Interdisciplinary Applications of Kinematics


Andrés Kecskeméthy · Veljko Potkonjak · Andreas Müller Editors
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Andrés Kecskeméthy, Veljko Potkonjak, and Andreas Müller (Eds.)

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Preface

The present proceedings collects 14 papers that were selected after a rigorous peer review for the First Conference on Interdisciplinary Applications in Kinematics, held in Lima, Peru, from January 9–11, 2008.

The objective of the conference was to bring together researchers from different fields where kinematics plays a role. This includes not only theoretical fields where kinematics is traditionally established, but in particular applications in which kinematics might contribute new perspectives for practical applications. Examples are the areas of biomechanics, industrial machinery, molecular kinematics, railway vehicles and many others.

The participation of 16 researchers from 10 countries shows the strong interest these topics find in the scientific community. Moreover, the site of the conference in Peru not only proved to be very successful, but also helped to foster the international scientific cooperation in this region, which has outstanding potentials.

We thank the authors for submitting their valuable contributions for this conference as well as the reviewers for performing the reviews in due time. We also thank the publisher Springer for the timely implementation of this book and the valuable advices during the production process. We are very grateful to the Universidad de Piura Campus Lima, the Pontificia Universidad Católica del Perú as well as the University of Duisburg-Essen for sponsoring this conference and contributing to its success. Our special acknowledgements go to the Förderverein Ingenieurwissenschaften Universität Duisburg-Essen (Association of Friends of Engineering Science of the University of Duisburg-Essen) for their valuable contribution to the funding of the present proceedings. Last but not least, we thank the International Federation for the Promotion of Mechanism and Machine Science IFToMM for the ideal support by offering its patronage for this conference.

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DOUBLE-RING POLYHEDRAL LINKAGES

Karl Wohlhart

Institute for Mechanics
Graz University of Technology
e-mail: wohlhart@tugraz.at, web page: http://www.mechanik.tugraz.at/

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Abstract. In this paper we present a new type of over-constrained spatial linkages obtained by inserting planar double-ring mechanisms (modules) into the faces of a polyhedron so that they form closed networks over the polyhedron after being interconnected by appropriate gussets. Such linkages will be called “double-ring polyhedral linkages”. Though highly over constrained, these linkages are deformable with one degree of freedom. Recently it was shown that polyhedral linkages can be synthesized with single ring mechanisms as modules. Therefore the question arises: what is the advantage of using double-ring mechanisms as modules instead of single-ring mechanisms? The first answer is: double-ring polyhedral linkages show much greater global stability. This is proved by all manufactured models, and the reason is evident: the single-ring mechanism has twice as many degrees of freedom as there are sides in the polyhedral face into which it is inserted, while the double-ring mechanism is movable with only one degree of freedom. A second answer is: from a double-ring polyhedral linkages a variety of cup-like linkages can be found by simply dividing them into parts. In this paper we will first demonstrate on an example that polyhedral linkages can be derived from irregular polyhedra by inserting irregular double-ring mechanism into their faces. However, such bizarre linkages, of which nobody would expect that they are mobile, are only of theoretical interest. Therefore we will then concentrate on the five regular double-ring polyhedral linkages, which are found on the basis of the Platonian polyhedra. For some of the greater linkages we will also show partitions which are linkages in the form of cupolas. An example is also given where a double-ring mechanism is used to design a (non-polyhedral) hall-linkage.
INTRODUCTION

If we only know the theoretical structure of a mechanism (number of its links, joints and loops) but nothing about its metric dimensions, we are unfortunately unable to predict its true mobility. If the topological structure formula (Gruebler-Kutzbach) indicates mobility as equal or less than zero, then it can only be concluded that the mechanism in question will be a rigid structure if we change its metric dimensions arbitrarily and get the same result. For the given dimensions, however, it can only be concluded that the mobility of the mechanism cannot be less than the one indicated by the structure formula. Polyhedral linkages belong to the category of over-constrained linkages, which make them scientifically charming and attractive as they are, within certain limits, deployable and therefore practically applicable in engineering in many ways.

