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SPRING-TO-SPRING BALANCING AS ENERGY-FREE ADJUSTMENT METHOD IN GRAVITY EQUILIBRATORS

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ABSTRACT
Generally, adjustment of gravity equilibrator to a new payload requires energy, e.g. to increase the pre-load of the balancing spring. A novel way of energy-free adjustment of gravity equilibrators is possible by introducing the concept of a storage spring.The storage spring supplies or stores the energy necessary to adjust the balancer spring of the gravity equilibrator. In essence the storage spring mechanism maintains a constant potential energy within the spring mechanism; energy is exchanged between the storage and balancer spring when needed. Various conceptual designs using both zero-free-length springs and regular extension springs are proposed. Two models were manufactured demonstrating the practical embodiments and functionality.
Keywords: static balancing, spring-to-spring balancing, energy-free adjustment, storage spring, gravity equilibrator.

1 INTRODUCTION
A statically balanced system is designed such that a constant potential energy is established throughout its range of motion, often through the use of spring mechanisms or counterweights. The constant potential energy removes any preferred position of the system and thus, quasi-statically, the system can be moved without operating energy [1]. Equivalent descriptions of static balancing are ‘zero stiffness’ (changing from one configuration to another requires no force) and ‘neutral stability’ (the system is on the brink of stability and instability).

Often the principle of static balancing is used to counterbalance a mass, effectively rendering it weightless (*i.e.* a gravity equilibrator). A classical example of spring-based gravity balancing is the “Anglepoise” desk lamp [2], [3], while in the “Steadicam” [4] the principle is also used for vibration isolation. Other applications can be found in robotics where manipulators can become lighter and faster as the weight of the components needs no longer be lifted by the actuators [5], [6]. Another useful application is found in assistive devices, where statically balanced arm supports allow patients with a neuro-muscular disease to lift their arms [7], [8]. A less frequently explored option is the possibility to counterbalance multiple springs against one another [1]. This could for example be used to establish constant forces in machinery [9], or compensate for undesired elasticity in cosmetic gloves for prosthetics [10]. Moreover, as will be shown in this paper, the concept of spring-to-spring balancing can be used to adjust gravity equilibrators to varying payloads in an energy-free manner.

Generally speaking, adjusting a gravity equilibrator to a different weight (change of payload) requires energy, because for instance the balancer spring needs to be stretched. In many cases, such as for assistive devices, however, this is considered undesirable. Van Dorsser *et al.* [11] propose several methods to adjust statically balanced systems to different payloads in an energy-free fashion, of which three have already been discussed in detail [7], [12], [13].

The method discussed in this paper is totally different. It makes use of spring-to-spring balancing, where a first spring (the balancer spring) is used to balance a weight and a second one (the storage spring) is used for energy-free adjustment of the first spring. The present paper will demonstrate this to be a very versatile energy-free adjustment method with a large number of possible design embodiments and implementations.

This article is laid out as follows. First the theory of a basic gravity equilibrator is described, followed by means of energy-free adjustment thereof. The use of spring-to-spring balancing as a novel method of energy-free adjustment is explained, after which a range of possible conceptual designs is discussed. Finally, two prototypes of energy-free adjustable static balancers with storage springs are shown.

2 BASIC GRAVITY EQUILIBRATOR

This section will recapitulate the theory of the basic gravity equilibrator and the importance of zero-free-length springs, followed by a discussion of means to adjust the gravity equilibrator to different payloads in an energy-free fashion. A new adjustment method is introduced, based on the principle of a storage spring. Figures of the basic gravity equilibrators are indicated with a center of mass symbol.

2.1 ZERO-FREE-LENGTH SPRINGS

An important component in the design of perfect gravity equilibrators is the use of zero-free-length springs [9], [2], [14]. These springs are pre-tensioned to such a degree that their tension is proportional to their *length*, in lieu of their elongation. These springs are not readily available, but several techniques exist to coil helical extension springs with sufficiently high initial tension. Methods also exist to emulate their properties, either over a limited range of motion [15], or by making use of special constructions such as inverting a compression spring or using a wire-and-pulley mechanism [1].

2.2 CONSTANT POTENTIAL ENERGY

A statically balanced system has a constant potential energy. This implies that, quasi-statically, the potential energy in the system U_p is equal to the sum of the potential energy of the masses U_m and the energy stored in the springs U_s. For the basic gravity equilibrator as shown in Fig. 1 with a zero-free-length spring, this can be written as:

$$U_p = U_m + U_s = mgL\cos\varphi + \tfrac{1}{2}ks^2 \tag{1}$$

where:

$$s = \sqrt{a^2 + r^2 - 2ar\cos\varphi} \tag{2}$$

Here m is the payload mass, g the acceleration of gravity, L the length of the weight arm, φ the angle between the vertical and the weight arm, k the spring stiffness, a the distance between the pivot and the fixed spring attachment point, and r the distance between the pivot and the spring attachment point on the weight arm. For a mechanism to be in equilibrium, the energy function must be at a local minimum, and therefore

$$\frac{\partial U_p}{\partial \varphi} = -mgL\sin\varphi + akr\sin\varphi = 0 \tag{3}$$

For this moment equilibrium to hold in any configuration, that is, for any φ, the following condition for static balancing arises:

$$mgL = akr \tag{4}$$

If this condition is met, the mechanism is in equilibrium for any configuration in its workspace. Alternatively, to accommodate a given constant (gravity) force F_m, the following condition should be met:

$$F_m = \frac{akr}{L} \tag{5}$$

This clearly shows the possibilities for adjusting the balancing properties: by varying a, k, r or L, different masses can be statically balanced. However, most existing adjustment techniques require a change of length of the balancing spring, which is associated with mechanical work. In many scenarios this is considered undesirable, and hence means to perform this adjustment in an energy-free fashion have been sought [11].

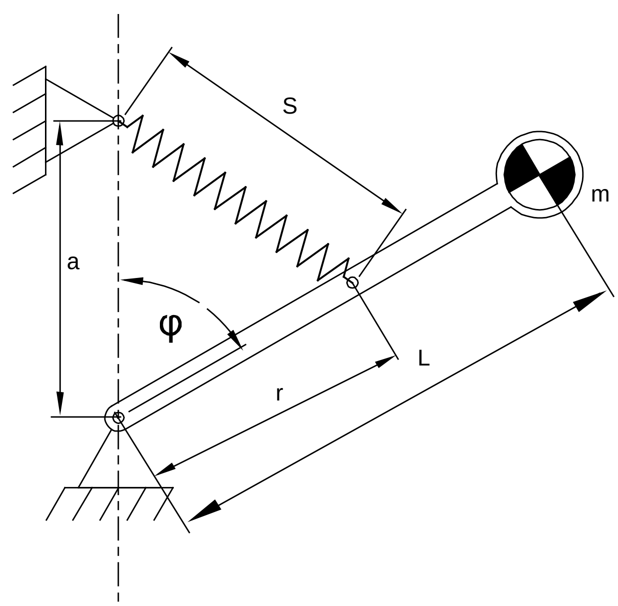


Figure 1: Basic gravity equilibrator using a zero-free-length spring balancing a mass *m* with lengths *a, r, L,* which satisfy the balancing condition (4) for any angle *φ*.

