Inherent Gravity Force Balance in Moving Architecture with New Designs

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Abstract

Moving large architectural structures normally is only possible for solely horizontal motions and for structures balanced with large counterweights in order to omit the direct influence of gravity on the actuation forces, which otherwise are enormous. While vertical motions are desired, using counterweights has multiple disadvantages: they generally are huge for which they require a lot of space in the design, they are difficult to integrate in the design, and because of the large weights, the structural loads to hold the counterweights become enormous for which designs with high strengths are necessary. This altogether makes counterweights expensive and unattractive.

This work presents the design approach of inherent balancing applied for moving architecture and shows how balanced structures can be obtained that need no counterweights. In these designs the architectural elements balance one-another with which balance is fully incorporated within the design. Three design approaches for inherently balanced moving architecture are presented that are based on the balanced pantograph linkage as building block, which are classified as designs by combining balanced pantographs, by patterning bisected balanced pantographs, and by incorporating balanced pantographs. Design examples are illustrated and new conceptual designs are presented of a circular and an oval balanced umbrella canopy, a balanced 'Tipi tent', the balanced 'Inside-out house', the balanced Wing-type bascule bridge, the balanced 'Flipper building', and the balanced 'Turnround roof'.

Keywords: Inherent gravity force balance, Design method, Moving architecture, Deployable structure, Linkage

Introduction

The beauty of moving (kinetic) architecture is based on its geometry of motion. Designed structures considered as linkages with movable joints, having the capability to express wonderful alternating shapes, either for aesthetics or for functionality. In practice however, designs can only be realized if they can be produced sufficiently stable and safe. Because of the large dimensions of architectural objects, the weights of elements such as façades and roof sections are significant for which an enormous (driving) power is needed to withstand the gravity force to move the structure or to hold it in place. This is also at high risk since the structure can collapse by failure of the driving power.

Because of these difficulties most of the developed large moving architecture has only horizontally moving elements for which gravity plays no significant role besides friction [1]. In case of vertical motions, designs exist having incorporated balance masses or counterweights to eliminate the effects of gravity, which for instance is common in movable bridges [2]. However, these balance masses are in general enormous of size and weight, increasing the structural forces and the complexity of the design significantly. Therefore it is an expensive solution which in many cases is not even possible to implement.

A relatively new balance method is the method of inherent balancing which aims at designing moving structures that are balanced without the need of balance masses, resulting into lightweight solutions [3,4]. Inherently balanced linkage architectures then are used as a starting point in the design from which a variety of inherently balanced linkage designs are derived. The simplest inherently balanced linkage architecture is the balanced pantograph.

The goal of this article is to show how a balanced pantograph linkage can be used as a building block in the design of inherently balanced vertically moving architecture. First the pantograph linkage is explained together with its balance conditions. Subsequently three approaches are presented for composing inherently balanced architectural designs by (1) combining balanced pantographs, (2) patterning bisected balanced pantographs, and (3) incorporating balanced pantographs. For each approach illustrations of practical design examples are presented including new concepts.

The balanced pantograph linkage as a building block

Figure 1 shows a pantograph linkage, which can be considered as a specific version of Sylvester's pantograph or a modified version of Scheiner's pantograph from 1603 [3,5]. It consists of the parallelogram linkage P_1AP_2S with link lengths a_1 and a_2. In A there is a revolute joint between links AP_1 and AP_2, in P_1 there is a revolute joint between links P_1A and P_1S, in P_2 there is a revolute joint between links P_2A and P_2S, and in S there is a revolute joint between links P_1S and P_2S. In S there is also a revolute joint with the fixed base about which the pantograph can move with two degrees of freedom. These motions can be observed by rotating either link P_1S or link P_2S about the base joint S. All links are considered rigid.

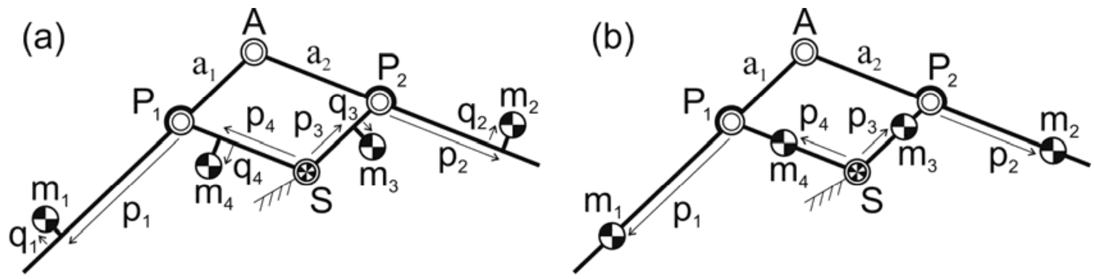

Figure 1: Pantograph linkage balanced with its center of mass in base joint *S* for any pose, shown for (a) the general situation and for (b) the situation when all links are mass symmetric.

Each of the four links has a mass m_i with the mass center located at a distance p_i from one of the link joints and at a distance q_i normal to the line through the link joints, as illustrated in Figure 1a. The conditions for which the common center of mass (common CoM) of the four links is located precisely in joint *S* for any pose are named the force balance conditions and can be written as [3]:

$$m_1p_1 = m_2a_1 + m_3p_3 \quad (1)$$

$$m_1q_1 = m_3q_3 \quad (2)$$

$$m_2p_2 = m_1a_2 + m_4p_4 \quad (3)$$

$$m_2q_2 = m_4q_4 \quad (4)$$

This means that when these conditions are fulfilled, the pantograph is gravity force balanced for any motion with a stationary common CoM in *S*.

