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SURVEY PAPER

Gravity compensation in robotics

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ABSTRACT

The actuator power required to resist joint torque caused by the weight of robot links can be a significant problem. Gravity compensation is a well-known technique in robot design to achieve equilibrium throughout the range of motion and as a result to reduce the loads on the actuator. Therefore, it is desirable and commonly implemented in many situations. Various design concepts for gravity compensation are available in the literature. This paper proposes an overview of gravity compensation methods applied in robotics. The examined properties of the gravity compensation are disclosed and illustrated via kinematic schemes. In order to classify the considered balancing schemes three principal groups are distinguished due to the nature of the compensation force: counterweight, spring or active force developed by an auxiliary actuator. Then, each group is reviewed through sub-groups organized via structural features of balancing schemes. The author believes that such an arrangement of gravity compensation methods allows one to carry out a systematized analysis and provides a comprehensive view on the problem.

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1. Introduction

Many robotic systems are operated at low speed to ensure the different tasks. In this situation, gravitational torques generated by the masses of links are often much greater than dynamic torques. Thus, gravity compensation is beneficial by which a robotic system can be operated with relatively small actuators generating less torque. The potential energy of such a robotic system is constant (or quasi-constant) for all possible configurations which lead to the self-balancing of the mechanical system. Nature of the forces that must compensate gravity and its emplacement in the robotic systems may be diverse. In the present paper, the typical gravity compensation solutions are systematized and their effectiveness is considered. The criteria for systematization of gravity compensation methods can be various: main applications, structural particularity, nature of balancing force, etc. The given systematization is not the only way and can be modified according to the subjective preferences of each researcher. However, the author believes that the arrangement of compensation methods into groups, which present the nature of compensation force and then into sub-groups, which present the structural features, provides a comprehensive view on the problem.

It should be noted that the gravity compensation can also be achieved by optimal control of input torques. In this case, the control law combines terms that cancel the gravity effects on the robot link dynamics with a PD-type error feedback on the motor variables. However, in this survey, the mechanical solutions of the gravity compensation will only be reviewed.

The given systematization can be presented as follows:

2.	Gravity compensation by counterweights
2.1.	Gravity compensation by counterweighs mounted on the links of the initial system
2.2.	Gravity compensation by counterweights mounted on the auxiliary linkage connected with the initial system
3.	Gravity compensation by springs
3.1.	Balancing by springs jointed directly with manipulator links
3.2.	Balancing by using the cable and pulley arrangement
3.3.	Balancing by using auxiliary systems
3.3.1.	Balancing by using an auxiliary linkage
3.3.2.	Balancing by using a cam mechanism
3.3.3.	Balancing by using a gear train
4.	Gravity compensation by using auxiliary actuators

The advantages and drawbacks of the compensation methods are disclosed and the design particularities of the gravity compensation of each section are reviewed via various examples.

It should be noted that the given systematization is arranged by principal groups. It is obvious that it is also possible to combine the different balancing approaches,

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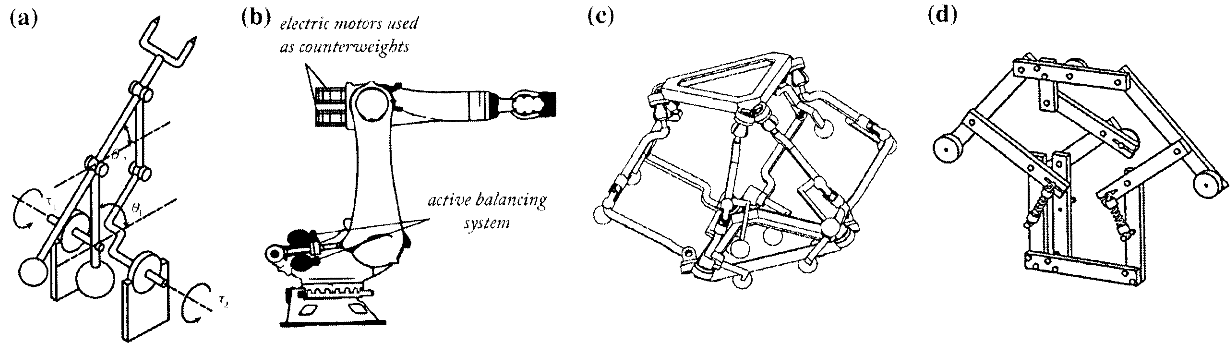

Figure 1. Gravity compensation by counterweighs mounted on the links: serial (a, b) [9,10] and parallel (c, d) manipulators [12,14].

such as a balancing by counterweights combined with springs or cams combined with counterweights, etc.

Finally, a conclusion summarizing the reviewed methods and techniques of the gravity compensation, as well as the perspectives is given.

2. Gravity compensation by counterweighs

The use of counterweights has been applied to the design of mechanical systems for a long time.[1–3] The classical approach consists in adding counterweights in order to keep the total centre of mass of moving links stationary. With regard to the several approaches employed for the redistribution of movable masses, the developed design concepts could be divided into two principal sub-groups denoted as 2.1 and 2.2.

2.1. Gravity compensation by counterweighs mounted on the links of the initial system [4–14]

It is obvious that the adding of the supplementary mass as a counterweight is not desirable that it leads to the increase of the total mass, overall size of the robot-manipulator and the efforts in joints. That is why in many constructions of industrial robots, for example KUKA R360 or PUMA 200, the masses of the motors are often used for gravity compensation (Figure 1).[10]

The review slowed that the gravity compensation by counterweights mounted on the links is more appropriate for serial and planar parallel manipulators. It is much more difficult for spatial parallel manipulators.

Gravity compensation has been successfully applied on hand-operated balanced manipulators (HOBM). The balanced manipulator is a handling system with a simple mechanical system in which the manipulated object in any position of the workspace is balanced.[15] Such a state of constant gravity cancellation allows displacements of heavy objects manually.

