Mechanism and Machine Theory 92 (2015) 240–256

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

A combinatorial search method for the quasi-static payload capacity of serial modular reconfigurable robots

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ARTICLE INFO

Article history:
Received 14 May 2014
Received in revised form 28 May 2015
Accepted 29 May 2015
Available online xxxx

Keywords:
Modular reconfigurable robot
Genetic algorithm
Workspace search
Payload capacity
Reconfiguration analysis

ABSTRACT

This paper presents a new combinatorial search method for the quasi-static stiffness performance evaluation and payload capacity analysis of serial modular reconfigurable robots (MRRs). The goal in this paper is to optimize the external payload capacity to achieve a global set of satisfactory kineto-elastic performance requirements for all module configurations. This problem exhibits considerable numerical complexities since the maximum payload capacity is dependent on a large number of possible module configurations, the worst-case stiffness poses for each configuration, and multiple kineto-elastic performance requirements. Therefore, to alleviate these difficulties, the problem is decomposed into an elimination search algorithm to reduce the configuration search space, a genetic algorithm to directly search the configuration workspaces and find the worst-case stiffness poses, and a bisection method to determine the maximum payload capacity at the worst-case configurations and poses. It is demonstrated that the worst-case stiffness search method in this paper is superior in computational time and numerical accuracy compared to previous hierarchical or incremental search methods, which require searching through a pre-determined number of poses. Through case studies, the new combinatorial search method is proven to be computationally efficient and can obtain accurate results for the worst-case stiffness poses and maximum payload capacity.

1. Introduction

Positional accuracy remains one of the leading concerns in mechanism analysis, and component stiffness is one of its main affecting factors. In general, tip position inaccuracies are caused by deflections due to applied payloads, self-weights of the joints and links, and robot vibration. Although serial modular reconfigurable robots (MRRs) can be reconfigured to perform different motion tasks, their stiffness performance for a known task usually does not match that of a non-reconfigurable mechanism designed only for performing the task requirement in a single configuration repeatedly. Throughout this paper, "configuration" refers to the initial joint module axes directions where all joint motion variables are set to zero, and "pose" refers to the position and orientation of an MRR after the joints rotate from their initial configuration setup. When joint module axes are reconfigured, the maximum stiffness and payload limits for assembled MRRs can change drastically. Therefore, for robots that undergo quasi-static motion, kineto-elastic analysis is an essential tool to analyze the aforementioned causes of structural inaccuracies over a robot's workspace. Furthermore, quasi-static payload analysis is important for stationary robot positioning tasks such as part inspections, where parts that are too heavy can cause significant link deflections, leading to large errors in measurement. For open-chain MRRs, considerable research

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http://dx.doi.org/10.1016/j.mechmachtheory.2015.05.016

has been conducted for MRR kinematics [1] and rigid-body dynamic models [2]. Other research involved automated kinematic calibration methods to improve the pose accuracy of multiple MRR configurations [3,4]. However, little attention has been paid to the analysis of serial MRRs with modules that exhibit inherent structural flexibility.

In the current literature, kineto-elastic analysis has been extensively studied for parallel reconfigurable robots [5,6]. However, there is a lack of research contributions for the kineto-elastic analysis of serial MRRs, which are more susceptible to adverse stiffness issues than their parallel counterparts. This is due to the fact that the load of the entire robot is carried on a single base joint for serial MRRs, rather than multiple base joints. Although recent studies on serial MRRs include stiffness models [7,8], the variation in stiffness and payload capabilities for multiple configurations were not presented. For typical serial robots with minimal joint length offsets, the most critical stiffness pose is known to occur at maximum arm stretch, which can be easily determined by visual inspection. However, due to the larger joint sizes in serial MRRs, their shapes can become quite complex and it can be shown that with increased joint elasticity, the worst-case stiffness performance can widely vary with different module configurations as opposed to just one, thereby affecting the payload capacity. Previous researchers [9,10] developed control methods to improve the payload capabilities of serial MRRs using spring-assisted joints to achieve static balancing. However, the maximum payload capacity for multiple joint module axis reconfigurations was not thoroughly investigated, and it is not known which configurations are the best or worst performing based on their examples. Therefore, more research to assess the stiffness performance and payload requirements for multiple MRR configurations is warranted.