The pantograph shown in Figure 1a is the general balanced case with mass asymmetric elements, i.e. the link CoMs are located off the line through the link joints with $q_i \neq 0$. The specific balanced case when all links are mass symmetric, i.e. when the link CoMs are located on the lines through the link joints with $q_i = 0$, is illustrated in Figure 1b. This design is a little simpler and may be preferred in practice. The shape of the pantograph links does not need to be straight, they can have any curvature or shape as long as the link CoMs are located at the balanced locations. In the next sections it will be shown how the balanced pantograph can be applied as a building block in the design of gravity force balanced moving architecture.

Architectural designs by combining balanced pantographs

Balanced pantographs can be combined in a variety of ways without losing the overall balance properties. Figure 2 shows the conceptual design of a movable balanced *Tipi tent* in two poses. It consists of three pantographs with curved links in series as a moving frame together with tent fabric to close the surfaces in between. The front and the back pantograph are supported by

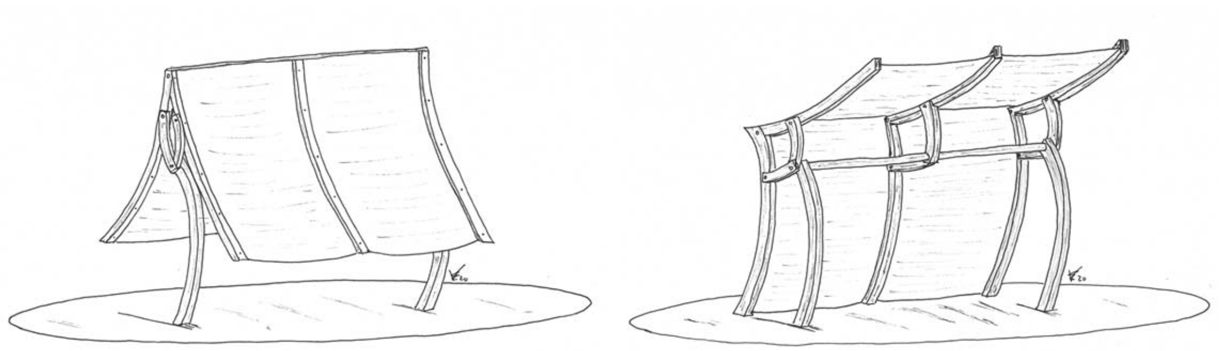

Figure 2: Conceptual design of a balanced *Tipi tent* in two poses, composed of multiple pantographs in series with fabric in between.

curved pillars which also hold a horizontal beam that is supporting the central pantograph in the middle. The center of mass of all the movable parts is at the height of the horizontal beam for any of its poses. In principle this structure can be observed as a single pantograph as in Figure 1a but with a large depth, balanced for the conditions (1-4) and accomplished with three harder sections for the frame with softer parts in between.

Balanced pantographs can also be combined as shown in Figure 3 in which two of them are placed oppositely and are connected with a revolute joint in *B*. In this configuration each pantograph is balanced individually for the conditions (1-4), independent of the location of *B* and of its motions. Based on this combination, Figure 4 shows the conceptual design of the *Inside-out house*, a building where the inside and the outside become one [3]. This design allows the roof to be pulled down causing the house to open up by upwards motion of the façades for balance. Because of its inherent balance, this motion requires minimal efforts to overcome solely potential friction in the moving joints. Each side of the house can be compared to the Tipi tent in Figure 2 with the center of mass of each side located for any of its poses in the pivot *S* of the supporting pillar.

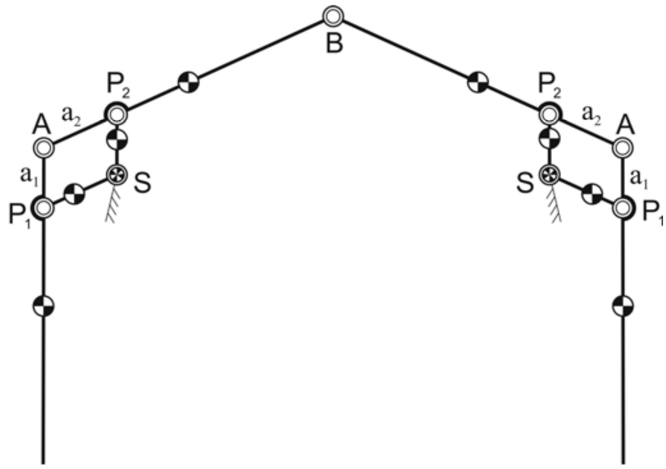

Figure 3: Inherently balanced composition by combination of two balanced pantographs placed oppositely and connected with a revolute joint in *B*. The two joints *S* are the two base pivots.

