Mechanism and Machine Theory 112 (2017) 43–60

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmachtheory

Research paper

Design and analysis of a 3-link micro-manipulator actuated by piezoelectric layers

Mohamad T. Ahmadian[a,b,*], Hamed Jafarishad[b]

[a] *Center of Excellence in Design, Robotics and Automation, Sharif University of Technology, Tehran, Iran*
[b] *School of Mechanical Engineering, Sharif University of Technology, Tehran, Iran*

ARTICLE INFO

Article history:
Received 19 June 2016
Revised 13 December 2016
Accepted 14 December 2016

Keyword:
Micro-manipulator
Piezoelectric
Static analysis
Kinematics
Finite element method

ABSTRACT

The purpose of this paper is to design and analyze a 3-link micro-device proposed as a micro-manipulator. This micro-manipulator includes 3 micro-beams as links connected to one another with no conventional or flexural joints. While the structure of the micro-manipulator is monolithic, end-effector workspace is achieved through deflection of links which is actuated by piezoelectric layers. By combining static analysis of the links through a multilayer piezoelectric beam model and kinematic analysis of the micro-manipulator, inverse kinematic has been solved utilizing the Taylor series expansion technique and the perturbation method. The obtained results through the present model reveal that the end-effector can provide a workspace of several microns with nano-accuracy. The required piezoelectric voltage for certain end-effector displacement was evaluated, and the error of inverse kinematic was investigated. A finite element model was also constructed to evaluate micro-manipulator behavior. The results show there is a good agreement between the analytical model and the finite element method. Avoiding complex geometry, the micro-manipulator offers a simple structure with a more feasible manufacturing process while it provides acceptable workspace for the end-effector with high accuracy.

1. Introduction

Micro-electromechanical systems (MEMS) is a technology at micron scale with the advantages of miniaturization, low power, low weight, high and fast performance. Micro-manipulators, micro-robots, micro-pumps, micro-mirrors and micro-resonators are some of the devices using MEMS technology which can perform different functions.

The micro-manipulators are one type of the MEMS devices which are mostly used for micro-assembly and micro-handling [1]. Micro-assembly is the process of building a micro-structure with micro-substances. Assembling process at a micron scale is similar to the process used in macro-scale macro-robots. However, there are different aspects such as accuracy in micro-assembly process [2]. The accuracy required for a micro-manipulator is about submicron while the highest accuracy that a macro-robot can achieve is about tens of microns. Although micro-assembly is considered a difficult task in micro-systems technology, various types of micro-manipulator have been suggested so far [3,4]. In micro-handling or micro-manipulation, the duty of micro-manipulator is manipulating the micro-particles, involving pushing, pulling, cutting, picking, placing, positioning and orienting, by utilizing a mechanism with a high positioning accuracy and elaborate motion

* Corresponding author.
E-mail address: ahmadian@sharif.edu (M.T. Ahmadian).

http://dx.doi.org/10.1016/j.mechmachtheory.2016.12.002
0094-114X/

of the end-effector [5]. Parallel mechanisms are mainly utilized for micro-manipulation [6,7]. However, some serial mechanisms have been proposed as well [8]. In general, micro-manipulators have tens of microns for a range of workspaces with nano-accuracy.

In most micro-manipulators, compliant mechanisms are employed as structures. Compliant mechanisms are flexible monolithic structures with notches and holes, without use of any conventional joints. Manufacturing a compliant mechanism at micron-scale is feasible through Electrode Discharge Machining (EDM) technique. In this type of mechanism, the motion of micro-manipulators is achieved through deflection of specific part of structure known as flexural joint. The flexural joints are parts of the structure with less rigidity that is caused by inhomogeneous geometry. These joints deform much more compared to other parts, under load. The absence of conventional joints makes manufacturing process easy and the mechanism free of backlash, friction, lubricant. This results in higher precision and makes it appropriate for a clean environment [9]. An application of the compliant mechanism is micro-grippers [10]. Micro-grippers are mechanisms which have the task of picking up and releasing micro-particles. They can also be employed as end-effectors. In micro-manipulation, end-effectors play an important role [1]. Micro-grippers widely use piezoelectric materials as an actuator [10,11]. A mechanism of micro-gripper with flexural joints can realize parallel movements through piezoelectric actuation [12]. To avoid any damage to objects such as biological cells, force sensation in micro-grippers is required in a micro-manipulating process. Electrostatic actuation and capacitive force sensing can be employed together for micro-manipulation accompanied by force sensing [13]. Of course, other approaches such as employing piezoelectric materials are also suggested for force sensing in micro-grippers [14,15].

