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Efficient block matching using improved particle swarm optimization with application to displacement measurement for nano motion systems

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A B S T R A C T

This paper is devoted to the micro vision based displacement measurement for a nano-positioning stage with the aid of a single camera. For this purpose, a pinhole imaging model as well as corresponding Jacobin matrix is established, with which an efficient block matching (BM) algorithm is developed based on the particle swarm optimization (PSO) algorithm. In particular, an improved PSO algorithm is developed by proposing a new fitness updating strategy (FUS) such that the particles' migration can be performed with an efficient way in the whole optimization process. The improved PSO can significantly speed up the optimization process, but meanwhile resulting in a coarse-level estimation result. The full search algorithm (FSA) is thus performed on the coarse-level result in order to achieve the final fine-level result. The effectiveness of the presented method was demonstrated using the testing data acquired from an experimental platform, where comparative studies with those existing benchmark methods were also provided. The comparison results show that the method achieves a significant improvement on computational efficiency without loss of accuracy, which implies it has a better balance/trade-off between the measurement accuracy and computation efficiency in real applications.

1. Introduction

Micro/nano motion systems have emerged as one of the key enabling technologies in precision engineering fields, such as scanning probe microscopy (SPM), semiconductor lithography and memory storage [1–3]. To achieve nano scale accuracy of the motion systems, feedback control approaches are widely employed [4], where the displacement of the motion stage needs to be measured accurately and tracked continuously for error compensation purposes. Existing methods on displacement sensing with nano resolution include laser interferometer [5,6], optical encoder based sensor [7], grating coupling based sensor [8–10], capacitive sensor [11–13], RGB/gray camera [14–17], etc. The above sensing techniques are summarized in Table 1, where descriptions on each method are provided with comparisons of advantages and disadvantages. More recently, the applications of such systems have been successfully extended to more sophisticated nano/micro-scale manipulations supporting advanced tasks such as nano-assembly [18], cell injection/micromanipulation [19–22]. In such situations, image/vision based measurement methods are desirable with many obvious advantages such as independency on mechanical structures, more flexibility and compatibility with complex motions [16,23].

With such a motivation, a single camera based micro vision problem is explored for the displacement measurement of a nano-positioning stage. Relevant studies along this line of research include, but not limited to, the use of block matching (BM) [17,24,25], optical flow [26–28], Fourier phase spectrum [29,30], etc. Among them, the BM method is believed to be highly effective in practice. Successful attempts on the BM method have been reported extensively, which use the full search algorithm (FSA) as seen in [25,31,32]. Note that the computational complexity of FSA is very significant, which is determined as the level of $O(R^2)$ where R is the size of a square search space. To address this problem, fast FSA methods have been proposed by adjusting/limiting the size of search space [17,33], with the sacrifice of the risk of the so-called *local-optima* which might lead to fatal matching errors [34].

Alternatively, the *global-optima* matching based methods are also explored by virtue of optimization algorithms, e.g., the genetic algorithm (GA) and the particle swarm optimization (PSO) algorithm. In particular, the PSO algorithm has been demonstrated to be more effective and applicable for alleviating the issue of local-optima than the GA [35]. But it is also found that the PSO methods cannot compete well with fast FSA methods in term of computation speed [36], which attracts continuous research efforts on improvements of PSO based BM methods as seen in [36–38].

The aim of the present paper is to develop an enhanced displacement measurement method for the nano/micro positioning stage discussed in [39], by proposing a new *coarse-to-fine* method with the integration of

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Table 1
An overview of displace measurement methods used in nano/micro systems.

Sensor	Description	Advantages	Limitations	Example references
Laser interferometer	Utilize light interference to measure the distance	High accuracy and real-time response	Simple to be blocked and strict installation location requirements	[5], 2003[6];, 2015
optical encoder based sensor	Guided by translational compliant mechanisms to measure the 1-DOF input or output	High accuracy and real-time response	Unfeasible or difficult to directly measure the multi-DOF output motion	[7], 2017
Grating coupling based sensor	Measurement feedback device using optical principle of grating	High resolution and real time response	Only can be used in 1-DOF motion estimation	[8], 2017[9];, 2017[10];, 2016
Capacitive sensor	Based on capacitive coupling, it can detect and measure any motion that is conductive or has a dielectric difference from the air	High resolution and real-time response	High cost and only can be used in 1-DOF	[11], 2016[12];, 2017[13];, 2017
RGB/gray camera	Use micro computer vision to measure the displacement	Can be used in multiply-DOF system, low cost and visible	Low sampling rate	[14], 2007[15];, 2014[16];, 2013[17];, 2017