2.3 PRACTICAL EMBODIMENTS OF BASIC GRAVITY EQUILIBRATORS

In practice, one aims to use conventional springs instead of zero-free-length springs, for the latter are rather difficult to manufacture and often limit the working range of the mechanism. Furthermore, it is our intention that the mechanisms discussed in this paper are (theoretically) exactly statically balanced, meaning that if perfectly constructed, the balancing properties and energy exchange will be perfect. Special care must be taken to achieve this. The simplest way to emulate the properties of a zero-free-length spring is to use a standard spring with a wire-and-pulley construction [1] (see Fig.2a-b). However, a balancing error will be introduced by the pulley because the wrap angle of the wire (β) will depend on the position of the weight arm (φ). Consequently the wire length is not always exactly proportional to the spring elongation (and thus force) required for exact balancing. Some optimisation is possible by reducing the size of the pulley and carefully positioning the pulley horizontally to reduce the error, but the balancing will remain inexact [16]. There exist exact solutions to this problem [17], [18], [1], by introducing (at least) two additional pulleys (see Fig. 2c-d). The three pulley solution ensures that the same amount of wire is always wrapped around the pulleys ($\sum \beta_i$ = constant), regardless of the position of the weight arm, and therefore the elongation of the wire will be exactly proportional to the distance between the axes of the pulleys at all times. This three-pulley solution will reappear on several occasions in the description of the *spring-to-spring* balancers.

2.4 ENERGY-FREE ADJUSTMENT OF BASIC GRAVITY EQUILIBRATOR

Several methods for energy-free adjustment of statically balanced systems have been proposed in van Dorsser *et al.* [11]. The *Simultaneous Displacement* method [7] changes the distances *a* and *r* simultaneously, in such a way that the spring length does not change (and hence no work is required). The product of *a* and *r*, however, does change, and hence so does the balancing setting. (Eq. 5). The *Virtual Spring* method [13] works by replacing the single zero free length spring of the basic static balancer by two substitute zero free length springs. These springs generate a virtual spring with the same spring properties as the initial spring, but with a unique difference: the virtual spring length can be adjusted without external energy, by rotating the substitute springs in a coordinated fashion using a pantograph. Effectively, this virtual spring and pantograph construction changes the value of *a*, without elongation of the substitute springs. A third type of energy-free adjustment is called the *K-type adjustment* and works by changing the spring stiffness of the balancer spring by changing the number of engaged coils when it is at its rest length [12]. The fourth method, the *Storage Spring* method, is novel and is the topic of this paper.

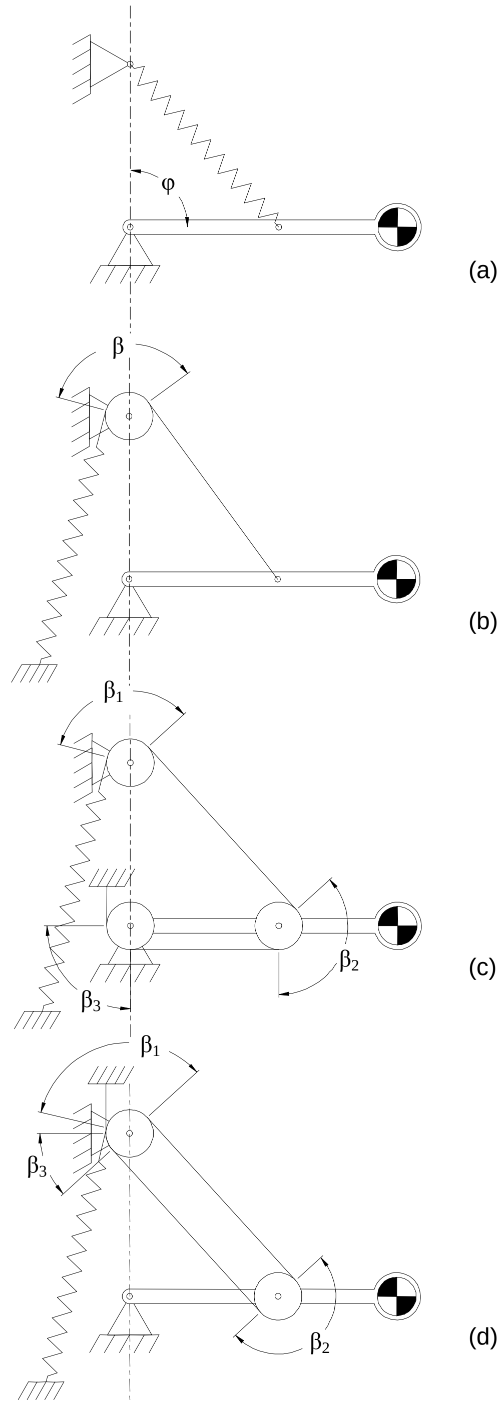


Figure 2: A basic gravity equilibrator using a zero-free-length spring (a) can be replaced by a conventional spring using a wire and pulley (b) but it will be a non-exact solution as the wrap angle β will depend on the position of the weight arm (φ). This can be resolved by employing a three-pulley solution (c-d) where the total length of wire wrapped around the pulleys will always be constant (sum of wrap angles β_i is constant) and the solution will therefore be exact.

2.5 ENERGY-FREE ADJUSTMENT OF BASIC GRAVITY EQUILIBRATOR USING A STORAGE SPRING

The basic gravity equilibrator can be adjusted to different payloads by changing the length of the balancer spring (preferably by changing distance *a*). The novelty of this paper lies in the concept of changing the length of the balancer spring, without need for external work. This is achieved by the introduction of a *storage spring*. The storage spring supplies or stores the energy needed to adjust the balancer spring of the gravity equilibrator to a new payload. In essence, the storage spring mechanism maintains a constant potential energy within the spring mechanism; energy is exchanged between the storage and balancer spring when needed (Fig. 3a). Consequently the adjustment mechanism can also be considered a statically balanced system, and is referred to as a *spring-to-spring balancer*.

The working principle of the combination of the gravity equilibrator with the spring-to-spring balancer is illustrated in Fig. 3. When the weight arm is in a horizontal configuration, it is locked, so that the balancer spring can be adjusted to accommodate the new payload by moving its attachment point along the vertical without affecting the weight arm. The balanced mass is proportional to the distance ‘a’ along the vertical. This can be seen from rewriting the balancing condition (5):

$$m = \frac{akr}{gL} \tag{6}$$

The spring energy required for (or released by) this adjustment is exchanged with the storage spring. The total energy stored in the balancer is given by equation (7).

$$U_s = \tfrac{1}{2}ks^2 = \tfrac{1}{2}k(a^2 + r^2) \tag{7}$$

Because the distance r is always constant, the energy involved in changing is equal to $\tfrac{1}{2}ka^2$. It is this energy that is either stored in or retrieved from the storage spring (Fig 3c), when adjusting the gravity equilibrator to a new mass. Adjustment of a balancing mechanism with the aid of a storage spring can be done in an energy free fashion as long as the following condition is met.

$$\tfrac{1}{2}ku_s^2 + \tfrac{1}{2}ka^2 = C \tag{8}$$

Here u_s is the elongation of the storage spring.

