Gravity Balancing of a Seven-DOFs Hybrid Manipulator

Amanpreet Singh, Ashish Singla*, Sanjeev Soni

Abstract

The main focus of this work is to perform the gravity balancing of a seven degrees-of-freedom (DOFs) hybrid manipulator. A hybrid manipulator is a combination of open- and closed-loop chains and contains planar and spatial links. Gravity balancing is an important aspect for robotic manipulators, especially for serial manipulators, where with increase in number of links, the gravitational effect of succeeding links increases on preceding joints. This leads to reduced positional accuracy, low payload carrying capacity, and high power requirement of the serial manipulator. In such situations, gravity compensation needs to be provided in order to improve the performance. In this paper, the concept of gravity balancing is used and extended for a hybrid manipulator. The gravity balancing for hybrid manipulators has been demonstrated on the case study of a hybrid manipulator, which is to be used for medical surgery.

Keywords: Hybrid manipulator, gravity balancing, zero-free-length spring, spatial link.

1 Introduction

Gravity Balancing is an important aspect for robotic manipulators, especially for serial manipulators. Because, in serial manipulators as the number of links keeps on increasing, the gravitational effect due to the weight of succeeding links and joints keeps on increasing on preceding joints [1]. This leads to degradation of performance in terms of positional accuracy, load carrying capacity, and power requirement to operate the manipulator etc. In order to improve the performance, gravity compensation is provided. A robotic manipulator is referred to as gravity balanced, if joint actuator inputs are not required to keep the system in static equilibrium at any configuration. Also, a manipulator is said to be statically balanced, if it remains in static equilibrium at its any possible configuration. The mathematical conditions like the potential energy of system remains constant due to change in its configuration, centre of mass does not change inertially, the system remains gravity balanced for every configuration because of the presence of counterweights, can be given to a gravity-balanced system [2]. Further, these conditions can be achieved by, attaching the counterweights to each link of the manipulator (at centre of mass), using springs at appropriate places, as the potential energy of system and the spring remains invariant with configuration of the manipulator, and locating the centre of mass using auxiliary parallelograms.

In literature, gravity balancing has been broadly classified into two categories – *active gravity balancing* and *passive gravity balancing*. In active gravity balancing, actuator power is continuously supplied to keep the system in static equilibrium. To accomplish this, either additional actuators are used, which results in increasing the size, mass and complexity of manipulator, or primary actuators are used, which degrades the dynamic performance of the manipulator [1]. This method of gravity balancing demands large power requirements, because generally more than half of the available actuator power is used in gravity compensation.

However, the problem of large power requirement (in the case of active gravity compensation) can be handled by using counter weights or springs [3, 4], which is termed as passive gravity compensation. In passive gravity compensation, counter weights are added to make the perpendicular distance between centre of mass and joint axis to be zero. As compared to active gravity balancing, the power requirement in this case reduces considerably, which leads to significant improvement in the dynamic performance of the manipulator. However, addition of weights leads to an increase of inertia, complexity and volume of manipulator [4]. So, it is preferable to use the spring elements with or without auxiliary links.

The passive mechanical methods for gravity balancing of variety of manipulators has been proposed by Nathan and Kumar [1] and Agrawal and Fatteh [2]. The first method was based on energy approach i.e gravitational potential energy of manipulator is countered to strain energy of springs, by using spring elements, cables and cam shaped pullies and the second method was based on hybrid strategy which uses spring elements as well as auxiliary parallelograms. Further, Agrawal and Fatteh has used this method in their work of gravity balancing of class of industrial robots with anthropomorphic designs [3]. Both of the methods used the springs with auxiliary links to provide gravity compensation. The proposed methods has advantages, over gravity balancing with counter weights, like it is mechanically simple, lower system inertia, lesser energy input.