The term 'balanced manipulator' shows that in the operating procedure of these systems is very important to achieve an accurate compensation of gravity. Many studies and design concepts have devoted to the gravity compensation of these manipulators by counterweights.[15–25] It was shown that for the balancing of these manipulators it is necessary to apply to the pantograph mechanism a sinusoidal balancing moment. The general approach for determination of balancing conditions was proposed by the study of the motion of the centre of mass of the pantograph actuator.[20] In many HOBM, the balancing by counterweights is combined with actuators, which carried out an active balancing. This part will be discussed in Section 4.

2.2. Gravity compensation by counterweights mounted on the auxiliary linkage connected with the initial system.[26–35]

At first, let us define an auxiliary linkage. We will use this term for any mechanical system that mounted between the balancing element and the initial structure of a robot. The goal of these linkages is to improve the compensation and design conditions via optimum location of balancing elements. The examples given in Figure 2 demonstrate the serial manipulators comprising auxiliary systems equipped with counterweights. In [28] also proposed to cancel the weight of the payload via a moving counterweight (Figure 2(b)). Such an approach has also been used in [29–31].

The counterweight balancing of the mine detection vehicle with a pantograph manipulator has been studied in [32]. It has been shown that the robot arm with properly dimensioned balancing counterweights can efficiently actuated with very low power and energy consumption.

The study [36] provides the methodology and index to evaluate the influence of gravity compensation on the dynamic performance of manipulators. On the base of the PUMA 560 robot, it is shown that the application of

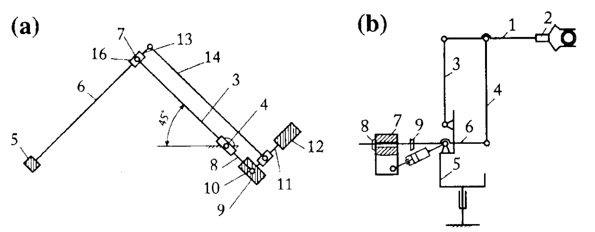

Figure 2. Gravity compensation by counterweights mounted on the auxiliary linkage connected with the initial system.[27,28]

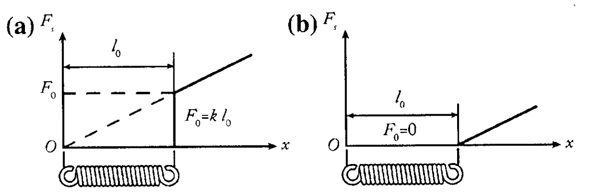

Figure 3. Force-length characteristics of zero-free length (a) and non-zero-free length springs (b).

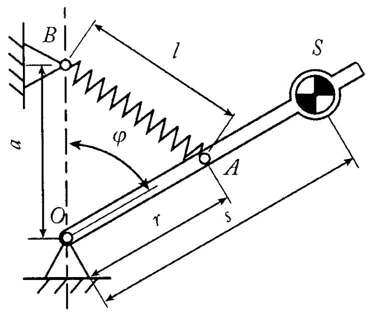

Figure 4. Gravity compensation of a rotating link.

the auxiliary linkages is better than the counterweights mounted on the moving links. A similar study has been carried out in [37]. The advantages and disadvantages of using a counterweight or a spring for the gravity balancing are also discussed in [38]. Their effects on the system's natural frequencies are illustrated using numerical examples and the three-dimensional finite element analysis as a mathematical tool for finding the natural frequencies.

In [39] was proposed the balancing of the SCARA robot by means of a counterweight or a spring. The obtained simulation results showed that for low-speed motions the counterweight balancing is more efficient, while for high-speed motions the elastic balancing is advantageous.

Many schemes illustrate the parallel manipulators comprising auxiliary systems equipped with counterweights. However, the industrial applications of such approaches are often quite complicated because of limitation of the overall size of manipulators and the possibility of collision of extended moving links carrying counterweights.

At the end of this section, it may be noted that there are also studies devoted to the reactionless manipulators, i.e. the high-speed manipulators which apply no reaction forces or moments to the mounting base during motion. It can be reached when the shaking force and shaking moment of the manipulator are cancelled. This goal is usually achieved by adding counterweights or auxiliary linkages in order to keep the total centre mass of moving links stationary. Thus, it becomes evident, that the cancellation of the shaking force by redistribution of movable masses leads to the constant potential energy of the manipulator and as a result to the compensation of the gravity. However, it should be emphasized that the aim of the shaking force balancing is the cancellation of the variable dynamic loads on the frame of high-speed manipulators and not the minimization of input torques. For this reason, in the studies concerning the reactionless manipulators, the gravity compensation is not a goal but only a result due to the balancing of inertia forces. Moreover, the increase of the accelerations of moving links leads to the increase of the inertia forces and the complete gravity compensation by adding counterweights in dynamic operation brings to the increase of the input torques. So, taking into account that the aim of this investigation is the review of the design concepts permitting the reduction of actuator efforts in static operation, the studies devoted to the reactionless manipulators are not included.

3. Gravity compensation by springs

Firstly, let us disclose the properties of two types of springs which are used for gravity compensation in robotic systems: zero-free length and non-zero-free length springs. The author believes that it is important to provide a comprehensible and short background on these two types of springs. It will be particularly useful for young scientists and engineers.

Zero-free length spring is a term for a specially designed coil spring that would exert zero force if it had zero length. That is, in a line graph of the spring's force versus its length, the line passes through the origin (Figure 3(a)) [40,41].

