Robotics and Computer-Integrated Manufacturing 27 (2011) 124–134

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

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

Six-DOF micro-manipulator based on compliant parallel mechanism with integrated force sensor

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ARTICLE INFO

Article history:
Received 24 March 2010
Received in revised form
6 June 2010
Accepted 23 June 2010

Keywords:
Micro-manipulator
Compliant parallel mechanism
Force sensor
Stiffness mapping
Workspace

ABSTRACT

This paper describes the design of a micro-scale manipulator based on a six-DOF compliant parallel mechanism (CPM), which is featured by piezo-driven actuators and integrated force sensor capable of delivering six-DOF motions with high precision and providing real-time force information for feedback control. Particularly, the position and screw-based Jacobian analyses of the CPM are presented. Then, the compliance model and the workspace evaluation of the CPM are proposed in order to account for the compliance and obtain design guidelines. Finally, the integrated sensor is introduced. The static features of such a mechanism include high positioning accuracy, structural compactness and smooth and continuous displacements.

1. Introduction

Micro-manipulator is an apparatus used to physically interact with a sample under a microscope, where a level of precision of movement is necessary that cannot be achieved by the unaided human hand [1]. And it is has been developing widely and rapidly as its potential applications in various fields such as optical fiber alignment, micro-device assembly and patch clamp experiments in biological research [2–5]. Parallel mechanisms are novel robotic architectures that offer unprecedented dexterity, rigidity and precision when interacting with the environment. Therefore, more and more micro-equipments are made of hybrid and parallel structures to acquire perfect performance. However, conventional parallel mechanisms always suffer from errors such as backlash and friction. Recently, some researchers use the flexure hinges instead of conventional rigid joints to remove the friction at joints and backlash. Unfortunately, most of the existing micro-manipulator mechanisms are featured by one–five-DOF motions [2–8], which is insufficient for the needs of manipulations. Therefore, six-DOF micro-equipments, which could extend workspace and capability of the manipulators, require further research. Otherwise, for new micro-technology products, still there are many challenges to be solved such as lack of real-time force feedback and compliance modeling.

As illustrated in Fig. 1, the structure of a micro-manipulation system, in general, includes: manipulator, human–machine interface, controller, embedded sensors and actuators and microscope. The sensors can be categorized into two major types: external sensors such as microscope and internal sensor such as force sensor. In what follows, we are dedicated to design a novel piezoelectric actuator-based device with integrated force sensor based on CPM, which could be used as a six-DOF micro-manipulator as well as a micro-displacement or a micro-force sensor.

2. Micro-manipulator

Most of the six-DOF parallel manipulators described in the literature contain six limbs [9,10]. However, the more limbs the manipulator possesses, the more complicated that will be. Therefore in this study, we adopt a six-DOF parallel mechanism based on three inextensible limbs, as shown in Fig. 2(a). All joints are flexure hinges as their notable benefits such as compactness, no friction losses and no backlash. It consists of three identical kinematic limbs and each limb connects the platform to the base with flexure universal joints. The lower ends of limbs are connected to planar flexure-based stages that provide two-DOF movement in the base plane. The motion is obtained by moving

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doi:10.1016/j.rcim.2010.06.018

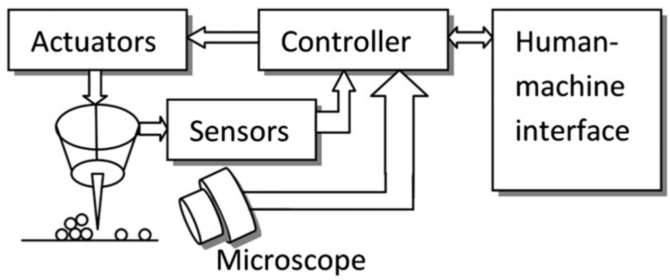

Fig. 1. Structure of the micro-manipulator system.