Another approach for gravity balancing is to make use of springs of zero-free-length. Dorsser et al. [5], Nathan [6], Pracht [7], Streit, B.J. Gilmore [8], Streit and Shin [9], used the spring of *zero-free-length* and *auxiliary* links, for gravity balancing of robotic manipulators. A zero-free-length spring [10] can be described as a linear spring whose length is zero, when no external load is applied on it. In other words, in these springs, spring force [5] is proportional to total length of spring rather than elongation. A spring of zero free length can be obtained with suitable combination of normal springs. Gravity balancing can also be done by means of springs of zero-free-length only i.e. without the use of auxiliary links. The same has been reported by Deepak and Ananthasuresh, to statically balance a general tree structured linkage loaded with linear springs or constant forces [10], static balancing of four bar linkage [11] and other linkages [12]. Lin et al. [13] also uses the zero free length springs to design a gravity balanced general-spatial-serial type manipulator.

A perfect gravity balancing can be achieved by using springs of zero-free-length. The springs of positive and negative-free-length can be assembled, to produce a spring of zero-free-length. However, with this arrangement and through use of auxiliary links, there is considerable space requirement to accommodate these. This is not desirable in some of the practical applications, as it increases the complexity of mechanism and limits the range of motion of links. In this context, Herder [14] described several gravity equilibrators providing the perfect static balancing, by making use of normal springs instead of springs of zero-free-length.

The different methods of gravity balancing presented above have been applied by different researchers [15, 16] for balancing of a variety of robotic manipulators. In this context, active gravity balancing has been used by Bassan et al. [15] to balance the micro-manipulator. The first joint axis of the micro-manipulator has been balanced completely using prescribed gravity balancing method whereas the second joint axis was balanced partially. Further, remaining unbalanced gravitational forces in second joint axis has been compensated by using springs. The counterweights have been used by Abolmaesumi et al. [16] to gravity balance an inherently safe, light and backdrivable robot.

2 Case Study: A Hybrid Manipulator

A hybrid manipulator is described as a combination of serial and parallel chains [17] or a mixture of open and closed-chains or a sequence of parallel mechanisms [18, 19].

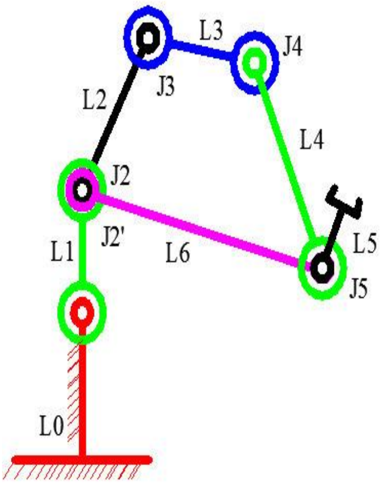


Figure 1-(a): A hybrid manipulator, integration of open and closed loop chains.

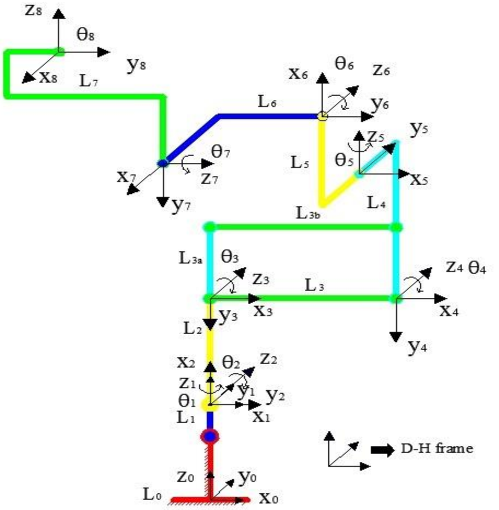


Figure 1-(b): Basic mechanical structure and link description of MMA.

Such a manipulator removes the deficiencies of serial, lower payloads, less accuracy and precision, heavy structure, and parallel manipulators [20]. These manipulators have accuracy comparable to parallel manipulator and workspace comparable to serial manipulators. For example, in the case of serial manipulators and lesser workspace, existence of singular points within the workspace in the case of parallel manipulators [20].

