

**Design, Modeling and Control of a Compliant
Parallel XY Micro-motion Stage with Complete
Decoupling Property**

by

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Master of Science in Electromechanical Engineering

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**Faculty of Science and Technology
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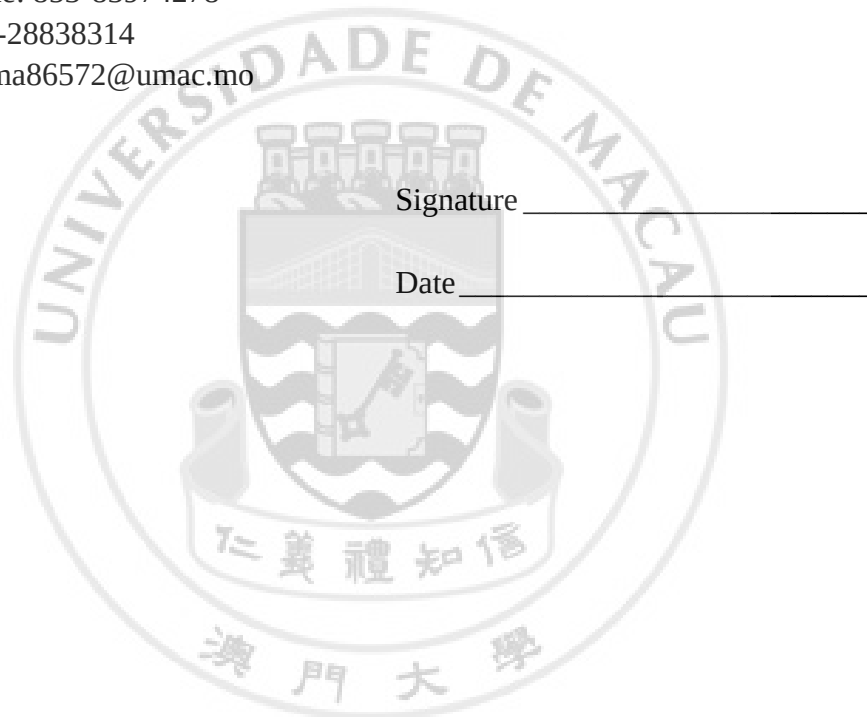
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Abstract

DESIGN, MODELING AND CONTROL OF A COMPLIANT
PARALLEL XY MICRO-MOTION STAGE WITH
COMPLETE DECOUPLING PROPERTY

by Jiming Huang

Thesis Supervisor: Professor Yangmin Li
Master of Science in Electromechanical Engineering

A novel compliant parallel XY micro-motion stage is proposed to fulfill positioning and manipulation with micro- or nanoscale precision. With a symmetric 4-PP structure, the XY stage has complete decoupling property. The stage is driven by piezoelectric actuators (PZT), and right-circular flexure hinge is adopted to convey the movement. Double four-bar flexure is chosen as the prismatic joint because of its better stiffness performance than double parallelogram flexure.

The compliance model of the mechanism is built using simplified compliance matrix method, and then the kinematics, workspace and stress are analyzed. Lagrange's equation is employed to derive the dynamic model of the mechanism. The dimensions are optimized using particle swarm optimization (PSO) algorithm in order to maximize the natural frequencies. Finite element analysis (FEA) result indicates that the XY stage with optimal dimensions has a linear force-deflection relationship and ideal decoupling property. The first-mode natural frequency is as high as 720.52 Hz, and the stage has the potential to achieve a $105\ \mu\text{m} \times 105\ \mu\text{m}$ square workspace. To cope with the hysteresis existing in the PZT, the control system is constructed by a proportional-integral-derivative (PID) feedback controller with a feed-forward hysteresis compensator based on Preisach model.

