Scissor Mechanisms for Transformable Structures with Curved Shape

The “Jet d’Eau” Movable Footbridge in Geneva

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Abstract

In this paper we focus on transformable structures and more specifically on structures that can change from a flat shape to a curved shape in a continuous process. We present a method for building a mechanism from any kind of curve that can be flattened by modifying only one degree of freedom. Such mechanisms are based on scissor-pair mechanisms; recently, their technology has been improved to be able to match all sorts of curved shapes. We applied this method in a contemporary ongoing project at the "Jet d'Eau" in Geneva, a structural footbridge spanning 12 meters over a thin lake channel. This footbridge consists of 30 couples of stainless-steel scissors that can be either flat or raised and in the raised position looks like a wave with a sinusoidal geometry. This footbridge resolves a public mobility issue and combines wheelchair and gentle mobility with boat passing in the lake channel: When the footbridge is horizontal, the deck is flat and pedestrians can pass even if in a wheelchair while the boat traffic is closed; when the footbridge is raised, the deck becomes stairs so that pedestrians can pass on it and boats can navigate underneath.

Keywords:
scissor mechanisms, transformable structure, curved shape, movable bridge, movable footbridge, Geneva

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1. Introduction

There are many different types of movable bridges around the world, most of which use basic movements such as translation or rotation. Generally these bridges allow only one traffic mode: The pedestrian traffic is stopped when fluvial traffic is active and vice versa. Indeed, most movable bridge structures are made with discontinued mechanisms, so that the deck is interrupted by a gap when the bridge is raised.

In June 2013, an association for the mobility of handicapped people launched a project to provide a large public access to the "Jet d'Eau" in Geneva. The aim was to build a timber deck 4 m wide to enlarge the existing jetty from the early 20th century made of stone which provides access to the harbour.

In its place, we developed a movable footbridge to allow the passing of wheelchairs and pedestrian traffic in the resting position, while boat-passing and non-wheelchair pedestrian traffic remain possible in its raised position. Construction on site commenced in October 2015 and should be finished by the end of June 2016. Figure 1 shows two renderings of the footbridge in the resting and raised positions.

2. Issue

In order to avoid an interrupted structure with a gap in the deck, we needed to develop a mechanical system with continuous transformation of its shape, such as stretch movements or homothetic transformations. Our research focussed on a fundamental issue: *How to build a curved structure that can transform itself into a flat structure?* The aim was to build a structure with only one degree of freedom that can be transformed without stress or damage to its continuity, as shown in Figure 2. We focussed our study on structures of constant height.

3. Sources of Inspiration

Mechanical systems with one degree of freedom are rare. The most popular is the scissor mechanism found in engines such as cranes, man-lift platforms, accordion barriers, trivets, and toys.

One of the objects inspiring our structure was the Hoberman Sphere, a small toy invented in the 1990s by Chuck Hoberman (Hoberman 1991, US Pat. 4942700) based on a pair of scissors that maintain a constant angle while moving and allows the creation of expanding circles. Chuck Hoberman carried out several projects using this mechanical concept, some of which reached architectural dimensions such as the Iris Dome (Hoberman 1991, US Pat. 5024031).

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Figure 1. Top: In the resting position the footbridge is flat and allows wheelchairs and pedestrian traffic to pass. Bottom: In the raised position the footbridge is curved and allows boat-passing underneath the bridge as well as non-wheelchair pedestrians to pass over the bridge by walking on stairs. Courtesy of Christian Tellols.

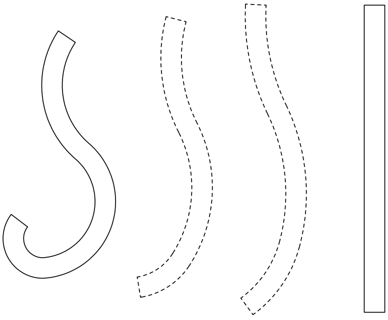

Figure 2. The expected transformation must be continuous, dictated by only one parameter.

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The scissor mechanism was developed in 1965 by Perez Pinero (Pinero 1965, US Pat. 3185164) as a movable theatre structure and rediscovered in 1974 by Theodore Zeigler (Zeigler 1974, US Pat. 3968808) for a collapsible structure. It has since been intensely studied and improved, in particular by Escrig and Valcarcel (1993, 71-84), and then by Kassabian, You and Pellegrino (1999, 45-56). It has also been widely used in applications for deployable/retractable roof structures. Called pantographic scissors by Hanaor and Levy (2001, 211-229), this mechanism led to many derived concepts as a pair of scissors where the pivot is in the centre, a pair of scissors where the arms do not have the same length, a pair of scissors where the arms are angulated as in Hoberman Sphere, and a pair of scissors where the pivot can slide along one arm in a slot. Not to forget all the combinations of the various scissors concepts. Indeed, despite the huge range of existing scissors concepts, seldom did they actually lead to a concrete project.

In a recent article, X. Chen and L. Liu (Zhang et al. 2016) present a topological method for building a scissor structure that matches a target shape as precisely as possible starting from a given source shape. Unlike this global generative approach, we propose a simplified approach that allows us to choose a solution by exploring different possibilities.