Obviously, a coil spring cannot contract to zero length because at some point the coils will touch each other and the spring will not be able to shorten any more. Zero length springs are made by manufacturing a coil spring with built-in tension, so if it could contract further, the equilibrium point of the spring, the point at which its restoring force is zero, occurs at a length of zero. In practice, zero length springs are made by combining a 'negative length' spring, made with even more tension so its equilibrium point would be at a 'negative' length, with a

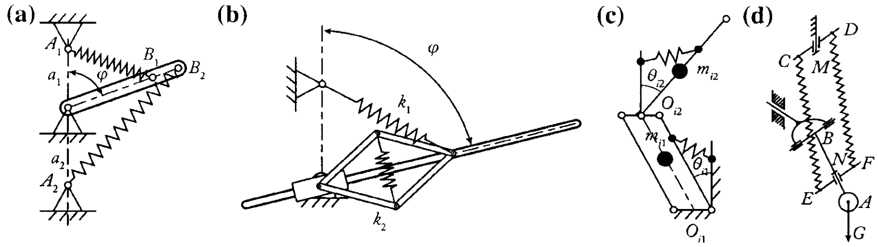

Figure 5. Gravity compensation by springs jointed directly with the manipulator links: (a) [56]; (b) [49]; (c) [54]; (d) [55].

piece of inelastic material of the proper length so the zero force point would occur at zero length.[42,43]

In order to better understand the difference between the zero-free and non-zero-free length springs, let us consider the gravity compensation of a rotating link (Figure 4).

It is obvious that the potential energy of this system will be constant, if the moment of the gravitational forces will be fully balanced by the moment of the elastic force of the spring, i.e.

$$mgs \sin \varphi = \left(F_{sp} ar/l\right) \sin \varphi \tag{1}$$

where m is the mass of the rotating link, $s = l_{OS}$ is the distance of gravity centre S from axis O, φ is the angle between the vertical axis and the link axis, $F_{sp} = F_0 + k(l - l_0)$ is the elastic force of the spring, F_0 is the initial force of the spring (the initial force is the internal force that holds the coils tightly together), k is the stiffness coefficient of the spring, l_0 is the initial length of the spring, $a = l_{OB}$ is the distance of point B from axis O, $r = l_{OA}$ is the distance of point A from axis O and $l = l_{AB}$ is the length of the spring at current angle φ.

One can see from Equation (1) that a fully gravity compensation can be achieved when $F_0 = kl_0$, i.e. when a zero-free length spring is used. In the case of a non-zero-free length springs with $F_0 = 0$ or $F_0 \neq kl_0$, only partial gravity compensation of a rotating link can be achieved.

It is important to emphasize that the use of a zero-free length spring for complete gravity compensation is basically used when the spring is connected directly with the robot links and such a necessity mainly disappears when the spring is connected with the robot links via a cable or an auxiliary mechanism. This property has been discussed in Section 3.2.

To preserve the structure of the systematization adopted above, i.e. the first step of classification by the nature of compensation forces and the second step by the structural features, let us gather the spring compensators in following three sub-groups: 3.1–3.3.

3.1. Balancing by springs jointed directly with manipulator links [44–71]

Examples of the gravity compensation by springs jointed directly with manipulator links are shown in Figure 5. Such an approach has been also applied to the spatial manipulators.[72–75]

Hereinafter, it will not be considered the determination of balancing spring parameters because mathematical approaches are usually based on the fact that the potential energy remains invariant with configuration of the system. Thus, author considers that it is not advantageous to provide these conditions. However, it is useful to present various schematic particularities of balancing methods, which can provide useful information about diverse design concepts of balancing solutions.

In order to create springs with adjustable stiffness the 'Jack spring' concept has been developed.[76,77] It is based upon the principle of adding and subtracting coils from a spring. Thus, with this method, by changing the number of coils in a spring, the actual or intrinsic stiffness of the spring is structurally changed. A simple and practical method to adjust the number of coils was proposed in [78].

In [79] has been presented an approach for the stiffness modelling of robots with the spring equilibrators, which are located between the manipulator links. The aim of this approach is to replace the gravity equilibrator by an equivalent non-linear virtual spring integrated in the corresponding actuated joint. Efficiency of the developed approach and its industrial value has been confirmed by an application example.

In [80] has been presented the design and analysis of the modular gravity compensated manipulators. Modular advantages and kinematic decoupling have been disclosed. It has been shown that the decoupling simplifies the kinematic equations reducing the order of complexity of calculation.

The gravity balancing of the leg was solved in [81,82]. The gravity balancing mechanism, proposed in these studies, consists of two springs with the same stiffness

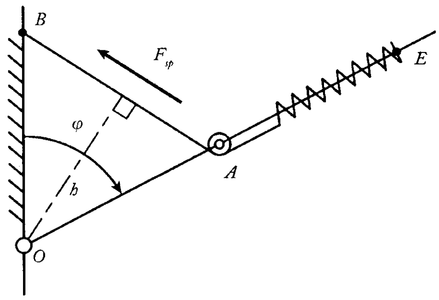

Figure 6. Simple scheme of the gravity compensation by a spring, a cable and a pulley.

coefficients: one compression and another extension connected with the shank of the leg and permitting the complete gravity compensation of the leg's weight. In order to improve the gravity compensation quality, the spring mass has been included in the balancing condition. It was shown that the mass of the balancing spring increases the unbalanced moment and it cannot be neglected. The numerical simulations showed that the error caused by neglect of the spring mass can be reached until 8%.[82]

Various design concepts have been also developed for adjustment of gravity equilibrators.[66,83–87]

3.2. Balancing by using the cable and pulley arrangement [87–97]

The adding of the cable and pulley allows full compensation of gravity by using non-zero-free length spring.

Let us consider a simple example in order to see the effect of the additional cable in the gravity compensation of a rotating link (Figure 6).

The condition of the gravity compensation (1) can be rewritten as:

$$mgs \sin \varphi = F_{sp} h \tag{2}$$

where $h = (ar/l_{AB}) \sin \varphi$. Thus, Expression (2) is similar to (1) when the length l of the spring is equal to l_{AB}. However, in this case, thanks to the cable, it is possible to consider that $l_{AB} = l - l_0$, which leads to the condition $mgs = kar$, with $F_0 = 0$. So, the rotating link can be balanced with non-zero-free length spring.

Figure 7 shows various examples of the gravity compensation by using the cable and pulley arrangement.

