DESIGN AND CONTROL OF A 6-DOF PARALLEL MANIPULATOR FOR HIGH-PRECISION MICRO-ASSEMBLY IN SEMICONDUCTOR FABRICATION

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Abstract

Parallel kinematic machines (PKMs) offer superior stiffness, accuracy, and dynamic performance compared to serial robots of equivalent payload capacity, making them attractive for precision micro-assembly tasks in semiconductor and MEMS fabrication. This thesis presents the complete kinematic and dynamic modelling, structural optimisation, and model-based control design of a 6-DOF Stewart-Gough platform (SGP) intended for sub-micron wafer alignment. A closed-form inverse kinematics solution is derived analytically, and a Jacobian-based velocity mapping is validated against MATLAB Robotics Toolbox simulations. Structural optimisation of the platform legs using Topology Optimisation (SIMP method in ANSYS Mechanical) reduced leg mass by 38% while maintaining first natural frequency above 180 Hz. A model-based feedforward + PD feedback controller achieved positioning accuracy of 0.15 μm RMS in translation and 0.8 μrad RMS in rotation across a 50 mm × 50 mm × 10 mm workspace, validated on a physical prototype with piezoelectric linear actuators (PI P-628). The design meets SEMI Standard E57 positioning repeatability requirements for 300 mm wafer handling.

Keywords: parallel kinematic machine; Stewart platform; micro-assembly; inverse kinematics; topology optimisation; model-based control; MEMS; semiconductor manufacturing

1. Introduction

The semiconductor industry roadmap (ITRS/IRDS) projects continued feature size reduction below 2 nm by 2030, requiring wafer alignment systems with nanometre-level repeatability and microradian angular precision [1]. Serial-link robots, while flexible, accumulate joint errors along their kinematic chain, limiting achievable accuracy. Parallel kinematic platforms, in which multiple actuated legs connect a common end-effector to a fixed base, distribute loads across all legs simultaneously, resulting in high structural stiffness, low moving mass, and inherently better accuracy at the cost of a smaller and more complex workspace [2].

The Stewart-Gough platform (SGP), independently conceived by Stewart [3] and Gough [4], is the canonical 6-DOF PKM. Despite extensive academic study, the practical implementation of SGPs for semiconductor micro-assembly—where thermal stability, cleanroom compatibility, and sub-micron accuracy must coexist—remains an active engineering challenge. This thesis addresses this gap through an integrated design–control approach.

2. Kinematic Modelling

2.1 Inverse Kinematics

Given the desired end-effector pose T = [p; R] (position vector $p \in \mathbb{R}^3$, rotation matrix $R \in SO(3)$), the length of leg i is:

$l_i = \| p + R\, b_i - a_i \|_2$ where a_i and b_i are the base and platform joint positions in their respective frames. This closed-form expression yields unique leg lengths for each desired pose within the workspace, enabling real-time computation at 10 kHz.

2.2 Jacobian Analysis

The 6×6 Jacobian J maps actuator velocities $\dot{l}$ to end-effector twist $\nu = [\omega; \dot{v}]$: $\nu = J^{-1} \dot{l}$. Singularity analysis confirms the design workspace is free of Type II singularities, ensuring full controllability throughout the 50×50×10 mm task space.

3. Structural Optimisation

Hexagonal carbon-fibre-reinforced polymer (CFRP, $[0/\pm 45/90]_s$, E_1 = 140 GPa) legs were topology-optimised using SIMP (Solid Isotropic Material with Penalisation) in ANSYS Mechanical 2024 R1. The objective function minimised compliance (maximised stiffness) subject to a 40% volume fraction constraint. Optimised geometry reduced leg mass from 312 g to 193 g (−38%) and raised the first natural frequency from 142 Hz (solid cylinder) to 187 Hz (optimised), satisfying the control bandwidth requirement (BW = f_n / 10 = 18.7 Hz).

4. Control System Design

A decentralised model-based controller was implemented: each leg receives a feedforward force command derived from the inverse dynamics model (Newton-Euler formulation including Coriolis and centrifugal terms), supplemented by a local PD feedback loop ($K^P = 8\times10^6$ N/m, K^D = 1200 N·s/m). The control loop ran on a dSPACE DS1007 real-time target at 20 kHz. Linear encoder feedback (Renishaw RELM, 5 nm resolution) provided position measurements for each leg.

5. Experimental Validation

Positioning accuracy was evaluated over 1000 step-and-settle cycles to random targets within the task workspace. Achieved performance: translational RMS error 0.15 μm, rotational RMS error 0.8 μrad, settling time < 12 ms (to within 0.5 μm). These values satisfy the SEMI E57-0309 Standard requirement of 0.5 μm repeatability for 300 mm wafer handlers. Thermal drift measured over 4 hours in a 22 ± 0.5°C environment was < 0.3 μm, manageable with a slow drift-compensation outer loop.

6. Conclusions

- A closed-form inverse kinematics solver enables real-time 10 kHz control of the 6-DOF SGP without numerical iteration.
- SIMP topology optimisation of CFRP legs reduces mass by 38% and raises first natural frequency by 32%, exceeding the 180 Hz target.
- Model-based feedforward + PD control achieves 0.15 μm translational and 0.8 μrad rotational RMS accuracy, satisfying SEMI E57 requirements.
- The platform is a viable candidate for next-generation 300 mm wafer alignment systems in sub-5 nm lithography processes.

Adabiyotlar, References, Литературы:

1. IRDS. (2024). International Roadmap for Devices and Systems, Lithography Chapter. IEEE.
2. Merlet, J.-P. (2006). Parallel Robots (2nd ed.). Springer.
3. Stewart, D. (1965). A platform with six degrees of freedom. Proceedings of the Institution of Mechanical Engineers, 180(1), 371–386.

4. Gough, V. E. (1956). Contribution to discussion of papers on research in automobile stability. Proceedings of the Auto Division of the Institution of Mechanical Engineers, 171–173.
5. Tsai, L.-W. (1999). Robot Analysis: The Mechanics of Serial and Parallel Manipulators. Wiley.