Доклади на Българската академия на науките
Comptes rendus de l'Académie bulgare des Sciences

Tome 76, No 10, 2023

ENGINEERING SCIENCES

Electronics

A THREE-LINK GRAVITY-BALANCED MECHANISM FOR OPERATING ROOM ASSISTANCE

Onur Denizhan

Received on May 1, 2023
Presented by Ch. Roumenin, Member of BAS, on July 31, 2023

Abstract

The compensation of gravity is not a new problem and gravity-balanced mechanisms have been extensively studied. Some of these studies present practical applications of the gravity-balanced mechanisms, while others focus on the theoretical modelling of the mechanism. In this study, a practical application, a gravity-balanced planar robotic manipulator for operating room assistance is presented. In this design, an auxiliary parallelogram with two linear springs is utilized to accomplish gravity compensation. As a passive gravity-balanced mechanism, it does not have any actuators. The novelty of the mechanism is the exchangeable end-effector and changeable spring attachment location accordingly. The simulation results show that the designed mechanism is gravity-balanced in all configurations. The presented mechanism in this study can also be extended to solve a multi-link gravity balance problem.

Key words: gravity-balanced mechanisms, static balancing, gravity compensation, three-link mechanisms

Introduction. A mechanism is called a gravity-balanced mechanism if its total potential energy remains constant over time. Balancing gravity is not a new problem, and gravity-balanced mechanisms have been extensively studied and designed. Gravity compensation can be classified as active and passive. Active compensation involves a set of actuators or primarily joint actuators, while passive compensation involves counterweights or springs instead of actuators. Some

DOI:10.7546/CRABS.2023.10.11

mechanism designs include both passive and active gravity compensation components. In passive compensation, the springs use stored potential energy to counterbalance gravitational loading [1].

A number of designs, methodologies and techniques of gravity compensation have been studied: A simple technique for gravity balancing is proposed by Rahman et al. [2]. In this article, an articulated gravity compensation with linear springs mechanism is introduced and different applications are also shown. Another gravity compensation mechanism for the lower limb rehabilitation is introduced by Nakayama et al. [3]. In this article, pulleys and springs are used and all components are embedded in the links because of safety of patients. Experimental verification is also presented in this study. Another lower limb exoskeleton for walking assistance is introduced by Zhou et al. [4]. In this study, alongside the spring mechanisms, a pair of mating gears is also used. An active gravity balanced planar mechanism by using auxiliary parallelograms is introduced by Agrawal et al. [5]. Auxiliary parallelograms are attached to the centre of mass of the mechanism and experiment results show how their approach is effective in this study. Another auxiliary parallelogram application for the gravity compensation is introduced by Agrawal and Fattah [6]. In this study, passive and active gravity compensation components are used together for the spatial robotic manipulators. Another gravity-balanced leg orthosis mechanism is introduced by Banala et al. [7] for the robotic rehabilitation. In this article, hybrid method (active and passive compensation components together) is used for the leg orthosis. A statically balanced non-powered arm support design is presented by Cardoso et al. [8]. In this study, the mechanism has four degree-of-freedom and four different concepts are investigated. Design of two spatial gravity compensation devices are presented by Herder and Tuijthof [9]. One of these devices is a four degree-of-freedom arm-like mechanism and it is balanced by two springs. Another device in this study is a six degree-of-freedom general suspension unit and it is balanced by a single spring. Another gravity-balanced leg orthosis is introduced by Agrawal and Agrawal [10]. In this article, two or three links planar chains are balanced by using non-zero free length springs for gravity balancing. Without using any extra mechanism such as a parallelogram, static balancing of mechanisms is investigated by Denizhan [11, 14] and Denizhan and Chew in [12, 13]. In these studies, the torsion and extension springs are used for static balancing of four-bar mechanisms in the presence of coulomb friction.