The spring energy required for (or released by) this adjustment is retrieved from or stored in a storage spring (spring-to-spring balancing). To this end, the springs are interconnected by a parallelogram linkage [1]. After adjustment, the spring-to-spring balancer is locked, the weight arm unlocked and the new mass is balanced again. Clearly, the maximum mass that can be balanced is limited by the spring energy stored in the storage spring beforehand (Fig. 3a). The conceptual design of the gravity equilibrator and spring-to-spring balancer can take place more or less independently, and the two can subsequently be combined into a functional energy-free adjustable balancer.

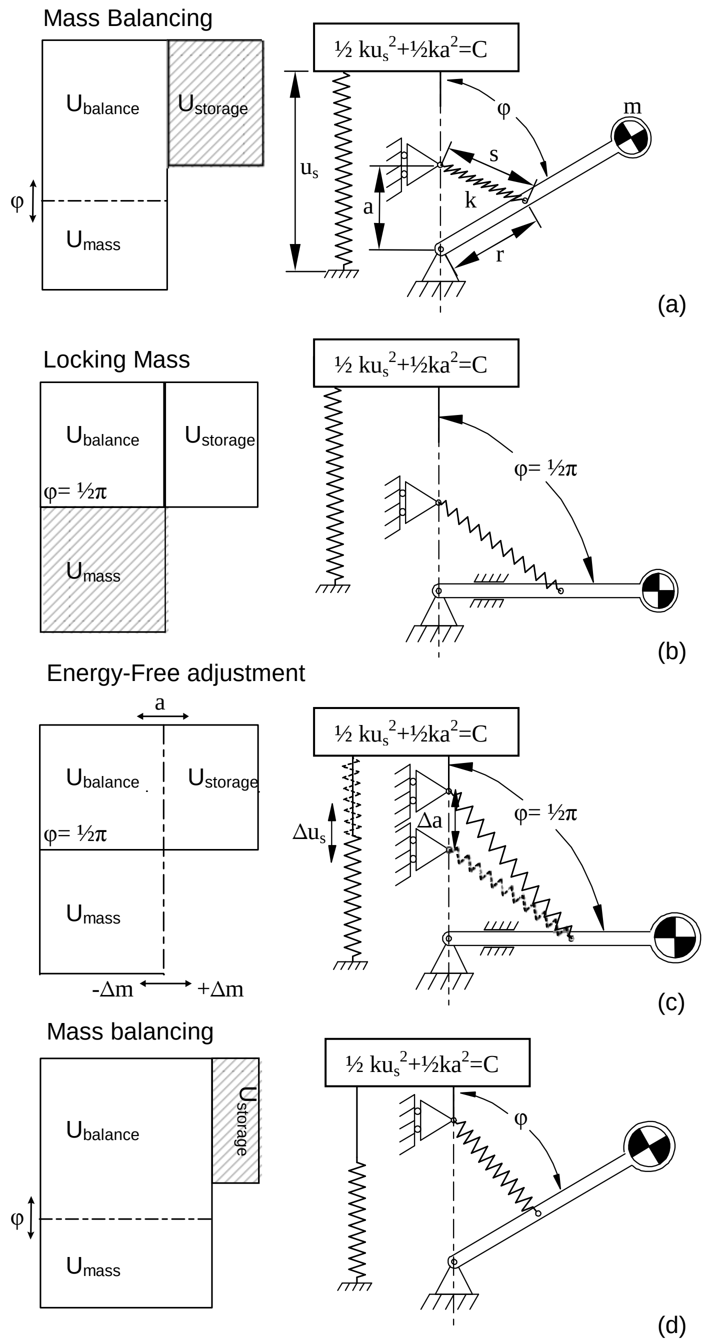


Figure 3: Schematic representation of the energy-free adjustment process of the basic gravity equilibrator.(a). When balancing the mass, energy is exchanged between the mass and the balancer spring, and the energy in the storage spring ($U_{storage}$) is kept constant (b). Subsequently, the mass is locked. (c) During adjustment, the potential energy of the mass is kept constant, and energy is exchanged between the storage spring and balancer spring until it has been adjusted to correspond with the potential energy of the new mass (d). After adjustment, the energy in the storage spring is kept constant, while energy is again exchanged between mass and balancer spring.

3 SPRING-TO-SPRING BALANCING

This section will discuss a variety of spring-to-spring balancers, which can be used to adjust the basic gravity equilibrator to different payloads. A spring-to-spring balancer differs from basic gravity equilibrators because in spring-to-spring balancers only the total amount of spring-energy is kept constant. The potential energy as a result of gravity is considered of no influence. The general idea is the ability to change the length of the balancer spring without any external energy by storing the required energy in, or retrieving it from, a storage spring. To achieve this, the elongations of the two springs must be coordinated in such a fashion that all spring energy is transferred. The total energy must be constant (C) and can be written as given in equation (9):

$$\tfrac{1}{2}k_1u_1^2 + \tfrac{1}{2}k_2u_2^2 = C \tag{9}$$

Here u_1 and u_2 can be regarded as the elongation of the balancer and storage spring, respectively. Therefore a quadratic relationship between the two spring elongations must be established. Often the spring-to-spring balancers are first designed using zero-free-length springs and then transformed into practical implementations using conventional springs, while preserving the exact balancing properties [19]. It was also deemed practical to keep the springs fixed to a frame and always oriented in the same direction. Furthermore, in practice the masses of the adjustment mechanism parts themselves might become an important selection criterion, because if their mass cannot be balanced, the adjustment mechanism will tend to seek a preferred position.

3.1 STORAGE SPRING: BASIC SPRING-TO-SPRING BALANCER

Shown in Fig. 5a is the most basic version of the spring-to-spring balancer, consisting of a single link and two zero-free-length springs. The attachment points of the springs and the link pivot must be collinear. The condition for static balancing will now be derived. The total spring energy in the system is given by the following expression.

$$U_{\text{spring}} = \tfrac{1}{2}k_1u_1^2 + \tfrac{1}{2}k_2u_2^2 = C \tag{10}$$

This is equivalent to:

$$\begin{aligned} &\tfrac{1}{2}k_1\left(a_1^2 + r_1^2 - 2a_1r_1\cos\varphi\right) + \\ &\tfrac{1}{2}k_2\left(a_2^2 + r_2^2 - 2a_2r_2\cos\left(\pi-\varphi\right)\right) = C \end{aligned} \tag{11}$$

Considering this should hold true for any value of φ, the balancing condition for the basic balancer simply follows as

$$k_1a_1r_1 = k_2a_2r_2 \tag{7}$$

Extending this basic balancer to using two parallel regular springs is shown in Fig. 4b and c, where Fig. 4b shows an inexact solution using a wire and pulley system and Fig. 4c an exact solution using the three pulley technique.