In the wake of the pioneering work of H.F. Verheyen on expandable polyhedral structures [1] a great number of papers have appeared on the subject of over-constrained expandable linkages [2-11]. A common feature of the polyhedral linkages synthesized so far is that they are globally closed. All of them have been derived on the basis of closed regular or irregular polyhedra and differ only in the kind of modules (basic components) which are inserted into the polyhedron faces and the kind of multiple rotor joints that interconnect them. It has been shown [5] that for the synthesis of polyhedral linkages essentially three different types of modules are used: stretching stars, whirling stars and ring chains. These modules are link groups which are highly mobile mechanisms themselves (their mobility depends on the number of polygon sides of the polyhedral face into which they are inserted). “Closure” is therefore a precondition for the necessary reduction of the mobility of the final over-constrained linkage to only one degree of freedom. Moreover, in the physical sense the global stability of these polyhedral linkages is poor, i.e. all the unavoidable backlashes in the linkage sum up. Recently it was shown [12] that in two cases these elementary very mobile modules can be exchanged for similar modules which are mobile with only one degree of freedom: the stretching star can be exchanged for a double stretching star and the whirling star for a double shield mechanism. This kills two birds with one stone: on the one hand the synthesized polyhedral linkages are globally much more stable, and, on the other hand they offer a variety of possibilities of varied partitioning them into “cupola linkages”. But what about the single-ring modules? Can similar modules with only one degree of freedom also substitute them? Yes, double-ring modules can exchange the single-ring modules.

2. DOUBLE-RINGS MECHANISMS

Planar and spatial double-ring mechanisms (irregular and regular) are treated in [13]. While deforming, these mechanisms retain the similarity of the net from which they are derived.

Figure 1: First type of an irregular double-ring mechanism
We shall distinguish between two types of double ring mechanisms that differ in the generating net. Figure 1 shows the first type: the reference net consists of an outer and an inner line-polygon whose corresponding corner-points are connected by straight lines. Together with the midpoints of the connecting lines the midpoints of the inner polygon determine the triangular links of the inner ring, while the corner-points and the midpoints of the outer polygon, together with the mid-point of the connecting lines determine the quadrangular links of the outer ring. Figure 2 shows the second type of double ring mechanisms: the inner and the outer line-polygons are identified, the inner ring is equal to the outer ring, but the identical links in the rings turn in opposite directions if the double link mechanism deforms.

3. IRREGULAR TETRAHEDRAL LINKAGES

Figure 2: Second type of an irregular double-ring mechanism

Figure 3: How to synthesize an irregular double-ring tetrahedral linkage
Both types of double rings referred to above, can be used as modules to synthesize irregular polyhedral mechanisms. This will be only show for the cases of the two types of irregular double-ring tetrahedral linkages. The synthesis can start with the net of a given irregular tetrahedron, whose four faces, the basis \( B_1B_2B_3 \) and the side-faces \( K_1B_1B_2 \), \( K_2B_2B_3 \), \( K_3B_3B_1 \), are displayed in a common plane (Figure 3). In the basis \( B_1B_2B_3 \), an arbitrary double-ring net can be installed so that every two sides of its outer polygon lie on the sides of the basis. Therewith the double-ring mechanism in the basis is fully given. A second arbitrary double-ring-net may then be inserted into side face \( K_1B_1B_2 \) so that two sides of its outer polygon coincide with two sides of the outer polygon in the basis. With the net, the second double-ring mechanism is given. Into the side face \( K_2B_2B_3 \), another double-ring net can be implanted, under the limiting condition that the position of two sides of its outer polygon on the sideline \( B_2K_2 \) is already predetermined. With this net, the third double-ring mechanism is given. Into the side face \( K_3B_3B_1 \), a double-ring-net can finally be installed whose outer polygon is predetermined. Only its inner polygon can be chosen arbitrarily. With this net the fourth double-ring mechanism is fixed.

