Mechanism and Machine Theory 61 (2013) 156–167

Contents lists available at SciVerse ScienceDirect

Mechanism and Machine Theory

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

A theoretical study of weight-balanced mechanisms for design of spring assistive mobile arm support (MAS)

Po-Yang Lin [a], Win-Bin Shieh [b], Dar-Zen Chen [a,*]

[a] Dept. of Mechanical Engineering, National Taiwan University, Taipei 10617, Taiwan
[b] Dept. of Mechanical Engineering, Ming Chi University of Technology, New Taipei 24301, Taiwan

ARTICLE INFO

Article history:
Received 3 April 2011
Received in revised form 10 August 2012
Accepted 12 November 2012
Available online 7 December 2012

Keywords:
Mobile arm support
Gravity balance
Stiffness matrix
Upper limb exoskeleton

ABSTRACT

This paper studies the underlying theory of weight-balanced mechanism for the design of a class of spatial mobile arm support (MAS), a spring assistive MAS. Conventional designs of spring assistive MAS and their associated spring balancing techniques are analyzed based on the stiffness matrix analysis in order to highlight the structural novelty of the proposed MAS design concept. This MAS comprises two ideal zero-free-length springs directly installed to the arm mechanism without using any auxiliary link. Through the passive assistance provided by the springs, the MAS can facilitate the arm movement in space by the complete weight compensation of the upper limb at any possible posture. The design is believed to have benefited from its simple structure and the easiness of adjustment compared to other conventional designs. The conceptual design of the MAS is proposed and followed with a simulation model. The gravity balancing is verified with an example of a quasi-static motion. The results show that the MAS is capable of fully balancing the weights of user's upper limb and the device during the full range of motion.

1. Introduction

Mobile arm supports (MASs) are the mechanical devices that support the weight of the arm and so provide assistance to shoulder and elbow motions through a linkage of low friction joints [1]. MASs were originally designed to increase independence for feeding function, but they have subsequently enabled thousands of people with upper extremity impairments to achieve other functional activities, including grooming, hygiene, writing, telephoning, household tasks, and recreational and vocational activities [2]. Various types of MASs have been proposed over years, such as the foot-operated feeder by the Georgia Warm Springs Foundation back in 1936 [3], the Barker Feeder by E. H. Barker at about the same time, the Jaeco MAS around 1950s [4], and recently the WREX [5,6], the ARMON [7] and the Freebal [8].

Limitations of the traditional MAS design include its conspicuous appearance, problems of doorway clearance, and the complexity of fitting the device for individual users to engage in particular activities. Nowadays, several applicable MASs are preferably designed in form of passive exoskeleton devices, suggesting no actuators and sensors being used, these devices can be safer, less expensive and even lighter. The exoskeleton-type MAS design is structurally and kinematically aligned to the arm of the user, this facilitates in navigating the arm through doorways and narrow spaces, and also, the applied assistive forces can be transmitted more uniformly on the subject's arm.

Without actuators and sensors, gravity balancing techniques are required to passively counterbalance the gravitational forces of the arm and the MAS itself. Passive gravity balancing technique in mechanisms is able to achieve the complete gravity compensation at *any* configuration of the mechanism. A MAS with passive gravity balancing function can provide the exact amount of support at any possible posture of the arm without overstretching it. Passive gravity balancing technique encompasses

* Corresponding author. Tel.: +886 2 3366 2723; fax: +886 2 2363 1755.
E-mail address: dzchen@ntu.edu.tw (D.-Z. Chen).

0094-114X/$ – see front matter
http://dx.doi.org/10.1016/j.mechmachtheory.2012.11.003

a variety of methods, e.g. the counterweight methods [9,10], the cam linkage methods [11,12] and the spring balancing methods [13–19]. Among these, the spring balancing methods are particularly favorable for the MASs since spring elements can be generally benefited from the light weight, small additional inertia, easiness for adjustments and cheap cost.

Most conventional spring balancing techniques use auxiliary links or linkages added to the mechanism to provide suitable attachment points for the springs [15–19]. However, the auxiliary links increase the system inertia as well as its structural complexity. This paper discloses the underlying theory of some of the famous spring balancing techniques and presents a theoretical study for the design of a class of a spatial spring assistive MAS without using auxiliary links, which is believed to be a novel design concept, simple in structure, and easy to be adjusted for individuals of distinct arm length and weight.