The gravity compensation with non-circular pulleys and springs has been examined in [92,93]. After preliminary verification of the design methodology for a single pendulum system, the authors extend the weight

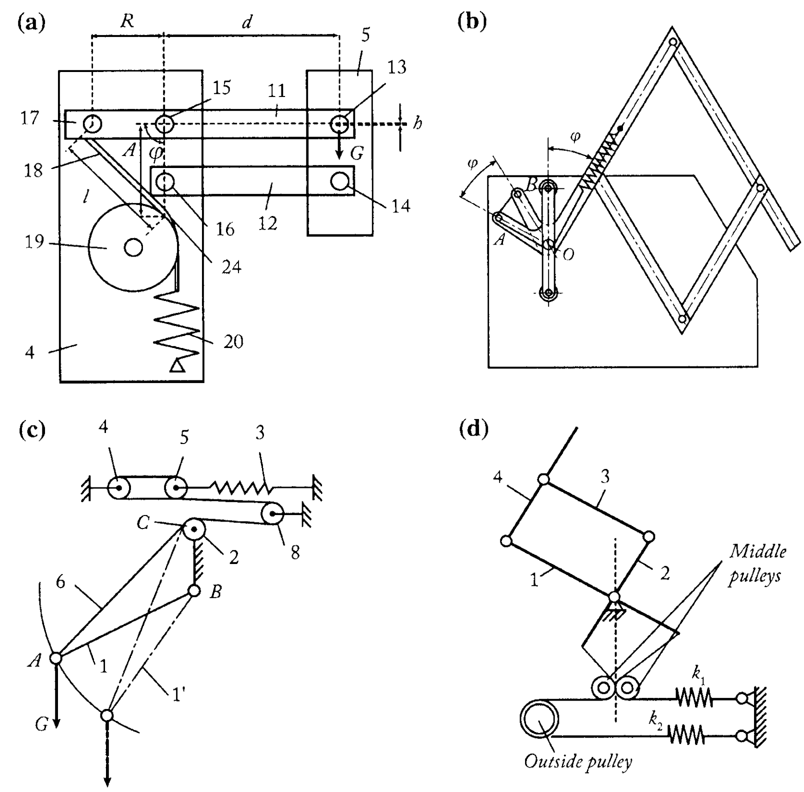

Figure 7. Gravity compensation by using the cable and pulley arrangement: (a) [88]; (b) [89]; (c) [90]; (d) [91].

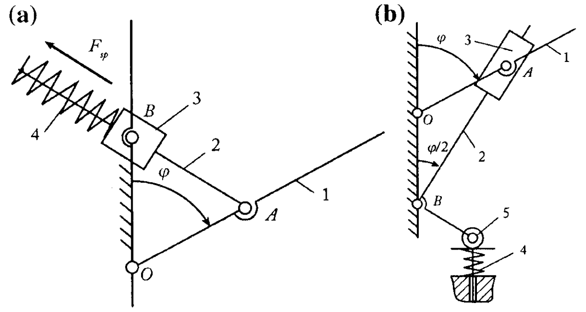

Figure 8. Gravity compensation by the auxiliary mechanisms.[105,116]

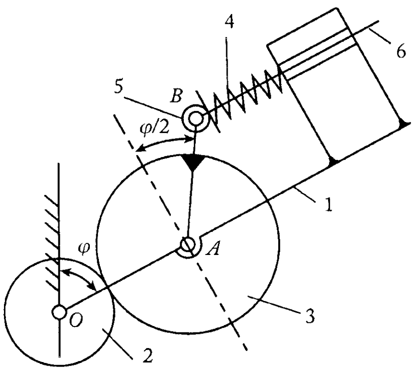

Figure 9. Gravity compensation by using gears.[136]

compensation mechanism to the two degrees of freedom parallel five-bar linkage arm. It has been shown that the introduction of the weight compensation mechanism reduces the maximum static torque up to 50–80%. The spiral pulley with spring has been also used in [94,95].

The new modular balancing approach has been also developed in the series of manipulators called 'Float Arm'.[98–100] The various techniques are used in order to create weight-compensation mechanisms via combination of the pulley wired with springs or counterweights.

As rightly mentioned in [91], the several error sources in the pratical implementations decrease the efficiency of the gravity compensation with springs and pulleys. Errors are mainly caused by the non-linearity of the springs due to the manufacturing tolerance. Often the nominal values of the calculated springs are different to the real values. Therefore, the values of springs' stiffness must be adjusted. Another error source is the radius of the pulleys.

3.3. Balancing by using auxiliary mechanical systems [101–136]

The auxiliary mechanisms have the same effect that the cables and the pulleys. In most cases, they allow the gravity compensation by using non-zero-free length springs. Let us consider two illustrative examples.

Figure 8(a) shows an equilibrator in which rotating link 1 is connected with coulisse 2 and slider 3. The added links of the mechanism allows the complete compensation of the gravity of the rotating link 1 by using a non-zero-free length compression spring.

Another solution is given in Figure 8(b). In this case, the lengths of links of the mechanism must satisfy to the condition $l_{OA} = l_{OB}$ leading to the displacement of the spring proportional to sin $(\varphi/2)$, which ensure the compete gravity compensation of the rotating link 1. This condition was also applied to the design of the gravity equilibrator by using a gear train (Figure 9).

The design solutions via adding an auxiliary mechanism can be arranged into three sub-groups: 3.3.1–3.3.3.

3.3.1. Balancing by using an auxiliary linkage [101–119]

The examples of the design concepts carried out by adding auxiliary mechanisms (3.3.1) with corresponding references are given in Figures 10–13.

The following two schems shown in Figure 11 illustrate the gravity compensation by using compression springs mounted on the guides. The compression springs are chosen to have a force-deflection characteristics to account for the gravitational moment and the geometry of the mechanism.

The advantages of these equilibrators consists in hight rigidity of the system because they don't contain auxiliary elements having the tendency to reduce the balancning accuracy. However, as discussed earlier, the errors due to the manufacturing tolerances of links can decrease the quality of the gravity compensation.