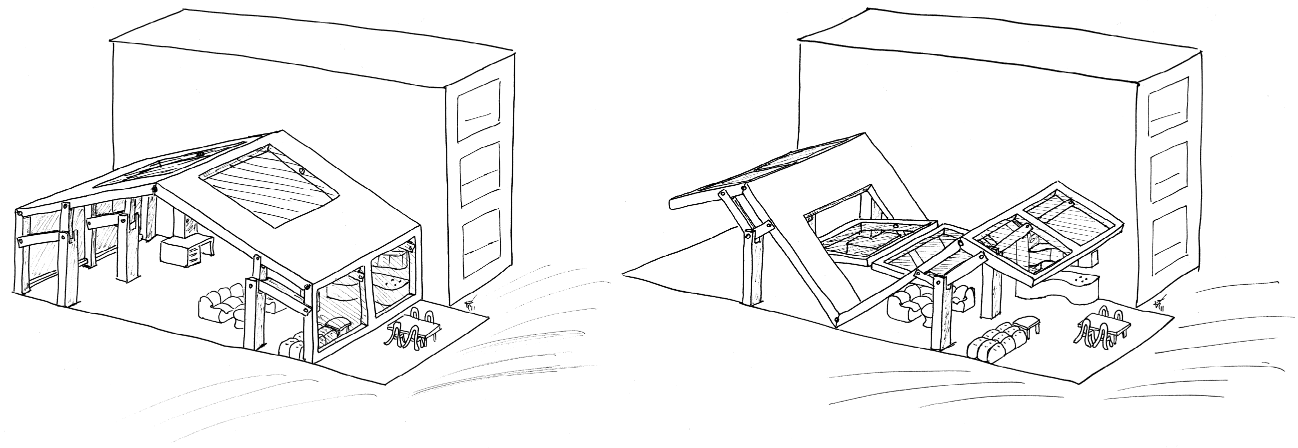

Figure 4: Conceptual design of the *Inside-out house*, a building where the inside and the outside become one. By pulling the roof down the façades move upwards for perfect balance (2011 [3]).

Architectural designs by patterning bisected balanced pantographs

A balanced pantograph can be bisected along line *z* as illustrated in Figure 5, which is the line through *S* and *A* in the pantograph of Figure 1. The pantograph is divided and the motion of each side is constrained to one degree of freedom by a slider along line *z* in *A*. The two halves can be separated with an offset *d* by additional links in between, which means that joint *S* in Figure 1 is divided into two separate joints *O*. The center of mass however remains in the middle at line *z*.

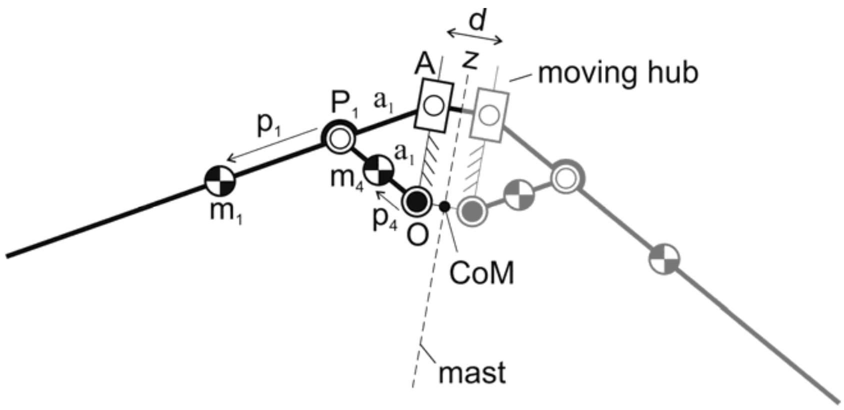

Figure 5: Bisected balanced pantograph, which is half of the balanced pantograph to be used in designing patterns of (spatially) moving balanced structures.

The bisected balanced pantograph can be applied in the design in a variety of ways. When the lengths a_1 and a_2 are equal then the bisected half of the balanced pantograph can be used as a building block to obtain various (spatially) balanced patterns. When a_1 and a_2 are unequal then patterning is only possible for specific and more complicated conditions. For simplicity only the former case will be discussed here.

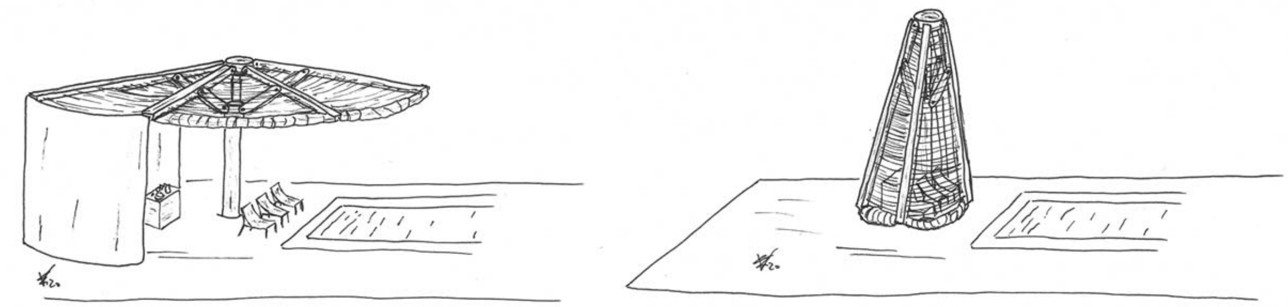

Figure 6. Conceptual design of a circular balanced umbrella canopy of which the upper hub moves up and down to close and open the canopy.

Figure 6 shows a conceptual design of a large size circular balanced umbrella canopy in two poses. This type of composition was studied in detail in [5] and consists of 5 bisected balanced pantograph arms of Figure 5, circularly oriented about the vertical mast. Contrary to common umbrella canopy designs where the top is fixed, here the top part is the moving hub, moving up and down to close and open the canopy, respectively, while the center of all masses remains stationary at the lower fixed hub which is part of the mast. Also the weight of the fabric cover can be included, independent of hanging straight down as shown on the left side or of being rolled up as illustrated on the right side in the illustration of the opened pose.

Because of its inherent balance, independent of its size and weight it can be opened and closed with minimal effort. When closed, the canopy is very compact with the size of the fixed and moving hub determining the size of the internal space, which may be useful for storage. More knowledge about the circular pattern possibilities for circular umbrella canopy designs can be found in [5].

