Mechanism and Machine Theory 101 (2016) 36–49

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Design of a static balancer with equivalent mapping

Chang-Hyun Cho[a], Woosub Lee[b,c,*]

[a]Chosun University, Dept. of Mechanism & Systems, College of Engineering, Engineering building 1, 309 Pilmun-daero, Dong-gu Gwangju 501-759, South Korea
[b]Robotics and Media Institute, Korea Institute of Science and Technology, 5 Hwarang-ro 14gil, Seongbuk-gu Seoul 02792, South Korea
[c]HCI & Robotics, KIST Campus, Korea University of Science and Technology, 217 Gajeong-ro,Yuseong-gu Daejeon 305-350, South Korea

ARTICLE INFO

Article history:
Received 12 August 2014
Received in revised form 26 January 2016
Accepted 27 February 2016
Available online 28 March 2016

Keywords:
Static balancer
Gravity compensator
Spring
Design method
Space mapping

ABSTRACT

This paper proposes a design method of a static balancer with multi-dof unit gravity compensators. The design method based on the space mapping method is extended to a multi-dof gravity compensator space. A multi-dof gravity compensator can be equivalently represented with one-dof gravity compensators applying the design method. An equivalent mapping matrix is determined between rotation angles of a multi-dof gravity compensator and those of one-dof gravity compensators. That is, characteristics of a multi-dof gravity compensator are described in the one-dof gravity compensator space. Complexity and variety originated from the multi-dof can be overcome using the equivalent mapping matrix during designing a static balancer with multi-dof gravity compensators. The design of a static balancer with multi-dof gravity compensators is conducted: 1. perform the design only with the one-dof gravity compensator space to determine the base mapping matrix between the joint and the one-dof gravity compensator space, 2. applying the equivalent mapping matrix to the base mapping matrix. Various designs are obtained. Results of simulations show that the total potential energy is invariant for all poses.

1. Introduction

Static balancing has been studied for several decades [1,2]. One degree-of-freedom (dof) gravity compensators were proposed for rotational motion [2]–[7]. Cam mechanisms are applied to one-dof gravity compensators [5,7]. The gravity compensators for four-bar and slider–crank mechanisms are designed with a single spring [8]. A 2-dof gravity compensator for the roll-pitch rotations is presented in that the bevel gears are utilized [9]. A 3-dof gravity compensator for the yaw–roll–pitch rotations with a single spring is proposed [10]. A static balancing method for a general n-DOF revolute and spherical jointed rigid-body linkages has been developed [11]. The gravity balancing considering the mass of a spring has been studied [12].

The unit gravity compensators in the previous researches applied to a multi-link and multi-dof manipulator. Gravity compensators for a 5-bar mechanism are proposed in Refs. [4]–[5]. A parallelogram is utilized [10,13]. A hybrid concept has been developed [14]. A gravity compensator for a parallel mechanism is suggested using balance springs [15].

The energy method is recently utilized to obtain the spring coefficient of a gravity compensator [5,6,9,14,15]. Streit and Gilmore proposed a design method considering potential energy in that the total potential energy of the springs and the

* Corresponding author. Tel.: +82 2 958 6429.
E-mail addresses: chcho@chosun.ac.kr (C. Cho), robot@kist.re.kr (W. Lee).

http://dx.doi.org/10.1016/j.mechmachtheory.2016.02.017

manipulator mass has been investigated [16]. A design method for an n-spring balancer for a one-link system with two-dof rotation has been proposed, wherein the spring parameters were derived by investigating a general expression of the total potential energy [17].

Determination of the number of springs and their location is difficult in most cases, when the dof of a mechanism increases and a mechanism has spatial motions. A design method has been proposed wherein springs are directly installed between links for a planar manipulator, and the stiffness block matrix is suggested [18]. A design method in the basis of the space mapping of is proposed which can determine the number and locations (or kinematic constraints) of unit gravity compensators simultaneously [19]. Since only one-dof unit gravity compensators are utilized, impractical designs are suggested for a high-dof manipulator. Thus, the gravity compensator space of Ref. [19] should be expanded to a multi-dof space to overcome limitations originated from the one-dof unit gravity compensator space. Since various multi-dof gravity compensators exist, a general expression of a multi-dof gravity compensator is necessary to overcome variety of multi-dof gravity compensators.

