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A Systematic Approach for the Jacobian Analysis of Parallel Manipulators with Two End-Effectors

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ABSTRACT

Parallel manipulators with two end-effectors (PM2Es) enable the design of gripping robots with high dynamic performance. The gripping action is enabled by internal, relative degrees of freedom (DoFs) between the two end-effectors. Many standard methods for the analysis and control of parallel manipulators rely on a Jacobian, where a complete Jacobian analysis includes constraint relations. These constraint relations have not been consistently included in previous analyses of PM2Es, while they are specifically relevant for PM2Es because constraints play an important role in the static force analysis of a PM2E. This is because wrenches applied by the actuators can be transferred to the end-effectors through internal constraints, an effect which is not captured by kinematic relations alone. This paper presents a systematic approach to perform the Jacobian analysis of PM2Es, which is based on screw theory, and that takes all constraint relations into account. The approach is applied to a PM2E with three legs and one internal closed-loop chain. An example mechanism was built to experimentally validate the resulting Jacobian analysis using a static force analysis.

1. Introduction

Gripping is an important aspect of many modern robotic systems, such as pick-and-place robots [1,2], microassembly robots [3,4], and haptic devices [5,6]. An important category of grippers are those which mechanically engage an object in a multi-point contact [7,8].

For many applications a driving requirement is dynamic performance, which asks for robotic systems with a high stiffness-over-inertia ratio. Despite their advantageous stiffness-over-inertia ratio, only few mechanically gripping robots are based on parallel manipulators (PMs). A PM can have all actuators located at the base, which significantly reduces the effective inertia. However, the standard solution for adding a gripping capability to a PM is to connect an additional, dedicated gripper in series to the end-effector as, for example, in Ref. [3]. Because of its placement at the end-effector, the inertia of a gripper can significantly degrade the dynamic performance of the resulting manipulator.

Parallel manipulators with two end-effectors (PM2Es) are a relatively novel class of PMs and form a promising alternative solution for gripping robots. PM2Es are an interpretation of parallel manipulators with a configurable platform [6,10–14], where a closed-loop chain replaces the rigid platform of a traditional PM. This architecture enables the design of gripping robots with all motors located at the base, which is beneficial for the overall dynamic performance. The first example of such gripping robot was

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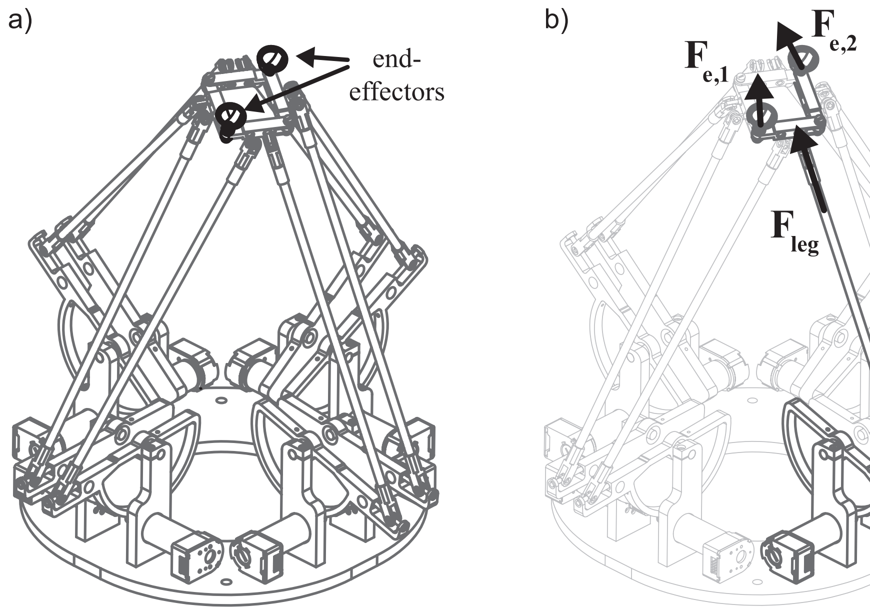

Fig. 1. a) A parallel manipulator with two end-effectors (PM2E) interacts with the environment via two specific bodies, where b) wrenches applied by the legs can be transferred to the end-effectors through internal constraints.

introduced by Yi et al. [10], where the whole closed-loop chain acts as the gripper. This paper focuses on PMCPs where two specific bodies of the closed-loop chain interact with the environment, which is illustrated in Fig. 1 for the overactuated 7-DoF haptic master device introduced by Lambert and Herder [6]. Therefore, the term PM2E is preferred.

For the analysis and control of PMs a Jacobian is used [15–18] and therefore various researchers have focused on the Jacobian analysis of PM2Es. Yi et al. [10] differentiated the inverse kinematic relations to obtain an expression for the Jacobian. Mohamed and Gosselin [9] performed a Jacobian analysis based on a set of loop-closure equations that must be solved simultaneously. Lambert et al. [13] applied a stepwise approach in which they first obtained an expression for the motion of the connection point of each *leg*, which is a serial chain that connects the internal closed-loop chain to the base as illustrated in Fig. 2a. They then developed a Jacobian based on the relations between allowed end-effector motions, motions of the leg connection points and motions of the actuators. Nabat et al. [12] considered the end-effector velocity state of their manipulator as the combination of a platform twist and an additional velocity term to represent the internal platform motion.

More recently, Hoevenaars et al. [19] made a first attempt to generalize the Jacobian analysis of PM2Es based on screw theory

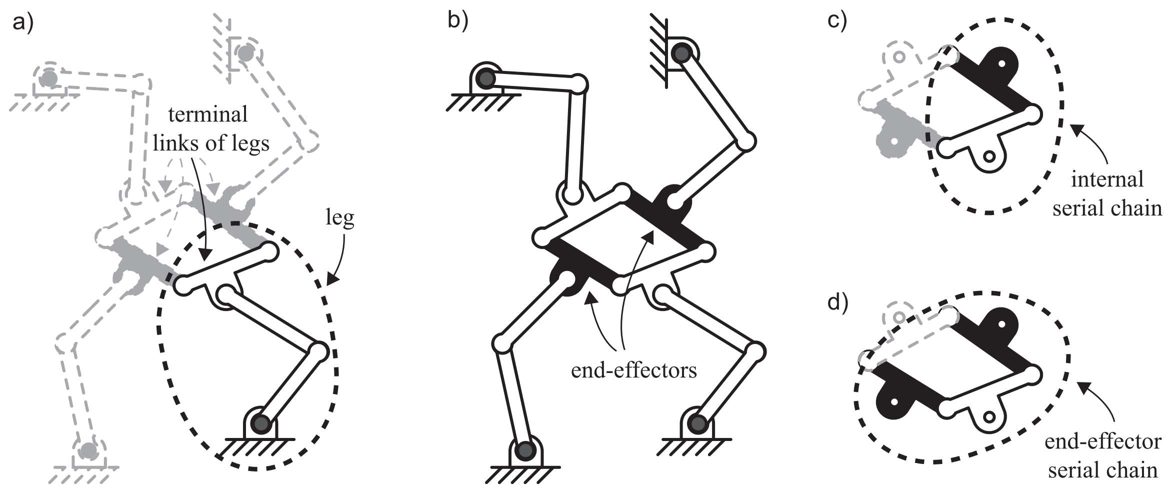

Fig. 2. A planar manipulator as described in Ref. [9], for which are indicated a) the terminal links of the different legs, b) the fact that two terminal links need to be designated as end-effectors, c) one of the four internal serial chain, and d) one of two end-effector serial chain.