Another source of inspiration is the Rolling Bridge, located in London and designed by Thomas Heatherwick in 2004. This footbridge consists of a structure moved by seven pairs of hydraulic cylinders that can transform themselves into a circle by rolling.

This interesting project opens up new possibilities by using engine technology and robotics in architecture and structural engineering.

4. Curve with Scissor Mechanism

First of all, we looked at traditional scissor mechanism whereby the scissor pair comprises two arms linked together at a central pivot. Here, the scissor always forms a rectangle, with the length of each side changing when the arms revolve around the pivot. Since we only studied structures with a constant height, each scissor must have the same height h.

When the central pivot is shifted vertically, the scissor changes its shape from a rectangle to a trapezium, as shown in Figure 4.

The trapezium is an interesting element that allows us to build curved shapes thanks to its two inclined sides.

It is possible to build many different trapezium chains to run along any curve. For a standard path p and a common height h for each trapezium, the chain results upon choosing a starting angle γ for the first element; each following angle is then determined by symmetry, see Figure 5.

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Figure 3. Sources of inspiration using a scissor mechanical system. Left: a scissor crane. Middle: a widespread trivet. Right: the Hoberman sphere.

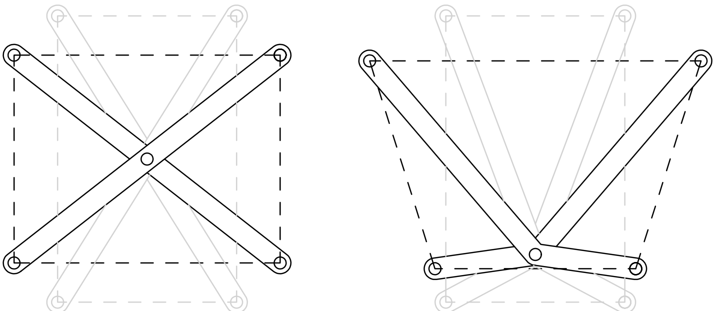

Figure 4. Left: the traditional scissor maintains a rectangular geometry while moving. Right: a scissor with the central pin shifted down, causing the geometry to change from a rectangle to a trapezium.

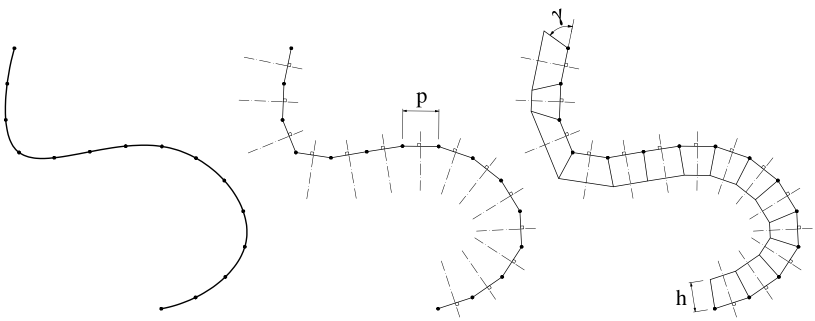

Figure 5. Elaboration of a trapezium chain. A given curve is discretised into a polyline with a constant path, the angle γ determining the trapezium chain. Many chains are possible. It is also possible to have a different path p for each trapezium.

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In order to build the scissor inside the trapezium chain, we have to solve an equation with several parameters. Indeed, all scissors are linked by one side so they have to fit the same conditions: same height h, path p, and angle a between both inclined sides.

5. Solution of the Trapezium Equation

Even if each trapezium has a different shape, they have the same height h and a base b, which corresponds to the polyline path; only the angle α is different. The goal is to find the position of the central pivot C such that, when arm L and arm l rotate of θ, their horizontal projections match to form a rectangle (see Fig. 6).

The result of transforming the trapezium into a rectangle led us to build all existing scissors possibilities for a given trapezium, even though these possibilities might not be compatible with one another for building a chain. The next step consisted of choosing the valid solution among all these possibilities.

The whole family of possibilities is drawn on the left side of Figure 7 for a theoretical case. For each angle a, the curve represents the rectangle height h', depending on the pivot position ratio ρ; each curve represents a family of scissors that have the same angle α and can transform itself into a rectangle.

From these curves we have to choose which ones match the expected height and intersect the horizontal line $h' = 1.7\,m$. Some angles might not intersect this line. Typically, on this graph, it is not possible to find the same height h' for an angle $a = 6°$ and an angle $a = 40°$. This means that, if the curvature of the shape leads to a trapezium with both angle values in the same trapezium string, there is no way to find a solution.

To solve that problem, it is possible to bring down a curve that does not intersect the expected height h' by decreasing the trapezium base b and with it path p.

At the top right of Figure 7, several curves are shown for a path decreasing from $1.34\,m$ to $0.50\,m$. When p reaches that last figure, the curve intersects the horizontal line $h' = 0.17\,m$, making it possible to embed the scissor with $\alpha = 40°$ into the trapezium chain.

Varying the path of the trapezium makes it is possible to target a wide range of angle α and allows it to work on a wide range of curves.

6. Helix with a Constant Path

As an example from the previous section, we apply the method described to a helix (see Fig 8).