This article focuses on a three-link passively gravity-balanced mechanism to be used as an assistive robot for the operating room. Zero-spring length is used to passively balance the weight of the robot and its end-effector. Note that the springs exert zero force when they have zero-spring length. This study focuses solely on the mechanical design and calibration of spring-assisted passive gravity compensation. The novelty of the design resides in its exchangeable end-effector and variable position of the springs accordingly. An intuitive quick attach and

release mechanism enables the user to rapidly interchange the tool at the end-effector, and graduations on the proximal vertical reference link enables the users to modify the position of the springs in order to gravity balance a particular tool. The purpose of the gravity compensation is to assist the surgeon with tasks that require a fixed steady position susceptible to fatal twitch and parasitic movement by a human. The simulation results show that the designed mechanism in this study is gravity-balanced in different configurations.

The design of the three-link gravity-balanced mechanism. In this study, the designed mechanism can be divided into three parts: the base, the passively gravity-balanced links and the end-effector. All of these parts, auxiliary parallelograms and linear springs are shown in Fig. 1. The base is the section of the mechanism that is attached to the fixed reference, and serves as an immobile attach point for the springs and auxiliary parallelogram. In this design, the base is completely fixed, but one can easily envision the base to have one degree-of-freedom about its vertical axis of symmetry, without interfering with the planar dynamics of the gravity-balanced links as shown in Fig. 1.

The links in the mechanism are connected by rotating ball bearings, which allow one degree-of-freedom at each joint. The proximal link is connected to the base through two linear springs. To maintain a vertical and invariant reference frame for attaching the second set of springs, the proximal link has been equipped with an auxiliary parallelogram. The second set of springs is attached to the vertical side of the parallelogram on one end and to the distal link on the other. The end-effector can rotate freely around ball bearings at the end of the distal link, providing one degree-of-freedom. As mentioned earlier, the end-effector features a quick attach and release mechanism, making it easier to switch between tools for various operating room assistive tasks. In addition to that, the vertical reference

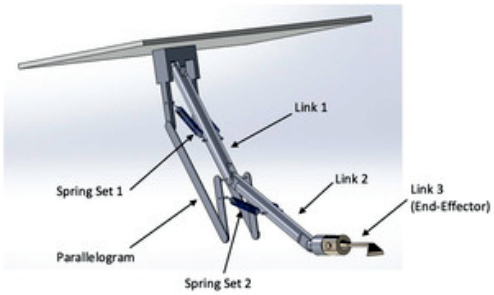


Fig. 1. The CAD design of the gravity-balanced three-link mechanism

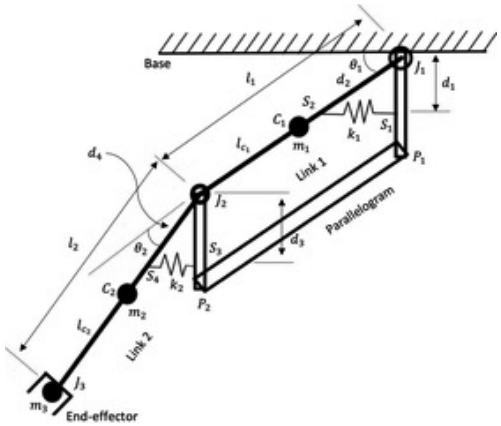


Fig. 2. Schematic draw of the planar three-link gravity-balanced mechanism

link at the base is equipped with pre-defined graduations that allow the user to adjust the gravity balancing to match the specific tool being used.

Figure 2 shows schematic design of the three-link planar gravity-balanced mechanism. As indicated in Fig. 2, J_1, J_2 and J_3 refer to joints 1, 2 and 3, respectively. The parameters l_1 and l_2 are the lengths of the Links 1 and 2, respectively. The parameters m_1, m_2 and m_3 are the mass of the Links 1, 2 and 3 (end-effector), respectively. C_1 and C_2 indicate centre of mass locations of Links 1 and 2, respectively. The end-effector mass (m_3) is located at the Joint 3 (J_3). The attachment locations for Spring 1 are S_1 and S_2, while the attachment locations for Spring 2 are S_3 and S_4. The angle θ_1 denotes the angle of Link 1 with respect to the horizontal axis, and the angle θ_2 indicates the angle of Link 2 relative to the Link 1. The parameters k_1 and k_2 present the constants of Springs 1 and 2, respectively. The parameter d_1 denotes the vertical distance from Spring 1 attachment location on the parallelogram to Joint 1 ($|J_1S_1|$), the parameter d_2 represents the length from the Spring 1 attachment location on Link 1 to Joint 1 ($|J_1S_2|$), the parameter d_3 denotes the vertical distance from the Spring 2 attachment location on the parallelogram to Joint 2 ($|J_2S_3|$), and the parameter d_4 represents the length from Spring 2 attachment location on Link 2 to Joint 2 ($|J_2S_4|$). The masses of the Links 1 and 2 are positioned at the midpoint of each link, and the parameters l_{c_1} and l_{c_2} indicate the distances of m_1 and m_2 from Joints 1 ($|J_1C_1|$) and 2 ($|J_2C_2|$), respectively.

