility to analyze the dynamic response of this type of sensors with a fully contactless vision-based technique. The attention is therefore not devoted to the specific dynamic characteristics of the considered sensor prototype, but rather on the features of the measuring system and on its applicability on sensor characterization.

2 3D printed MEMS-inspired sensors

In this work, we focus our attention on dynamic characterization of 3D printed MEMS inspired accelerometers prototypes, with particular reference to the single-axis accelerometers described in: [1] - [3] and shown in Figure 1.

![Figure 1: Model of the 3D printed sensor type 1 (left) and type 2 (right)](image)

The overall mass of the sensor prototypes tested in this work, including the frame, is $1.66 \times 10^{-3}$kg for sensor type 1 and $1.32 \times 10^{-3}$kg for sensor type 2. The frame size is 41x9.9x2.6mm for sensor type 1 and 35x9.6x4.1mm for sensor type 2.

3 Vision-based system for dynamic characterization of 3D printed sensors

The development and the validation of this type of sensors need to estimate the dynamic response of the suspended mass (also referred to as rotor). Due to the variability of the mechanical characteristics of 3D printed structures with the process parameters and with the characteristics of the alloy used in the production, it is fundamental to have a measuring system capable to estimate the response of sensor prototypes with a reasonable cost, to allow a wide application of a large number of different prototypes.
3.1 Candidate techniques for 3D printed sensors dynamic characterization

Since the sensor prototype is light and characterized by a very low mass, it is not possible to estimate its dynamic response using a classical accelerometer or any other contact technique, since the loading effect would completely modify the dynamic response of the sensor. Hence, it is fundamental to use a contactless technique, capable to estimate the 6 degrees of freedom motion of the rotor with sufficient resolution and a bandwidth. In principle, this type of measurement can be obtained with a 3D interferometer, however the need to estimate the motion of multiple points of the sensor impose to use a scanning approach, therefore using this type of measuring approach, only stationary tests can be done. Moreover, the cost of a 3D scanning interferometer is relevant.

Another potential option is to use a vision-based approach for the 3D characterization of the dynamic of the sensor prototypes. In particular, stereoscopy and pose estimation techniques are the most promising candidates. The advantage of the pose estimation approach is that, with this technique, only one high speed camera is sufficient, while for the stereoscopic approach at least two cameras are required. The use of pose estimation, not only allows to reduce the cost and the complexity of the hardware, but also allows to perform the measurement even in the case of a narrow optical access, since one point of view is sufficient.

The pose estimation technique was finally selected as the most suitable approach for the dynamic characterization of the 3D printed sensor prototypes described in this work. A brief overview on this technique is provided in the following.

3.2 Pose estimation technique: an overview

3D pose estimation is the problem of determining the transformation, in terms of rotation and translation, of an object, relying on its projection on the sensor of a camera. The target object must be rigid and have a set of features of known geometry that can be recognized in a reliable way in the acquired images. The position and orientation of the target can be estimated with respect to a fixed reference system, that coincides with the projection centre of the camera that records the scene (see [4] and [5]).

As described in [6], given 3D point in the field of view of a camera and provided that the optical parameters of the camera are known, it is possible to predict the point of the sensor where the image of the point is generated. This process is named image generation, or image formation. To estimate the position and the orientation of an object starting from its image projection, it is necessary to solve an inverse projection problem (Figure 3) usually referred to as pose estimation. To run pose estimation, it is necessary to previously calibrate the camera, in order to recover the parameters that describe the geometry of image formation and the aberration due to the optics. In this work the camera has been calibrated with the popular approach proposed by Tsai ([7]).

![Figure 3: Pose estimation technique as the inverse of the image formation process](image-url)
Although the inverse problem looks apparently simple, a solution in closed form is not reachable in practical applications, therefore an iterative solution has to be implemented. In this work, the implementation of the pose estimation is done in LabVIEW environment.

4 Experimental set-up and data processing

To analyze the dynamic response of each sensor prototypes, its external frame has been excited and both the 3D motion the frame and of the suspended mass have been estimated with pose estimation. Computing the transfer function between the motion of the rotor and the motion of the frame, the dynamic properties of the prototype are estimated.

4.1 High speed camera and targets for pose estimation

To run pose estimation, the images of a target of known geometry has to be acquired. In this work, two targets are used: one on the frame and the other on the suspended mass. Each target is composed of four circular blobs, placed on the corners of a rectangle. The center of gravity of the four blobs on the rotor coincides with the center of gravity of the four blobs on the frame. In this way the frame and rotor reference systems share the same origin and the same orientation of the reference axes. In Figure 4 two prototypes equipped with the target are shown, together with the target reference system and the coordinates of the centroid of each blob.