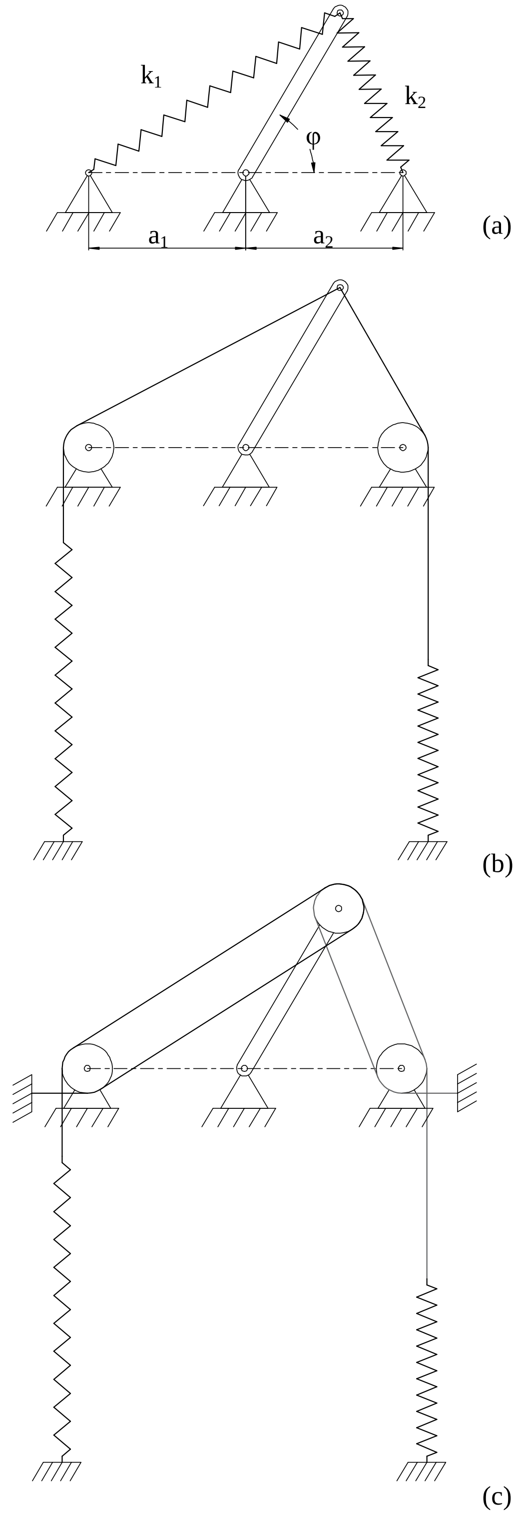


Figure 4a: the basic spring-to-spring balancer using zero-free-length springs is in equilibrium for any configuration of the bar (φ) provided the spring and bar attachment points are collinear and the following condition is met: $a_1k_1r_1 = a_2k_2r_2$. The balancer can easily be adapted to using conventional springs with either a non-exact or (**4b**) an exact solution (**4c)**.

3.2 STORAGE SPRING: BALANCED BAR

The basic spring-to-spring balancer can be modified and embellished by means of a series of modification rules, as described in detail by Herder [1]. Using kinematic inversion, the basic balancer can be transformed into a 'balanced bar' (see Fig. 5). It is obvious that the same energy calculation holds for the balanced bar as for the basic spring-to-spring balancer. This spring-to-spring balancer can also easily be modified to use conventional springs and still maintain exact balancing properties (Fig. 5b-c). An interesting practical aspect to this embodiment is that the mass of the balanced (symmetrical) bar is irrelevant, as it is always balanced about the pivot point.

A drawback of this variant and the previous one of the spring-to-spring balancer is that in practice not all spring energy can be exchanged. In the extreme configurations the pulleys will collide and therefore not all energy can be released from the springs. This means there will always be a certain minimum amount of energy in the balancer spring (minimum value for distance a), and there is thus a minimum mass that must be attached to the gravity equilibrator.

3.3 STORAGE SPRING: SLIDING LADDER

Another canonical form of the spring-to-spring balancer is referred to as the 'sliding ladder' (see Fig. 6). A bar slides along two orthogonal surfaces (similar to a ladder against a wall) and the two equal zero-free-length springs connected to the endpoints of the bar join at the intersection of the two surfaces. It can trivially be verified using Pythagoras' law that the energy stored in the springs is constant, regardless of the position of the ladder ($u_1^2 + u_2^2 = L^2$ = constant). This spring-to-spring balancer can also be extended to using conventional springs, and will be exact, even without the use of a three pulley mechanism; the total wire wrap angle is always constant. In the embodiment where the sliding surfaces are vertical and horizontal, the mass m of the sliding ladder could simply be balanced by shortening the vertical spring by $mg/2k$. In Fig. 6c, the mass cannot be balanced as easily and it will seek a preferred position under the influence of gravity.

3.4 STORAGE SPRING: BALANCED PARALLELO-GRAM

Starting from the sliding ladder with zero-free-length springs, and mirroring it across two orthogonal axes, a balanced parallelogram is obtained (see Fig. 7a-b). The parallelogram will be balanced in any configuration, as long as the stiffnesses of all springs are equal; the bars need not all be of equal length, as long as they constitute a parallelogram. Extending this particular method to using conventional springs is slightly more involved than in the previous examples of spring-to-spring balancers. In Figure 7c-f several possible embodiments are shown, using both extension and compression springs. The spring parallelogram has been used previously in the context of static balancing, although not purely in the form of spring-to-spring balancing, but in a combination of spring-to-spring and spring-to-mass balancing [20], [21]. The use of the parallelogram as a method for energy-free adjustment of the basic gravity equilibrators is shown in Fig. 8 [11].