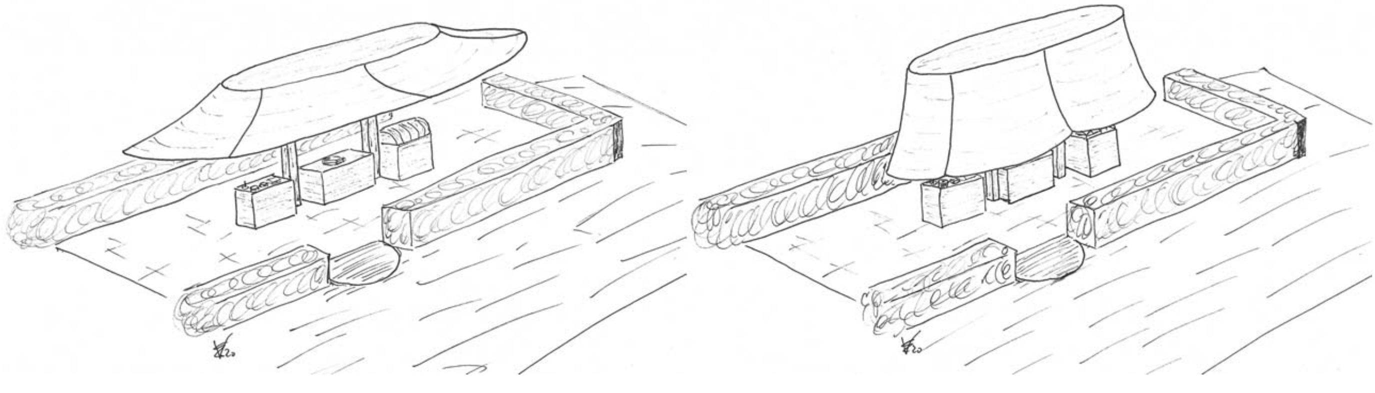

Figure 7: Conceptual design of an oval balanced umbrella canopy of which the elliptically shaped upper hub moves up and down to close and open the canopy.

Bisected balanced pantograph arms can also be composed in an elliptical pattern as illustrated in the conceptual design of an oval balanced umbrella canopy in Figure 7. Here the top is a large elliptically shaped moving hub, which moves up and down for closing and opening, respectively, similarly as the canopy in Figure 6. The fixed hub has the same size and shape and is supported by two masts. The number of bisected balanced pantograph arms in this design is not fixed, it is illustrated for 6 arms, 3 symmetrically placed on each side, but there can be more as well. The oval shape allows the umbrella canopy to cover a larger elongated area as compared to the circular umbrella canopy. This can be practical for instance to shade an outside buffet.

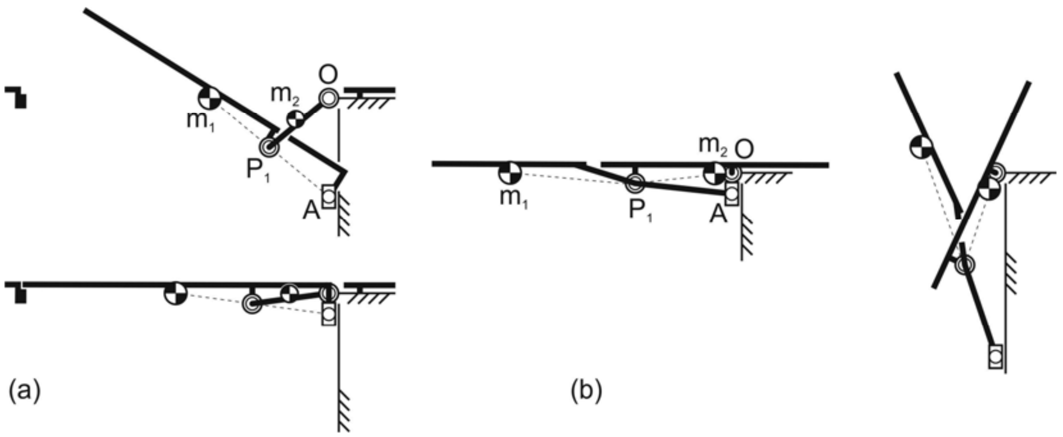

Figure 8: Gravity balanced retractable structures based on a single bisected balanced pantograph arm. In (a) there is one main architectural element while in (b) both links are applied as architectural elements.

Just a single bisected balanced pantograph can already be used to obtain gravity balanced designs. In Figure 8 it is illustrated how the bisected balanced pantograph arm of Figure 5 can be applied as a retractable structure. Since the structure is not a complete balanced pantograph the center of mass does not remain stationary, however it moves solely horizontally staying at the same height as *O* and therefore it is gravity balanced for all motions.

Figure 8a shows a design where link OP_1 is considered to hold the main architectural element AP_1, while Figure 8b shows a design where both links are main architectural elements. The design in Figure 8a was used for the concept of the *Wing-type bascule bridge* shown in Figure 9, a movable bridge balanced without counterweight. In this specific design the bridge is not perfectly balanced since it moves a little downwards when opening which is in order to compromise with the load of the wind. The actuation of the bridge consists of driving the slider in *A* up and down along its straight vertical path.