A prototype of the completely decoupled XY stage is fabricated with aluminum alloy AL7075-T6 using wire electric discharge machining (WEDM) technique. The static

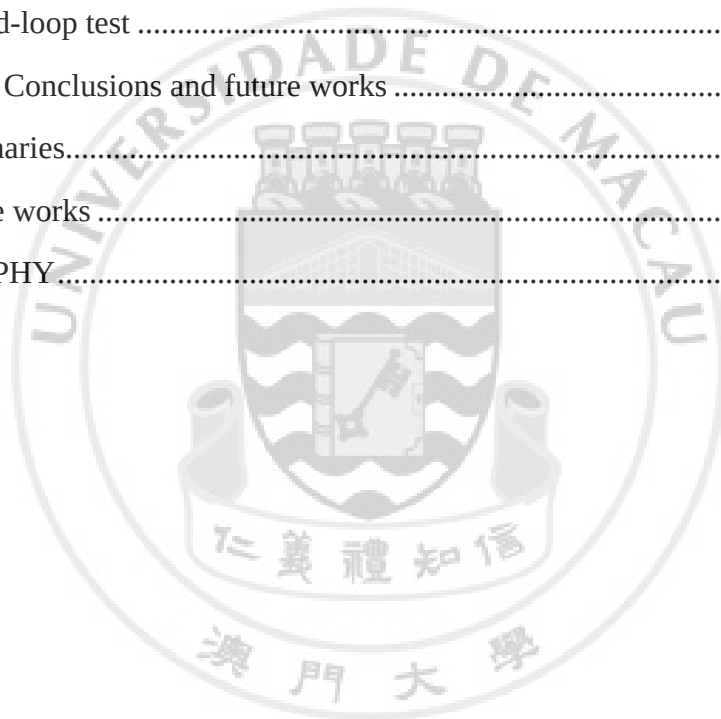
test shows that the XY stage has a $19.2\ \mu\text{m} \times 18.8\ \mu\text{m}$ rectangular workspace with coupling less than 5%. The numerical Preisach model of hysteresis is built according to the experimental data, and the control strategy is implemented by a personal computer (PC) with MATLAB software. With the closed-loop control system, the XY stage can complete positioning, tracking and contouring tasks with small error.



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NOMENCLATURE

- C_i^j : compliance matrix of i in coordinate j
- C_I : input compliance matrix
- C_{OI} : compliance matrix relating input force to output displacement
- c_i : compliance factor
- C_O : output compliance matrix
- D : actual displacement output of PZT
- D_I : input displacement
- D_O : output displacement
- D_{nom} : nominal maximum displacement output of PZT
- E : Young's modulus
- F_I : input force
- F_O : external force on the mobile platform
- f : natural frequency
- f_{pl} : preload of the PZT
- J : Jacobian matrix
- K : equivalent stiffness matrix of the micro-motion stage
- K_I : input stiffness matrix
- k_p : stiffness of PZT
- k_s : stiffness of spring load on PZT
- M : equivalent mass matrix of the micro-motion stage
- P_i^j : skew-symmetric matrix for translation from coordinate i to j
- $\overline{P}_i^j$: translation matrix of compliance from coordinate i to j
- R_i^j : matrix for rotation from coordinate i to j
- $\overline{R}_i^j$: rotation matrix of compliance from coordinate i to j

S_f : safety factor

T_i^j : transformation matrix of compliance from coordinate i to j

$u(t)$: input voltage to the PZT

$u_{\text{PID}}(t)$: control voltage from PID controller

$u_d(t)$: control voltage from the compensator

$w(\alpha, \beta)$: weighting function in Preisach model

$Y(\alpha_k, \beta_k)$: Preisach function of switching-value pairs (α_k, β_k)

$y(t)$: output displacement of PZT

$\gamma_{\alpha\beta}$: hysteresis relay

σ_y : yield strength

r, w, t, l_i, h_i : dimensions of the micro-motion stage



LIST OF ABBREVIATIONS

AFM: atomic force microscope
DAQ: data acquisition
DOF: degree of freedom
FEA: finite element analysis
GA: genetic algorithm
MEMS: microelectromechanical systems
P: prismatic
PC: personal computer
PID: proportional-integral-derivative
PRB: pseudo rigid body
PSO: particle swarm optimization
PZT: piezoelectric actuators
R: revolute
S: spherical
SISO: single-input-single-output
SMA: shape memory alloy
U: universal
WEDM: wire electric discharge machining



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DEDICATION

The author wishes to dedicate this thesis to his parents.