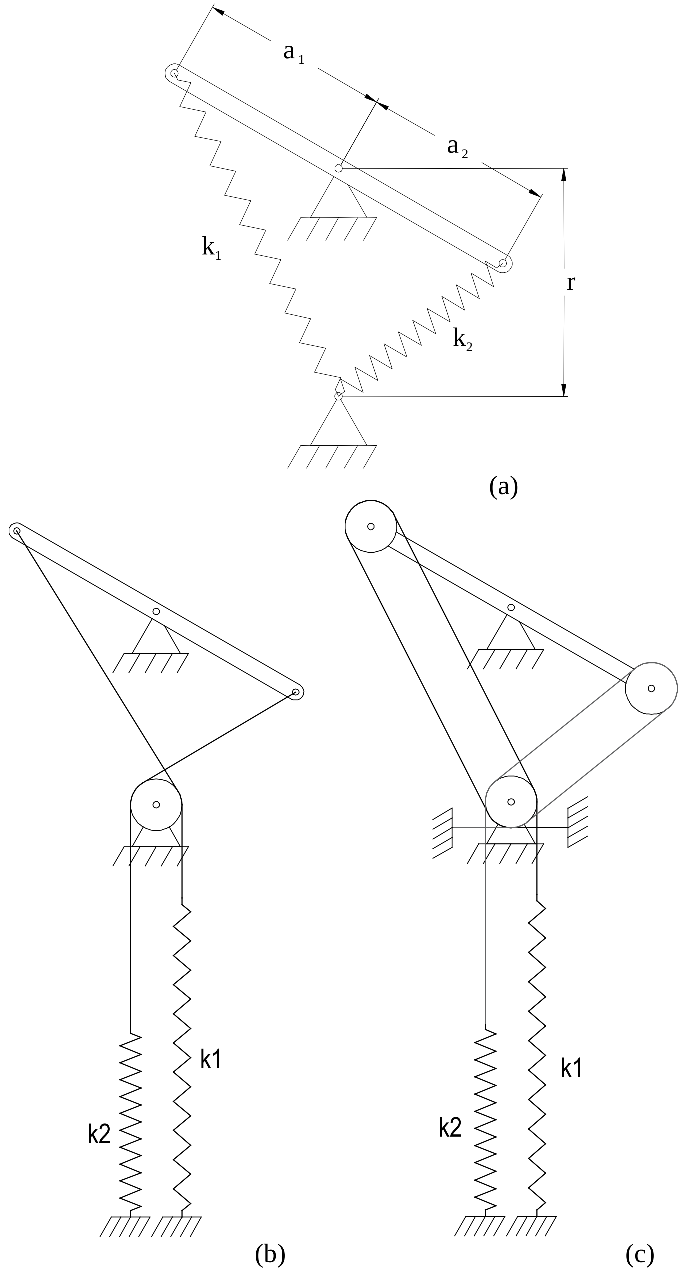


Figure 5: The balanced bar spring-to-spring balancer, (a) as a simple modification of the basic spring-to-spring balancer, where the fixed pivot point of the bar and springs are placed along a vertical and $a_1 k_1 r = a_2 k_2 r$ must be satisfied. Again this balancer can easily be adapted to using conventional springs with non-exact and exact solutions, for instance according to (b) and (c), respectively.

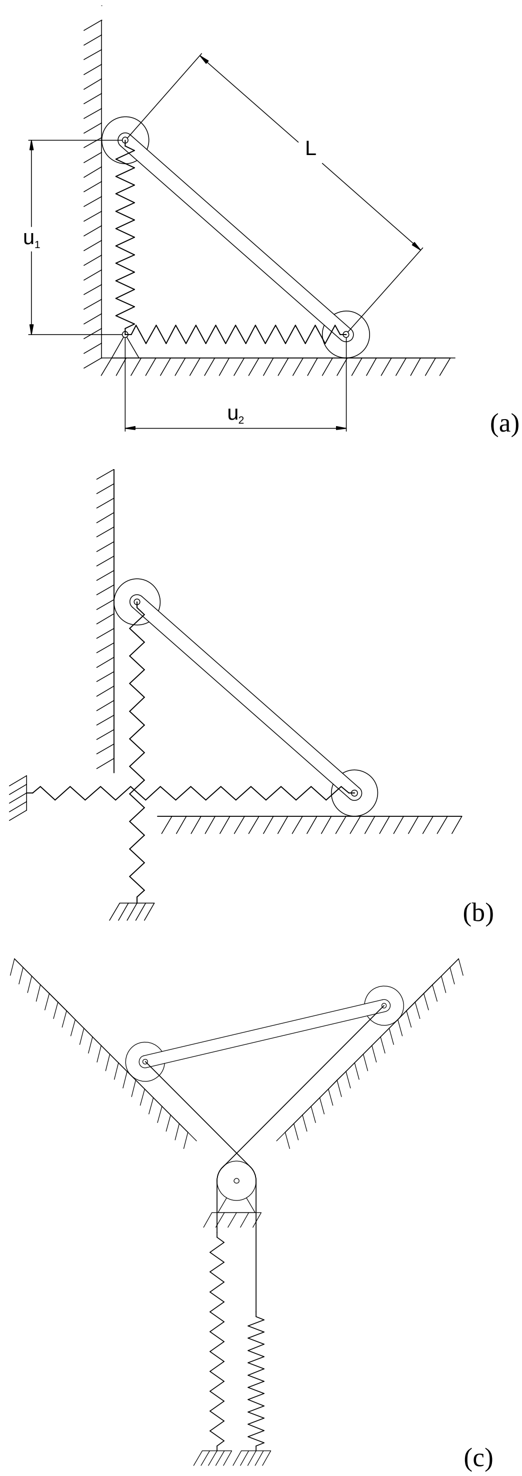


Figure 6: The ‘sliding ladder’ spring-to-spring balancer with two equal zero-free-length springs (a) merely requires the two sliding surfaces to be perpendicular to each other. Extending the balancer to using conventional springs is trivial by storing the rest length behind the sliding surfaces (b). A variant with the two springs vertical and parallel is shown in (c). Note that no three-pulley mechanisms are required as the wrap angle around the pulleys is constant at all times.

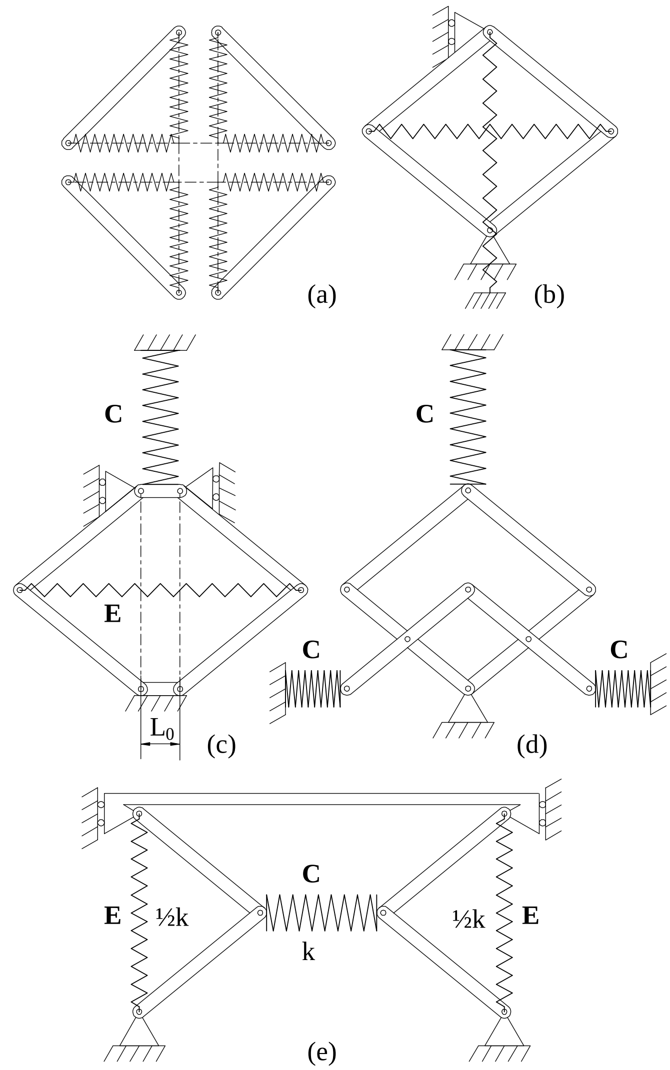


Figure 7: The parallelogram spring-to-spring balancer (b) can be considered as being constructed from four ‘sliding ladder’ balancers (a) adapted from [1]. It is in equilibrium for any position of its bars. The vertical spring is replaced by a conventional spring by storing its rest length outside the parallelogram. Other practical embodiments may include a combination of extension and compression springs, indicated by *E* and *C,* respectively. In (c) a compression spring is used in combination with a conventional extension spring by storing its rest length inside the parallelogram. In (d) three compression springs counterbalance each other. In (e) one compression spring balances two zero-free-length extension springs.

