Mechanism and Machine Theory 109 (2017) 296–312

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Research paper

Design of planar variable-payload balanced articulated manipulators with actuated linear ground-adjacent adjustment

Wei-Hsuan Chiang, Dar-Zen Chen*

Department of Mechanical Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan (R.O.C.)

ARTICLE INFO

Keyword:
Variable payload
Balanced
Spring
Ground
Adjustment

ABSTRACT

Supporting different payloads has been shown to be effective for developing a multitasking manipulator. This paper presents a method for designing a planar, statically balanced, articulated manipulator for supporting variable payloads. The balancing equations for the gravitational and spring elastic energies are developed using a stiffness block matrix, which represents interacting potential energies between the links. It is shown that the springs can be classified according to the roles they play in the balancing equations. Thus, the installation parameters can be divided into payload-dependent parameters (PDPs) and payload-independent parameters (PIPs). The admissible spring configurations for supporting variable payloads are determined using the required number of PDPs, and PDP adjustment devices are used to adjust PDPs as the payload changes. Based on the interrelation between PDPs and PIPs, the number of PDPs can be reduced through proper arrangement of PIPs. The displacement of different PDPs can be equalized to fit attachment points in the same adjustment device. Therefore, the number of PDP adjustment devices is minimized to one. Variable-payload balanced articulated manipulators with five springs and three degrees of freedom are shown as illustrative examples. The energy consumption is estimated accordingly.

1. Introduction

Statically balanced manipulators maintain equilibrium in any configuration. In recent years, several methodologies have been proposed to compensate for the weight of linkages. One such method is the counterweight method that balances a manipulator by supplying counterweights that cancel out the effect of link mass; however, this increases the system's inertia, and the operation may be worsened [1–4]. Another method is the spring-balancing method that uses spring forces to compensate for gravitational forces; consequently, the system's inertia remains small [5–10].

One of the spring-balancing approaches is to use auxiliary linkages. The method of parallelogram links ensures that vertical members exist at the end of each link. Therefore, a manipulator with multiple degrees of freedom (DOF) can be considered as a series of connected 1-DOF manipulators [11–14]. Agrawal et al. applied auxiliary parallelograms to human upper arm orthotic devices [15], human leg orthotic devices [16], and assistive devices for sit-to-stand tasks [17] to support people experiencing muscle weakness. This method can be further applied to spatial parallel platform mechanisms [18–21], and delta robots [22,23] to enhance their low-dynamic performance levels. However, auxiliary linkages tend to increase the inertia of the system. Also, the range of motion may be limited. For the improvement of these problems, Lin et al. proposed a stiffness block matrix (SBM) to explore the potential energies interacting between links of multiple-link planar articulated manipulators [24–26]. Those interacting potential

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* Corresponding author.
E-mail address: dzchen@ntu.edu.tw (D.-Z. Chen).

http://dx.doi.org/10.1016/j.mechmachtheory.2016.12.001
Received 13 May 2016; Received in revised form 15 November 2016; Accepted 1 December 2016

energies can be compensated by various approaches without auxiliary linkages. Although the configurations of springs may be relatively complex, the locations at which those springs must be installed can be derived easily. Therefore, the aim of this paper is to determine the location of the springs.

With the increasing usage of support or assistive equilibrators, supporting variable payloads has been shown to be effective for multitasking manipulators, such as robotic arms, surgical light assistance devices, and monitor support devices. Therefore, balanced devices that support variable payloads have been developed. To maintain static balance, the spring configuration should be altered for different payloads. Nathan proposed a static balancer in which spring attachment points can be self-adjusted [27]. Herder et al. proposed several energy-free adjusting concepts such as virtual springs [28], simultaneous displacement [29], spring stiffness [30], and storage springs [31]. Takesue et al. focused on the spring configuration of variable gravity compensation mechanisms. Two types of springs with a 90° phase difference can be used to compensate for variation in gravity without using wires [32]. Energy-free design is not a major concern in this context; adjustments may consume energy, some extra energy may be allowed into the system during the adjustment of the attachment points. However, these methods are focused on the compensation of gravitational and elastic forces between ground and ground-adjacent links. Information about interacting potential energies between multiple links is not sufficient. The designs of the auxiliary linkages may require alterations to adapt them to the needs of a multiple-link manipulator. Therefore, this paper focuses on the spring configuration of multiple-link planar articulated manipulators and estimation of the energy consumption during adjustment.

