博士学位论文

（学术学位论文）

多维压电功能单元创成及多自由度宏微操控研究

RESEARCH ON CREATION OF MULTI-DIMENSIONAL PIEZOELECTRIC FUNCTIONAL UNITS AND MULTI-DEGREE OF FREEDOM MACRO-MICRO MANIPULATIONS

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多维压电功能单元创成及多自由度宏微操控研究

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RESEARCH ON CREATION OF MULTI-DIMENSIONAL PIEZOELECTRIC FUNCTIONAL UNITS AND MULTI-DEGREE OF FREEDOM MACRO-MICRO MANIPULATIONS

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摘 要

精密多自由度操控技术及其载体是半导体制造、主动光学、微纳操控、微装配、显微探测等领域依赖的共性基础。这项技术主要涉及电磁致动、电热致动、静电致动和压电致动四种原理。其中，压电致动利用压电材料的逆压电效应实现运动输出，具有响应快、分辨力高、电磁兼容性好、无需传动机构、结构简单等独特优势，已成为精密多自由度操控技术的优选方案。本文针对当前压电操控领域面临的多维运动生成难、运动尺度跨越难、多功能运动拓展难等关键挑战开展研究工作，相关研究可推动压电操控技术的理论创新与应用发展。

针对从压电陶瓷电致变形到压电功能单元多维运动的生成难题，开展了压电功能单元创成与多维运动生成研究。研究了单一压电陶瓷伸缩和双层压电陶瓷贴片弯曲的运动机制。提出了弯曲致动单元“平面阵列组构”的创成方法和“正反对称弯曲组合”的多维运动生成方法，构建了一款可实现横向二维弯曲和纵向一维平移的十字梁压电致动单元。分析了一维到三维运动的生成原理，依托静力学建模和有限元仿真开展了参数化分析，检验了创成和运动生成方法的可行性。提出了环形压电陶瓷“空间叠层组构”的创成方法和“多维微观变形累积”的多维运动生成方法，构建了一款可实现横向二维弯曲和纵向一维伸缩的空间叠层压电致动单元。分析了使用单分区、二分区和四分区环形压电陶瓷的典型激励方案，利用仿真检验了该单元创成和运动生成方法的有效性。

针对从压电功能单元多维运动到执行末端微纳运动的拓展难题，开展了多维压电功能单元的直驱式压电微操控研究。首先，面向反射镜和操作针的多自由度、微尺度和高分辨力运动操控应用，采用机械固连直驱运动拓展方法，将反射镜和操作针作为执行末端与十字梁压电致动单元进行机械固连，分别研制了一款反射镜末端两自由度压电操控器和一款操作针末端三自由度压电操控器。阐述了它们的机电设计和多自由度运动原理，采用有限元仿真进行了的模拟分析。对于反射镜末端两自由度压电操控器，开展了开环特性测试，以及闭环定位和跟踪特性测试；通过实验检验了其在非接触式二维光束微操控中的应用有效性。对于操作针末端三自由度压电操控器，开展了输出位移和输出力特性测试；检验了其在 500μm 直径微球非接触式姿态操控中的应用有效性。综合检验了十字梁压电致动单元结合机械固连直驱运动拓展方法实现多自由度微操控的可行性。

针对执行末端兼备大运动范围和高分辨力的跨尺度操控实现难题，开展了多自由度压电操控器的跨尺度运动实现方法研究。以球型转子为运动末端，提出了单点多维致动的运动拓展方法，一方面，以十字梁压电致动单元为基础，延续直驱运动拓展方法构建了一款单点二维压电致动器，研制了一款面向大行程两自由度旋转运动的压电操控器，依托动静摩擦作用实现了运动范围拓展，对操控器的输出特性进行了研究。面向100mrad级大范围两自由度非接触式光束操控需求，以反射镜作为执行末端，开展了集成多轴姿态传感器的应用拓展设计，研发闭环控制系统并开展了应用试验。另一方面，以空间叠层压电致动单元为基础，构建了一款单点纵弯弯三维压电致动器，研制了一款面向跨尺度的两自由度旋转压电操控器；提出了一种主动控制摩擦临界条件的跨尺度操控方法。开展了操控器的特性研究，运动尺度跨越水平为 2.73×10^5，利用致动器电控纵向运动成功实现了运动模式的动态切换，且将静摩擦稳定扫描频率提升约 10 倍。综合而言，单点多维致动实现了球型转子大范围旋转运动的转换和拓展，显著提升了运动尺度跨越水平。