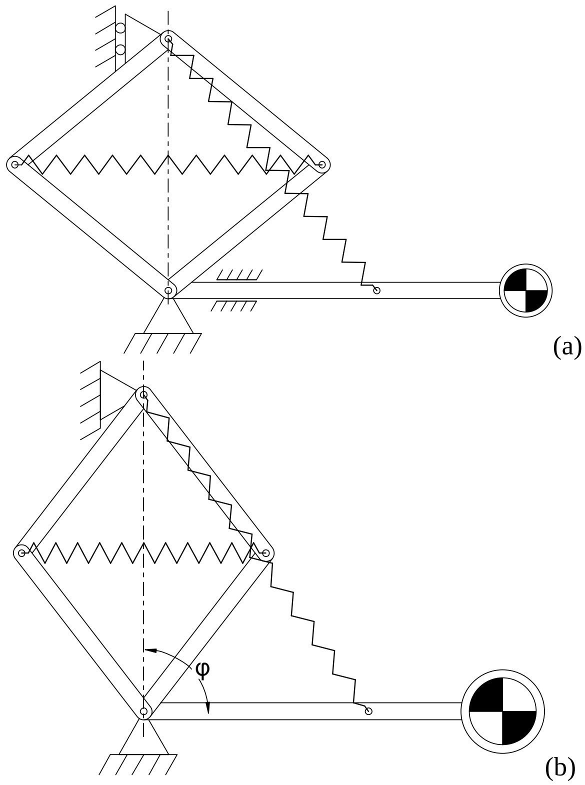


Figure 8: The parallelogram spring-to-spring balancer employed as storage spring for the gravity equilibrator (using zero-free-length springs). In the horizontal position the weight arm is locked and the height of the parallelogram can be changed in an energy-free way (a). Once adapted to the new weight (b), the top end of the parallelogram is fixed and the system is again statically balanced for any φ.

3.5 STORAGE SPRING: ROLLING LINK MECHANISMS

The spring-to-spring balancers described previously have all been linkage-based. The concept can also be extended to rolling link mechanisms, with their inherent advantage of low friction and reduced number of components [22]. Several rolling link based spring-to-spring balancers have already been described in Carwardine [23] and Herder [1], and will not be repeated here. However, recently a novel rolling link spring-to-spring balancer was developed [24] which features conventional springs and exact balancing properties. The working principle and boundary conditions of this rolling link mechanism will be discussed, before describing a practical implementation in the next section. The rolling link mechanism (Fig. 9) consists of a bar rolling over a fixed support disk. The wires connected to the springs run over a pulley towards fixed disks, one on either end of the bar. As can be seen in Fig. 9 the mechanism works by creating two isosceles triangles with length *L/2* lying back to back. From trigonometry it follows that the angle between the two triangles is equal to $\pi/2$ at all times. Now it is clear to see with Pythagoras' law that the total energy stored in the system is constant, namely

$$U_p = \tfrac{1}{2}k(u_1^2 + u_2^2) = \tfrac{1}{2}kL^2 \quad (12)$$

It remains to determine the necessary diameters of the rolling links and pulleys to make this possible for every position of the rolling bar, and prove that the total wrap angle of the wire ($\sum \beta_i$) is constant throughout the range of motion and that the balancing mechanism is therefore exact. The radii for the rolling links and pulleys follow from the requirement that the wires must always run parallel to the isosceles triangles (see Fig.9). The relationship between the radius of the rolling links (r_r) and pulleys (r_p) can therefore be written as

$$r_r = r_p\sqrt{2} \quad (13)$$

Now we must show that the wire length is solely dependent on the rotation angle φ, and that the wrap angle is therefore constant. As can be determined from Fig. 9, the wire length s is given by

$$\begin{aligned} s(\varphi) &= \beta_1(\varphi)r_p + u_1(\varphi) \\ &+2r_p + \beta_2(\varphi)r_p + C \end{aligned} \quad (14)$$

where C is a constant. Although the wrap angles β_i both depend on the angle φ, their sum is always equal to $\pi/2$ (see Fig. 9). As a result the wire length s becomes

$$s(\varphi) = u_1(\varphi) + 2r_p + \frac{\pi}{2}r_p + C \quad (15)$$

and the change in wire length is therefore equal to the change of length u_1

$$\frac{\partial s}{\partial \varphi} = \frac{\partial u_1}{\partial \varphi} \quad (16)$$

Thus the spring-to-spring balancing is exact, as the wire length is exactly proportional to the spring elongation. An additional advantage of this mechanism is that it allows full energy exchange between the springs. In its extreme positions (when the rolling bar is vertical) the pulleys will just touch, but the spring will be completely at its rest length.

3.6 STORAGE SPRING: SNAIL CAM

Another approach to obtaining the desired transfer function between the elongations of the balancer and storage spring is a "snail cam". Tidwell *et al.* [25] describe the equations for snail cam based gravity equilibrators, but these can also be adapted for spring-to-spring balancing. The cam shapes are calculated by prescribing moment equilibrium about the cam axis. A disadvantage would be the inexact balancing at the extremes of the working range of the corresponding spring-to-spring balancer, as infinitely long moment arms would be necessary to maintain moment equilibrium when one of the spring forces approaches zero and the other is maximal.