Please note that the two springs of the equalibrator shown in Figure 11(a) have the same stifness. The combined interaction of two springs provides the variation of the compensation moment by a sine law.

In therapeutic situations, therapists often apply full or partial support to a paretic limb to help reduce the effect of gravity on the patient's motion. This is extremely difficult to do during walking, where the weight of the leg may create problems for the patient whose muscles are weak or lacks normal neuromuscular control due to a neurological insult.[137] Hence, new devices have been developed, which can compensate the weight of the lower and upper extremity in all configurations.[137–153]

Let us consider an example of gravity compensation on the patient's motion by using an auxiliary linkage.

The design concept given in Figure 12 (see [144,152]), which was used for the gravity balancing of the leg, is based on the following hybrid method: at the first, the centre of mass of the leg is geometrically located using a

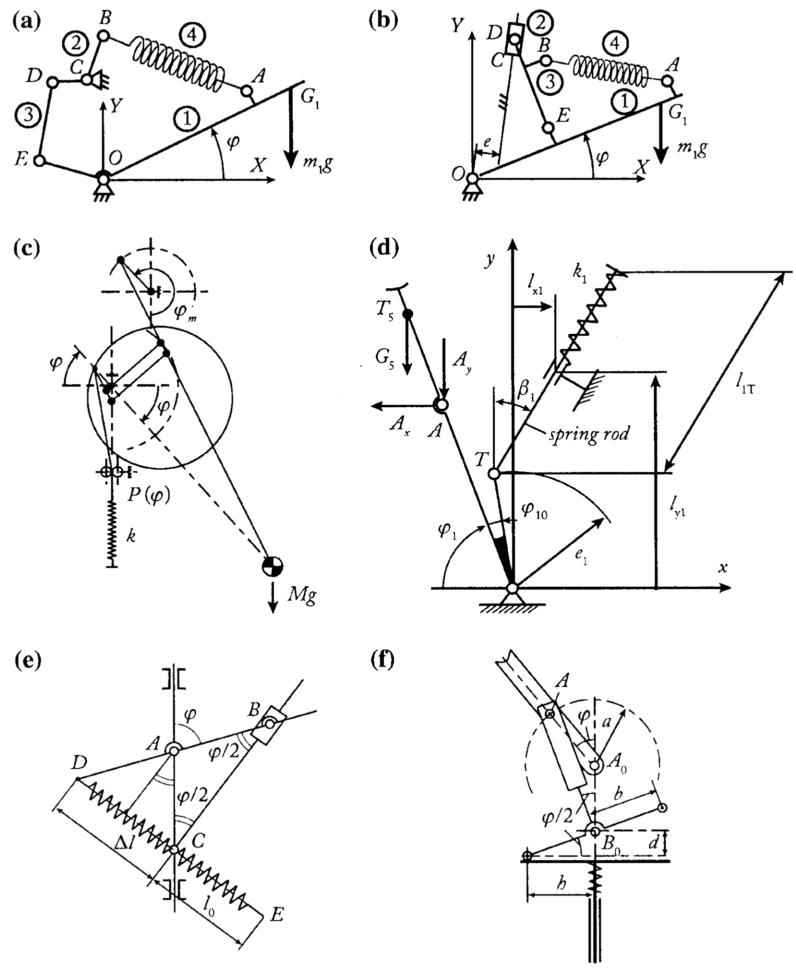

Figure 10. Gravity compensation by using auxiliary linkages: (a) and (b) [110]; (c) [112]; (d) [102]; (e) [113]; (f) [114].

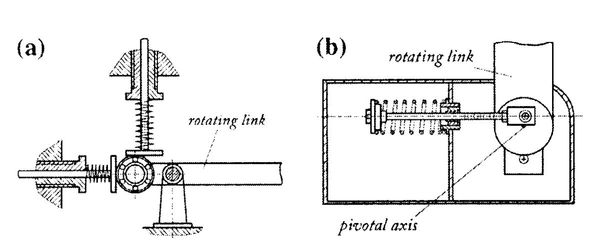

Figure 11. Gravity compensation by using auxiliary linkages with compressing springs: (a) [115] and (b) [118].

parallelogram mechanism, then the springs are placed at suitable positions in order to fully compensate the effect of gravity over the range of motion.

It should be added that the effects of the friction on the gravity balanced orthosis was also disclosed. [145,150,154,155] The friction torque can be compensated by a low power motor mounted on the joint of the gravity balanced orthosis. The advantage of such an approach consists in combination of passive gravity balancing of the leg with the active compensation of friction torque using a low-power motor. The numerical simulations have showed that the error caused by neglect of the spring mass and friction torques can be reach until 20%.

Using the auxiliary linkages and the springs, the gravity compensation of links having translational and vertical motion has also been studied. Four illustrative examples are given in Figure 13.

The primary equations of static equilibrium between the vertical load P (Figure 13) and the elastic forces of springs (F_{sp}) bring to the conditions of complete gravity compensation.

In [156], the gravity compensation of a gantry system has been proposed (Figure 14). The arm 1 of the robot carried out the horizontal motion by using a carriage 4 which is mounted on the frame 2 and equipped pulleys 5, 6, 10 and a cable. When the carriage moves in horizontal direction the rotation of the device 3 ensure a constant tension in cable and the link 11 keeps a stable position.

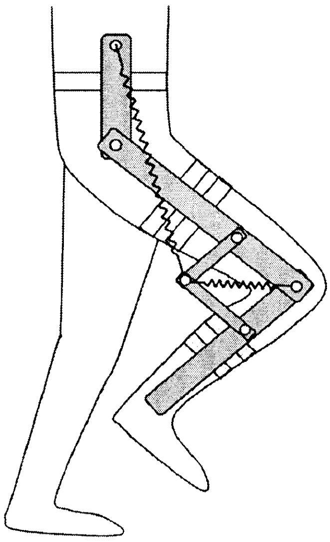

Figure 12. Basic components of gravity balancing mechanism.[144]

When the arm 1 moves in the vertical direction the device 3 locks its rotation, which brings a transmission carried out by using links 7, 8, 9 and 11. As a result, the rocker 11 rotates about its axis and drives the spring equilibrator. A similar research has been also carried out in [157].

