

Development of a Leader–Follower Kinematic Control System for a Cable-Driven Hyper-Redundant Serial Manipulator

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Abstract

Hyper-redundant manipulators enhance dexterity and flexibility, enabling operation in confined and complex environments where conventional robotic arms face limitations. This paper presents the development of a leader–follower kinematic control system for a cable-driven hyper-redundant serial manipulator intended for inspection and exploration tasks in highly constrained spaces. The proposed system utilises a tele-operated joystick to control the end-effector, while a leader–follower strategy generates the corresponding motion of the manipulator body. A mathematical kinematic model describing the relationships among motors, cables, joints, and the end-effector was developed and implemented in MATLAB/Simulink. A prototype manipulator was used to validate the kinematic relationships and evaluate proportional feedback control for position error correction. Simulation studies conducted using the MATLAB Robotics Toolbox demonstrated the effectiveness of the proposed control architecture in achieving stable trajectory tracking and coordinated manipulator motion. The results indicate that leader–follower control provides a practical solution for controlling cable-driven hyper-redundant manipulators in confined-space applications.

Keywords: Hyper-redundant manipulators, cable-driven robots, leader–follower control, kinematic modelling, teleoperation, confined-space inspection

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1. INTRODUCTION

Robotic systems designed for operation in confined and cluttered environments require high manoeuvrability, flexibility, and adaptability. Hyper-redundant manipulators, characterised by possessing significantly more degrees of freedom than required for conventional positioning and orientation tasks, provide these capabilities through their snake-like or continuum-inspired structures (Chirikjian & Burdick, 1994a). Such robots have attracted attention in inspection, search-and-rescue, infrastructure maintenance, and minimally invasive surgical applications due to their ability to navigate complex environments while avoiding obstacles (Chirikjian, 2015).

The control of hyper-redundant robots remains challenging because of their high-dimensional kinematics and actuator coordination requirements. Traditional inverse kinematic approaches often become computationally intensive as the number of degrees of freedom increases (Chirikjian & Burdick, 1994b). Leader–

follower control strategies have emerged as an intuitive solution in which the robot's head or end-effector acts as a leader while subsequent segments follow the generated trajectory. This approach simplifies teleoperation and enhances navigation through constrained pathways.

This study presents the development of a leader–follower kinematic control system for a cable-driven hyper-redundant serial manipulator. The objective is to establish and validate the kinematic relationships between actuators, cables, and joints and to evaluate the effectiveness of proportional feedback control for trajectory tracking.

2. LITERATURE REVIEW

Hyper-redundant manipulators were extensively studied by Chirikjian and Burdick (1994a), who introduced modal approaches for efficient kinematic modelling of

highly articulated robotic systems. Their research showed that backbone-curve representations could make hyper-redundancy much easier to work with.

Subsequent research highlighted the advantages of hyper-redundant robots in obstacle avoidance, grasping, and locomotion within constrained environments (Chirikjian & Burdick, 1994b). More recent reviews have emphasised their applications in search-and-rescue, medical robotics, and infrastructure inspection, where manoeuvrability is essential (Chirikjian, 2015).

Cable-driven architectures provide additional benefits by relocating heavy actuators away from the manipulator body, thereby reducing weight and improving flexibility. However, accurate control requires a thorough understanding of cable-joint interactions and compensation for cable-induced nonlinearities. Leader–follower approaches have been proposed to simplify teleoperation and reduce operator workload while maintaining intuitive control of robot motion (Zaraki et al., 2021).

3. Methodology

3.1 System Architecture

The proposed system consists of a cable-driven hyper-redundant serial manipulator controlled through a tele-operated joystick. The joystick provides operator commands that define the desired end-effector position and orientation. These commands are translated into motor actions through a kinematic control framework.

3.2 Kinematic Modelling

The control system was developed by first establishing the mathematical relationships between motor rotations, cable displacements, and joint angles. These relationships form the basis of the forward kinematic model used to determine manipulator configuration from actuator inputs. The leader–follower strategy assumes that the end-effector acts as the leader, generating a trajectory that is sequentially followed by downstream segments. This approach enables smooth motion through confined spaces while maintaining the overall shape of the manipulator.

3.3 Control Design

A proportional feedback controller was implemented to minimise position errors between the desired and actual joint positions. The controller gain was experimentally tuned using a physical prototype. Position feedback was continuously monitored to ensure accurate trajectory tracking and motion stability.

3.4 Simulation and Validation

The kinematic model and control system were implemented in MATLAB/Simulink. Validation was performed through prototype experiments and simulation using the MATLAB Robotics Toolbox. The evaluation focused on trajectory-following performance and system responsiveness.

4. RESULTS AND DISCUSSION

The prototype experiments confirmed the predicted relationships between cable displacement and joint motion. The proportional controller successfully reduced positioning errors and improved trajectory-following performance.

Simulation results demonstrated that the leader–follower architecture generated smooth and coordinated manipulator movements. The control system maintained stable operation during trajectory changes and effectively propagated motion commands from the end-effector throughout the manipulator structure.

The findings indicate that leader–follower control is particularly suitable for teleoperated inspection tasks where intuitive operator control and manoeuvrability are required. Furthermore, the modular nature of the kinematic framework allows future integration of advanced feedback mechanisms and autonomous navigation capabilities.

5. Conclusion

This paper presented a leader–follower kinematic control system for a cable-driven hyper-redundant serial manipulator designed for operation in confined environments. Mathematical modelling of the actuator-cable-joint relationships enabled the development of a kinematic control framework implemented in MATLAB/Simulink. Prototype testing and simulation studies demonstrated the feasibility of the proposed approach and validated the effectiveness of proportional feedback control. Future work should investigate adaptive control strategies, sensor fusion, and autonomous path-planning techniques to further enhance manipulator performance in real-world inspection applications.

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