Figure 1-(a), shows a hybrid manipulator which is a combination of open and closed loop chains. The IRB260, a combination of two parallelogram linkages made by ABB Company, is an example of hybrid manipulator whose kinematic study has been performed by Shi et. al [21]. Other hybrid manipulators being considered in the literature are Cassino Hybrid Manipulator, ARTISAN from Stanford, USA, HRM from Korea Institute of Machinery and Materials, Korea, UPSarm from the California University, Davis (USA) etc. [20].

In the previous section, different techniques of gravity balancing available in the literature, have been reviewed. These techniques include the gravity balancing by means of (a) springs of zero-free-length with or without auxiliary links and, (b) normal springs. However, some of the practical applications restricts the use of auxiliary links and zero-free-length springs, as it creates two problems− i) an increase in complexity of the mechanism; ii) limits the range of motion of links, which is undesirable in applications requiring precise movements.

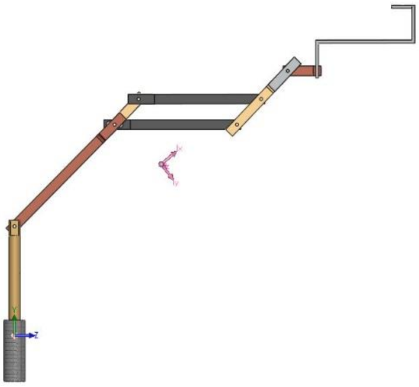


Figure 2: Assumed pose of the considered hybrid manipulator.

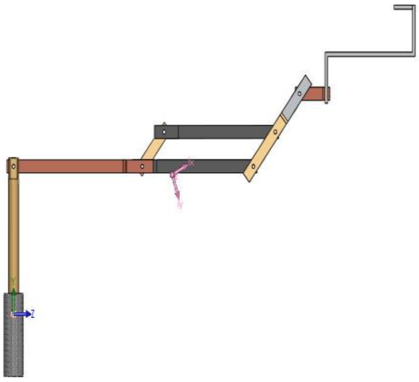


Figure 3. Maximal unbalanced pose of the hybrid manipulator.

In present work, an effort has been made to statically balance a 7-DOF hybrid manipulator (as shown in Fig.1-(b), [22]) for medical applications (MMA). In this hybrid manipulator, the use of external auxiliary links is highly undesirable because, it restricts the motion of surgeon's hand during a surgical task. That is why, auxiliary links are not preferred for the gravity balancing of the MMA.

In this work, normal springs are used for the gravity balancing. Here, the respective joint torques are countered with the resisting-torques provided by the springs attached to the consecutive links of MMA. In Section 3, the design of the normal spring for static balancing of MMA is presented. For gravity balancing, the MMA is assumed in an appropriate pose, as shown in Fig. 2. The idea behind this pose is that the surgeon can easily reach horizontal as well as vertical positions. However, the moments are calculated for a maximal gravity-loaded configuration i.e where the effect of the gravity is most pronounced. This configuration is shown in Fig. 3.

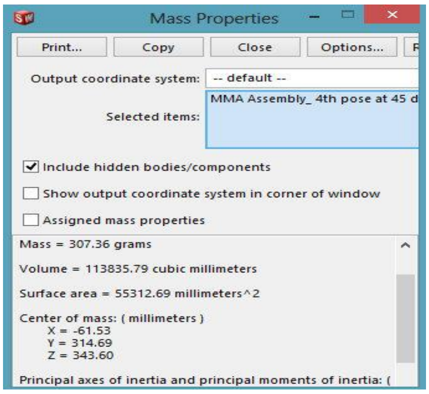
3 Spring Design for Gravity Balancing

A spring for each pair of the links is designed in two steps. In first step, torque induced at a joint under consideration is calculated. Thereafter, the resisting torque is provided through suitably designed springs.

3.1 Calculation of Joint Torques

Figure 3, shows the MMA in a pose at which joint torque is maximum at the joint between links $L_1$and L_2 (also see the Fig. (6-a)). The distance between the joint and point of attachment of spring is fixed, which means that the free length of spring is fixed. In order to compute the centre of mass, MMA was modelled in SolidWorks with aluminium alloy (Alloy 1060 with density 2700 kg/m^3) as its material. Thereafter, from the mass-property analysis, the centre of gravity of MMA is calculated.

