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Performance analysis and optimization of a five-degrees-of-freedom compliant hybrid parallel micromanipulator

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ABSTRACT

There are generally two main directions for the investigation and development of parallel manipulators, namely macro/meso stream and micro/nano stream, in which the former one has been thoroughly investigated in recent decades, while the latter one still remains many performance related open issues that significantly affect their application potentials in critical situations such as high-precision automated cell manipulation. Improving the overall performance of parallel manipulators is the bridge to connect the academia and industry for the great development and real-world application. This research is to develop a novel methodology called performance decomposition and integration for governing the design optimization process of complicated micromanipulator. A new five degrees-of-freedom (DOF) compliant hybrid parallel micromanipulator which is configured with five identical PSS limbs and one constraining UPU limb is proposed as a case study. The performance visualization, finite element analysis, and dimensional optimization are implemented. The proposed methodology is applicable for the design improvement of different kinds of compliant/parallel mechanisms.

1. Introduction

For the past several decades, parallel mechanisms/manipulators can be found for extensive applications including three-dimensional printers, machine tools, and vehicle simulators, picking and placing tools, sensors and robots [1–8]. Although a major portion of these applications are not fully commercialized and needs further improvement, it has been commonly recognized with the continuing effort of several decades, parallel manipulator has become one of the main branches of the family of mechanisms and robotic systems due to their natural merits many aspects [9–14].

Regarding performance parallel mechanisms, the global researchers have conducted huge work on from design, analysis to control [15–18]. However, due to the limitation of capabilities, conventional manipulators cannot well adapt to the rapid change of critical applications where reliability, robustness and resilience are highly demanded. More efficient methodologies, especially in micro/nano applications for parallel manipulators, are highly required to guide the development of compliant manipulators. In this scenario, a paradigm called as performance decomposition and integration (PDI) is proposed. Performance decomposition is necessary to explore the macroscopic characteristics of a complicated system in a microscopic method. A system may have many performance indices. Integration is a universal notion that ranges from component level to system level. For a robotic system, the methodology of performance integration covers the measures from integrated design and optimization. To explore the overall performance of a complex system, it will be firstly divided into several sub-criterions based on PDI. These sub-criterions are investigated and managed separately. Then, a united index can be built to examine the comprehensive performance and consequently improve it with performance integration.

As a case study, a 5-DOFs compliant hybrid parallel micromanipulator (CHPMM) is proposed. It is configured with five identical PSS limbs and one constraining UPU limb. A multi-layer amplification mechanism based prismatic joint is designed for each limb and the piezoelectric actuator will be placed at the center position of the active prismatic joint. In each limb, two flexures based spherical joints are connected either with the prismatic joint or with the moving stage, respectively. An embeddable passive UPU limb is applied to constrain the mobility of the proposed manipulator into 5DOF. For the content of this paper, the analysis of kinematic model and Jacobian matrix is conducted. Three essential performance indices, i.e. dexterity, manipulability and workspace, are derived and visualized. The finite element analysis is performed to observe the mechanism behavior. Finally, dimensional improvement is implemented based on hybrid optimization algorithm.

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2. Conceptual design and kinematic modeling

The computer-aided design (CAD) model of the proposed CHPMM is shown as Fig. 1. It can be observed that this mechanism has five identical limbs which are featured as prismatic–spherical–spherical structure, within which the prismatic joint is a multi-layer compliant structure. There is a complicated passive constraining limb inside of this mechanism, which is connected with the base and the moving platform with one universal joint respectively. Between the two universal joints of the embedded limb, a novel passive prismatic joint is proposed. Five electric-piezos are mounted at the edge of the base platform to actuate the external identical limbs. The inside embedded limb constrain the