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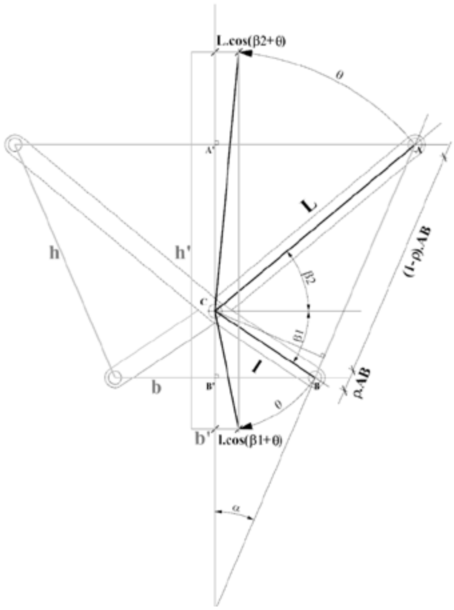

Boundary conditions:

$l + L > h'$

$|CA'| \geq |CB'|$

$\beta_2 + \theta < \pi/2$

$\beta_1 + \theta < \pi/2$

Rectangle condition:

$L.\cos(\beta_2+\theta) = l.\cos(\beta_1+\theta)$

Rotation solution:

$$\theta = atg\left(\frac{l.\cos\beta_1 - L.\cos\beta_2}{l.\sin\beta_1 - L.\sin\beta_2}\right)$$

Figure 6. Diagram of the trapezium. By turning θ, the arms L and l form a rectangular geometry.

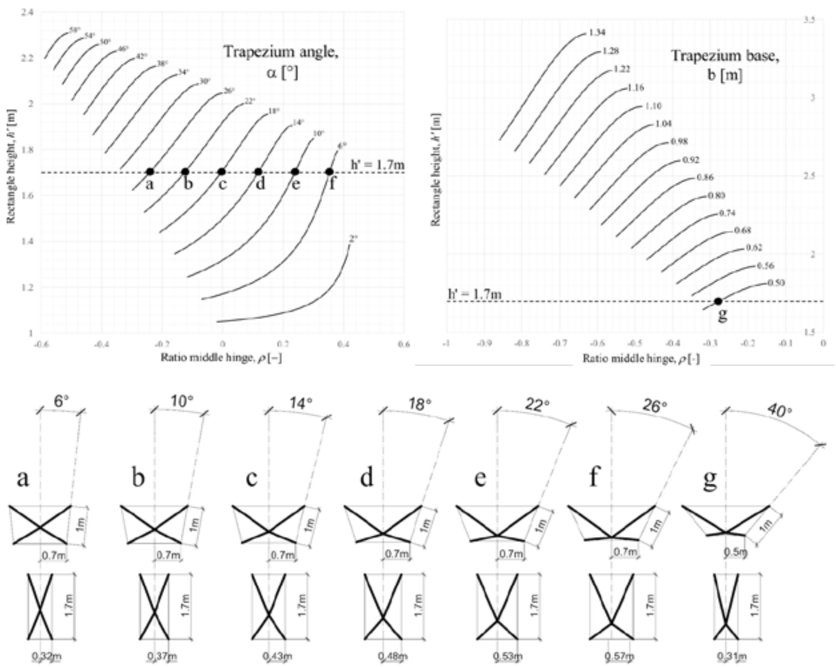

Figure 7. Top left: Graphic of the whole string of trapezium possibilities for different trapezium angles. In this theoretical case, the graphic is based on a trapezium base b = 0.7 m and a side length h = 1 m. Top right: Graphic of the whole string of trapezium possibilities with a = 40° for different trapezium bases. Bottom: Images of the scissors in the trapezium position and in the rectangle position.

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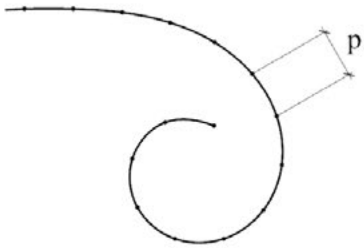
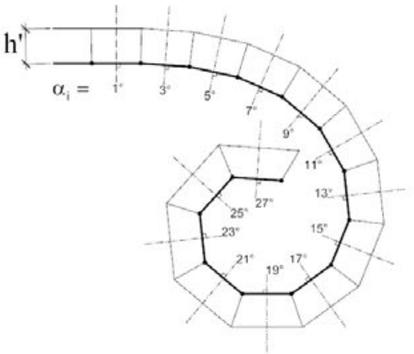
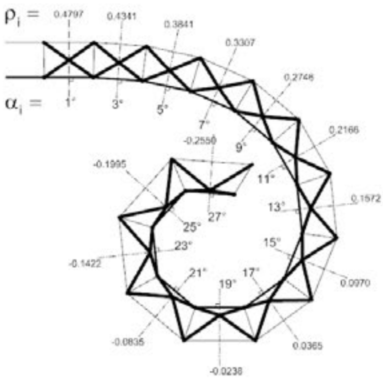


The helix curve is segmented into a polyline with a constant path p = *25 cm.*



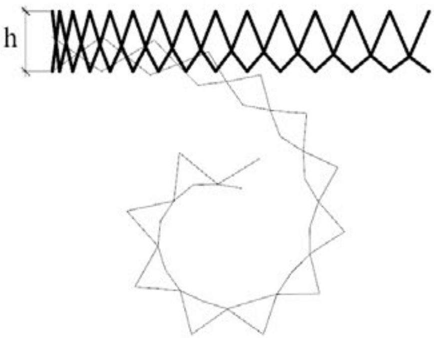
A trapezium string is built with a single height *h' = 18 cm* and each angle of trapezium is determined.