The derived planar double-ring mechanisms (Figure 4), consisting of twelve links held together by eighteen rotor joints, are over-constrained but deformable with one degree of freedom. With the number of loops \( L = 7 \) and the number of relative degrees of freedom \( \sum f = 18 \) the topological structure formula (Grübler-Kutzbach) yields for their mobility: \( m = -3 \). The range of their deformability is rather limited by link interference if the two rings are deforming in the same plane. By displacing the inner ring (orthogonally to its plane) the mutual interference between the rings cannot be avoided but reduced, and thus the range of the mobility considerably extended. The four double-rings, all activated by the same angle \( \phi \), can be inserted into the faces of tetrahedra whose dimensions are reduced by the factor \( \cos \phi \), and can be interconnected by twelve appropriate rotor bijoints (gussets). Figure 5
shows 3D-pictures of the synthesized double-ring tetrahedral linkage in two phases. As this spatial linkage does not show any symmetry and shows no special dimensions, nobody would expect that it is not a rigid structure but a movable linkage.

If we start with the second type of double-ring mechanism shown in Figure 2 and proceed in the same manner as before, we find the second irregular double-ring tetrahedral linkage.
which is shown in Figure 6. From Figures 5 and 6 it can be seen that the working space of the first linkages is considerably greater than that of the second. As irregular double-ring polyhedral linkages are more of theoretical than practical interest, we do not continue with irregularity but turn our attention to a variety of regular double-ring polyhedral linkages.

4. REGULAR DOUBLE RINGS IN TRIANGULAR-FACED POLYHEDRA

As the faces of a Platonian polyhedron are identical and their perimeters are regular polygons, the double rings used as modules to “mobilize” a Platonian polyhedron must be rotor-symmetric. For the triangular faces of the Platonian tetrahedron, the octahedron and the icosahedrons the following two types of planar double-rings shown in Figure 7 and Figure 8 can be used.

![Figure 7: First type of a regular double-ring mechanism](image)

![Figure 8: Second type of a regular double-ring mechanism](image)

These double-ring mechanisms are complexes of two homogeneous kinematics chains of an equal number of links connected by rotor-joints. The inner ring of the first type of double-ring consists of six identical links that have the form of equilateral triangles with side length $r$, and its outer ring consists of identical links in the form of isosceles triangles with the basis length $2r$ and the side-lengths $2r/\sqrt{3}$. The angle $\phi$ can be activated between $\phi = 0°$ and $\phi = 30°$ if the two rings are located in the same plane, but if they can overlap each other, than $\phi$ ranges from $\phi = 0°$ to $\phi = 60°$. The side length $S$ of the triangular faces of the polyhedrons depends on $\phi$: 

$$S_{\text{max}} = 4\sqrt{3}r$$

$$S_{\text{min}} = 2\sqrt{3}r$$

$$S_{\text{max}} = 6r$$

$$S_{\text{min}} = 3\sqrt{3}r$$
\[ S(\varphi) = 4\sqrt{3} r \cos \varphi. \]

In the second double-ring the inner and the outer rings move in different but parallel planes. All links of this double-ring mechanism are identical, they have the form of isosceles triangles with a lateral side length \( r \) and a basis length \( r\sqrt{3} \). The angle \( \varphi \) goes from zero to \( \varphi = 30^\circ \) and the length \( S(\varphi) \) of the triangular faces of the polyhedrons into which this double-ring can be inserted as a module is given by:

\[ S(\varphi) = 6r \cos \varphi. \]

Polyhedral linkages based on the first type of double-ring shown in Figure 7 reduce their maximal size to their minimum size by the factor \( S_{\text{min}} / S_{\text{max}} = 1/2 \) if its inner and outer rings, move on different planes. If these rings move in the same plane, the linkage size reduction factor is only \( S_{\text{min}} / S_{\text{max}} = \sqrt{3} / 2 = 0.866 \). For polyhedral linkages based on the first type of double-ring shown in Figure 8 the size reduction factor is also only \( S_{\text{min}} / S_{\text{max}} = \sqrt{3} / 2 = 0.866 \).

