Mechanism and Machine Theory 64 (2013) 111–130

Contents lists available at SciVerse ScienceDirect

Mechanism and Machine Theory

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

Modeling, design, and control of 6-DoF flexure-based parallel mechanisms for vibratory manipulation ☆

Thomas H. Vose [a,*], Matthew H. Turpin [b], Philip M. Dames [b], Paul Umbanhowar [c], Kevin M. Lynch [c,d]

[a] MathWorks, USA
[b] University of Pennsylvania, USA
[c] Northwestern University, USA
[d] Northwestern Institute on Complex Systems, USA

ARTICLE INFO

Article history:
Received 11 May 2012
Received in revised form 19 October 2012
Accepted 17 December 2012
Available online 28 February 2013

Keywords:
Vibratory manipulation
Parallel manipulators
Controlled vibration
Programmable vector fields

ABSTRACT

Small amplitude periodic motion of a 6-degree-of-freedom (DoF) rigid plate causes rigid parts on the surface to slide under the influence of friction as if immersed in a configuration-dependent velocity field. A plate whose motion is fully programmable is therefore a simple yet versatile manipulator. To develop such a manipulator, this paper addresses the design and control of a 6-DoF parallel mechanism intended for small-amplitude, high frequency vibration. We derive a linear model for the class of parallel mechanisms consisting of a rigid plate coupled to linear actuators through flexures. Using this model, we discuss manipulator design geared toward either universal parts feeding or single task automation. The design process is formulated as a constrained optimization over a design space that includes the geometry of the manipulator (actuator orientations and flexure attachment points) and the viscoelastic properties of the flexures. Finally, we present a frequency-based iterative learning controller for tracking periodic plate acceleration trajectories in $\mathbb{R}^6$ for all designs. Experimental data collected from our PPOD2 manipulator is used to validate the model and demonstrate the performance of the controller.

1. Introduction

This paper addresses the modeling, design, and control of six-degree-of-freedom (6-DoF) parallel manipulators consisting of a rigid plate connected to linear actuators by flexure joints. Our motivation lies in using these manipulators to control the motion of parts on the plate's surface through programmable vibration-induced sliding.

In previous work we showed that the motion of rigid parts in sliding contact with a periodically vibrating plate can be described with an *asymptotic velocity field* mapping each part configuration to a unique velocity [1–8]. As the plate vibrates, the part's cycle-averaged velocity converges to the field much as the motion of a leaf in a stream converges to the local flow of the water. Fig. 1 shows pennies sliding on a periodically vibrating plate that causes them to move as if immersed in a whirlpool. Treating the pennies as point masses, their trajectories are well approximated by integral curves of a two-dimensional asymptotic velocity field. The exact form of the field depends on the friction coefficient and the parameters describing the plate's periodic motion. A diverse set of fields, including ones with source, sink, and saddle points, can be generated by a plate with 6-DoF motion capability. Applications of these fields include simultaneous manipulation of many parts, part sorting, and sensorless part feeding.

☆ This work was supported by NSF grants CMMI-0700537 and IIS-0964665 as well as an NSF Graduate Research Fellowship to Tom Vose.
* Corresponding author at: MathWorks, 3 Apple Hill Drive Natick, MA 01760, Tel: +1 847 467 1070.
E-mail addresses: tom.vose@mathworks.com (T.H. Vose), mturpin@seas.upenn.edu (M.H. Turpin), pdames@seas.upenn.edu (P.M. Dames), umbanhowar@northwestern.edu (P. Umbanhowar), kmlynch@northwestern.edu (K.M. Lynch).