The drawback of the systems designed for balancing of links with vertical motion consists in relatively small vertical displacements. In order to eliminate this drawback, the supplementary transmission mechanisms can be used, for example pantographs, polyspasts or gear trains.

3.3.2. Balancing by using a cam mechanism [117–123]

The advantage of the adding of an auxiliary mechanism consist also in increase of free parameters of the system which allows one optimize the gravity compensation by applying the linkage synthesis methods.

In these balancing schemes, using the conservation of energy and balance conditions, it is shown that the optimal profiles of cams can be found in order to compensate the gravity of links or a payload. In [123] (Figure 15(c)), it has been shown that a payload with vertical displacements can be balanced by using a linear spring with constant stiffness if a cam with Archimedes' spiral is used.

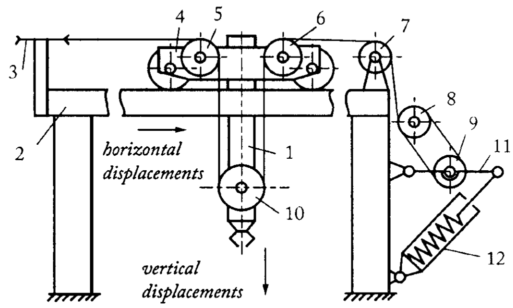

Figure 14. Gravity compensation of the robot with the vertical and horizontal translational motions.[156]

3.3.3. Balancing by using gear trains [127–136]

A general equation of inertia force for both a gravity balancer by counterweight and spring has been derived in [158]. The two equations were compared and the conditions that make the spring balancer superior were investigated.

At the end of this section, it should be added that the spring compensation has also been studied for the spatial robotic systems [75,110,120,159–166].

4. Gravity compensation by using auxiliary actuators [167–177]

In this case, a pneumatic or hydraulic cylinder is connected with manipulator links [10,167–169] or directly with the moving platform.[170] There are also some approaches based on counterweights, which are fluid reservoirs connected with an auxiliary actuator. Continuous gravity compensation is achieved by the pumping of the fluid from the first reservoir-counterweight to the second [171] (Figure 17).

Electromagnetic effects were also used [172].

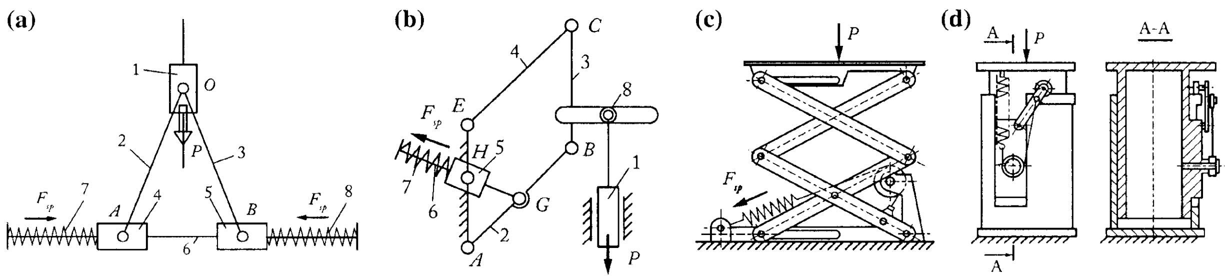

Figure 13. Gravity compensation of the link with the vertical translational motion: (a) and (b) [136], (c) [204]; (d) [205].

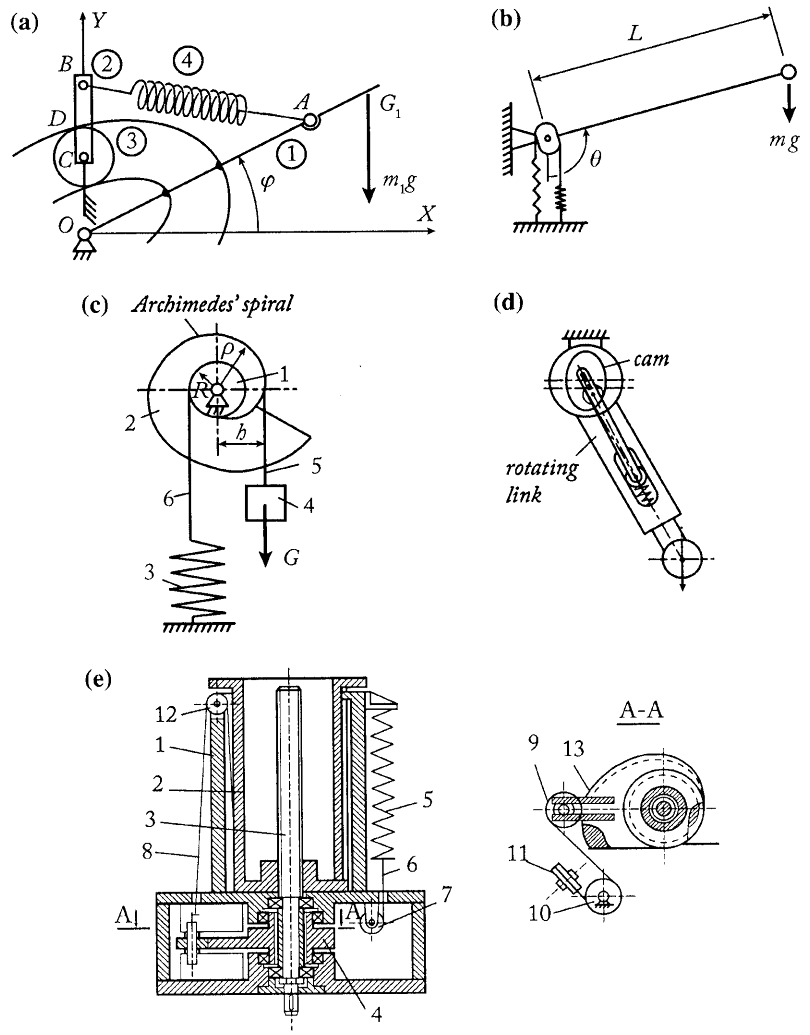

Figure 15. Gravity compensation by using cam mechanisms: (a) [120]; (b) [125]; (c) [121]; (d) [123]; (e) [124].

