

# Displacement measurement system for inverters using computer micro-vision



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## ABSTRACT

We propose a practical system for noncontact displacement measurement of inverters using computer micro-vision at the sub-micron scale. The measuring method of the proposed system is based on a fast template matching algorithm with an optical microscopy. A laser interferometer measurement (LIM) system is built up for comparison. Experimental results demonstrate that the proposed system can achieve the same performance as the LIM system but shows a higher operability and stability. The measuring accuracy is 0.283  $\mu\text{m}$ .

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## 1. Introduction

Compliant mechanisms, owing to advantages of simple structure, no friction or wear, high precision, long life and so on, play a significant role in the design of micro-mechanical structures for micro-electro-mechanical systems [1,2]. It has attracted many attentions in recent years. Topology optimization is a basic approach for the design of compliant mechanisms [2]. Generally, in order to investigate the performance of the topology optimization in a quick and direct way, displacement inverters are used [1–7]. During the past few years, displacement inverters have become a typical example in the topology optimization. Zhu et al. presented a two-step elastic modeling method for topology optimization of the compliant mechanisms and the displacement inverters were taken as major numerical examples [2]. Ramrakhiani et al. utilized the displacement inverter problem to demonstrate the effectiveness of the elements which were designed by the topology design [3]. Saxena et al. used the displacement inverter as synthesis examples to verify the structural property [4]. In addition, Kim et al. [5], Ansola et al. [1] and so on [6–8] employed the displacement inverters to check performance of their designs. With rapid developments of compliant mechanism design, the displacement inverters will be more widely used in

the future. Since the displacement inverters are usually small and thin, and constructed by special grids [1–8], it is a challenging work to detect their displacements.

The LIM is one of the widely used methods to measure the displacements of the inverters. The measurement accuracy can reach to nanoscale. However, environmental conditions such as humidity, air temperature and pressure, usually bring interference to the measuring results even though a precision stabilized laser source and accurate environmental compensation are utilized. Moreover, a reflecting device is needed to be mounted on the inverter. It is not convenient when the inverter's grids are too big or beam elements are too small. The weight of the reflecting device may also cause deformation to the inverter, which can affect the measurement accuracy. Hsieh et al. introduced a grating-based interferometer for six degrees of freedom displacement and angle measurement [9]. The system of their method is complex and inconvenient for the general use. Berkovic et al. recommended many optical methods for distance and displacement measurements [10]. Some other researchers such as Cofaru et al. [11], Mudassar et al. [12] and Yuan et al. [13] developed image processing techniques and vision-based techniques for displacement measurements. Both a strong robustness and high accuracy are achieved by these techniques and the system setups are quite simple.

To the best of our knowledge, few literatures have been presented for the displacement measurement of the inverters utilizing the computer micro-vision in the compliant mechanism

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design. In this paper, we describe a practical system for the displacement measurement of the inverters using the micro-vision-based technology, which can acquire a high accuracy. The setup of the proposed system is much simpler and cheaper than the LIM system, but the accuracy of the proposed system is the same as the LIM system and the operability and stability of the proposed system are much higher. This system can give a great help for the compliant mechanism design.

## 2. Methodology

The system setup is sketched in Fig. 1 and the actual experimental setup of the system is shown in Fig. 2. The whole workstation includes an inverter in combination with a piezoelectric translator (PZT) driver system, a PC and an imaging system. The PZT is a stack piezoelectric translator PST 150/7/60VS12, which is a preloaded PZT from Piezomechanik in Germany. The PZT is installed inside the inverter which is mounted on a vibration-free positioning platform. The imaging system consists of an optical microscope with a controllable zoom (magnification from  $0.71 \times$  to  $4.5 \times$ ), and a CCD camera (JAI CV-A2, black and white) with a resolution of  $1500 \times 1200$ . The pixel size of the CCD camera is  $4.4 \mu\text{m}$ . A  $10 \times$  objective is used, which has a depth of field of  $3.5 \mu\text{m}$ . During the experiment, the total magnification of the system is  $15.54 \times$ . The pixel space of the CCD camera is  $C_x = C_y = 0.283 \mu\text{m}/\text{pixel}$ .

The displacement measurement process of the proposed system, which is based on the template matching, is composed of a coarse search and a fine search. The coarse search is to find out the potential regions that the centroid point of the template might be in. The fine search is to determine the accurate location of the template in the reference images. Let  $I(x, y)$  denote the intensity value of the image  $I$  with the size  $M \times N$  at the point  $(x, y), x \in \{1, \dots, M\}, y \in \{1, \dots, N\}$ . Similarly, let  $T(x, y)$  be the intensity value of the  $m \times n$  template  $T$  at the point  $(x, y)$  where  $m \leq M$  and  $n \leq N$ . In order to determine the potential regions, a testing function for evaluating the error between the template and the candidate image is defined as Eq. (1) [14],

$$\varepsilon(x_k, y_k, i, j) = |I(x_k + i, y_k + j) - T(x_k, y_k) - \bar{I}(i, j) + \bar{T}|, \quad (1)$$

where  $(x_k, y_k)$  represents the randomly selected coordinate which is nonrepeating,  $k = 1, 2, \dots, m \times n$ ,  $i = 1, 2, \dots, M - m + 1$ ,  $j = 1, 2, \dots, N - n + 1$ ,  $\bar{I}(i, j)$  and  $\bar{T}$  are the average gray-scale values of the reference and the template image, respectively, which are