The height *h'* is chosen according to the graphic at the top of Figure 7, to produce a solution for every angle α_i.



For each trapezium we place the central pivot according to the ratio ρ, which is calculated based on the trapezium angle α.

The scissor geometry is unique once the parameters h and p_i have been chosen. Angles α_i are not chosen, but rather depend on the curve geometry.



When one scissor rotates, the whole scissor chain flattens. The rectangle height h = 31 cm.

In this example the first scissors are narrower to the left; this could be modified by increasing the path in this area.

Figure 8. Construction sequence of the scissor string construction for a helix example.

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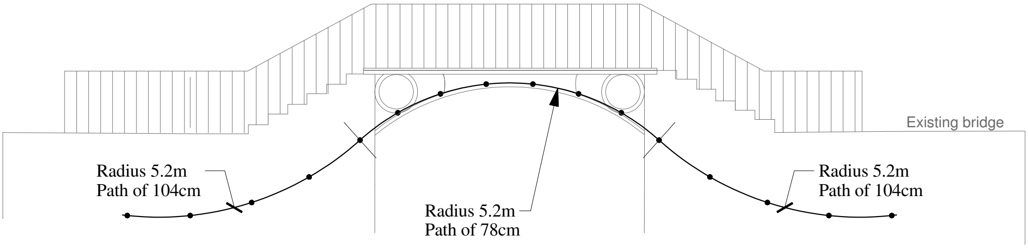

Figure 9. The curve for the scissor string is copied from the shape of the existing bridge, which remains unchanged. The height for clear boat passage is a strong requirement, leading to the shape of the curve, which consists of three circular arcs with identical radius r = 5.2 m.

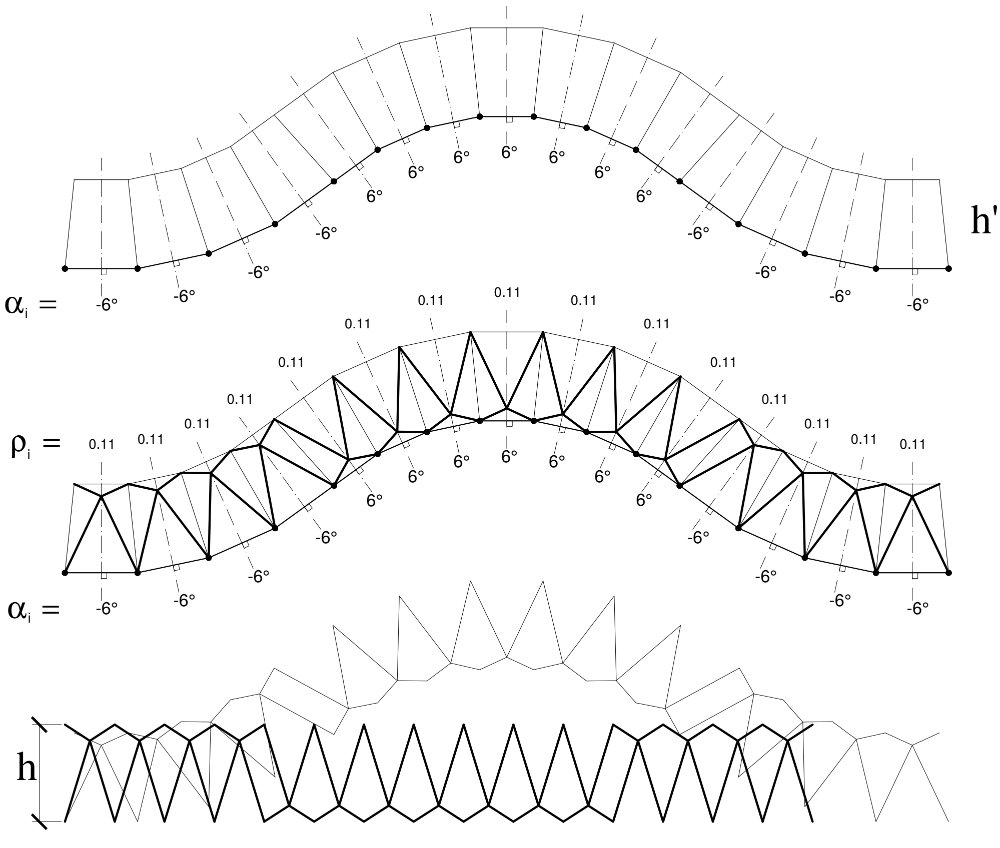

Figure 10. The initial curve permits building 15 trapeziums with same height h = 1.20 m and same angle $\alpha = \pm 6°$. The path is p = 74 cm in the middle and p = 104 cm at both edges.