针对宏微尺度对象的多功能多自由度跨尺度操控难题，提出了多点多维致动的运动拓展方法，研制了一款新型四指压电操控器。提出了四指协同动作的运动操控方法，进而为该操控器规划了 13 种典型的功能手势；探究了四指压电操控器实现宏观物体大尺度和小尺度运动操控的工作模式。通过仿真和实验研究了四指压电操控器的基本特性。以平板物体为例，研究了压电操控器的 2L（直线）+1R（旋转）大尺度运动操控特性，以及 3L+3R 小尺度运动操控特性。研发了一套四指压电操控器专用的软硬件集成驱控系统，检验了操控器对不同形状、尺寸和材质物体的高适应性操控能力；探究了该操控器系统在构建多自由度操控平台实现多自由度定位，以及用作机械臂末端执行器实现微物体抓取和搬运方面的应用潜力。综合检验了多点多维致动运动拓展方法用于多类型物体的多功能、多自由度和跨尺度运动操控可行性。

关键词：压电驱动；多维度；运动拓展；跨尺度运动；多自由度操控

Abstract

Precision multi-DOF manipulation technology and its carrier have become the common basis for the fields of semiconductor manufacturing, active optics, micro-nano manipulation, micro assembly, micro detection, etc. This technology mainly relates to four actuation principles, including electromagnetic, electrothermal, electrostatic and piezoelectric ones. Here, piezoelectric actuation refers to an actuation technology using inverse piezoelectric effect of piezoelectric material to achieve motion output. It holds unique merits of fast response, high resolution, good electromagnetic compatibility, no transmission mechanism, simple structure, etc., and becomes a preferred solution for precision multi-DOF manipulation technology. This dissertation aims at the key challenges in the field of piezoelectric manipulation technology, such as the problem of multi-dimensional motion generation, the problem of cross-scale motion realization, and problem of multi-DOF motion expanding, to carry out deep researches. The relevant research can promote the theoretical innovation and application development of the piezoelectric manipulation technology.

Aiming at the problem of motion generation from the electrodeformation of piezoelectric ceramic to the multi-dimensional motion of the piezoelectric function unit, the research of unit creation and multi-dimensional motion generation are performed. The extending-compressing motion mechanism of single piezoelectric ceramic and the bending motion mechanism of double-layer piezoelectric ceramic slice are studied. A unit creation method of “planar array combination and construction” and a multi-dimensional motion generation method of “symmetric and asymmetric bending combination” are proposed, a cross-shaped beam piezoelectric actuation unit that can realize lateral two-dimensional bending and longitudinal one-dimensional translation is constructed. The generation principle from one-dimensional to three-dimensional motions is analyzed. The parametric analysis is performed by static modeling and FEM simulation, and the unit creation and motion generation methods are verified. A unit creation method of “spatial laminated combination and construction” and a multi-dimensional motion generation method of “multi-dimensional microscopic deformation accumulation” are also proposed. A

spatial laminated piezoelectric actuation unit is constructed to achieve lateral two-dimensional bending and longitudinal one-dimensional extending motions. The typical excitation schemes of the single-zone, two-zone and four-zone ring-shaped piezoelectric ceramics are analyzed, and its unit creation and motion generation methods are verified by FEM simulation.

