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A methodology for actuator failure recovery in parallel manipulators

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ABSTRACT

In this paper, the failure of parallel manipulators is examined considering the failure modes of manipulators. A methodology for investigating the effect of actuator/joint failures on the force/moment capabilities of manipulators is presented, and the criteria for full and partial recovery from these failures are established. The proposed methodology is valid for both planar and spatial parallel manipulators; in the case study and simulation, the planar manipulators are used as an example.

1. Introduction

Parallel manipulators are closed-loop manipulators in which the mobile platform (end effector) is connected to the base by several legs/limbs/branches, Fig. 1. Considering the actuation, parallel manipulators could be categorized as solid-link manipulators and wire-actuated manipulators. The solid-link parallel manipulators consist of kinematic chains of links with actuated (active) and passive joints. In the wire/cable-actuated manipulators (also referred to as the wire-suspended or cable-driven manipulators), the motion of mobile platform is controlled by wires/cables. Wires act in tension (could pull but not push) and cannot exert forces in both directions along their lines of action. Hence, in wire-actuated manipulators some form of redundancy, e.g., redundant wire or external force/moment is required.

Parallel manipulators could be designed to have high load capacity and dynamic characteristics; and low mass, cost and power consumption. Hence, their potential applications include both the terrestrial applications, such as manufacturing, entertainment, medical and service sectors; and the space applications. For some of these applications, fail-safe manipulators are crucial, e.g., when the device is used in surgery or in high speed operation. For tasks in hazardous environments and space/remote operations, human access to the manipulator could be very difficult, dangerous or impossible, while in some applications the downtime needs to be minimized.

Failure analysis of serial manipulators has received more attention compared to the parallel manipulators. Procedures for minimizing the jump in the norm of joint velocity vector of serial manipulators after joint failure were presented in [1,2]. In [3] the relative manipulativity index was used to investigate the Jacobian matrices of manipulators fault tolerant to joint failures. In [4] post-failure recovery from the full or partial loss of actuator torque in the closed-loop manipulators was investigated; utilizing actuation redundancy to compensate for the lost torque and modifying the task time to reduce the overall actuator torque requirement. In [5] the failure mode and effect analysis was performed to study the failure modes of parallel manipulators with their effects on the degree of freedom (DOF), actuation and constraint. Redundancy types, such as redundant DOF, redundant sensing, redundant actuation and redundant legs/branches, have been suggested for fault tolerant designs. The effect of redundancy in joint displacement sensing for parallel manipulators has been investigated to reduce the number of forward displacement solutions/assembly modes [6,7]; to allow the fixtureless calibration of manipulators [8]; and to facilitate the joint sensor fault detection, isolation and recovery [9]. Redundancy in actuation has been proposed to reduce the uncertainty/

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singularity configurations of parallel manipulators [10,11]. In [12] the task space was partitioned into major and secondary tasks in order to complete the major task and optimize a secondary goal such as actuator fault tolerance. The reduced motion of parallel manipulators due to active joint jam and the design modification to compensate for the accuracy degradation were investigated in [13,14]. Methodologies for the fault tolerance of parallel manipulators are required to compensate for their performance degradation after failure.

In this article, the failure of parallel manipulators is studied. Failure modes of parallel manipulators are discussed in Section 2. A methodology for recovering the lost force/moment capability due to the failure of joints and actuators is presented in Section 3. The kinematics and static modelling of planar parallel manipulators and simulation results for the loss of joint force/torque are reported in Section 4. The article concludes with Section 5.

2. Manipulator failure modes

Parallel manipulators could fail because of the failure of their components (e.g., links, active joints and passive joints), subsystems (legs/branches and end effector) and systems (mechanical, electrical, software and controller). If any of these failures affect the performance of manipulator such that the task cannot be completed as desired, then the manipulator is considered failed. Considering the mechanical system, parallel manipulators could fail because of the failure of a link (link breakage or undesired flexibility of link) and/or failure of a joint (joint breakage, joint jam, sensor failure, actuator failure and transmission failure). These failures could result in the loss of DOF, loss of actuation, and loss of motion constraint; in addition to loss of information, please refer to [5] for detailed discussion.

From the force point of view, the failure of manipulator occurs when the actuators (active joints) do not provide the required force/torque, e.g., when the actuator force/torque is lost partially or fully or the actuator is saturated. This could also arise when the joint is broken or its actuating mechanism malfunctions such that a different (zero, constant or limited) force/torque is provided by the joint.

3. Failure recovery methodology

In parallel manipulators, the mobile platform is connected to the base by a number of legs/branches, e.g., refer to Fig. 1. In general, each leg is a kinematic chain of links connected by joints. Because of the closed-loop configuration, not all of the joints of parallel manipulators are actuated, i.e., some of the joints are passive. For non-redundant actuation, considering the one degree of freedom joints such as revolute or prismatic joints, the number of active joints is equal to the DOF of the manipulator (Fig. 1, with active prismatic joints). For redundant actuation, one or more passive joints could be actuated (Fig. 2(a)), or another leg with one/more active joints could be included (Fig. 2(b)). In these cases, the number of actuators would be larger than the DOF of manipulator.

For parallel manipulators, the $n \times 1$ vector of joint forces/torques (force for actuated prismatic joints and torque for actuated revolute joints), $\boldsymbol{\tau} = [\tau_1\ \tau_2 \ldots \tau_{n-1}\ \tau_n]^T$, is related to the $m \times 1$ vector of forces and moments (wrench) applied by the mobile platform, $\mathbf{F} = \begin{bmatrix} F_x & F_y & F_z & M_x & M_y & M_z \end{bmatrix}^T$, with the $m \times n$ transposed Jacobian matrix $\mathbf{J}^T$ as

$$\mathbf{F} = \mathbf{J}^T \boldsymbol{\tau} = \left[\mathbf{J}_1^T\, \mathbf{J}_2^T \cdots \mathbf{J}_i^T \cdots \mathbf{J}_{n-1}^T\, \mathbf{J}_n^T\right] \boldsymbol{\tau} = \sum_{j=1}^{n} \mathbf{J}_j^T \tau_j \tag{1}$$

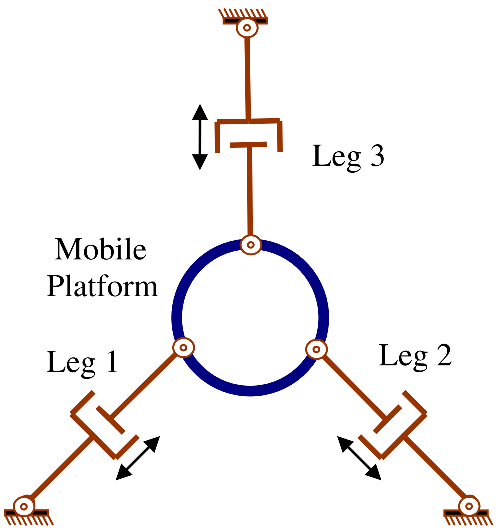

Fig. 1. Planar parallel manipulator.