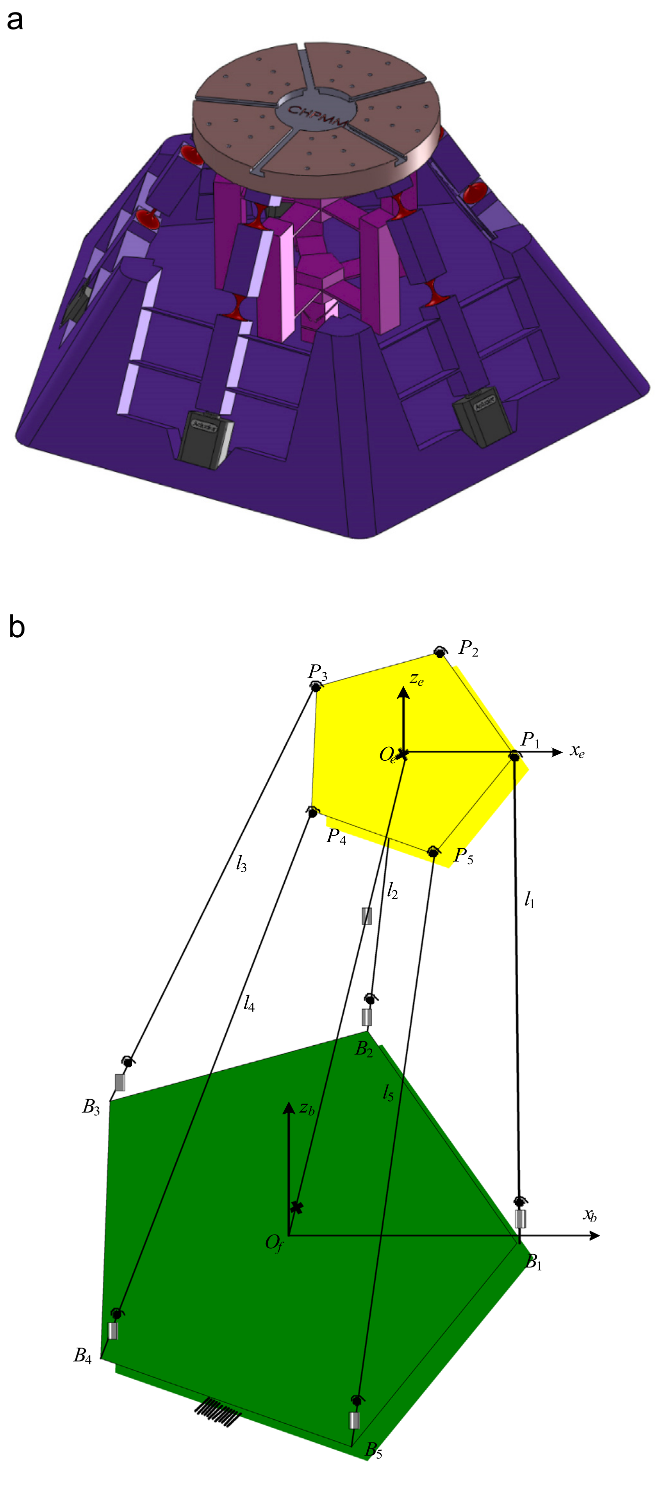

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Fig. 1. The proposed 5-DOF CHPMM: (a) the CAD model and (b) the kinematical structure.

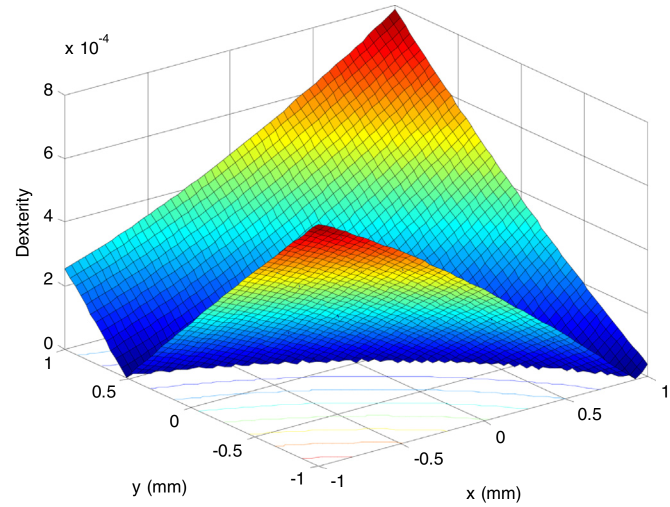

Fig. 2. The landscapes of dexterity.

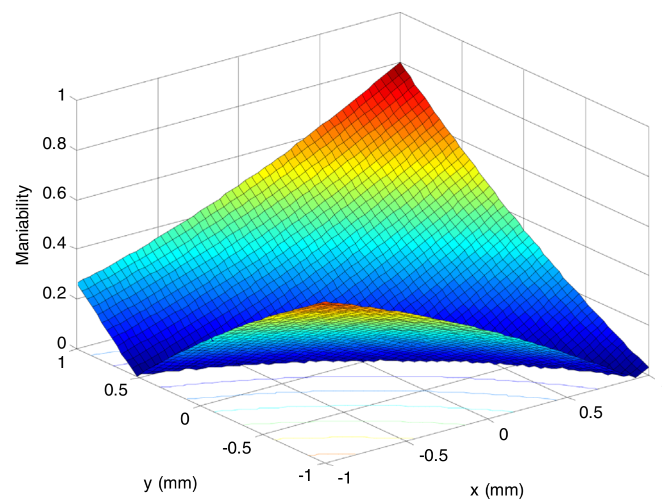

Fig. 3. The landscapes of manipulability.

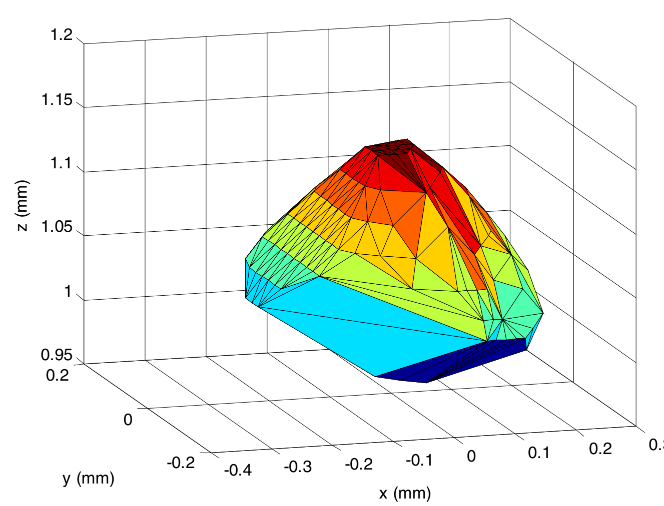

Fig. 4. The landscapes of workspace.