The torque induced at joint between links L_1 and L_2 can be calculated by using the mass properties (refer Fig. (5)), for the maximal gravity-loaded configuration of MMA. It is assumed that the weight of all links (except of L_0 and L_1, as it does not contribute any gravity load) acts through centre of mass. The masses of the different links of the MMA prototype are given in Table 1. In context to Fig. (6), the torque ($\boldsymbol{\tau}$) at the joint can be calculated as,

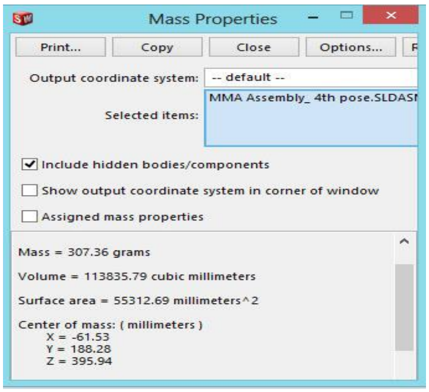


Output coordinate system: -- default --
Selected items: MMA Assembly_ 4th pose at 45 d

☑ Include hidden bodies/components
☐ Show output coordinate system in corner of window
☐ Assigned mass properties

```
Mass = 307.36 grams

Volume = 113835.79 cubic millimeters

Surface area = 55312.69 millimeters^2

Center of mass: ( millimeters )
	X = -61.53
	Y = 314.69
	Z = 343.60

Principal axes of inertia and principal moments of inertia: (
```

Figure 4: Mass properties of MMA in the pose shown in Fig. (2).



Output coordinate system: -- default --
Selected items: MMA Assembly_ 4th pose.SLDASI

☑ Include hidden bodies/components
☐ Show output coordinate system in corner of window
☐ Assigned mass properties

```
Mass = 307.36 grams

Volume = 113835.79 cubic millimeters

Surface area = 55312.69 millimeters^2

Center of mass: ( millimeters )
	X = -61.53
	Y = 188.28
	Z = 395.94
```

Figure 5: Mass properties at maximal gravity-loaded configuration Fig. (3).

$$\boldsymbol{\tau} = \sum_{i=2}^{n} w_i \times r_i = w_{eq} \times r_{eq}, \tag{1}$$

where,

w_i = weight of i^{th} link, in Fig. (2),
r_i = moment arm of i^{th} link w.r.t the joint axis of L_2 in Fig. (2),
w_{eq} = equivalent weight of all links shown in Fig. (3),
r_{eq} = equivalent moment arm of MMA shown in Fig. (3).

Using the above methodology, the joint torques are calculated on the first configuration, as shown in Fig. (2), is given as,

$$w_{eq} = 307.36 \text{ gms}, \qquad r_{eq} = 343.60 \times 10^{-3} \text{ m}.$$

$$\boldsymbol{\tau}_{Pose_1} = 307.36 \times 10^{-3} \times 9.8 \times 343.60 \times 10^{-3} = 1.0349 \text{ Nm} \tag{2}$$

Table 1: Masses of different links of MMA.

S.no	1.	2.	3.	4.	5.	6.	7.	8.	9.
Link (L_i)	L_2	L_3	L_{3a}	L_{3b}	L_4	L_5	L_6	L_7	Packing
Mass (g)	37.73	25.87	7.46	25.87	25.57	16.93	12.09	152.59	3.25

Similarly, the joint torque at the second assumed configuration, as shown in Fig. (3), is given as,

$$\boldsymbol{\tau}_{Pose_2} = 307.36 \times 10^{-3} \times 9.8 \times 395.94 \times 10^{-3} = 1.1926 \text{ Nm} \quad (3)$$

Now, the torques calculated in previous step must be balanced through the resisting-torque provided by the designed springs. Following relations can be formulated for this,

$$\boldsymbol{\tau}_{sp_1} = \boldsymbol{F}_{sp_1} \times r_1 \quad (4)$$
$$\boldsymbol{\tau}_{sp_2} = \boldsymbol{F}_{sp_2} \times r_2 \quad (5)$$
$$\boldsymbol{F}_{sp_1} = k \times x_1 \quad (6)$$
$$\boldsymbol{F}_{sp_2} = k \times x_2 \quad (7)$$

