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Approximate spring balancing of linkages to reduce actuator requirements

Sushant Veer [a], S. Sujatha [b,*]

[a] Department of Mechanical Engineering, University of Delaware, Newark, DE 19716, USA
[b] Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

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ABSTRACT

The potential benefit of applying gravity balancing to orthotic, prosthetic and other wearable devices is well recognized, but practical applications have been elusive. Although existing methods provide exact gravity balance, they require additional masses or auxiliary links, or all the springs used originate from the ground, which makes the resulting device bulky and space-inefficient. This work presents a new method that is more practical than existing methods to provide approximate gravity balancing of mechanisms to reduce actuator loads. Current balancing methods use zero-free-length springs or simulate them to achieve balancing. Here, non-zero-free-length springs can be used directly. This new method allows springs to be attached to the preceding parent link, which makes the implementation of spring balancing practical. The method is applicable to planar and spatial, open and closed kinematic chains. Applications of this method to a lower-limb orthosis and a manually-operated sit-to-stand wheelchair mechanism are presented. Results show considerable reduction in actuator requirements with practical spring design and arrangements.

1. Introduction

To considerably reduce the actuator requirements, gravity balancing has been used in anthropomorphic robots and other linkages that have to work against gravity. As the need for gravity balancing is well recognized, there are many techniques available. Exact (or perfect) static balancing of links can be obtained by adding counterweights, but this leads to an overall increase in inertial mass which is undesirable, especially if the application is to wearable devices such as orthoses, prostheses and exoskeletons. Static balancing using springs is more suitable for such applications since springs provide greater flexibility in attachment points.

Rahman et al. [1] present techniques for balancing a single link perfectly using zero-free-length springs and extend it to balancing an *n*-link open chain with the help of auxiliary links. Although the use of auxiliary links provides perfect balancing, the additional links occupy a lot of space and increase the mass and bulkiness of the mechanism. In addition, these techniques assume zero-free-length springs, which further contributes to the complexity of the design. Similarly, Streit and Shin [2] use zero-free-length springs for spring balancing of closed loop linkages. Agrawal and Agrawal [3] provide an approximate static balancing method using non-zero-free length springs but with the need for auxiliary links. Gopalswamy et al. [4] present an approximate static balancing technique for a parallelogram linkage using torsional springs. Carwardine [5] and Riele and Herder [6] present perfect balancing techniques using non-zero-free-length springs but their solutions have specific geometric configurations that may not be usable in every situation due to space and size limitations.

* Corresponding author. Tel.: +91 44 2257 4728; fax: +91 44 2257 4652.
E-mail addresses: veer@udel.edu (S. Veer), sujsree@iitm.ac.in (S. Sujatha).

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This work was inspired by the recent method devised by Deepak and Ananthasuresh [7] which provides for perfect gravity balancing using only springs and no auxiliary links. However, their method again requires zero-free-length springs or the simulation thereof using non-zero-free-length springs. In addition, all the springs in their technique have one end pivoted to the ground. These conditions pose considerable problems in many situations like wearable devices where cosmetic appearance and available space are major constraints.

There have been other techniques for approximate spring balancing and for determining optimal spring pivot locations. Segla [8] presents an optimization using genetic algorithm for a six-DOF robot mechanism with the gripper force as the objective function. Huang and Roth [9,10] use the principle of virtual work for placement of springs at apt positions. Mahalingam and Sharan [11] present an optimization for optimal location of spring pivots and relevant spring characteristics to reduce the unbalanced moment. Idlani et al. [12] present a technique with specified potential energy at precision points. Brinkman and Herder [13] present a technique for optimal spring balanced mechanisms by a method they call field fitting in which the energy field of the gravity balancer is matched as closely as possible to the energy field required for a balanced system. Here, we propose an optimization-based approximate spring balancing technique that helps predict the relevant spring parameters and spring pivot locations as well. The technique is presented in a generic fashion, which would allow it to be implemented in a variety of mechanisms.

This work is motivated by the need for practical implementation of balancing in mechanisms that have stringent space and mass constraints, like orthoses, prostheses and exoskeletons. Previous attempts at using gravity balancing for such devices have resulted in complex and bulky mechanisms [14–16]. Ciupitu et al. [17] propose some mechanisms in their work that have medical relevance, but all these mechanisms have springs attached to the ceiling, greatly hindering the mobility and increasing the space requirements.

The method used in this work, apart from being space efficient, makes design easier by eliminating the step that involves simulating zero-free-length springs with non-zero-free-length springs. Springs with non-zero-free-lengths can be directly used. The method is very general and can be applied to open and closed loop kinematic chains comprising planar or spatial mechanisms. We demonstrate the design of the springs for reducing actuation requirements for a lower-limb orthosis (open-loop) and a manually operated sit-to-stand wheelchair mechanism (closed-loop).

To overcome the requirement of locating one pivot of each spring on the fixed link [7], we investigated using child–parent connections to balance a serial chain of links. We show in the following section that exact balancing is not possible with this configuration, even with zero-free-length springs.

The paper is organized as follows: the next section proves that perfect spring balancing is not possible by child–parent spring connections for a two-link serial manipulator. Section 3 describes the problem formulation for approximate spring balancing of open-link planar chains, a four-bar linkage and open-link spatial chains. Section 4 presents examples — the method is applied to design gravity balancing of a two-link lower-limb orthosis, and to reduce the actuator requirement of a manually operated sit-to-stand wheelchair mechanism. Section 5 presents conclusions of the present work. The last section presents the nomenclature used.

2. Proof to show that perfect spring balancing is not possible by child–parent spring connections

We take the simple case of a two-link open kinematic chain connected by revolute joints as shown in Fig. 1. The notation used is as indicated in the nomenclature.

Zero-free-length springs are assumed in this section, for the sake of simplifying the proof. The total potential energy of the system is given by

$$PE = m_2 g r_2 \sin(\theta_2+\alpha_2) + m_3 g[r_3 \sin(\theta_3+\alpha_3) + l_2 \sin\theta_2] + \frac{1}{2}K_1\left(\|S_{21}-S_{12}\|^2\right) + \frac{1}{2}K_2\left(\|S_{23}-S_{32}-L_2\|^2\right). \tag{1}$$

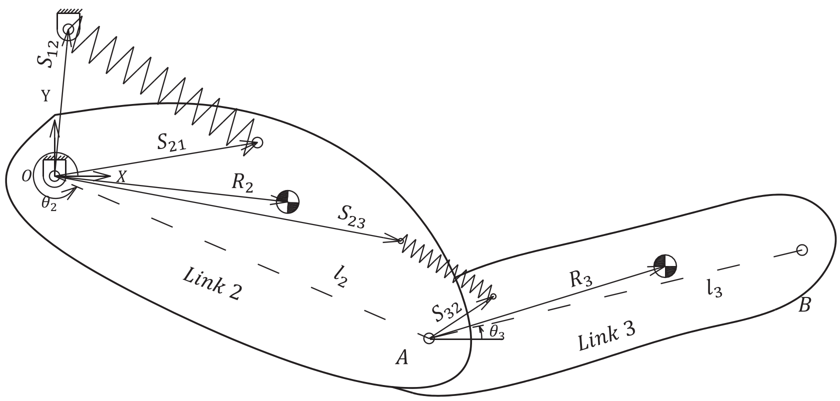

Fig. 1. Two-link open kinematic chain.