As mentioned in the introduction, this article focuses on the mechanical design of a passively gravity-balanced mechanism with a variable end-effector mass. The design of the gravity-balanced mechanism in this study has the following assumptions: There are not any control considerations for Links 1 and 2, the mechanism is gravity-balanced in the vertical plane, the springs and auxiliary parallelogram are massless, Links 1 and 2 have the same length and mass, the centre of mass points of Link 1 and Link 2 are located at their midpoints, and the centre of mass point of Link 3 is located at Joint 3 (J_3).

Problem formulation. This study investigates static analysis of the mechanism; hence, kinetic energy is not part of the analysis. For the static balancing, the total potential energy of the mechanism must be constant in all configurations of the mechanism. As shown in Fig. 2, the planar gravity-balanced mechanism has three links (with end-effector), two linear springs with an auxiliary parallelogram. The design introduced in this study uses zero free-length springs. The elastic potential energy and the gravitational potential energy of the system are calculated as follows:

Spring 1 potential energy:

$$V_{s_1} = \frac{1}{2}k_1\left(d_1^2 + d_2^2\right) - k_1 d_1 d_2 \sin\theta_1, \tag{1}$$

where parameter k_1 is the Spring 1 constant, parameter d_1 is vertical distance

between the Joint 1 (J_1) and Spring 1 fixed point on the parallelogram, parameter d_2 refers to the distance between Joint 1 (J_1) and the fixed point of Spring 1 on the Link 1 and the angle θ_1 is the angle of Link 1 relative to the horizontal axis.

Spring 2 potential energy:

$$V_{s_2} = \frac{1}{2}k_2\left(d_3^2 + d_4^2\right) - k_2 d_3 d_4 \sin(\theta_1 + \theta_2), \tag{2}$$

where parameter k_2 is the Spring 2 constant, parameter d_3 refers to the vertical distance between Joint 2 (J_2) and Spring 2 fixed point on the parallelogram, parameter d_4 is the distance between Joint 2 (J_2) and the fixed point of Spring 2 on the Link 2, and the angle θ_2 refers to the angle of the Link 2 relative to the Link 1.

The total spring potential energy can be written from Eqs (1) and (2):

$$V_{s_T} = \frac{1}{2}k_1\left(d_1^2 + d_2^2\right) + \frac{1}{2}k_2\left(d_3^2 + d_4^2\right) - k_1 d_1 d_2 \sin\theta_1 - k_2 d_3 d_4 \sin(\theta_1 + \theta_2). \tag{3}$$

Link 1 gravitational potential energy equation can be written:

$$V_{G_1} = m_1 g l_{c_1} \sin\theta_1, \tag{4}$$

where parameter m_1 refers to Link 1 mass, parameter g is the gravitational acceleration and parameter l_{c_1} is the length of the centre of mass point location of the Link 1.

Link 2 gravitational potential energy equation can be written:

$$V_{G_2} = m_2 g l_1 \sin\theta_1 + m_2 g l_{c_2} \sin(\theta_1 + \theta_2), \tag{5}$$

where parameter m_2 is the Link 2 mass, parameter l_1 refers to the Link 1 length, parameter l_{c_2} refers to the length of the centre of mass point location of the Link 2.

Link 3 (end-effector) gravitational potential energy equation can be written:

$$V_{G_3} = m_3 g l_1 \sin\theta_1 + m_3 g l_2 \sin(\theta_1 + \theta_2), \tag{6}$$

where parameter m_3 refers to the Link 3 (end-effector) mass and parameter l_2 is the Link 2 length.