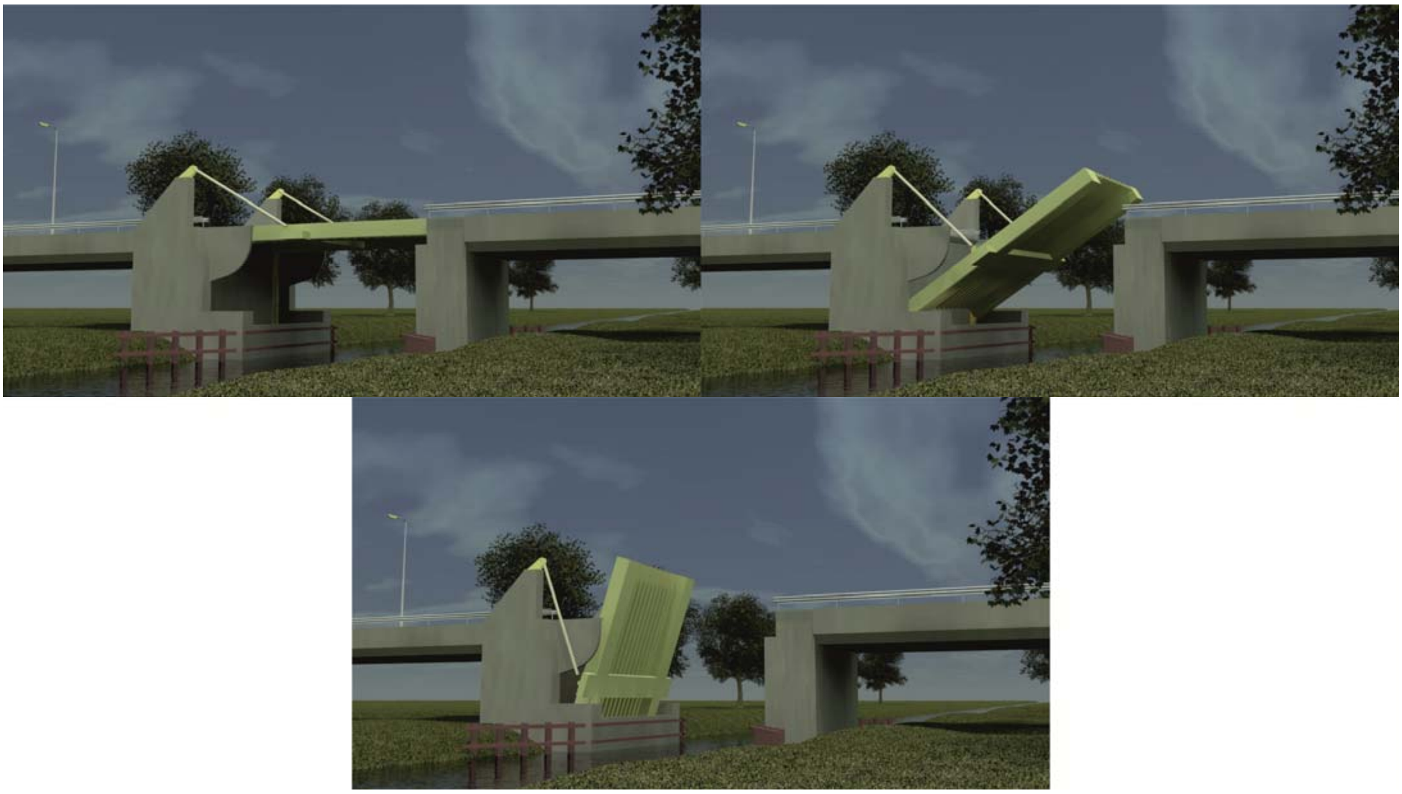

Figure 9: Conceptual design of the *Wing-type bascule bridge* which is balanced without counterweight (2012 [3])

Two Wing-type bridges can be combined in a pattern as illustrated in Figure 10 where they together form one large balanced movable bridge. Also they can be patterned as illustrated in Figure 11, which in fact is comparable with the full illustration in Figure 5. The advantage of the designs in Figure 11 with respect to the designs in Figures 8-10 is that they do not generate bending moments on the base pillars since their centers of mass remains stationary also in the horizontal direction. The design in Figure 11b shows the possibility for a slope where both sides of the bridge move asymmetrically for force balance.

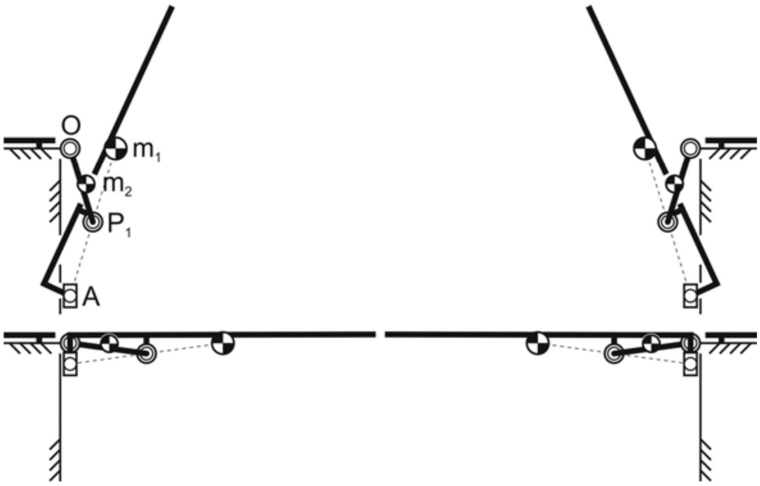

Figure 10: Mechanism of the *Double Wing-type bascule bridge* of two oppositely placed single balanced Wing-type bascule bridges.