PSO and FSA. In particular, an improved PSO algorithm is developed by proposing a new fitness updating strategy (FUS) such that the particles' migration can be performed with an efficient way in the whole optimization process. The improved PSO can significantly speed up the optimization process but with a coarse-level estimation result. The full search algorithm (FSA) is then performed on the coarse-level result to achieve the final fine-level result. The effectiveness of the proposed method will be demonstrated using the testing data acquired from the experimental platform, where comparative studies with existing benchmark methods are also provided. The comparison results show that the proposed method has a significant improvement on efficiency without loss of accuracy, which implies it can achieve a better balance/trade-off between the measurement accuracy and computation efficiency in real applications.

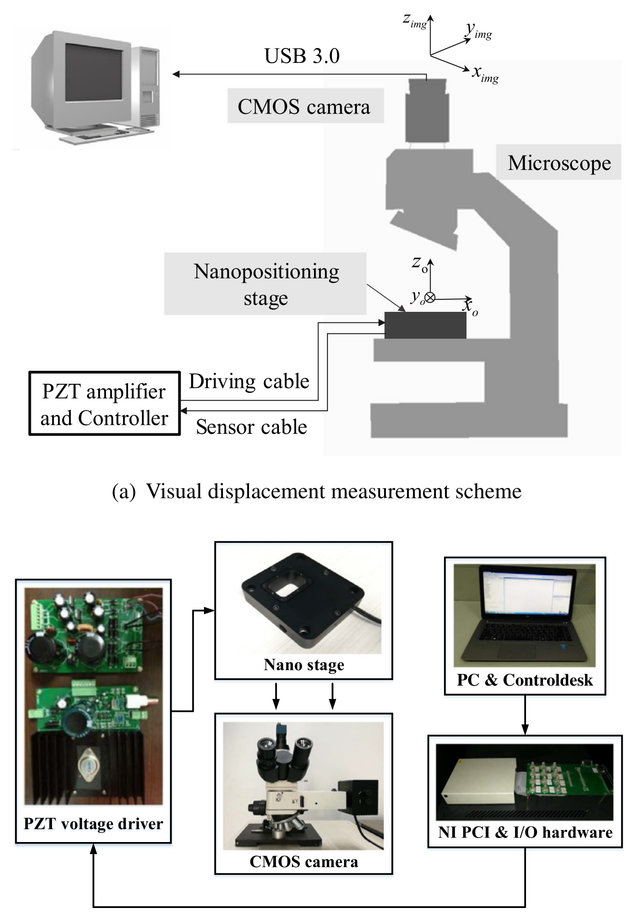
The rest of this paper is structured as follows. In Section 2, we describe the micro vision based nano-motion system and present the optical model, such that the Jacobin matrix between the image space and Cartesian space for the displacement measurement can be established. In Section 3, we present a solution to overcome the BM problem using the conventional PSO. To further improve the computational efficiency, we modify the PSO algorithm by the development of new FUS, and use FSA to achieve final result in Section 4. Evaluations on the proposed approach are provided in Section 5, where comparative studies are also given. In Section 6, we discuss some implementation issues on the proposed approach, followed by some concluding remarks in Section 7.

2. System description and problem formulation

In this section, we start with a brief description of micro vision system supporting nano-positioning of the motion stage reported in [39], where a single camera configuration is adopted. Based on the experimental system apparatus, we can derive the optical model of the CMOS camera.

2.1. The micro vision based nano positioning system

The micro vision based nano positioning system is depicted in Fig. 1, where a CMOS camera is used in the proposed visual displacement measurement scheme. The consideration of visual displacement measurement for this stage is driven by the needs of vision-guided purposes in design, validation as well as practical visual feedback applications. For these purposes, a micro vision system is designed as shown in Fig. 1(a), which includes, an investigated micro positioning stage with a mark, a microscope with a lighting system, a CMOS camera and a PC with CPU 3.7GHz and RAM 4GB. Meanwhile, the overall experimental apparatus



(a) Visual displacement measurement scheme

(b) Visual feedback based nano-manipulation experimental apparatus

Fig. 1. Components of the micro vision system.

in Fig. 1(b) consists of a one-dimensional nanopositioning stage with a stroke of 123 μm. With the visual displacement feedback, an overall control system is implemented using Matlab/Simulink and its real time control package xPC Target, where a high bandwidth voltage amplifier is designed to drive the piezo actuator and National Instruments (NI) PCI-6251 I/O hardware is used to transmit reference input signals.