Workspace search methods are effective tools for quantifying the pose-dependent kineto-elastic performance of MRR configurations. In a previous study [11], a kineto-elastic workspace search was conducted to determine the configuration and pose with the highest translational tip deflections for MRR module stiffness design. However, the brute-force search method, which scanned through the robot poses one-by-one in the configuration workspaces using joint angular increments, can be proven to lack accuracy if large increments are used, and can lead to extremely high computational times with smaller increments. Similarly, in [12], an incremental search method was applied to a non-reconfigurable serial manipulator to determine the worst-case pose which yields the highest joint torques due to robot collision by hierarchically searching through the joint parameters and velocity directions one-by-one in their value ranges. Other kineto-elastic workspace search methods, such as [13], involved grid-based searches using inverse kinematics, which may be proven to be computationally expensive if only a maximum/minimum stiffness result is required. In [3], a hybrid method was used for the kinematic calibration of a small set of predefined MRR configurations with unknown geometric errors. A Monte Carlo method was used to generate several random poses for a configuration and the calibration was performed only at those poses using a genetic algorithm to achieve a robust solution. However, there was no heuristic function to directly evaluate the relative error between the random poses. Thus, without any knowledge about the relevance of the poses in a configuration's workspace, the worst-case poses might be completely missed or unaccounted for. Therefore, a more efficient and numerically accurate workspace search method is required to find the worst-case stiffness poses.

Many researchers included kineto-elastic indices to evaluate robot workspace performance. The condition number of the twist transformation matrix was evaluated in [11]. It was proven that this parameter was not as useful as directly searching for the highest deflections and torques. This was caused by two reasons: first, the transformation matrix terms do not have similar units, and second, the condition number of the twist transformation does not take into account module self-weights, as shown in [14]. Previously, other parameters such as stiffness ellipsoids were also derived assuming external end-effector payloads and do not take into account individual component self-weights [15,16]. Thus, direct evaluations of the deflections and torques are more reliable methods for assessing the stiffness performance of assembled MRR modules. For improving the kineto-elastic performance of robots, previous methods such as [5,6,10–12] focus on implementing physical design changes on MRR modules, such as re-designing link geometry and adding stiffening springs to the joints. However, re-designing existing off-the-shelf modules is often a costly procedure, requiring extensive machining and modifications to the joint modules. Instead, tuning the parameters that are external to the MRR structure, such as the external payload capacity or tool reaction force, can prove to be viable options to improve the kineto-elastic performance of MRRs.

In this paper, a new application is presented to improve the quasi-static stiffness performance of serial MRRs. Unlike the previous serial MRR module stiffness design methods, the goal in this paper is to instead optimize the maximum external payload capacity for a given set of MRR modules to in order to meet multiple kineto-elastic performance requirements for all configurations. The problem at hand presents considerable numerical difficulties mainly due to the large number of possible module configurations and determination of the worst-case stiffness poses for each configuration. Therefore, an analytical solution is rather difficult to obtain. To solve this problem, this paper introduces a new and effective combinatorial search methodology for the worst-case stiffness analysis and maximum payload determination for serial MRRs. This method combines an elimination search to reduce the total number of configurations to a smaller subset of feasible configurations, a genetic algorithm (GA) [17], or non-dominated sorting genetic algorithm (NSGA-II) [18], to search for the worst-case stiffness poses for each kineto-elastic requirement, and a bisection method for determining MRR payload limits for pre-defined static deflection, joint torque and stationary vibration requirements. In the following sections, details of the combinatorial search method are presented, along with a numerical case study.

2. Problem description and methodology

2.1. Serial MRR description

The type of open-chain MRR in this study consists of separate detachable revolute joint and link modules, as shown in Fig. 1. Each MRR module is initially configured with respect to a common global reference frame [19], where the lengths of the joint and link