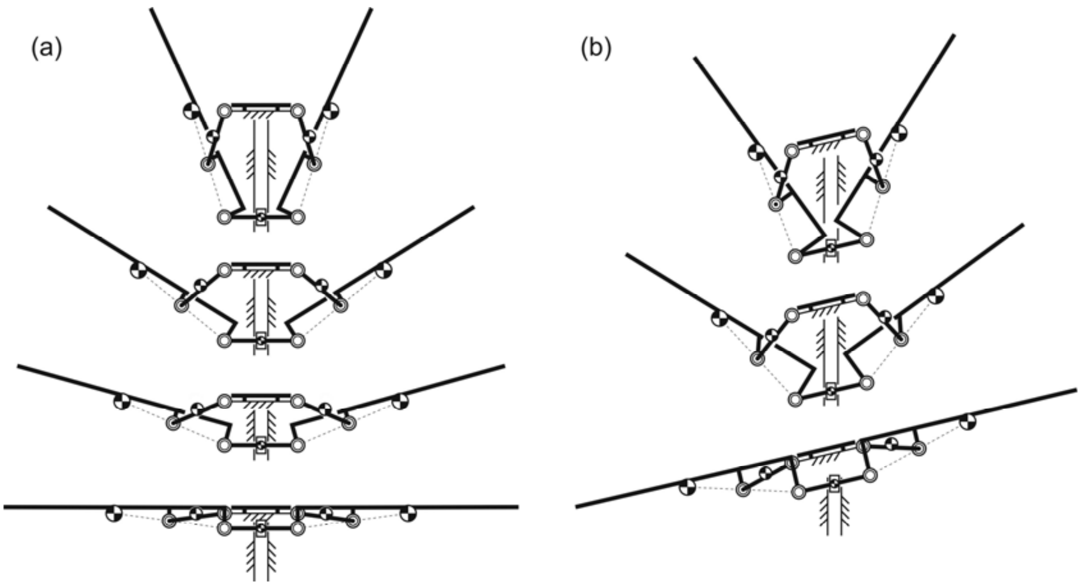

Figure 11: Mechanism of a balanced *Double Wing-type bascule bridge* with both wings on a central pillar which therefore does not experience any bending moments. Shown for (a) a horizontal road and (b) a road on a slope.

Although the mechanisms in Figures 8, 10, and 11 were explained in the context of balanced movable Wing-type bridges, they of course can also be imagined as being any other balanced retractable architectural structure.

Architectural designs by incorporating balanced pantographs

A third approach in this article for composing inherently balanced designs is by incorporating balanced pantographs. Various mechanisms can be found which include one or more parallelograms that can be transformed into pantographs and therefore have potential for an inherently balanced design. For instance the Peaucellier-Lipkin straight-line linkage consists of a parallelogram that can be transformed into the pantograph of Figure 1b as shown in Figure 12a [7]. In this linkage joints B_0 and B_1 are pivots with the fixed base and when moved as illustrated in Figure 13, point *S* traces a perfectly straight horizontal path. This motion can be seen as that the pantograph is being carried by the three other links. For straight-line motion the conditions $a_1=a_2$, $l_5=l_6$, and $l_7=|B_0B_1|$ must hold, which allows the size of the parallelogram to be altered independently from the size of the three carrying links.

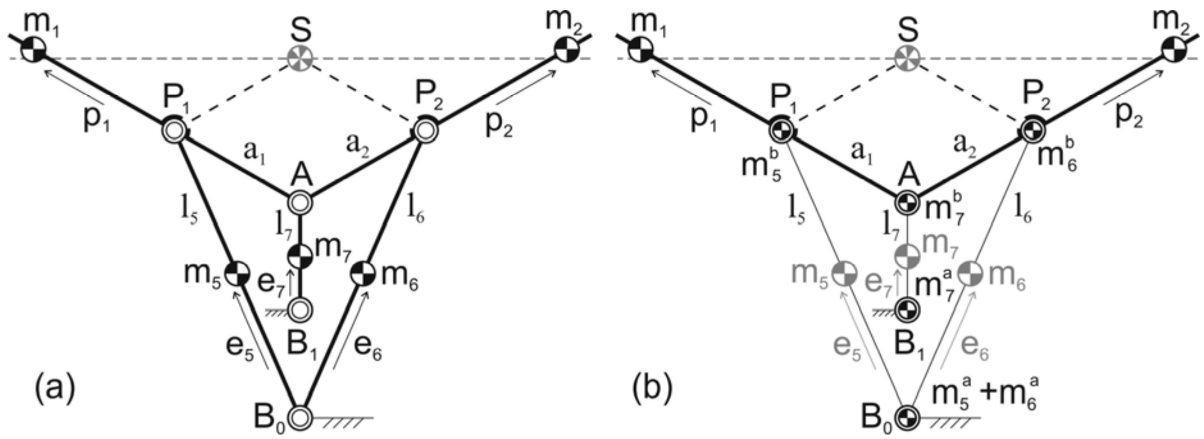

Figure 12: a) Balanced linkage based on the Peaucellier-Lipkin straight-line mechanism with the center of all moving masses in point S, which solely moves horizontally by means of an incorporated balanced pantograph with two virtual links; b) Equivalent mass model.

There are a variety of ways to balance the Peaucellier-Lipkin straight-line linkage among which the approach of balancing the linkage with respect to the point tracing the straight horizontal line [7]. Special and new here is the situation that in the design the straight line does not need to be traced physically, for which links P_1S and P_2S can be eliminated and then solely exist virtually. This results in very interesting possibilities for a balanced architectural design.