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7. The Curve of the Geneva "Jet d'Eau" Footbridge

At the beginning of the project, we had no preconceived idea of what material should be used to construct the footbridge. In order to keep the range of possibilities open, we decided to make all the scissors with the same geometry, in particular to allow for moulding process or jig fabrication.

The fact that every trapezium is identical means having every pair of scissors identical. The scissors in the middle are turned down and the scissors on the edges are turned up. One very interesting feature of this footbridge is that for the footbridge to be raised the mechanism has to be extended and for the footbridge to come back to its flat position it has to be shortened.

Once the scissor string was known, we built a structure from the mechanism. Each scissor became a structural beam. This structure must respect standard requirements for footbridges, in particular be stiff enough to carry the usual loads.

8. Static Condition

Supports for a moving bridge can be a decisive issue for the structural design. Here the mechanism has only one degree of freedom, so it does not need many supports to stand erect. However, in order to provide enough stiffness and control the deflections, we decided to vertically fix two points at each edge. Of these four support points, one has to be fixed and the three others have to slide horizontally (see Fig. 11).

The hydraulic cylinder acts as a structural section that can change its length by changing the inside pressure. Because of the four support points and the two hydraulic cylinders, the mechanism becomes statically indeterminate.

The sliding points are made of bronze wear plates between a rail and the scissor support plates. They add a further difficulty to the calculation because even if the wear plates have a low friction coefficient, the hydraulic cylinder has to fight the friction resistance in order to raise the footbridge.

The finite element model must simulate the friction since it has an important impact on the structural behaviour. When the horizontal reaction is lower than the friction resistance, the sliding support points become fixed and the footbridge changes its support behaviour. The finite element model demonstrates that maximum stress in the hydraulic cylinder occurs during the detachment phase at the start of the movement.

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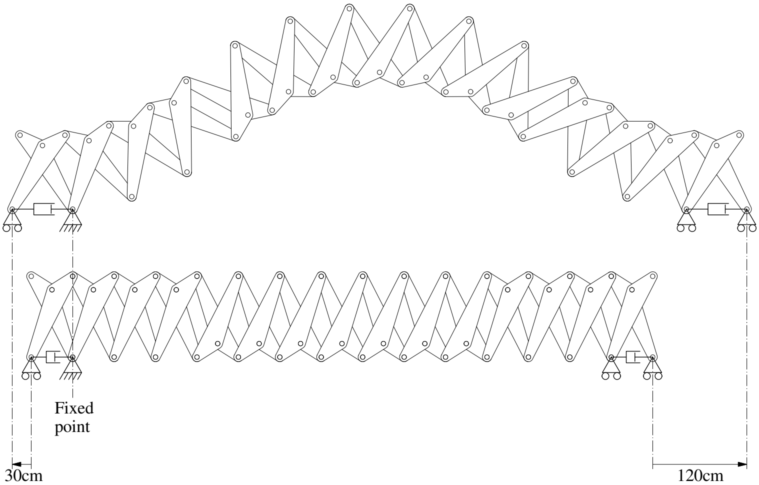

Figure 11. Diagram of the support system. Because of the fixed point position, the sliding points induce 30 cm of translation on the left and 1.20 m on the right.

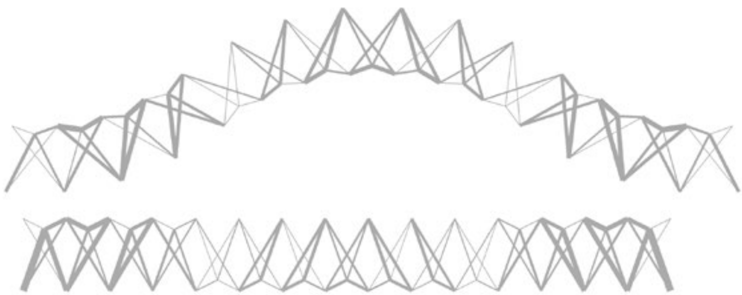

Figure 12. Optimisation of the structural members for the two positions accomplished with a strain-energy minimisation routine. The thickness of the line represents where steel must be placed to improve the stiffness of the whole structure.

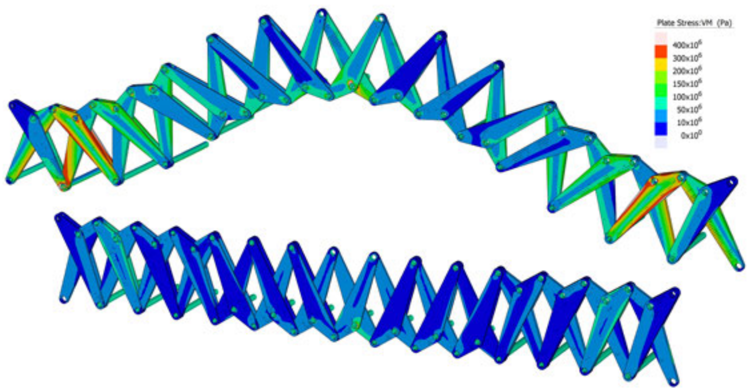

Figure 13. View of the final element model made with strand7, coloured with the VonMises stresses for the ultimate load state.