The total gravitational potential energy can be written from Eqs (4), (5) and (6):

$$V_{G_T} = [m_1 g l_{c_1} + m_2 g l_1 + m_3 g l_1]\sin\theta_1 + [m_2 g l_{c_2} + m_3 g l_2]\sin(\theta_1 + \theta_2). \tag{7}$$

The total potential energy should be the sum of elastic potential energy and gravitational potential energy:

$$V_T = V_{s_T} + V_{G_T} \tag{8}$$

$$\begin{aligned} V_T = {} & \frac{1}{2}k_1\left(d_1^2 + d_2^2\right) + \frac{1}{2}k_2\left(d_3^2 + d_4^2\right) - k_1 d_1 d_2 \sin\theta_1 - k_2 d_3 d_4 \sin(\theta_1 + \theta_2) \\ & + [m_1 g l_{c_1} + m_2 g l_1 + m_3 g l_1]\sin\theta_1 + [m_2 g l_{c_2} + m_3 g l_2]\sin(\theta_1 + \theta_2). \end{aligned} \tag{9}$$

The total potential energy needs to be constant in all configurations to achieve gravity balancing for the mechanism. If the total potential energy is the constant, the following equation can be written:

$$\frac{\partial}{\partial_\theta}(V_T) = 0. \tag{10}$$

By using Eqs (9) and (10), the following equations can be written:

$$m_1 g l_{c_1} + m_2 g l_1 + m_3 g l_1 = k_1 d_1 d_2, \tag{11}$$

$$m_2 g l_{c_2} + m_3 g l_2 = k_2 d_3 d_4. \tag{12}$$

Equations (11) and (12) can be written as function of mass of Link 3 (m_3) for the different load of end-effector. Thus, change of the end-effector will be possible:

$$d_2 = f(m_3) = \frac{m_1 g l_{c_1} + m_2 g l_1 + m_3 g l_1}{k_1 d_1}, \tag{13}$$

$$d_4 = f(m_3) = \frac{m_2 g l_{c_2} + m_3 g l_2}{k_2 d_3}. \tag{14}$$

By using Eqs (13) and (14), attachment locations of the Spring 1 and Spring 2 on Link 1 and Link 2, respectively, can be changed for the gravity compensation when the end-effector mass (m_3) is changed.

Results and discussion. The motion of the mechanism is simulated to verify the introduced gravity-balanced mechanism in this study. For better understanding, simulations are also performed on non-gravity-balanced mechanisms. While the gravity-balanced mechanism has an auxiliary parallelogram with two linear springs for gravity compensation, the non-gravity-balanced mechanism has only links and does not have any attached components. The following parameter values are assigned for the simulation: $m_1 = 0.06$ kg, $m_2 = 0.06$ kg, $m_3 = 0.01$ kg, $k_1 = 2.5$ N/m, $k_2 = 1$ N/m, $l_1 = 1$ m, $l_2 = 1$ m, $l_{c_1} = 0.5$ m, $l_{c_2} = 0.5$ m, $d_1 = 0.5$ m, $d_2 = 0.8$ m, $d_3 = 0.5$ m and $d_4 = 0.8$ m.

Figure 3 shows the potential energy of Links 1 and 2 along with the total potential energy for the not gravity-balanced mechanism during the simulation. Since the mechanism does not have any attached springs, the links undergo free oscillation during the simulation. The potential energy curve exhibits an up and down pattern during the five seconds of simulation, as seen in Fig. 3, due to the free oscillation of the links. As shown in Fig. 3, the potential energy fluctuation of Link 1 ranges between -2.5 J and -4.6581 J while the potential energy fluctuation of Link 2 ranges between -9.8296 J and -8.9753 J. The sum of the potential energies of Links 1 and 2 is displayed as the total gravitational potential energy in Fig. 3, and its fluctuation ranges between -12.3296 J and -13.6334 J. The gravitational potential energy values are negative in Fig. 3 since the centre of mass location of the links is below the reference axis. As seen in Fig. 3, the Link 1