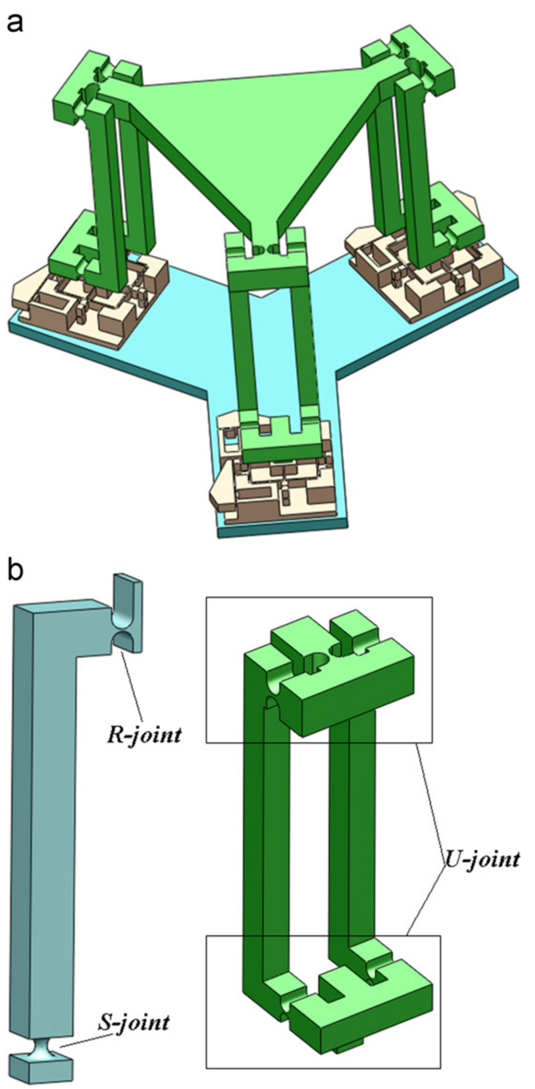

Fig. 2. A virtual prototype of the proposed micro-manipulator (a) and possible structures of the limb (b).

the lower ends of its three limbs on its base plate. Universal joints could be replaced by a spherical joint at one end and a revolute joint at the other end of each limb to enable that has four-DOF. The possible limbs are shown in Fig. 2(b). In this study, we employ the limb with two universal joints. One of the axed of the upper universal joint is collinear with the limb, while the other axis of the upper universal joint as well as one of the axes of the axes of the lower universal joint are always perpendicular to the limb. Hence, the degree-of-freedom value of the manipulator is

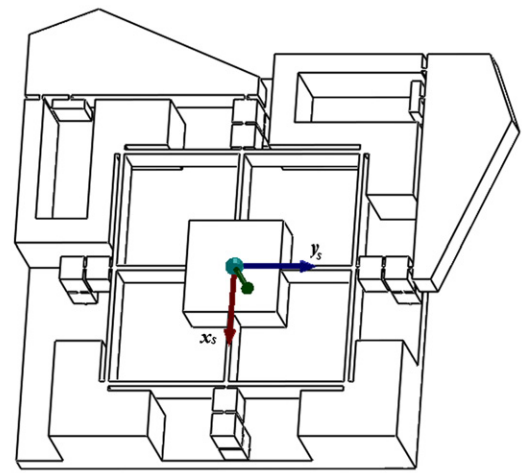

Fig. 3. CAD model of the stage based on flexure hinges.

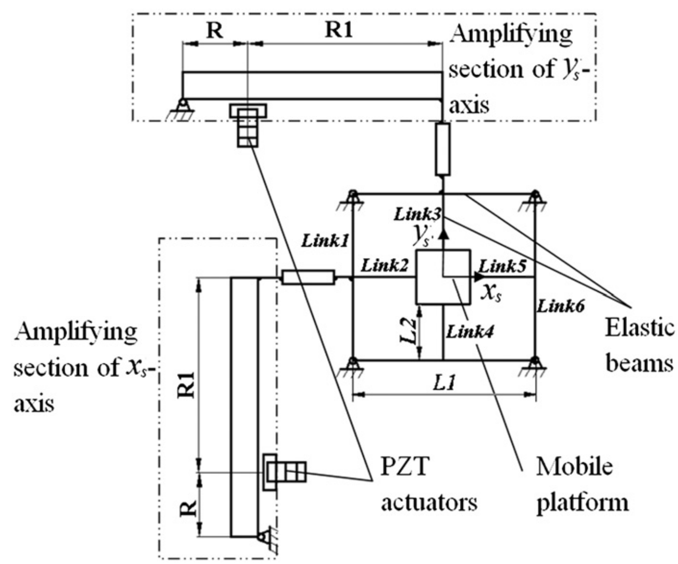

Fig. 4. Schematic representation of the two-DOF stage with PZT actuators.

given by

$$F=\lambda(n-j-1)+\sum_i f_i=6(8-9-1)+18=6 \tag{1}$$

2.1. Two-DOF stage

Figs. 3 and 4 represent the designed two-DOF piezoelectric stack-actuated stage based on flexure hinges and elastic beams. The stage consists of two piezoelectric stack actuators that provide the acquired input displacements and forces along the x_s-axis and y_s-axis, respectively, amplifying sections that connect the actuators and the output stage and amplify the displacements provided by actuators, a mobile platform as the output stage, and elastic beams connect the amplifying sections and the mobile platform. The stage adopts flexure hinges at all joints and has identical kinematic structure along the x_s-axis and y_s-axis.

When the limb in amplifying section of the x_s-axis is driven by the PZT actuator with a displacement Δd and a force F whereas the limb in amplifying section of the y_s-axis remains un-driven, the limb will rotate around the left end and the right end will