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9. Structural Behaviour

While the shape is transforming, the span increases and each scissor rotates, so the distribution of stress changes significantly during the rise. The raised position causes higher stress in the scissors than the horizontal position, though for the joining components it is different. The structural design must cover all middle positions of the movement; we proceed to a non-linear analysis with Strand7 by increasing the length of each cylinder and then analyse the results at each increment.

Figure 12 shows the material repartition needed to obtain the best structural behaviour. The situation is almost the same for both positions though slightly different at the edges. Obviously, all scissors do not work the same, so even with the same shape we need to find a way to adapt the resistance differently to each of them.

At this point of the project, the materials used in the structure become the main concern. For durability reasons we choose a stainless steel suited to outside exposure, the lake atmosphere and the Jet d'Eau clouds. We agreed on duplex stainless steel 1.4462, which has the advantage of having a good corrosion resistance, high toughness to limit wear and high proof strength ($R_{p0,2}$ = 500 MPa) (see Fig. 13).

The scissors plates are linked on each side with transoms Ø88 mm and 12 mm thick, which create a steel frame for transversal stability. The transoms belong to the primary structure and also support the deck and the stair frames.

A model analysis shows that the structure has a low frequency in both positions, especially for the first lateral mode. The footbridge should thus be sensitive to pedestrian traffic excitation, but in reality no such effect can be felt when people walk on it in the flat position. In the raised position, the horizontal vibration is perceived only at the very top of the stairs. Further measurements showed that employing most assemblage in bronze strongly increases the damping ratio and limits the discomfort due to the dynamic excitation (see Fig. 14).

The overall weight of the footbridge is about 16 tons, which breaks down as follows:

- Scissor plates : 10,130 kg
- Pin connectors : 800 kg
- Transoms : 1,220 kg
- Actuators : 750 kg
- Stair and deck : 3,400 kg

The force in the hydraulic cylinders reaches 11 tons when raising the footbridge; maximum reaction in the support is about 21 tons in serviceability state.

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	Raised position	Flat position
First lateral mode	1.8 Hz - 1.7 Hz	2.3 Hz - 1.8 Hz
First vertical mode	3.6 Hz - 4.4 Hz	5.7 Hz - 7.5 Hz

Figure 14. Table of the natural frequency of the structure. The first value is calculated from the FE model, and the second value is measured in situ.

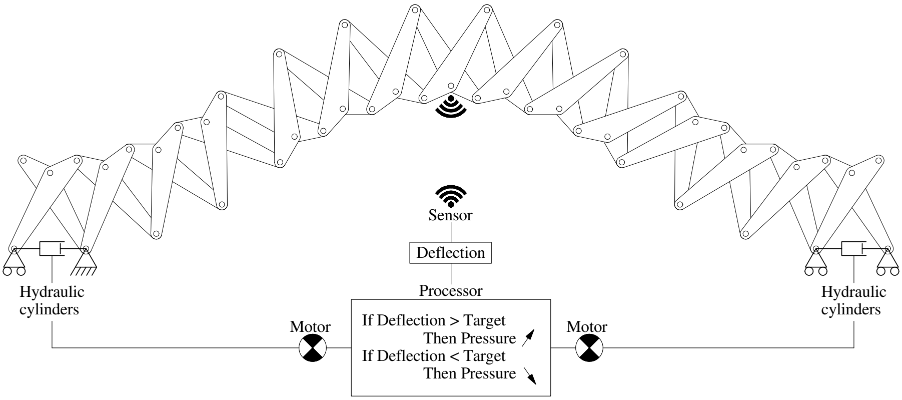

Figure 15. Scheme of the hyperactive concept. The sensor, the processor, and the motors are part of the structure and must be permanently active.

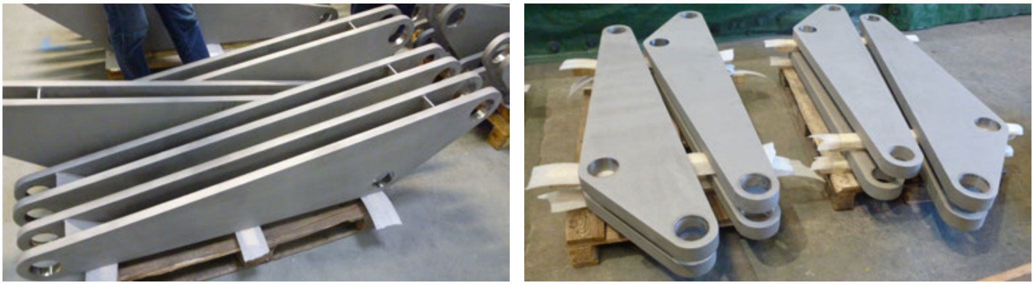

Figure 16. Left: The 2 x 30 mm thick plates. Right: The 60 mm thick plates, which comprise the edge scissors.