The layout of this paper is as follows. Section 2 presents the principle of gravity balancing techniques with springs. A general gravity-spring system is described by a stiffness matrix proposed by Lin et al. [14]. In Section 3, two existing spring balancing techniques using the auxiliary link method, which are both applied to planar 2-DOF (degree of freedom) serial kinematic chains, are investigated. In Section 4, a planar 2-DOF spring balancing arm without using auxiliary links is proposed. In Section 5, the planar 2-DOF design is extended to a spatial 4-DOF MAS by two additional rotational DOFs on the shoulder to accommodate the spatial kinematics of the upper extremity. With only two embedded springs, the 4-DOF MAS is capable of achieving static balance in spatial motion. In Section 6, a methodology for tuning the level of gravity compensation is proposed. The MAS is modeled and simulated in ADAMS. The simulated results shown in Section 7 justify the gravity balancing capability of the design.

2. Principle of gravity balancing with springs

2.1. The stiffness block matrix representation

To generally describe the configuration of a planar n-link articulated mechanism, let $\mathbf{q}_i$ be a unit vector fixed on link i ($i=1, 2, \ldots, n$) of the mechanism where link 1 is ground. The n-dimensional vector space spanned by $\mathbf{q}_1, \mathbf{q}_2, \ldots, \mathbf{q}_n$ defines the configuration of the mechanism. In the system, assume that all springs are *zero-free-length springs* working within their linear ranges, and the spring forces and the gravitational forces are conservative forces and configuration dependent. Hence, any force vector $\mathbf{f}$, can be expressed in a linear combination of $\mathbf{q}_i$'s as

$$\mathbf{f} = \sum_i \mathbf{F}_i \mathbf{q}_i \tag{1}$$

where $\mathbf{F}_i$ is a 2×2 constant coefficient matrix of $\mathbf{q}_i$, representing the rotation and scaling of $\mathbf{q}_i$.

Denote $\mathbf{p}$ as the position vector from the origin of the global coordinate system to the point where the force $\mathbf{f}$ is applied. For example, if $\mathbf{f}$ is the gravitational force of a link and $\mathbf{p}$ is the position vector of the mass center of the link, $\mathbf{p}$ can be expressed as

$$\mathbf{p} = \sum_i \mathbf{P}_i \mathbf{q}_i \tag{2}$$

where $\mathbf{P}_i$ is a 2×2 constant coefficient matrix of $\mathbf{q}_i$, representing the rotation and scaling of $\mathbf{q}_i$.

Hence, the potential energy contributed by the forces and their associated positions can be obtained as

$$U = \int \mathbf{f}^{\mathrm{T}} d\mathbf{p} = \sum_{i,j} \mathbf{q}_i^{\mathrm{T}} \mathbf{K}_{ij} \mathbf{q}_j \tag{3}$$

where $\mathbf{K}_{ij}$ is a 2×2 constant matrix derived from Eqs. (1) and (2) as

$$\mathbf{K}_{ij} = \mathbf{F}_i^{\mathrm{T}} \mathbf{P}_j. \tag{4}$$

Component matrix $\mathbf{K}_{ij}$ is the potential energy due to a relative angular position $\theta_{ij}=\cos^{-1}(\mathbf{q}_i^{\mathrm{T}}\mathbf{q}_j)$ of links i and j, and is also referred to as the stiffness component matrix between links i and j [14]. Hence, matrix $\mathbf{K}_{ij}$ is in energy unit, e.g. N–m.

In the spring-gravity system, both the gravitational potential energy U_{G} and the elastic potential energy U_{E} can be expressed in the form of Eq. (3). The total potential energy of the system U_{T}, i.e. the sum of U_{G} and U_{E}, can be further written in a block matrix form as

$$U_{\mathrm{T}} = \frac{1}{2} \mathcal{Q}^T \mathcal{K} \mathcal{Q} \tag{5}$$

where $\mathcal{K}$ and $\mathcal{Q}$ are respectively $2n\times2n$ and $2n\times1$ matrices as

$$\mathcal{K} = \left[\mathbf{K}_{ij}\right] \tag{6}$$

$$\mathcal{Q} = [\mathbf{q}_i]. \tag{7}$$