0094-114X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.mechmachtheory.2012.12.007

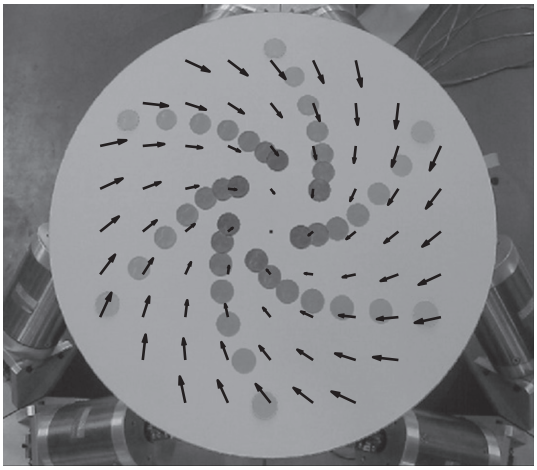

Fig. 1. Multi-exposure overhead image of six pennies on the PPOD2 moving in an asymptotic velocity field resembling a whirlpool. Time interval between images is 0.75 s. Plate diameter is 15″. Vector arrows are theoretical asymptotic velocities computed numerically based on friction coefficient and plate motion.

To create these fields, we have built 6-DoF parallel manipulators with flexures rather than traditional joints and bearings to avoid nonlinear effects due to friction, backlash, and micro-impacts; such nonlinear processes make controlling the plate difficult for the small-amplitude, high-frequency motion typically encountered during operation. Flexures that behave like simple linear viscoelastic elements are particularly advantageous for designing controllers to track arbitrary periodic plate motions; in fact, the iterative learning controller we discuss in this paper exploits the fact that the overall system dynamics are approximately linear. Flexure-based manipulators are also intriguing because they expand the design space. For example, the response of the plate at frequencies of interest can be tuned by fabricating flexures with desired stiffness and damping.

In addition to the viscoelastic properties of the flexures, the full manipulator design space includes inertial, geometric, and actuator properties. This paper focuses primarily on the geometric portion of the design space, which includes actuator orientations and flexure-to-plate attachment points. We consider how to design two very different devices within this space: a universal manipulator and a single-task manipulator. A universal manipulator should be able to perform a wide variety of manipulation tasks by generating different asymptotic velocity fields on command. This means it should be able to generate a large set of periodic plate motions (utilizing the plate's full 6-dimensional configuration space within $SE(3)$) with minimal control effort. At the other extreme, a single-task manipulator need only create a single field (or family of closely related fields) as efficiently as possible. For both types of manipulator, we formulate the design problem as a constrained optimization of an appropriate objective function.

Although our particular application is vibration-induced sliding manipulation on a 6-DoF plate, the tools we develop in this paper are applicable to manipulators with uses other than sliding manipulation and that possess fewer than 6-degrees-of-freedom: the model we develop describes any flexure-jointed parallel manipulator with linear actuators undergoing small amplitude motion; the cost function in the design optimization process can be changed to achieve design goals for other applications; and the iterative learning controller can be used to track periodic plate trajectories for any manipulator whose dynamics are well approximated by a controllable linear system.

The rest of the paper is laid out as follows. In Section 2 we describe two manipulators that we have built (the PPOD and the PPOD2). Related work on flexure-jointed parallel manipulators and vibration-induced sliding manipulation is reviewed in Section 3. In Section 4 we present a linear model of flexure-jointed parallel manipulators driven by linear actuators and compare it to experimental data collected from the PPOD2. In Sections 5 and 6 we discuss the design problem and explore the design space for a universal manipulator and a single-task manipulator. In Section 7 we describe the iterative learning control algorithm that drives the linear and angular accelerations of the plate to desired periodic trajectories in $\mathbb{R}^6$. The tracking ability of the controller is verified with experimental data from the PPOD2. Conclusions and future work are discussed in Section 8.

2. PPOD and PPOD2

Fig. 2 shows the 6-DoF manipulator we built as an initial prototype to create asymptotic velocity fields. It consists of six audio speakers mounted vertically on a common grounded base and coupled to a common plate through flexures. This mechanism, dubbed the PPOD (Programmable Parts-feeding Oscillatory Device), was sufficient to demonstrate some fields (i.e., fields with maximum part speeds of several centimeters per second), but its design was ad hoc and the space of periodic plate trajectories it could track was limited.

Our most recent manipulator, the PPOD2 (Figs. 1 and 3), has more powerful voice-coil actuators (H2W NCM05-28-180-2L), stiffer flexures, and actuator orientations more conducive to generating plate motions in the horizontal plane. Due to better