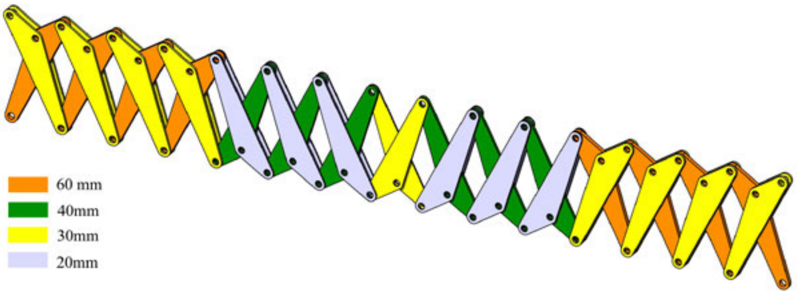

Figure 17. The scissors' colour depends on the thickness value. At the edges, the plates are 60 mm thick and 2 x 30 mm thick. In the middle, plates are 40 mm thick and 2 x 20 mm thick.

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10. Hyperactive Structure

Having hydraulic cylinders in the structural system means that the structure is permanently active, like a muscle in a living being. This opens a huge field of innovation for structural design called hyperactive structures.

One of its first applications is the clear distinction between ultimate state and serviceability state. The resistance of the structural element can be designed according to the ultimate limit state; the serviceability limit state could be managed separately.

Indeed, in order to respect the serviceability or to reduce the deflection, we have to manage the stress inside the hydraulic cylinders because it acts directly on the shape. In practice, when deflection is too high, we can increase the pressure in the cylinders to balance the deflection and vice versa (see Fig. 15).

Sensors are necessary to analyse the structure state and to determine the deflection value. A post-process state is also necessary to inform the hydraulic cylinder, which is commonly used in robotics and in mechanical engineering. These technologies can also be used for bridges.

One of the main advantages of this scheme is to provide a lightweight structure with high performance and reactive behaviour. In his paper "Pumping vs. Iron", Gennaro Senatore et al. (2011) presented some interesting results about this topic.

As explained above, the weak point of such structures is the dynamic behaviour. With dynamic excitation, the hydraulic cylinders don't have time to be reactive to stop the vibration. In such a case, a complete dynamic study must be done by taking into account the damping, which is very high and helpful for these mechanisms.

11. Double Shear Plate

To produce the pair of scissors, we had to find a method providing high accuracy. Even a tiny deviation or distortion in a pivot positioning could stop the assembly or prevent the mechanism from working correctly. Welds and laser cuttings are prohibited in that degree of accuracy as they would distort the steel plates too much. Therefore, we chose water-cutting technology, which can cut plates up to 100 mm thick with a low temperature and thus not cause damage to the form. Then, the plates were machined to drill the holes for the pivot pins (see Fig. 16).

To manage the difference of stress distribution inside the structural scissors, we decided to change the plate thickness: More stress implies more thickness. In the middle, we put a thin plate to reduce the weight, because this area has a major influence on the vertical deflection.

In the end we chose four different plate thicknesses (20, 30, 40, and 60 mm) for building the structure. Each plate is joined in double shear with the next

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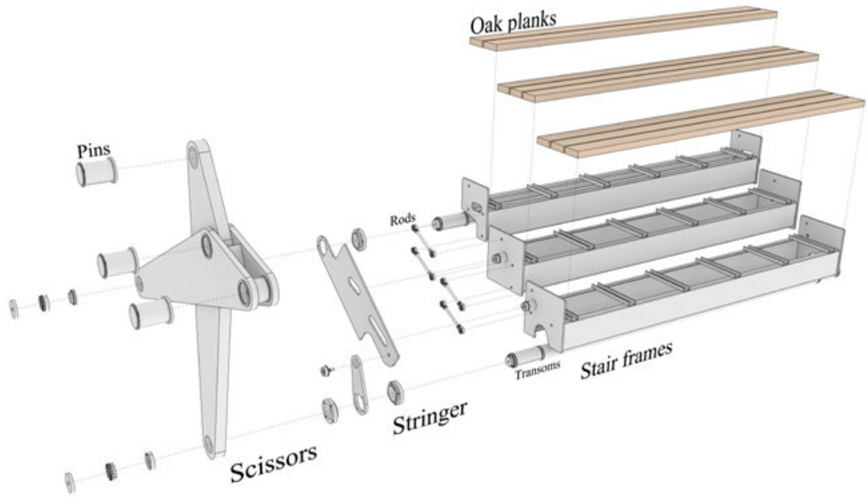

Figure 18. Exploded view of the fabrication model. Stringers control the vertical position of each stair frame with a slot. Each stair frame is linked with two rods to next frame. The frames slide into the slots of the stringer. There is no gap between the treads.

neighbour plates; for instance, the 60 mm plate is joined to 2 x 30 mm plates in order to transfer correctly the stress and to avoid eccentricity in the pin rods (see Fig. 17).

In the middle, the thickness of the plates is reduced to 40 mm and 2 x 20 mm, respectively, in order to give more lightness in this area and have greater influence on the deflection. The middle scissor is different from the others: It is a scissor with single shear plates of 30 mm, which allows it to have a fully symmetric structure.

12. Stair and Deck

The particularity of the footbridge is the transforming deck. As mentioned above, we wanted to allow pedestrians to cross the footbridge even when it is raised. To this end, we put a mechanical deck in place which follows the bridge transformation by evolving into a stair. This mechanism comprises two basic parts: The first is the stair stringer, which is linked to the scissor with a rod to rule the slope of the stair; the second is the stair frame, which slides in the stair stringer to reach the correct position. The treads are made of oak planks, and the rises are included in the stair frame.