Eqn. (4) gives the torque acting at the same joint when MMA has a pose as shown in Fig. (2). It can be seen from Table 1, the mass of the manipulator, after adding all of the masses, is found as 310.36 gms, which is found in close agreement with the mass reported by Solidworks. The $\boldsymbol{F}_{sp_1}$ and $\boldsymbol{F}_{sp_2}$ are the spring forces for poses shown in Figs. (2) and (3) respectively. Also, equivalent figures are shown as Fig. 6-(a) and 6-(b) respectively. Symbols, r_1 and r_2 are the perpendicular distances between pivot point and an axis of the spring, k is the stiffness of spring and x_1, x_2 represents the deformations of the springs for prescribed poses shown in Figs. (2) and (3) respectively. Now, as there is no deformation of spring in the pose, Fig. (2), assumed for gravity balancing, so $x_1 = 0$.

With reference to Fig. (6-a), the free-length of spring can be calculated by applying the *Sine law* to $\Delta\ ODE$. From geometry of triangle (ODE), it can be derived that,

$\angle B = \angle C$ and $\angle A = 135^0$ $\Rightarrow \angle B = \angle C = 22.5^0$

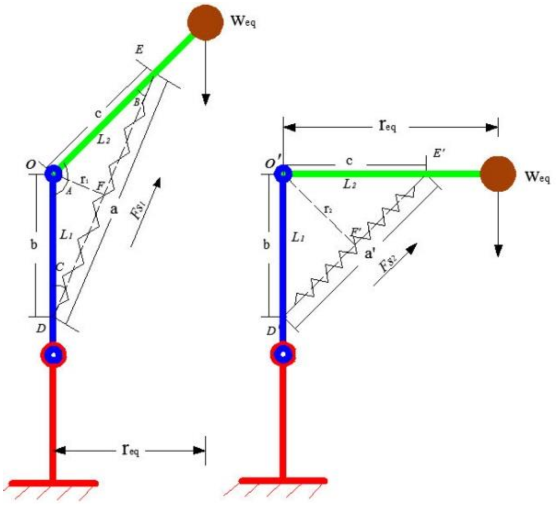


Figure 6-(a): Spring of free-length $L_f = a$, attached at a distance b on link L_1 and c on linkL_2, from pivot point O such that b = c. Figure 6-(b): The pose of MMA at which joint torque is maximum at point O'.

According to Sine law:

$$\frac{a}{sinA} = \frac{b}{\sin B} \tag{8}$$

$$a = \frac{b \times \sin A}{\sin B} = 28 \times \frac{sin135^0}{\sin 22.5^0}$$

$$a = 51.7372 \text{ mm.} \tag{9}$$

From $\Delta\, ODF$:r_1 $= OD \times \sin C = 28 \times \sin 22.5^0$

$$r_1 = 10.7151 \text{ mm} \tag{10}$$

Also, deformation (x_2) of spring, when rotating link L_2 from the assumed home position (Fig. (6-a)) to a position as shown in Fig. (-b), can be calculated as,

$$x_2 = (a - a')$$

Applying Pythagoras theorem to, $\Delta\, O'D'E'$ for a' and $\Delta\, O'D'F'$ for r_2:

$a' = 39.5979$ mm, $x_2 = 12.1392$ mm, $r_2 = 19.7989$ mm.