The gravity compensation technique developed in [173–175] uses remote counterweights connected to the robot via a hydraulic transmission. As it has been shown in [174], the built prototype of the 7-DOF robot is able to adapt its balancing counterweights to a payload of up to 10 kg, which was a maximal payload for the tested prototype.

However, it should be noted that many gravity compensation methods are applicable only for planar parallel manipulators.

The gravity compensation of spatial parallel architectures is a complicated problem because it can be achieved either by unavoidable increase of the total mass of moving links or by a considerably complicated design of the initial parallel mechanism.

It seems that an optimal approach is to combine an auxiliary linkage with pneumatic or hydraulic cylinders.

An illustrative example is shown in Figure 18.

The suggested approach involves connecting an auxiliary mechanism to the initial structure, which generates a vertical force applied to the manipulator platform.[176,177]

The studies concerning the gravity balancing are generally devoted to gravity compensation due to the constant weight. In [178], a variable gravity compensation mechanism has been proposed. It uses two types of linear springs and changes the equilibrium position of one.

It should be also noted that the complete compensation of gravity often requires numerous complex mechanical add-ons or unavoidable addition of mass. This is the reason why methods of partial gravity compensation have been also developed.[179,180]

The gravity compensation of the parallel cable-driven mechanisms has been also studied.[181] It has been shown that by using non-linear springs in parallel with motors, it is possible to maintain the minimum torsions in cables

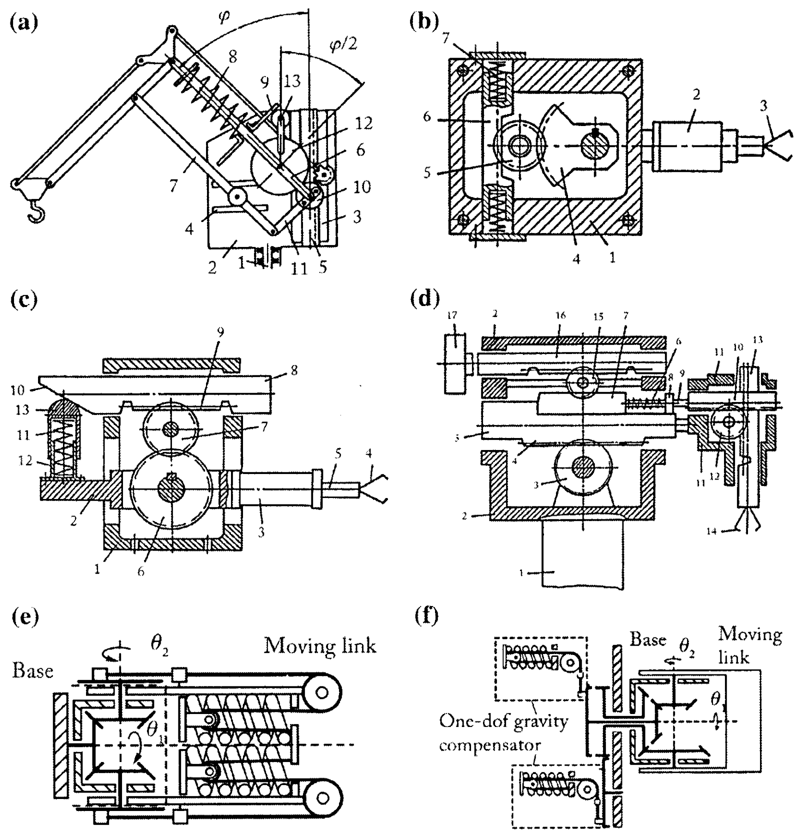

Figure 16. Gravity compensation by using gears: (a) [127]; (b) [129]; (c) [130]; (d) [131]; (e) [134]; (f) [135].

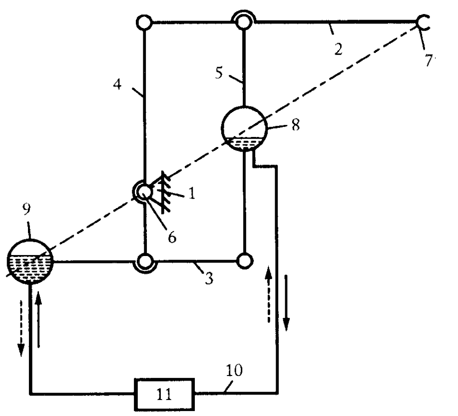

Figure 17. Continuous gravity compensation accomplished by the pumping of the fluid from the first reservoir-counterweight to the second.[171]

and as a result to minimize the static loads over its entire workspace.

In [182] a method for the automated movement of a gravity-compensated payload and an automated handling system for gravity compensation of the payload were presented (Figure 19). It involves supporting a payload by a holding unit that is connected with an end-effector flange of the robot for automatically moving of the load body. The similar studies were successfully carried out in [183,184].

Let us also consider the gravity compensation for the manipulators in which the vertical motion is decoupled from other Cartesian degrees of freedom that this case has some particularity. In the latter situation, only one degree of freedom needs to be gravity compensated in order to eliminate actuator torque due to the weight of the moving parts and the payload.[185–187]

The specificity of this technique is easy to see on the example of the PAMINSA manipulator (Figure 20).[186,187]

The particularity of this architecture is the decoupling of the displacements of the platform in the horizontal plane from its translation along the vertical axis. Such a decoupling allows the cancellation of the gravity loads on the actuators which displace the platform in the horizontal plane.[186]

In the arm proposed in [16], for gravity cancellation a modular gravity compensation technique has been used.