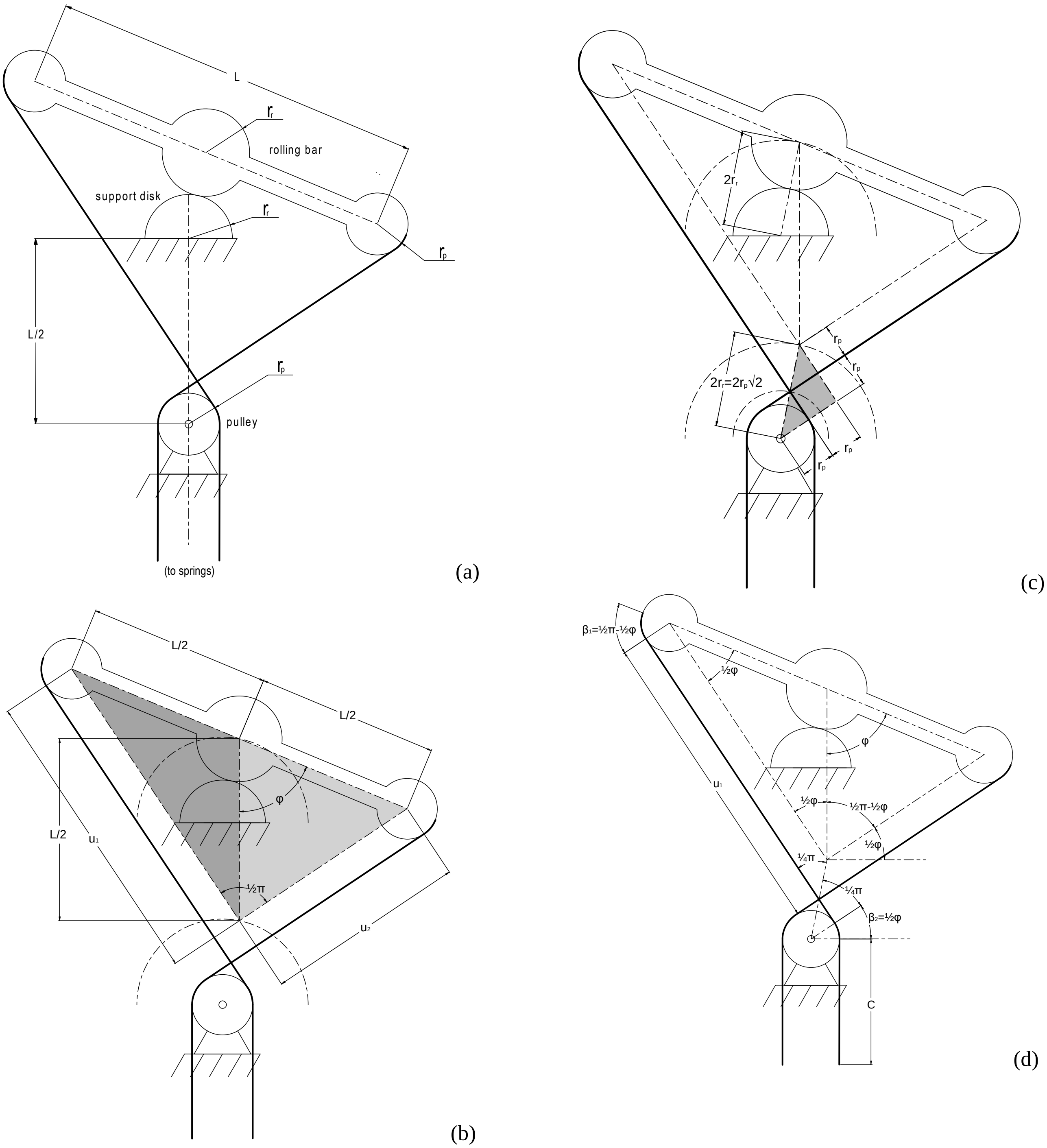


Figure 9: The rolling link spring-to-spring balancer (a) consists of a bar rolling on a support disk, with two fixed pulleys on either end. The wires connected to the springs run over the fixed disks at the end of the rolling bar. As shown in (b) the system works by creating two isosceles triangles having one side with length *L/2* lying back to back. In order for the wires to be parallel to the isosceles triangles (c) the radius of the rolling links r_r must be equal to $r_p 2^{½}$. In (d) the wrap angles of the wire are determined, and it is shown that $\sum \beta_i = \frac{1}{2}\pi$,independent of φ.Therefore the balancing is exact.

4 PROTOTYPES OF STORAGE SPRING FOR ENERGY-FREE ADJUSTMENT

4.1 GRAVITY EQUILIBRATOR WITH PARALLELOGRAM BALANCER

In order to clearly demonstrate the capabilities and working principle of the storage spring, a demonstrator model was constructed (see Fig.10) using the parallelogram spring-to-spring balancer (see Fig.8). The model makes use of actual zero-free-length springs, which are coiled with increased initial tension (k=0.166N/mm, F_0=24N, L_0=142mm). These springs are hard to come by, but they greatly simplify the model and thereby make the model very suitable for demonstration purposes. The mass of the parallelogram system itself is compensated by lowering the bottom of parallelogram with respect to the axis of the weight arm by $m_p g/k$, where m_p is the mass of the parallelogram. This generates a constant upward force equivalent to the weight of the parallelogram.

When a change of payload is desired, the balancer arm is moved into the horizontal position where it rests against a mechanical stop. The parallelogram is then unlocked, and the top vertex is moved to its lowest position. After the payload has been changed, the top vertex of the parallelogram can be moved upward until the mass becomes weightless, upon which the parallelogram is locked and the system is once again balanced. This model can be adjusted for payloads between 0 and 3kg, which are balanced over a height of 0.5m. There is very little friction in the balancer, and it is therefore very sensitive to disturbances such as uneven ground. There is some friction when adjusting the parallelogram to the new payload, but this is small compared to the weight being balanced.

Figure 10: Practical implementation of a gravity equilibrator using the parallelogram storage spring principle with zero-free-length spring as shown in figure 8. In the configuration shown the parallelogram is locked (black knob). When the weight arm is in horizontal position it can be locked, in which case the parallelogram can be unlocked and moved upwards (for a greater payload) or downwards (for smaller payload).

4.2 GRAVITY EQUILIBRATOR WITH ROLLING LINK BALANCER

The rolling link based spring-to-spring balancer [24] was implemented in a prototype of an energy-freely adjustable statically balanced kitchen cabinet. The combination of the kitchen cabinet with the rolling link adjustment mechanism and its practical embodiment are shown in respectively Fig. 11 and Fig. 12. while details of the rolling link mechanism are shown in Fig. 13. In this situation the mass of the empty kitchen cabinet is balanced by a separate balancing mechanism, and the energy-free adjustable balancer can balance additional payloads between 0 and 35kg. The kitchen cabinet automatically adjusts itself to an altered payload. This is done with the aid of a release mechanism that only releases the rolling link when the cabinet is in horizontal position. Due to a small imbalance of the rolling link, the rolling link will automatically adjust itself to a zero payload. As a result the kitchen cabinet is heavily underbalanced and locked in horizontal position by two chains. After altering the payload the rolling link can be rotated effortlessly until the balance is restored, the cabinet is now rendered weightless. In fact it may be slightly overbalanced and will float a little upward. As a result the release mechanism will relock the rolling link into place. Although the design of the rolling link spring-to-spring balancer looks more complicated than for instance a ‘balanced bar’, the choice is well justified by the low friction, large reduction of number of parts, its exact balancing properties and full energy exchange. One drawback of this system is the difficulty to balance the mass of the adjustment mechanism itself, because without mass compensation it will tend towards a preferred position. A possible solution with a zero-free-length spring is shown in Fig. 14.