The equations of resisting torque can be formulated as:

$$\boldsymbol{\tau}_{sp_1} = \boldsymbol{F}_{sp_1} \times r_1 = k \times x_1 \times r_1 \tag{11}$$

$$\boldsymbol{\tau}_{sp_2} = \boldsymbol{F}_{sp_2} \times r_2 = k \times x_2 \times r_2 \tag{12}$$

Subtracting Eq. (11) from Eq. (12) and substituting values of all quantities, we get,

$$\boldsymbol{\tau}_{sp_2} - \boldsymbol{\tau}_{sp_1} = k \times x_2 \times r_2 - k \times x_1 \times r_1$$

For static balancing,

$$\boldsymbol{\tau}_{Pose_1} = \boldsymbol{\tau}_{sp_1} \text{and } \boldsymbol{\tau}_{Pose_2} = \boldsymbol{\tau}_{sp_2}$$

From Eqns. (2) and (3),

$$k(12.1392 \times 19.7989 - 0 \times 10.5171) \times 10^{-6} = 0.1577$$

$$\Rightarrow k = 656.146$$

Thus, required stiffness of spring is: $k_s = k \times F_s = 656.146 \times 1.15 =$ 754.57 N/m (13)

Specifications of the designed spring are,

1) Fixed Parameters**:** - The free length (L_f), mean coil diameter (D) and wire diameter (d) are kept fixed for design of spring. These are 51.73mm, 14mm and 1.5mm respectively.
2) Designed Parameters: - By using the fixed parameters the other design parameters of spring are calculated and are mentioned in Table 2.

Table 2: Parameters of the designed springs.

S.No	**Spring parameters**	**Empirical relation**	**Designed value**
1.	Number of turns (N)	$\frac{Gd^4}{8D^3k_s}$	25
2.	Slenderness ratio	$\frac{L_f}{D}$	3.69
3.	Solid length (L_S)	$(N \times d)$	37.5 mm
4.	Spring index (C)	$\frac{D}{d}$	9.33
6.	Pitch (p)	$\frac{L_f}{N-1}$	2.16 mm

In the above analysis, hard drawn wire spring steel considered as spring material (G=80 $\times 10^9$ N/m^2). With the help of prototype of the MMA space available for spring attachment i.e. free-length (L_f) of the spring is given by Eqn. (9). By using it, the mathematical calculations are performed to compute the stiffness of the spring. For the same factor of safety (F_s) is taken as 1.15.

At this point, it is important to mention that free length was decided, to maintain slenderness ratio of the designed spring to be less than four, to avoid buckling of spring. The two design parameters, mean coil diameter and wire diameter, which remain invariant from the space limitation viewpoint are given as above. Further, by using the standard empirical relations, other parameters of spring have been calculated given presented in Table 2.

Ultimately, the above described procedure was repeated for the linkages of the prototype to achieve the desired gravity balanced MMA.

4 Conclusions

In this paper, design of a helical spring, for the gravity compensation of a 7-DOF hybrid manipulator has been presented. In the present work, helical springs without auxiliary link were used for the gravity balancing because these offer least obstruction to the operator especially in medical applications. The respective joint torques (due to gravity) were counterbalanced by the stiffness/resisting torque provided through the designed springs. A virtual prototype of the hybrid manipulator was modeled in Solidworks to calculate the joint torques and other mass properties of the links. Mass properties were compared with the developed prototype of the manipulator. Further, the same approach was extended for the design of springs required for other links of MMA.

References

[1] Nathan Ulrich and Vijay Kumar, *"Passive gravity compensation for robot manipulators"*, Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), pp. 1536–1541, Sacramento, CA (1991).

[2] Sunil K. Agrawal and Abbas Fattah, *"Gravity balancing of spatial robotic manipulators"*, Journal of Mechanism and Machine Theory, vol. 39, pp. 1331–1344, (2004)

[3] Sunil K. Agrawal and Abbas Fattah, *"Gravity-balancing of classes of industrial robots"*, International Conference on Robotics and Automation (ICRA), pp. 2872–2877, Orlando, FL (2006).

[4] I. Simionescu, L. Ciupitu, Luciana Ionita, I. Ion and M. Ene, *"Elastic systems for static balancing of robot arms"*, In proceedings of 13th World Congress of Machine and Mechanism Science, pp. 19-25, Guanajuato, México (2011).

[5] Wouter D. van Dorsser, Rogier Barents, Boudewijn M. Wisse and Just L. Herder, *"Gravity balanced arm support with energy-free adjustment"*, ASME Journal of Medical Devices, vol. 1, pp.151–158, (2007).