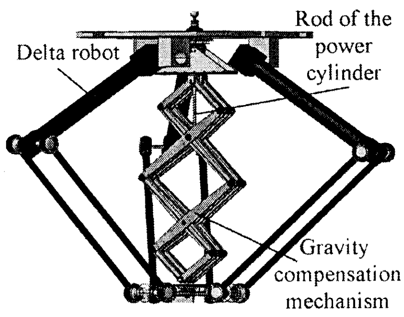

Figure 18. Gravity compensation of the Delta Robot.[177]

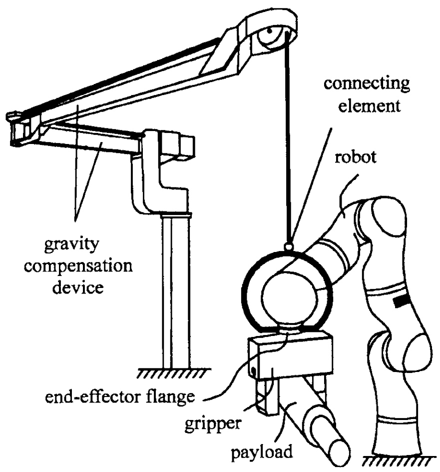

Figure 19. Automated movement of a gravity-compensated payload.[182]

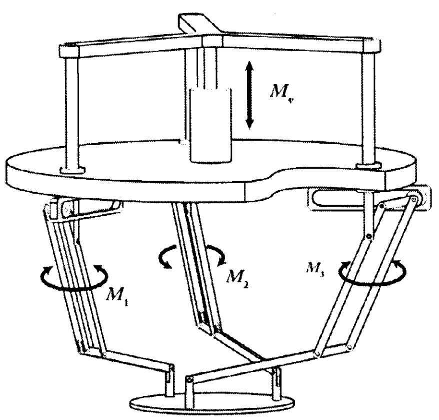

Figure 20. PAMINSA.[186]

In this case, a pneumatic cylinder is used for elimination of gravity effects.

It should also be noted the active balacning of the HOBM. Two principal ways for gravity compensation of the HOBM exist which depend on the structural architecture of the manipulator and the type of actuation: either the movements of the carrying mechanical system are decoupled and the force of gravity of the payload is canceled during its movement in the horizontal plane, in this case only during vertical movements a compensation must be provided, either the actuators provide permanent compensation for any position of the payload. In the last case, the load weight measurement for performing the movement control is requisted. The general approach for determination of gravity compensation is based on the study of the motion of the centre of mass of the carrying mechanical system with payload and optimal control of the drivers.

Another promising field of gravity compensation by using actuators is the development of walking assist devices with bodyweight support.[188–194]

MoonWalker is a lower limb exoskeleton [188], which is able to sustain part of a user's bodyweight. This system can be used for rehabilitation, to help people having weak legs, or to help those suffering from a broken leg, to walk. The main characteristic of MoonWalker is that a passive force balancer provides the force to sustain bodyweight. It is controlled using an actuator that requires very low energy to work on flat terrains, as it is used only to shift that force the same side as the leg in stance. That motor is able also to provide a part of the energy to climb stairs or slopes. The authors believe that this approach can help improving energetic autonomy of lower limb exoskeletons.

SJTU-EX [189] is a powered lower extremity exoskeleton designed to assist and protect soldiers and construction workers. It comprises a rechargeable battery as the power supply, two pseudo-anthropomorphic legs and a backpack-like frame to mount varieties of loads. In this concept a parallel mechanism with two degrees of freedom is introduced in place of the hip and knee for a better load-support capability. Springs are mounted on both the active and passive joints in order to eliminate the effect of gravity.

Honda's experimental walking assist device [192–194] helps support bodyweight to reduce the load on the user's legs while walking. This could lead to reduced fatigue and less physical exertion. Honda's device lightens the load on the user's legs and helps maintain a centre of gravity via special mechanisms developed by the company. There are plenty of use cases for this product helping people afflicted with mobility issues or leg problems. It can also be used for rehabilitation.

Design concepts of passive gravity-balanced assistive devices for sit-to stand tasks were also developed.[195–197]

Several types of upper arm exoskeletons and spring assistive arm supports were also designed. The gravity compensation problems of these devices were also studied.[141,198–202]

In [203] was developed a passive exoskeleton to minimize joint work during walking. The exoskeleton makes use of passive structure, called artificial tendons, acting in parallel with the leg. Artificial tendons are elastic elements that are able to store and redistribute energy over the human leg joints.

5. Conclusion

Despite its ancient history, gravity compensation methods continue to develop and new approaches and solutions are constantly being reported. New physical aspects are introduced into the problems of gravity compensation, as the friction compensation by active driving systems or the improvement of the compensation accuracy by taking into account the spring's mass. It seems promising the development of new gravity compensation solutions for the exoskeletons, rehabilitation devices and walking assist devices. The use of active and passive actuations allows a significant reduction of the size and weight of walking assist devices with bodyweight support.

However, the several error sources in the practical implementations decrease the efficiency of the gravity compensation in robotics systems. Errors are mainly caused by the non-linearity of the springs due to the manufacturing tolerance. Often the nominal values of the calculated springs are different to the real values. Other error sources are the manufacturing tolerances of equilibrator's links, their stiffness and clearance in joints. In the case of auxiliary linkages, the balancing is carried out for discrete positions due to the non-linearity of transmission characteristics, which leads to an approximate balancing.

It is hoped that this overview will be useful to the readers, and provide reference on the wealth of contributions made in the field of the gravity compensation in robotics.

Disclosure statement

No potential conflict of interest was reported by the author.

Notes on contributor

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