![Sensor prototypes equipped with the target on the rotor and on the frame (top) and geometry of the targets (bottom)](image)

Target geometry $\mathbf{P} (x, y, z)$ [mm]:

- Blobs on the rotor:
  - 1 $(2, 3, 0)$
  - 2 $(2, -3, 0)$
  - 3 $(-2, -3, 0)$
  - 4 $(-2, 3, 0)$

- Blobs on the frame:
  - 5 $(8, 3, 0)$
  - 6 $(8, -3, 0)$
  - 7 $(-8, -3, 0)$

Since the goal of this work is to estimate the first natural frequencies of the sensor prototypes up to 500Hz, the camera has to ensure a frame rate larger than 1kHz, to prevent aliasing. The adopted camera is Mikrotron EoSens mini2 high-speed camera with 100mm focal length ZEISS optics. The maximum
frame rate achievable with this camera depends on the resolution; in this work the frame rate was set to 3kHz, while the exposure time was 80µ. To ensure a proper illumination for the short exposure time, a lighting system composed by two high power LED lights by Smart Vision Lights model SC75-WHI-W 75mm has been created.

4.2 Excitation techniques
The excitation is provided imposing a vibration to the frame of the sensors. Three different excitation types have been used: impulse, harmonic and random.

Impulse excitation is obtained by fixing the prototype frame to a support and creating the impulses with a small hummer. This simple solution was adopted for a first analysis of the dynamic response of the sensor prototypes. To excite the sensor prototype with harmonic and random input, the frame of the sensor under test was mounted on an electromagnetic shaker (Ling Dynamic Systems (LDS) V400 Series), shown in Figure 5 and controlled with a function generator.

![Figure 5: 3D printed sensor prototype equipped with the circular patterns for pose estimation mounted on the electromagnetic shaker (left) and the full set-up with the high speed camera (right)](image)

4.3 Image processing and pose estimation

The images acquired by the high speed camera appear black in bright background. To estimate the centroids of each black circle, the images are first binarized, then the blob analysis is applied (Figure 6, left). Morphologic operations are then applied to remove spurious blobs and to identify the eight correct bloc reliably.

Pose estimation provides the position and the orientation of both the target on the rotor and the target of the frame in the camera reference system. However, for the present application, a reference system integral with the sensor and with the axes parallel to the main dimensions of the sensor is more suitable.

Hence, the pose estimation data are expressed along the sensor reference system, shown in Figure 7. The rototranslation between the camera reference system and the sensor one, has been estimated by means of pose estimation, applied on images of the sensor in reference position (i.e. with no external excitation).
5 Results and discussion

In this section, some examples of measurements obtained with the developed vision-based measuring technique are shown, considering all the three excitation techniques. The first example is shown in Figure 8, where the measurement of the impulse response of the frame and of the rotor are presented for the case of sensor type 1. As can be seen in time domain graphs, the impulse excitation was applied at time 0.95s from the beginning of the acquisition.
The spectra in Figure 8 highlight the first natural frequencies: at 240 and 626 Hz for the translation along the X axis, and at 343 Hz for the rotation around the Z axis for sensor type 1. As well known, impulse excitation allows to quickly estimate the first natural frequencies, by means of a single and simple test. However, the use of other input techniques, such as random or harmonic excitation, allows to analyze the response of the system to a stationary excitation. In this way, the crest factor of the response is limited, reducing the risk to excite nonlinear responses of the structure, and contemporarily testing the system with a larger input energy ([8]).

The proposed vision-based measuring technique can be used to measure the response of any type of excitation. For example, Figure 9 shows the spectra of the response of both the frame and the suspended mass for the sensor type 2. The first natural frequencies are clearly visible as the peaks of the vibration of the suspended mass.

Finally, Figure 10 shows an example of measurements of the displacement along the Z coordinate, obtained in the case of harmonic excitation. In this case, the input is a harmonic displacement at the frequency of 181Hz applied to the external frame of the sensor with the electromagnetic shaker.
Figure 9: Example of the response of the 6 degrees of freedom of the 3D printed sensor type 2, with random excitation in frequency domain.

Figure 10: Displacement along the Z coordinate in the case of harmonic excitation at 181Hz (sensor type 2)
Both the sensors type 1 and type 2, after the shaker tests, reached the failure point due to fatigue damaging (periodic mechanical stress). For sure the fatigue phenomena play a crucial role in these structure and must be estimated. The developed vision system also allows to monitor the dynamic response of the sensor over long fatigue tests, to check when the degradation behaviour occurs.

6 Concluding remarks

A 3D vision system was developed to estimate the dynamic response of two sensor prototypes, obtained with additive manufacturing. The vision system is capable to measure the vibration of external frame and internal mass with a unique camera and pose estimation, allowing to measure the data for the dynamic analysis of the structure. The dynamic response of the 3D printed prototypes is analyzed with impulse, random and harmonic excitation. Experimental results proved that the developed measuring technique is suitable for the test of this type of sensors.

The need of a good spectral resolution coupled with a high frame rate are critical because of the overall amount of data to be acquired. Hence, an on the fly processing of the images can be developed to store only the estimated degrees of freedom.
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