[6] R. M. Nathan, *"A constant force generation mechanism"*, Journal of Mechanical Design, vol. 107, pp. 508–512, (1985).

[7] P. Pracht, P. Minotti and M. Dahan, *"Synthesis and balancing of cam-modulated linkage"*, In Proceedings of ASME Design and Automation Conferences (IDETC), vol. 10, pp. 221-226, (1987).

[8] D. A. Streit and B. J. Gilmore, *"Perfect spring equilibrators for rotatable bodies",* ASME Journal of Mechanical Design, vol. 115, pp. 604–610, (1993).

[9] D. A. Streit and B. J. Gilmore, *"Perfect spring equilibrators for rotatable bodies"*, ASME Journal of Mechanisms, Transmissions, and Automation in Design, vol. 111, pp. 451–458, (1989).

[10] S. R. Deepak and G. K. Ananthasuresh, *"Static balancing of spring-loaded planar revolute-joint linkages without auxiliary links"*, In proceedings of 14th National Conference on Machines and Mechanisms, pp. 37-44, NIT Durgapur, India (2009).

[11] S. R. Deepak and G. K. Ananthasuresh, *"Static balancing of a four-bar linkage and its cognates"*, Mechanism and Machine Theory, vol. 48, pp. 62–80 (2012).

[12] S. R. Deepak and G. K. Ananthasuresh, *"Perfect static balance of linkages by addition of spring but not auxiliary bodies",* ASME Journal of Mechanisms and Robotics, vol. 4, pp. 021104-1–021104-12, (2012).

[13] P. Y. Lin, W. B. Shieh, and D. Z. Chen, *“Design of a gravity- balanced general spatial serial-type manipulator”*, ASME Journal of Mechanisms and Robotics, vol. 2, pp. 021015-1-021015-7, (2010).

[14] Freek L. S. te Riele and Just L. Herder, *“Perfect static balancing with normal springs”*, In Proceedings of the ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE), pp. 1–8, Pittsburgh, PA (2001).

[15] Harmanpreet S. Bassan, Rajni V. Patel and Mehrdad Moallem, *“A novel manipulator for percutaneous needle insertion: design and experimentation”* IEEE/ASME Transactions on Mechatronics, vol. 14, pp. 746-761, (2009).

[16] Purang Abolmaesumi, Septimiu E. Salcudean, Wen-Hong Zhu, Mohammad R. Sirouspour, and Simon P. DiMaio, *“Image-guided control of a robot for medical ultrasound”* IEEE Transactions on Robotics and Automation, vol. 18, pp. 11-23, (2002).

[17] Carbone, Giuseppe, and Marco Ceccarelli. *"A stiffness analysis for a hybrid parallel-serial manipulator"*, Robotica, vol. 22, pp. 567-576, (2004).

[18] Tanio Tanev, *“Workspace of a hybrid (parallel-serial) robot manipulator”,* Problems of Engineering Cybernetics and Robotics, Bulgarian Academy of Sciences, vol. 56, pp. 3-9, (2006).

[19] Amanpreet Singh, Ashish Singla and Sanjeev Soni, “*Extension of D-H parameter method to hybrid manipulators used in robot-assisted surgery”*, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, SAGE Publications, vol. 229, pp. 703-712, UK, (2015).

[20] Gallardo-Alvarado, J. *“Kinematics of a hybrid manipulator by means of screw theory”,* Multibody System Dynamics, vol. 14, pp. 345-366, (2005).

[21] Jun Shi, Xiaorui Zhu and Zexiang Li, *“New method for kinematic analysis of a hybrid manipulator”,* Proceedings of the IEEE, International Conference on Information and Automation, pp. 207-211, Zhuhai/Macau, China (2009).

[22] Amanpreet Singh, Ashish Singla and Sanjeev Soni, *“D-H parameters augmented with dummy frames for serial manipulators containing spatial links*" The 23rd IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), pp. 975-980, Edinburgh, Scotland, UK (2014).