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Unified dynamics analysis of parallel manipulators: A joint-based approach and generalized inertia constraint matrix for parallel manipulators (GICM-P) framework

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Abstract

Parallel manipulators, a distinctive subset of closed-loop multi-body systems, are in high demand due to their precision-centric applications. This research introduces a unified approach to tackle both inverse and forward dynamic analyses of parallel manipulators, rooted in joint-based principles. The methodology dissects a given parallel manipulator into symmetric open-loop subsystems and a mobile body within either a planar or spatial context, depending on the manipulator's nature. Conventional practices, involving the introduction of joint cuts at relevant locations, are employed to partition the system into multiple open-loop subsystems. Subsequently, the joint coordinate-based approach, typically applied to open-loop systems such as industrial manipulators, is utilized to derive solutions. In particular, this approach focuses on forward dynamics by introducing the generalized inertia constraint matrix for parallel manipulators (GICM-P), a concept built upon the authors' prior work, originally addressing the GICM for general closed-loop systems. Notably, GICM-P aligns conceptually with the operational space inertia matrix (OSIM) designed for closed-loop systems elsewhere. However, unlike OSIM, which requires mapping joint-space inertia to operational-space inertia, GICM-P leverages acceleration-level constraints between subsystems and the moving platform through straightforward matrix operations. GICM-P offers a deeper understanding of the physics of the problem compared to OSIM, primarily due to its ability to explicitly express subsystem-level interactions via various block matrices – an aspect not previously documented. The paper provides explicit numerical values for GICM-P in the context of a spatial six degrees of freedom (6-DOF) Stewart platform and a planar 3-DOF parallel manipulator along with interpretations.

Keywords

Parallel manipulators, joint-level dynamics, Stewart platform, subsystem-level, GICM-P

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Introduction

Parallel manipulators represent a special class of closed-loop multi-body systems having symmetric architecture with a fixed base and a moving platform. The fixed base is connected to the moving platform via symmetric legs formed out of two or more physical links. Parallel manipulators are popular in instrumentation, robotics, and haptics applications for their increased accuracy, low apparent inertia, maximum payload capacity, and high structural stiffness. They are used as a motion platform in flight or vehicle simulators, in vibration isolation, as position and force/torque sensors, and as a manipulandum in haptic interfaces, etc.

Dynamic analyses of parallel manipulators in general are useful for their design analyses, control, and simulation. Specifically, inverse dynamics is used not only for finding required joint torques or forces to control the system at hand, but also to arrive at an optimal structural design. Forward dynamics, on the other hand, provides a thorough mathematical and physical understanding of the way these systems behave dynamically in response to the applied external torques/forces by the joint actuators and those due to interaction with an environment, and others. This understanding is essential for designing effective control algorithms on the systems which are yet to be realized physically and for debugging the sources of anomalous behaviour whenever it occurs.

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