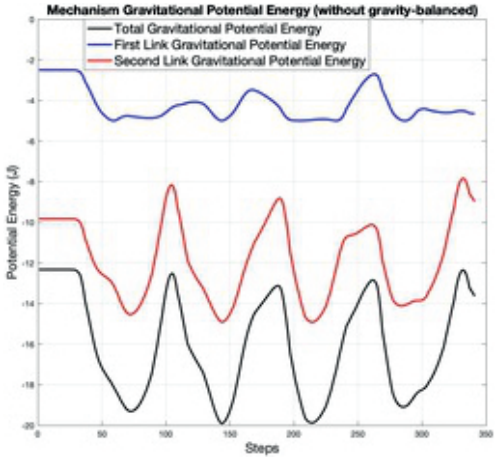


Fig. 3. The potential energy of the not gravity-balanced mechanism

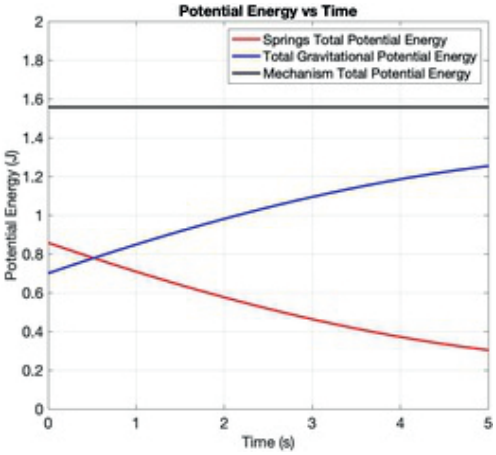


Fig. 4. The potential energy of the gravity-balanced mechanism

potential energy values are closer to zero compared to Link 2 since it is closer to the base.

As seen in Fig. 3, there is a notable fluctuation in the potential energy of Links 1 and 2. The main reason for this fluctuation is the free oscillation of the links, as the mechanism does not have any attached mechanism for gravity compensation. Therefore, the mechanism has free movement ability due to gravity. The potential energy of Spring 1 and Spring 2 decreases during the simulation. At the initial position of the mechanism, the potential energy of Spring 1 is 0.6125 J, and the potential energy of Spring 2 is 0.2450 J. At the final position of the mechanism, the potential energy of Spring 1 decreases to 0.2585 J, and the potential energy of Spring 2 decreases to 0.0454 J.

Figure 4 shows the change of potential energy of the mechanism components during 5 s of motion simulation. As seen in Fig. 4, during the motion of the mechanism, the total potential energy of the mechanism remains constant, but the total potential energy of the springs and gravitational potential change over time. According to Fig. 4, the total potential energy of the mechanism is 1.5575 J during the motion. In the first position of the mechanism, the total potential energy of the springs is 0.8575 J and the total gravitational potential energy is 0.7 J. During the motion, the total potential energy of the springs and gravitational potential energy change over time, and they are 0.3040 J and 1.2535 J, respectively, in the last position of the mechanism.

The results demonstrate that as the total gravitational potential energy increases, the total potential energy stored in the springs decreases. Nevertheless, the total potential energy of the mechanism remains constant. The essential aspect of the gravity-balanced mechanism is that the potential energy remains constant

for all configurations. Consequently, the proposed planar mechanism satisfies the condition for being a gravity-balanced mechanism by incorporating an auxiliary parallelogram and two linear springs, as demonstrated in this study.

Conclusion. This article presents a gravity-balanced robotic manipulator mechanism for the operating room. The presented mechanism is gravity compensated by using an auxiliary parallelogram and two linear springs. The mechanism does not have any actuator as a fully passive gravity-balanced mechanism. The simulation results show that the introduced mechanism in this study is gravity-balanced in all configurations. The presented gravity balancing methodology can be also used for the multi-link mechanisms for the gravity balancing.

Acknowledgements. The author wishes to express his gratitude to the Ministry of National Education of the Republic of Türkiye which indirectly made this work possible.

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Department of Electronics and Automation
Batman University
Kültür, Türkiye Petrolleri A. O. Blv.
72060, Merkez/Batman, Türkiye
e-mail: onur.denizhan@batman.edu.tr