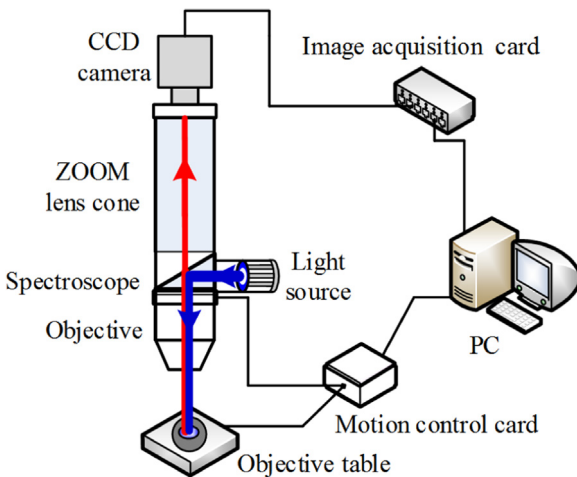


Fig. 1. The sketch map of the measuring system.

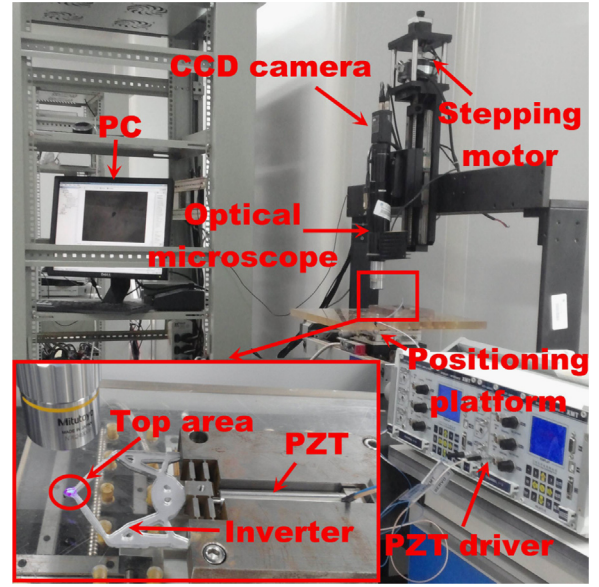


Fig. 2. The experimental setup of the micro-vision system.

expressed as follows:

$$\bar{I}(i, j) = \frac{1}{m \times n} \sum_{x=1}^m \sum_{y=1}^n I(x+i, y+j), \quad (2)$$

$$\bar{T} = \frac{1}{m \times n} \sum_{x=1}^m \sum_{y=1}^n T(x, y). \quad (3)$$

Then, a constant threshold  $T_{thr}$  is employed to test the accumulated errors as shown in Eq. (1). If the accumulated error exceeds  $T_{thr}$ , the calculation is stopped and the point  $(i, j)$  and the test number  $d$  are recorded, else the calculation will go on until  $k = m \times n$ . The surface detection function  $S(i, j)$  is expressed as

$$S(i, j) = \left\{ d \mid \min_{1 \leq d \leq m \times n} \left[ \sum_{k=1}^d \varepsilon(x_k, y_k, i, j) \geq T_{thr} \right] \right\}. \quad (4)$$

When the value of  $S(i, j)$  where the accumulated error exceeds  $T_{thr}$  are acquired, the corresponding points are considered as potential points. Then, each potential point is set as the centroid point of a corresponding square which is created with a side length  $L$ , where  $L$  represents the number of pixels. The squares are regarded as the potential regions. Unlike traditional template matching algorithms where the upper left point is usually taken as the reference point, the centroid point is selected as the reference point of the template in our algorithm, which is presented as

$$x = \frac{\sum_{x=1}^m \sum_{y=1}^n x \cdot T(x, y)}{\sum_{x=1}^m \sum_{y=1}^n T(x, y)}, \quad y = \frac{\sum_{x=1}^m \sum_{y=1}^n y \cdot T(x, y)}{\sum_{x=1}^m \sum_{y=1}^n T(x, y)}. \quad (5)$$

After that, the normalized cross-correlation (NCC) algorithm is used to calculate the precise location from the potential regions in the image. The computation process is repeated for every point in the potential regions and the NCC coefficient value is recorded correspondingly. The point with the highest score is selected as the final point. The NCC coefficient is defined as

$$R(i, j) = \frac{\sum_{x=1}^m \sum_{y=1}^n I(x+i, y+j) \cdot T(x, y) - m \cdot n \cdot \bar{I}(i, j) \cdot \bar{T}}{\sqrt{\sum_{x=1}^m \sum_{y=1}^n I^2(x+i, y+j) - m \cdot n \cdot \bar{I}^2(i, j)} \cdot \sqrt{\sum_{x=1}^m \sum_{y=1}^n T^2(x, y) - m \cdot n \cdot \bar{T}^2}}, \quad (6)$$

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