The stair is thus like a sheet lying on the footbridge; it follows the bridge transformation without resistance. The stability of the stair frame is provided by the rods that link the frames together (see Fig. 18).

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13. Conclusions

The "Jet d'Eau" footbridge of Geneva was specially designed to provide different traffic modes, such as wheelchair and gentle mobility, pedestrian traffic, and boat-passing. The traffic mode can't be active at the same time, but the project serves to reconcile the needs of all users according to their attendance rates.

The method we developed to build the scissors mechanism can be used for any kind of curved shape. In our project we used the sinus shape, though we can imagine different shapes for other applications. The method is flexible, since it is possible to modify a single parameter, like path or height, in order to discover different solutions. The scissors mechanism does not have high stiffness, but the deflection can be managed by a hyperactive behaviour and the vibration are balanced by the high damping ratio.

This project is an application of technologies stemming from the mechanical field to a civil-engineering task. The use of hydraulic cylinders is rare in civil engineering, but we have shown that it is effective for changing the geometry of the structure and also for enhancing the structural behaviour. It is relevant for the future development of buildings and civil works that can evolve in their forms and also adapts to suit multiple needs (see Fig. 19).

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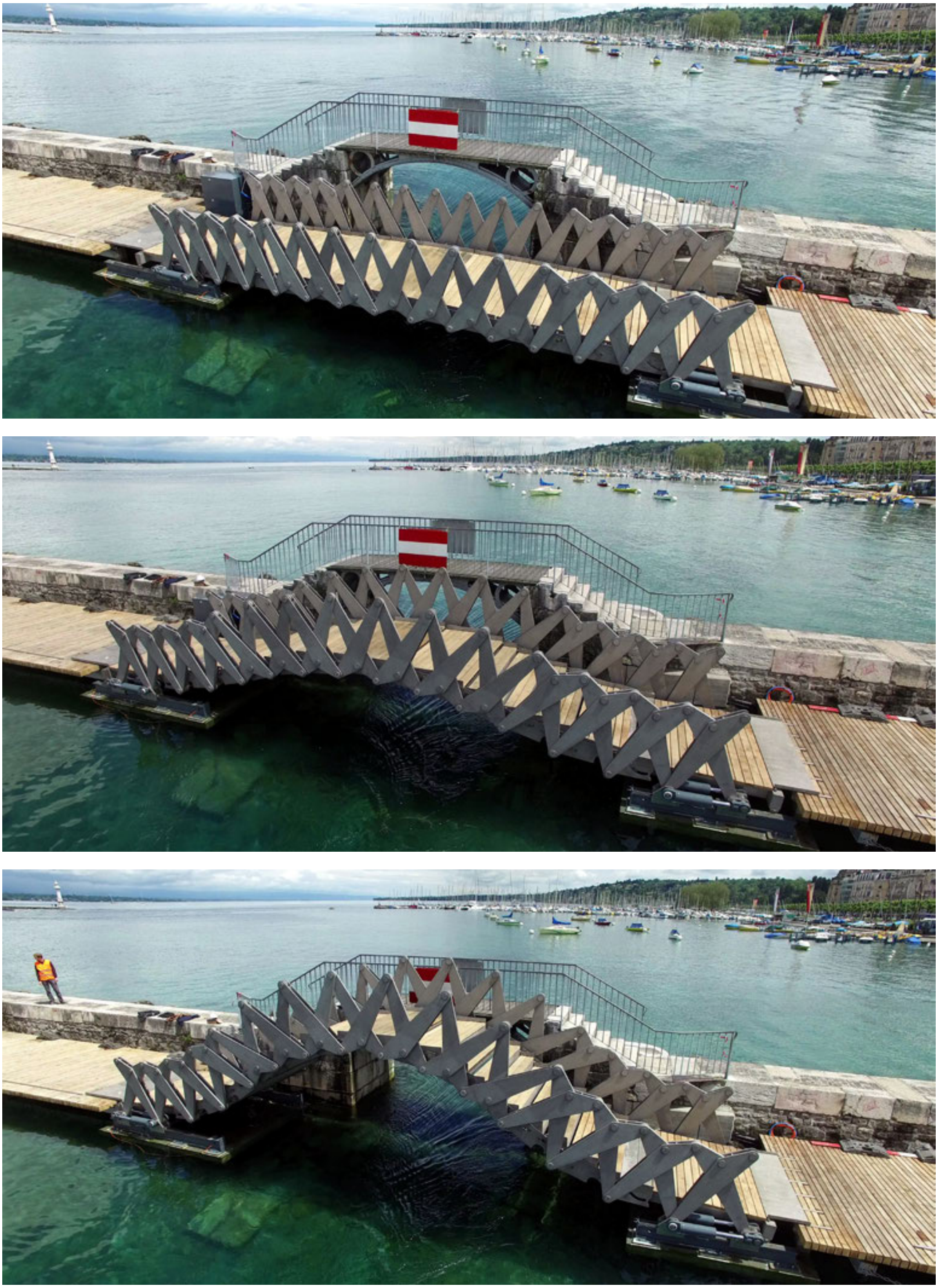

Figure 19. The footbridge in situ during the rise. The movement from flat to raised takes around 90 s.

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