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Nonlinear dynamic analysis and optimal trajectory planning of a high-speed macro-micro manipulator

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ABSTRACT

This paper reports the nonlinear dynamic modeling and the optimal trajectory planning for a flexure-based macro-micro manipulator, which is dedicated to the large-scale and high-speed tasks. In particular, a macro- micro manipulator composed of a servo motor, a rigid arm and a compliant microgripper is focused. Moreover, both flexure hinges and flexible beams are considered. By combining the pseudorigid-body-model method, the assumed mode method and the Lagrange equation, the overall dynamic model is derived. Then, the rigid-flexible-coupling characteristics are analyzed by numerical simulations. After that, the microscopic scale vibration excited by the large-scale motion is reduced through the trajectory planning approach. Especially, a fitness function regards the comprehensive excitation torque of the compliant microgripper is proposed. The reference curve and the interpolation curve using the quintic polynomial trajectories are adopted. Afterwards, an improved genetic algorithm is used to identify the optimal trajectory by minimizing the fitness function. Finally, the numerical simulations and experiments validate the feasibility and the effectiveness of the established dynamic model and the trajectory planning approach. The amplitude of the residual vibration reduces approximately 54.9%, and the settling time decreases 57.1%. Therefore, the operation efficiency and manipulation stability are significantly improved.

1. Introduction

In the fields of the micro-electro-mechanical system (MEMS), the biological engineering and the IC package, flexure-based stages and microgripper are popular devices to acquire high-precision positioning or grasp-hold- release manipulation [1–3]. The reason arose from that the compliant mechanisms (e.g. the amplification mechanism [4–6], the position adjustment mechanism [7–10] and the force detection beam [11,12]) deliver motions using elastic deformations of flexure hinges and flexible beams. As a result, they have unique merits, including high resolution, repeatable motion, free of frictionless and backlash, and so on [8,10]. Meanwhile, a large-scale and high-speed motion is also required in various high-through manipulation tasks (e.g. the osteoblast assembly in literature [13], the micropart manipulation in literatures [14,15], and the minimally invasive surgery in literature [16]). Note that the distances between the pick area and the place area are in millimeter level or even centimeter level. Hence, both large scale and high speed are required in these manipulation systems. Moreover, micro-objects usually have a vast number or restricted life span [17]. Therefore, the compliant stage or

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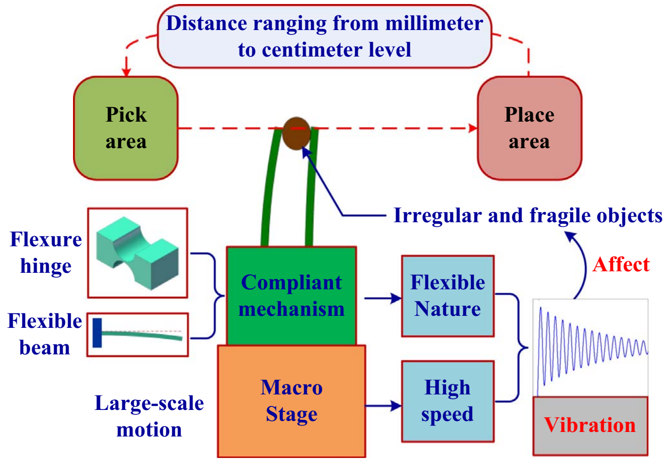

Fig. 1. Typical large-scale and high-speed manipulation tasks when flexure-based macro-micro manipulators are used.

the microgripper is mounted on the macro stage to construct a macro-micro manipulator [13,15,16].

However, the flexible nature of the flexure-based compliant mechanism leads to the presence of unwanted elastic vibrations during and after motion, as shown in Fig. 1. For instance, the undesirable residual vibration after the motion of the gripping arm in literature [13] is up to 25.9 μm, which is approximately 50% of its manipulation object. Moreover, the settling time (173 ms) accounts for 17.3% of its total manipulation time. The elastic vibration of the flexure-based mechanism decreases the positioning accuracy and operation efficiency. Meanwhile, the control of such a system becomes instable and extremely difficult. To guarantee the position accuracy and the manipulation efficiency, vibration control in the microscopic scale is indispensable and desirable.

To date, various vibration suppression methods, including the feedback control and the feedforward control, have been reported [18]. Generally, the feedback control (e.g. the fuzzy control [19,20], the PPF control [21] and the adaptive control [22,23]) can decrease the elastic vibration significantly. Nevertheless, the feedback controllers also require additional sensors and actuators, which restricts their application in microgrippers where the installation and work space are rather limited [11,12]. Alternatively, feedforward controllers, including the input command shaping and the trajectory planning approach, are developed. The input command shaping could effectively inhibit the vibrations arose from the input excitation. However, it is difficult to suppress a variety of vibration modes and a large amount of computations are needed [24,25]. On the other hand, the trajectory planning approach is proposing owing to its simplicity and effectiveness. To suppress the vibration of a two-link flexible manipulator, Abe [26] designed an optimal trajectory based on the cubic spline function and the particle swarm algorithm. Numerical simulations demonstrated that the residual vibration of the manipulator was reduced from 10 cm to a negligible level. Using exact equilibrium manifolds, Choi et al. [27] proposed a trajectory planning method for output tracking of a single-link manipulator (the length was 642 mm). The residual vibration with 20-cm amplitude was nearly compensated. Heidari et al. [28] developed the pontryagin's minimum principle to determine the optimal trajectory of a very flexible link manipulator (the length was 1000 mm) in point-to-point motion. The maximum amplitude of the residual vibration in x direction was reduced from 500 mm to 350 mm. Lou et al. [25] developed an optimal trajectory planning method for vibration reduction of a simple manipulator (the length is 620 mm). The amplitude of the residual vibration decreased about 10 times, and the settling time reduces from 10 s to 3.8 s. However, most reported literatures deal with a single-link manipulator in macroscopic scale, and the vibration is larger than millimeter level or even centimeter level. Limited investigation on the extension of trajectory planning approach to the macro-micro manipulator (in which the elastic vibration is in the microscopic scale) has been conducted. Moreover, both flexure hinges and flexible beams are widely used in the macro-micro manipulator, which makes the dynamic analysis and the vibration suppression remains essential but challenging. In addition, disturbances arose from the large-scale and high-speed motion present serious when the excited vibrations are in the microscopic scale.

To this end, the objective of this research is to establish the nonlinear dynamic model of a macro-micro manipulator, in which both flexure hinges and flexible beams are considered. Moreover, a suitable trajectory planning approach is proposed to suppress the undesirable residual vibration of microscopic scale. In particular, a flexure-based microgripper and a large-scale macro stage driven by a servo motor are focused. Using the pseudorigid-body-model (PBM) method, the assumed mode method and the Lagrange equation, the overall dynamic model is derived. Based on the model, the optimal trajectory is determined through the genetic algorithm. Both simulations and experiments have been carried out and verify the dynamic characteristics of the macro-micro manipulator and the efficiency of the trajectory planning approach.

The remainder of this paper is organized as follows. In Section 2, the configuration of the macro-micro manipulator is described, and the nonlinear system model is presented. Section 3 presents the dynamic analyses of the macro-micro manipulator, along with the trajectory planning approach. Section 4 describes an experimental apparatus of the macro-micro manipulator system, together with the test results and discussions. Section 5 presents the conclusions.