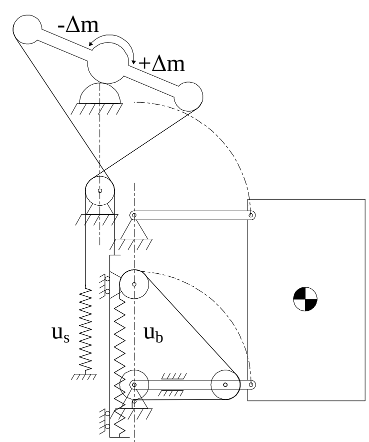


Figure 11: Practical implementation of rolling link adjustment mechanism in a kitchen cabinet. The kitchen cabinet moves in a 90° arc by means of a parallelogram, and its mass is balanced by a three-pulley basic gravity equilibrator attached to the bottom arm. When the cabinet is in its lowest position, it is fixed and the rolling link spring-to-spring balancer is unlocked. Mass can be added to or removed from the cabinet, and the balancer spring is adjusted accordingly by means of the rolling link balancer

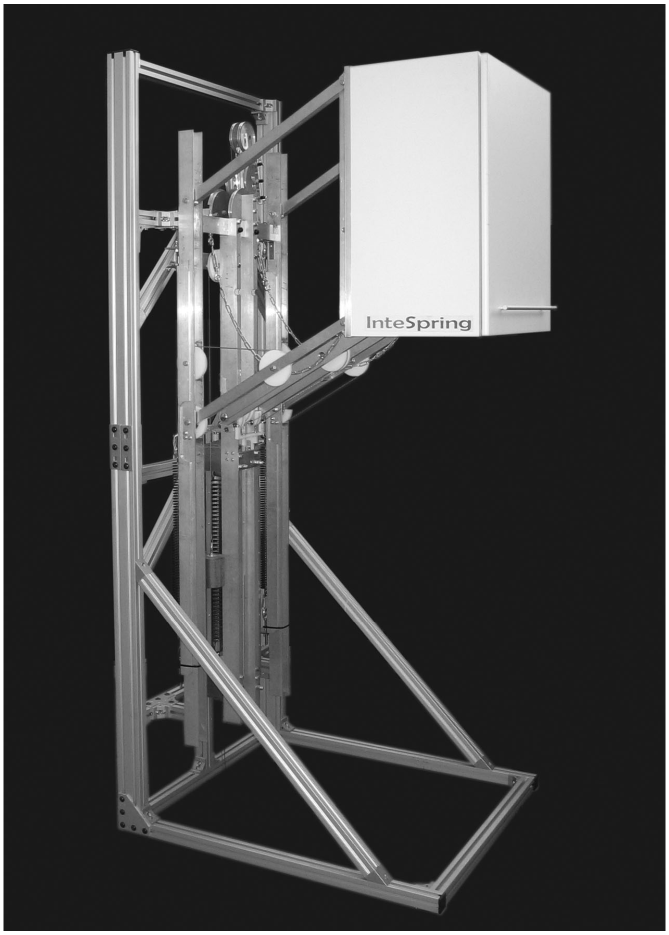
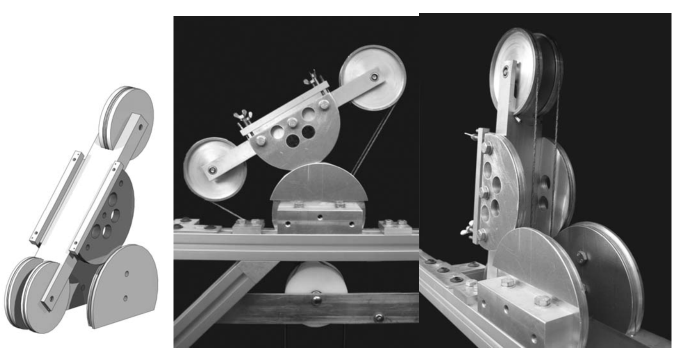


Figure 12: The actual embodiment of the practical implementation of rolling link adjustment mechanism in a kitchen cabinet. The schematic representation is given in figure 11.



(a) (b) (c)

Figure 13: The rolling link spring-to-spring balancing mechanism (a) as implemented in the balanced kitchen cabinet. Two parallel support disks are used, to allow the wires to pass through the centre. In (b) and (c) the actual embodiment is shown. The schematic representation is given in figure 9.

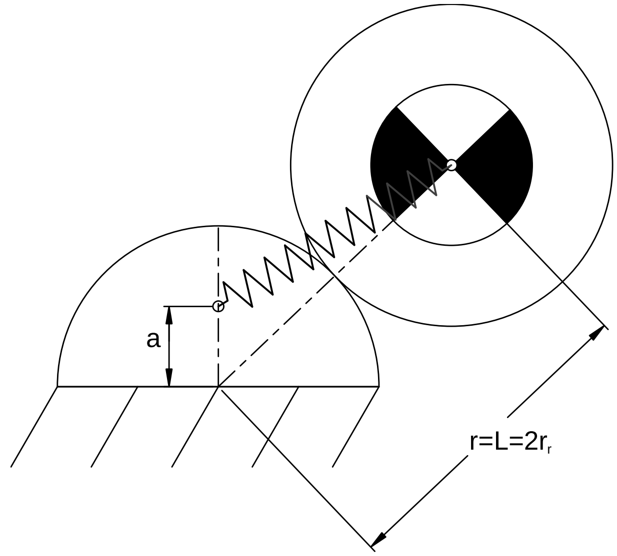


Figure 14: Solution to balance the mass of the rolling link. Assuming that the centre of mass of the rolling bar coincides with the centre of the rolling link, the mass can be balanced by means of a zero-free-length spring. Essentially it is a rolling link variant of the basic gravity equilibrator, and the dimensions are equivalent to the ones shown in Fig. 1. Distance *a* may of course be greater than the radius of the fixed disk.

5 DISCUSSION

The above provides an illustration of new means to obtain the required transfer function for the spring elongations to establish a complete energy transfer. One could imagine still other (exact or non-exact) methods for spring-to-spring balancing, which can be employed for energy-free adjustment of gravity equilibrators. Most classifications are based on the balancing condition (5). This condition gives insight in many possible ways of adjusting gravity equilibrators but it also restricts one to altering only one of multiple combinations of these variables. One could imagine that a more general balancing equation could be derived that gives insight in a whole new category of adjustment methods. Research is ongoing in this area.

6 CONCLUSION

A novel way to adjust gravity equilibrators to different payloads was proposed. The technique makes use of a storage spring, which supplies or stores the energy required for or released by adjustment of the balancer spring to a new payload. In effect, it is a spring-to-spring balancer on top of a gravity balancer. The spring-to-spring balancer preserves the total potential energy in the system by exchanging the spring energy between the balancer spring and the storage spring, when the balancer spring is adjusted to a new payload.

The fact that the gravity equilibrator and the spring-to-spring balancer can be designed independently, as well as the large number of possible variations for the spring-to-spring balancer, makes the storage-spring concept a very promising technology for energy-free adjustment of gravity equilibrators.

A prototype of the energy-free balancer was implemented in a kitchen cabinet, consisting of two balancing mechanisms, an adjustment mechanism and two locking mechanisms. One balancing mechanism (three-pulley system) balances the fixed mass of the cabinet of 21.7 kg and another balancing mechanism (rolling link) to balance the added mass between 0 and 35 kg. The whole cabinet can be displaced over a height of 55 cm. For every position the cabinet is well balanced also after readjustment for an altered weight. The forces (due to friction and unbalance) that are needed to displace the cabinet never exceed 5 N. Due to the special locking mechanism the cabinet 'senses' the added weight and automatically locks the adjustment mechanism when balance is achieved. A user can easily stack a pile of plates inside the cabinet. After loading the cabinet, a simple rotation of the rolling link spring-to-spring balancer leads to a restored balance and the cabinet with its new load can easily be displaced. The technology was patented and is already being applied in statically balanced products.

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