Aiming at the expansion problem from multi-dimensional motion of piezoelectric functional unit to the micro-nano motion of execution end, the research on direct-drive piezoelectric micro manipulation of the multi-dimensional functional unit is performed. Above all, for meeting the application requirements of multi-DOF, micro-scale and high-resolution motion manipulation of the mirror and the manipulating needle, a mirror-end 2-DOF piezoelectric manipulator and a manipulating-needle-end 3-DOF piezoelectric manipulator are developed respectively by using a mechanical-fixation direct-drive motion expansion method to connect the mirror and the needle with the cross-shaped beam piezoelectric actuation unit. Their mechanical and electrical designs, as well as multi-DOF motion principles are illustrated. Their output performance is simulated by FEM simulation. As for the mirror-end 2-DOF piezoelectric manipulator, its open-loop characteristics as well as closed-loop positioning and tracking characteristics are tested. Its effectiveness in non-contact and two-dimensional optical beam micromanipulation is verified by experiments. As for the manipulating-needle-end 3-DOF piezoelectric manipulator, its output displacement and output force characteristics are tested. The effectiveness of its application in non-contact attitude manipulation of a microsphere with diameter of 500 μm is verified by experiments. The feasibility of combining the cross-shaped beam piezoelectric actuation unit and the mechanical-fixation direct-drive motion expansion method to realize multi-DOF micro manipulation is demonstrated comprehensively.

Aiming at the realization problem of cross-scale manipulation with both large-range and high-resolution in an execution end, the realization method of cross-scale motion is studied for the multi-DOF piezoelectric manipulator. Specifically, taking the spherical rotor as the typical motion end, a method of motion expansion using single-point and multi-dimensional actuation is proposed. On the one hand, based on the cross-shaped beam unit, a single-point two-dimensional piezoelectric actuator is constructed adopting the method of direct-drive motion expansion. Then a

piezoelectric manipulator for large-stroke and 2-DOF rotary motions is developed, and the motion range is expanded by the dynamic and static friction actions. The output characteristics of the manipulator are studied. For meeting the requirements of large-scale over 100 milliradian, 2-DOF and non-contact beam manipulation, using the mirror as the execution end, the application expansion design of the manipulator integrating multi-axis attitude sensor is accomplished. A closed-loop control system of the manipulator is developed and the application test is performed. On the other hand, based on the spatial laminated unit, a single-point longitudinal-bending-bending three-dimensional piezoelectric actuator is constructed, and a 2-DOF rotary piezoelectric manipulator for cross-scale is developed. A cross-scale manipulation method is proposed to actively control the critical friction condition. The fundamental characteristics of the manipulator are studied, which realizes motion scale crossing level of 2.73×10^5. The dynamic switching of the motion mode is realized by electronically controlling longitudinal motion of the actuator, and the static stabilization scanning frequency is improved to about 10 times. In summary, the motion expansion method using single-point multi-dimensional actuation realizes the transformation and expansion of large-scale rotary motion of the spherical rotor, and significantly improves the crossing level of the motion scale.

Aiming at the problem of multi-function, multi-DOF and cross-scale manipulation for macro-micro scale objects, a motion expansion method using multi-point multi-dimensional actuation is proposed, and a four-finger piezoelectric manipulator is developed. A method with four-finger collaboration motion manipulation is proposed, and 13 typical functional hand gestures are planned for the manipulator. The working modes of the four-finger piezoelectric manipulator to realize large-scale and small-scale motion manipulations of macroscopic objects are investigated. The basic characteristics of the four-finger piezoelectric manipulator are studied by simulation and experiment. Taking the plate as an example, the 2L (linear) and 1R (rotational) large-scale motion manipulation characteristics and 3L+3R small-scale motion manipulation characteristics of the manipulator are studied. A drive and control system integrating hardware and software is developed for the four-finger piezoelectric manipulator, and the high-adaptability manipulation ability of the manipulator to the objects with different shapes, sizes and materials are verified. The application potentials of the manipulator system in constructing multi-

DOF manipulation platform to realize multi-DOF positioning, and as an end-effector of a robotic arm to realize grasping and moving manipulations of micro objects are studied. The feasibility of the motion expansion method using multi-point multi-dimensional actuation to realize multi-function, multi-DOF, and cross-scale motion manipulation is demonstrated comprehensively.

Keywords: piezoelectric actuation，multi-dimensional，motion expansion，cross-scale motion，multi-DOF manipulation