The conditions for which the new linkage in Figure 12a is gravity force balanced can be derived from [7] as:

$$m_1 p_1 = (m_2 + m_6^b + m_7^b) a_1 \quad (5)$$

$$m_2 p_2 = (m_1 + m_5^b + m_7^b) a_2 \quad (6)$$

with equivalent masses $m_5^b = m_5 \frac{e_5}{l_5}$, $m_6^b = m_6 \frac{e_6}{l_6}$, and $m_7^b = m_7 \frac{e_7}{l_7}$. Figure 12b shows an explanation of these equivalent masses with which the moving masses of links B_0P_1, B_0P_2, and B_1A are included in the joints of the pantograph and are included in the balance conditions of the pantograph. The mass of each of the three links is modelled with two equivalent masses of which the second parts $m_5^a = m_5 - m_5^b$, $m_6^a = m_6 - m_6^b$, and $m_7^a = m_7 - m_7^b$ are located stationary in the base pivots.

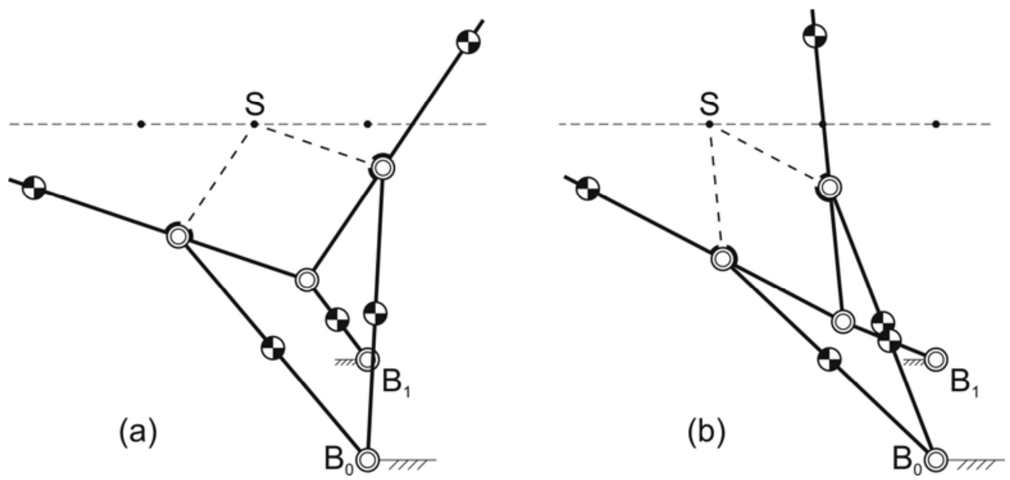

Figure 13: Gravity balanced linkage of Figure 12a for two poses left of the central pose to illustrate its motion.

Figure 14 shows the conceptual design of the *Flipper building* which is composed of two sections that are based on the balanced linkage in Figures 12 and 13. In this design the roof segments need to be significantly large or extended as compared to the supporting links, which is advantageous. Essentially the two roof segments balance mainly one another for which the influence of the mass of the supporting links on the design is marginal. As can be observed, this design allows a rather outstanding range of motion, from fully covering a large inner space to being deployed far away to the outside, yet shadowing a large outside space.

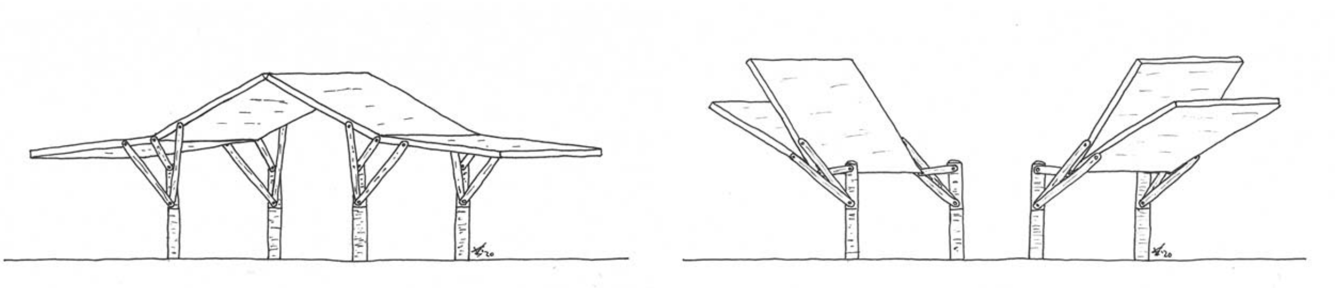

Figure 14: Conceptual design of the balanced *Flipper building* of which the roof can cover and uncover a large area in a spectacular way with a rather outstanding range of motion and deployability.

Another straight-line mechanism that is well-known is the Chebyshev linkage shown in Figure 15a [8]. It consists of the two links A_0A_1 and A_2A_3 with equal length (l_1=l_3) and a link A_1A_2 with half the length of the base link A_3A_0 (l_4=$2l_2$). For the condition that l_1:l_2=5:2, point *S* halfway link A_1A_2 traces an approximate straight line. In Figure 15b it is illustrated that this linkage has two pantographs as a geometrical basis which are combined in a configuration known as Burmester's focal linkage with *f* as focal point [8]. The Chebyshev linkage is composed of links aligned with these pantographs. In this case the pantographs are only used as a graphical tool for synthesis since in the real design in Figure 15a no mass of a pantograph link is directly present. The force balance condition for which the center of the moving mass of the linkage in Figure 15a is in point *S* for any motion can be written as:

$$(m_1^b - m_2 - m_3^b)\frac{l_2}{2} + m_2 e_2 = 0 \qquad (7)$$

with $m_1^b = m_1\frac{e_1}{l_1}$ and $m_3^b = m_3\frac{e_3}{l_3}$.