The method proposed in this paper is based on the SBM approach [24]. Previous studies of the SBM approach [24–26] have mainly focused on the compensation of fixed gravitational potential energy. In the present paper, however, the SBM approach is generalized for variable payloads. The adjustable installation parameters in the balancing equations, which must vary with the changes of the payload, are called payload-dependent parameters (PDPs). By contrast, the installation parameters for fixed locations are defined as payload-independent parameters (PIPs). The process of this paper is roughly summarized as follows. On the basis of the interrelation between the PDPs and the PIPs, the displacement of the PDPs can be expressed as a linear equation and the number of PDPs can be reduced through the proper arrangement of associated PIPs. Therefore, the PDP adjustment device can be implemented as a slider that can lock at any position along a perpendicular slide rail. Furthermore, all PDPs can be fitted on the same PDP adjustment device to minimize the required number of adjustment devices to one. The energy consumption during the adjustment is estimated based on the simulation results of the variation of total potential energy for a variable payload.

The remainder of this paper is organized as follows. Section 2 introduces the formulations of the elastic potential energy and gravitational potential energy represented by the SBM. On the basis of the summation of the gravitational and elastic SBMs, the spring installation parameters are classified according to the roles they play in the balancing equations. Section 3 describes the general criteria for admissible spring configurations for an n-link variable-payload manipulator (VPM). According to the number of required PDPs, balancing equations are derived from the nonzero component matrices of the summation of the gravitational and elastic SBMs. The formulation of the PDPs and PIPs is then explored according to the spring configuration. Section 4 expresses the displacement terms of the PDPs as an equation in terms of the PIPs. Some additional criteria for the installation of PIPs are determined to reduce and equalize the nonzero displacement PDPs. Section 5 presents the derivation of a planar 3-DOF VPM with five springs as a design example. The static equilibrium of quasistatic continuous motion is verified, and the energy consumption is estimated accordingly.

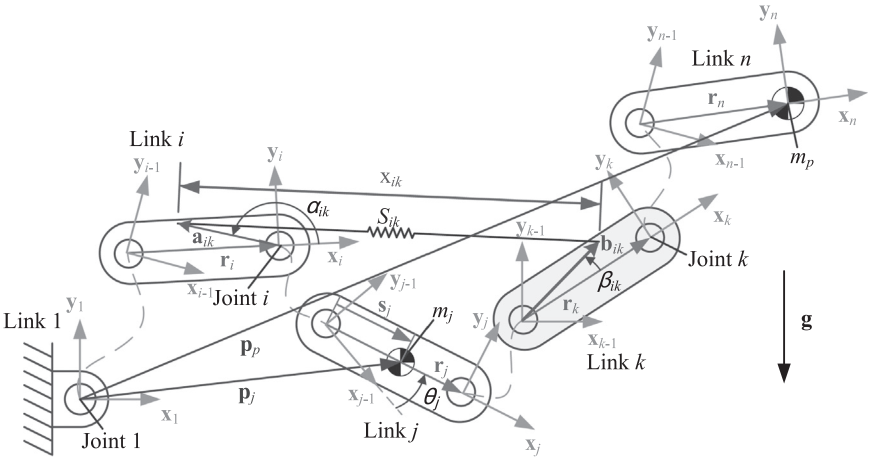

Fig. 1. Center of gravity position $\mathbf{p}_j$ of the n-link planar articulated manipulator and changeable payload fitted at the end effector of link n and S_{ik}, the spring connected between link i and link k.