Mechanism of industrial manipulators can be classified as serial, parallel or hybrid. The serial chains are the most common type of industrial robots with large workspaces and less computational complexity of the inverse kinematic. On the other hand, parallel mechanisms have higher accelerations and more accurate positioning as a result of their considerable stiffness and low inertias [16]. As mentioned before, compliant mechanisms use deflection of flexural joints instead of conventional types. However, employing flexural joints and the micro-manipulators scale make using actuators at joints infeasible [17]. This problem causes serial type mechanisms with difficulties. As a result, most researches have been done based on compliant parallel mechanisms (CPM) [18,19].

Compliant parallel mechanism with piezoelectric actuators is employed to design a 2-DOF micro-manipulator while flexural hinges are employed as revolute joints [5]. Flexural hinges are assembled in different configurations to build prismatic, revolute and cylindrical joints in a parallel mechanism and to enable the micro-manipulator to have translational 3-DOF. This can provide out of plane motions [20]. A 3D meso-manipulator using planar configurations in parallel mechanisms, which lead to more simple architecture and low-cost feasibility process, is designed for 3-dimensional motions [16]. Flexural joints can create spherical joint motions. Based on three inextensible limbs, connected to a platform, a 6-DOF micro-manipulator, integrated with force sensor, was designed. At each limb the universal joint was replaced with one spherical and one revolute joint [21]. A 6-DOF micro-manipulator with a 6-SPS mechanism, composed of lower and upper stages connected together through six chains with the same configuration, was designed and built. Each chain consists of two spherical joints and one prismatic joint. The experimental results show that the 6-SPS micro-manipulator can achieve nano-accuracy [22].

Beside compliant mechanism, there are also other approaches for micro-manipulation such as employing micro-cantileves. A micro-manipulator can utilize micro-cantilever for contact sensing, too. For a micro-cantilever, piezoelectric materials can be used in both actuating and sensing modes [23]. Two micro-cantilevers were designed to work as a micro-gripper with each micro-cantilever functioning like an arm. Utilizing piezoelectric materials, the micro-gripper can estimate forces and each arm can handle objects without damage [14].

The micro-cantilever has several uses aside from its function in micro-manipulators. One of its most known applications is in atomic force microscopy (AFM). The main aim of designing AFM was scanning and imaging. There are basically two approaches to AFM sensing process including optical laser and piezoelectric materials. Although optical laser is of high-resolution, it is very expensive and needs high precision in the optical alignment and adjustment. Piezoelectric materials are much easier to use. However, they are less accurate compared to the optical laser. Aside from optical laser and piezoelectric materials, there are also other methods for the sensing process such as capacitive and piezoresistive. A micro-cantilever, with four piezoresistives on its top, was designed to do force sensing in two parallel and perpendicular directions [24].

This study is about designing a micro-device for micro-manipulation. Most micro-manipulators utilize the compliant parallel mechanism as structure. However, due to its complicated geometry, when the scale of the manipulator tends to microscales, there will be difficulties and complexities in parallel mechanisms in the manufacturing process. In this paper, micro-cantilevers are chosen as the micro-manipulator's links, connected together through a serial chain. The actuation of the micro-manipulator is done through layers of piezoelectric materials. The piezoelectric actuator is capable of managing high resolution displacements in a range of 10 nm to 100 μm [25]. The piezoelectric materials have fast response speed and can be used as a sensor as well [14]. In this study, kinematic and static behavior of the micro-manipulator is investigated, and the dimensions of the workspace in terms of the length of the links and layers' characteristics are defined.

This paper is organized as follows. First, the configuration of the micro-manipulator is illustrated. Next, the mathematical model is established. Static and kinematic equations of the micro-manipulator are derived. Employing the Taylor series expansion and the perturbation method, inverse kinematic is solved. Then, based on the results, the accuracy of the solutions and the workspace of the micro-manipulator are investigated. In order to evaluate the validity of the mathematical model, finite element method (FEM) is employed. The results of the two approaches are then compared and discussed.