5. TETRAHEDRAL, OCTAHEDRAL AND ICOSAHEDRAL LINKAGES

Having prepared three different regular double-ring modules suitable for the insertion into the faces of a tetrahedron, an octahedron or an icosahedron, and being provided with a sufficient number of appropriate gussets (rotor bijoints), we can start with the construction of regular double-ring (triangular-faced) polyhedral linkages.
Figure 10: Octahedral linkages with three different modules at their maximal or minimal extension

Figure 11: Isothermal linkages with three different modules at their maximal or minimal extension (shown together with the icosahedra)
Figures 8, 9 and 10 show the synthesized linkages in two phases: their maximal or their minimal extension. In Figure 10 the icosahedra (serving as basis in the synthesis process) are included in the presentation to give a clearer view of the complex linkages. By dividing the icosahedral linkage two cupola linkages can be derived which are shown in Figure 12.

6. REGULAR DOUBLE RING IN A HEXAHEDRON

To “mobilize” a regular hexahedron we need double-ring mechanisms that consist of two homogeneous kinematic chains with eight equal links, held together by eight rotor joints. Figure
13 presents two equivalent types of such double rings. In both cases the angle $\varphi$ measuring the deformation runs from $\varphi = 0$ to $\varphi = \pi / 4$. The side length of the quadratic faces depends on $\varphi$ by:

$$S(\varphi) = 2r \left[ \frac{\sin \varphi}{\cos \frac{\pi}{8}} + 2 \frac{\sin \left( \frac{3\pi}{8} - \varphi \right)}{\sin \frac{\pi}{4}} \right].$$

This formula is valid for both types of double rings. A measure for the extensibility of the linkages, which can be synthesized with these double-rings as modules, is the relation

$$\frac{S_{\text{min}}}{S_{\text{max}}} = \frac{2(\cos \frac{\pi}{8})^3}{1 + \sqrt{2}} = 0.7071.$$ 

If the two rings in the first case move in the same plane, then the angle $\varphi$ only goes from $\varphi = 0$ to $\varphi = \pi / 8$. The extensibility factor would then be $S_{\text{min}} / S_{\text{max}} = 0.9239$. In the following we will exclude this case because of its poor practical applicability.

### 7. REGULAR DOUBLE-RING HEXAHEDRAL LINKAGES

Figure 14: Hexahedral linkages with two different modules at their maximal or minimal extension
The gussets needed for mounting together a double-ring hexahedral linkage with the first type of double ring (Figure 13) are all identical rotor bijoints with orthogonal axes. In the second type of double-ring each needs its proper gussets. Figure 14 shows two synthesized double-ring hexahedral linkages. This linkage can be divided into two parts, each of which is a linkage again (Figure 15). With the square double ring a variety of spatial linkages can be built up, e.g. a linkage hall as shown in Figure 16.

![Figure 15: Divided Double-Ring Hexahedral Linkages](image1)

![Figure 16: Linkage hall built up by square double rings (two phases)](image2)
8. REGULAR DOUBLE-RING IN A DODECAHEDRON

Double-rings mechanisms that can be inserted into the faces of a dodecahedron are shown in Figure 17 and Figure 18.

The side lengths of the faces of dodecahedron depend on the angle $\phi$ which measures the deformation of the double ring. For the first type of double ring in Figure 17 the side length $S$ is given by:

$$S_{\text{max}} = 2r \frac{\pi}{\cos(\pi/10)} (1 + \frac{1}{\cos(\pi/5)})$$

$$S_{\text{min}} = 2r \frac{\pi}{\cos(\pi/10)} (1 - \frac{1}{\cos(\pi/5)})$$

$$\Rightarrow S_{\text{min}} \leq S_{\text{max}}$$

$$S_{\text{min}} = \frac{5 + 3\sqrt{5}}{10 + 2\sqrt{5}} = 0.8090.$$

For the second type of double ring in Figure 18 the side length $S$ is given by:

$$S_{\text{max}} = 2\cos(\pi/10) \tan(\pi/5)$$

$$S_{\text{min}} = 2\cos(\pi/10) \tan(\pi/5)$$

$$\Rightarrow S_{\text{min}} \leq S_{\text{max}}$$

$$S_{\text{min}} = \frac{5 - \sqrt{5}}{2\sqrt{10} - 2\sqrt{5}} = 0.5878.$$