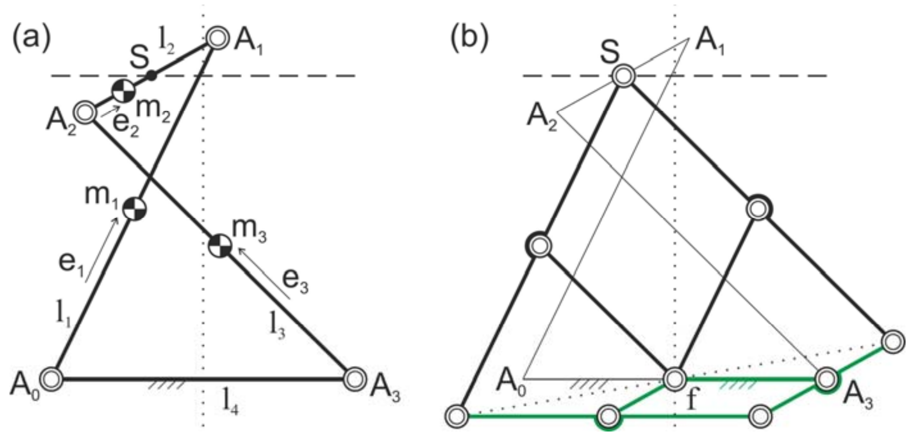

Figure 15: (a) Balanced Chebyshev approximate straight-line mechanism and (b) its geometrical basis with two pantographs in a composition known as Burmester's focal linkage.

Figure 16 shows the conceptual design of the balanced *Turnround roof* that is based on the linkage in Figure 15a. The roof is shown with a wave-shaped design, however it can have many other shapes as well. Beautiful of this concept is that the roof can move in an approximately balanced way from a perfect horizontal pose to a perfect vertical pose on either the left or the right side, exhibiting a significant balanced rotation of 180 degrees in total. This makes the design a façade and roof in one.

During motion, the center of mass in *S* moves slightly up with a maximum of 0.24% relative to base link A_3A_0 at about halfway the horizontal pose and both vertical poses. Since in these three poses the center of mass in *S* is at the lowest heights, these three poses are very stable with the mass helping to stabilize. This means, on the other hand, that some effort is needed to keep the roof in all other poses in between, although this effort is significantly small.

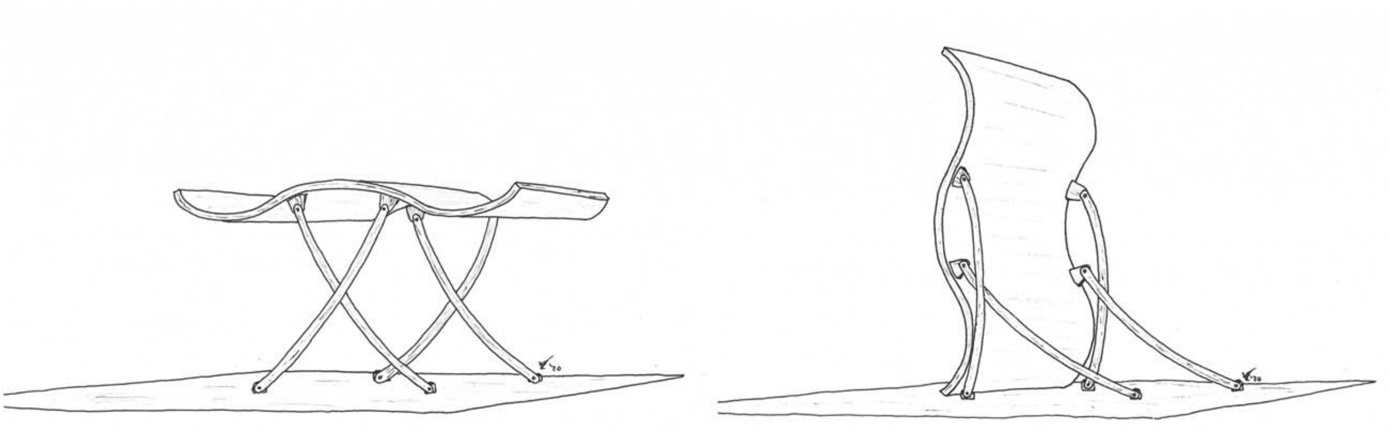

Figure 16: Conceptual design of the *Turnround roof*, a roof that can rotate from a perfectly horizontal pose to a perfectly vertical pose on both sides with almost perfect balance, making it a façade and roof in one.

Conclusion

In this paper it has been shown how inherently balanced vertically movable architecture can be designed based on a balanced pantograph linkage as starting point and as building block, resulting in designs without the need of counterweights. Three approaches for this were presented. The approach by combining balanced pantographs showed to be a straightforward approach to obtain designs with a variety of possibilities. Conceptual designs of a balanced *Tipi tent* and the balanced *Inside-out house* were presented. The approach by patterning a bisected balanced pantograph showed to lead to a complete other class of possible designs, from very simple to as complex as desired. Conceptual designs of a circular and an oval balanced umbrella canopy were presented and also of the *Wing-type bascule bridge*, a movable bridge balanced without counterweight. The third approach by incorporating balanced pantographs resulted in two very specific new solutions. The conceptual design of the *Flipper building* and of the *Turnround roof* were presented, showing large ranges of deployable motion.

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