This paper proposes a design method of a static balancer with equivalent mechanisms. The design method in Ref. [19] is applied to a multi-dof gravity compensator to obtain a general expression of a multi-dof gravity compensator. Note in this paper that a gravity compensator means a mechanism externally attached to the mechanism to be balanced. By the space mapping method, a multi-dof gravity compensator is decomposed with one-dof gravity compensators and a mapping relation is obtained. In this paper the mapping matrix between multi-dof and one-dof gravity compensator spaces is called as the equivalent mapping matrix. Thus, a multi-dof gravity compensator is equivalently represented with the one-dof unit gravity compensator space with the equivalent mapping matrix.

To obtain a static balancer with equivalent mechanisms the design is performed only with the one-dof gravity compensator space to determine the base mapping matrix between the joint and one-dof gravity compensator spaces at first. The base mapping matrix is reconfigured with the equivalent mapping matrix. Thus, the multi-dof gravity compensators are applied to a static balancer and the gravity compensator space is extended to the multi-dof space consequently. The face robot Mero in Ref. [20] is considered as a design example. Various designs indicate that mechanical complexity decreases using multi-dof gravity compensators. Computer simulations are conducted. Results of simulations show that the total potential energy is invariant for all poses. Comparison of this paper with Ref. [19], various designs are enabled by applications of multi-dof gravity compensators. One-dof gravity compensators are only utilized in Ref. [19], so one solution or design is only obtained. However, various equivalent designs are suggested by the proposed design method in this paper, since various constituents (i.e., one-dof and multi-dof gravity compensators) are enabled.

2. Design method with the space mapping

The design method in Ref. [19] is briefly introduced in this section.

2.1. Space mapping

Joint space is predetermined as $\Theta = [\theta_1, \theta_2, \cdots, \theta_n]^T \in R^{n\times1}$, where θ_i denotes the rotation angle of the i-th joint and n represents the number of joints. It is assumed that an unconstrained joint space is considered. The one-dof gravity compensator space is determined as $\Theta_{g1} = [\theta_{g1,1}, \theta_{g1,2}, \cdots, \theta_{g1,p}]^T \in R^{p\times1}$, where $\theta_{g1,j}$ and p denote the rotation angle of the unit one-dof gravity compensator and the number of rotation angles. The rotation angles of the gravity compensators (i.e., Θ_{g1}) are passively determined by the pose of the mechanism (i.e., Θ). Thus, functions or relations exist between the joint space and the gravity compensator space. Suppose that Θ_{g1} is computed with Θ as follows:

$$\Theta_{g1} = \mathbf{J}\Theta + \Phi \tag{1}$$

where $\mathbf{J} \in R^{p\times n}$ and $\Phi \in R^{p\times1}$. $\mathbf{J}$ denotes a mapping matrix between the joint space Θ and the gravity compensator space Θ_{g1}. Φ represents a vector of constant phase angles.

2.2. Potential energy in both spaces

Let ${}^0\mathbf{P}_i$ be the position of m_i with respect to the {0} frame. Then, the potential energy of mass m_i is obtained by

$$V_m = -\sum_{j=1}^{n} m_i \cdot \mathbf{g} \cdot {}^0\mathbf{P}_i \tag{2}$$

where $\mathbf{g}$ represents the gravitation vector. ${}^0\mathbf{P}_i$ is computed from $[{}^0\mathbf{P}_i; 1] = {}^0\mathbf{T}_i[{}^i\mathbf{P}_i; 1]$, where ${}^0\mathbf{T}_i = {}^0\mathbf{T}_1 {}^1\mathbf{T}_2 \cdots {}^{i-1}\mathbf{T}_i$ denotes the homogeneous transformation matrix. Since ${}^0\mathbf{T}_i$ is determined by $[\theta_1, \theta_2, \cdots, \theta_i]^T$, Eq. (2) represents the potential energy in the joint space.