THE COLLECTION OF REULEAUX MODELS

OF THE FACULDADE DE ENGENHARIA

DA UNIVERSIDADE DO PORTO, PORTUGAL:

BRIEF HISTORICAL NOTE AND CURRENT STATUS

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ABSTRACT
The Faculdade de Engenharia da Universidade do Porto (FEUP) owns a major collection of Reuleaux kinematical models.
The history of the purchase of this collection by the *Academia Polytechnica of Porto* (the predecessor of FEUP) in the late XIX century, and its early use in Porto is well documented and has been the object of several recent papers, circulated predominantly in Portugal.
The size – more than one hundred models – and the perfect state of conservation of the collection justify making the international community of experts in the history of machines and mechanisms aware of this heritage.
The communication will be arranged in two separate sections.
Firstly, a brief reference to the components of the collection will be made. The man behind that purchase, Joaquim de Azevedo Albuquerque, creator of the *Gabinete de Cinemática da Academia Polytechnica* (Kinematical Unit at the Polytechnical Academy) , will be evoked. The circumstances of the purchase and the initial use of the collection in the teaching of Mechanics and in the dissemination of science will be mentioned.
Secondly, some examples of the use of the collection nowadays will be given, including - further to the basic visual use of some models as support of relevant concepts - the 3D computational modeling and virtual animation of several complex collection items by third year Mechanical Engineering and fourth year Management and Industrial Engineering degree students of FEUP.

KEYWORDS
Kinematical models, Kinematics, Franz Reuleaux, Reuleaux kinematical models, 3D Computational modeling, Virtual animation

THE FEUP COLLECTION OF KINEMATICAL MODELS

In 1875 Professor Franz Reuleaux published his fundamental book on the Theory of Kinematics [1]. That year in Porto's higher technical school — *Academia Polytechnica do Porto* (APP) — all the students of the different grades in Engineering had a course on Rational Mechanics and Kinematics. This was a result of the influence of the French Mechanics school of the *École Polytechnique de Paris*, with L.-B. Francoeur, Ch. Laboulaye and Edm. Bour, whose books [2-4] have been successively adopted in Porto. When Franz Reuleaux's book appears at the *Academia Polytechnica do Porto*, in the 1877 French translation, the book by Edm. Bour — *Cours de Mécanique et Machines - Cinématique*, 1865 - was adopted in the Kinematics course. In this book by Bour two parts were already clearly defined and individualized: the first part studied "what produces the movement of a solid in space"; whereas the second part presented a Theory of Mechanisms.

In the 1878-79 academic year the teaching of Kinematics Theory was made with the presentation of a restricted number of models, used only as didactic instruments intended to be seen by the students. There were wood models of a capstan, a windlass, a crane, a crab and two wood and cast iron models of two gears with cylindrical (spur gear) and conical wheels (bevel gear).

Professor Reuleaux's book, in the French translation, was firstly acquired by the school library in the academic year of 1878-79. At that moment Professor Joaquim de Azevedo Albuquerque – a civil engineer graduated at the *Academia Polytechnica do Porto* in 1861 – was responsible for the 3rd Chair - Rational Mechanics and Kinematics.

Fig. 1 - Joaquim de Azevedo Albuquerque (1839 – 1912)

Joaquim de Azevedo Albuquerque (1839 – 1912) was an alumnus of the *Academia Polytechnica do Porto*, of the Civil Engineering – public works degree, graduated in 1861. After graduation he was a teacher of the *Liceu Nacional do Porto* (High School of Porto) teaching Elementary Physics, Chemistry and Mathematics. In 1876 he competed for Professorship of the 1st Chair (Analytical Geometry), was approved and began teaching the 2nd Chair (Differential and Integral Calculus) at the *Academia Polytechnica do Porto*. Since 1877 he taught the 3rd Chair (Rational Mechanics and

Kinematics), and was appointed full professor of that Chair in 1885. In 1877 he created the *Gabinete de Cinemática da Academia Polytechnica do Porto* (Kinematical Unit at the Polytechnical Academy of Porto). In 1876, as the more recent professor, he was appointed Secretary of the *Academia Politécnica do Porto*. The professorial career of Professor Joaquim de Azevedo Albuquerque came to a close in 1909. He was a founder member of the *Sociedade de Instrução do Porto* (Porto Instructional Society), an organization for the dissemination of knowledge and pedagogical methods, and was elected President of that Society in 1883.

After one year of teaching Kinematics using Edm. Bour's book, Joaquim the Azevedo Albuquerque adopts the book of Franz Reuleaux, in the French translation (book plus atlas) for the academic year of 1878-79, and in May 1881 the syllabus of the Franz Reuleaux Kinematics course was officially adopted by the *Academia Polytechnica do Porto*. Some years later Professor Joaquim de Azevedo Albuquerque explained that he adopted the Reuleaux method and book because he thought that, with them, Kinematics as a science was getting out of a critical state. This critical state was characterized by the lack of a guide for the labyrinth of the ever increasing number of different mechanisms. In the words of J. A. Albuquerque, the method and book of F. Reuleaux overcame that situation "*by a deep transformation, solidly established in logical, simple and clear principles, that revealed the genetic laws of the mechanisms, and gave to the science the deductive character that it was missing*", [5].

It would be interesting to know how the Professors of the *Academia Polytechnica do Porto* became aware of the book by Franz Reuleaux. This is not documented, but among the books published in those days, available in the APP library - and presently in the Libraries of the *Universidade do Porto* -, there is a small booklet published in 1876 where Th. Beck presents an essay on a Note (N.22) in the original treatise of Franz Reuleaux, with the title: *"Note to the F. Reuleaux Kinematics through a question: is friction an action or a reaction ?"* [6]. This title, and the text of the essay, is sufficiently provocative to allow the speculation that it might be one of the sources of interest on the book by Franz Reuleaux in Porto.

The experience of Professor Joaquim de Azevedo Albuquerque with teaching the Reuleaux Method — lectures presented orally and supported by formulas and figures previously written on the three blackboards of the classroom — made it clear that *"although the treatise is illustrated with schematic or figurative drawings, the student of this method needs special qualities of imagination, capacity for space vision, and the knowledge of several aspects of the machines construction (technical capacity) to profitably apply the Franz Reuleaux System"*.

This problem was perceived by Franz Reuleaux when he developed his method for the study of Kinematics and began to direct the construction, by a manufacturer of industrial and scientific instruments, of a set of models of mechanisms. In the treatise by Franz Reuleaux there is no direct reference to the constitution or to the need for those collections of models, but didactic figures of some mechanisms are presented. The original Kinematics Models Collection was developed for the *Technische Hochschule zu Berlin* and was composed of 800 specimens.

This collection of models was made available to the scientific community thanks to the commercial relation of Franz Reuleaux with the Gustav Voigt Mechanische Werkstatt, of Berlin, that in 1888 had a catalog of 248 kinematics models. Other scientific instrument manufacturers, like Schröder in Darmstad, have also developed some Reuleaux kinematics models.

The kinematical models have a common building technique: components are made of

different alloys, ensuring durability; some models also use glass, and wood was used to build the stands. The scale used in the models design is well chosen, and colors used are sober.

Fig. 2 - Cardano's coupling by Voigt (left) and by Schröder (right), belonging to FEUP

The academic board of the *Academia Polytechnica do Porto* approved in 1880 the acquisition of the Gustav Voigt kinematics models, paid, with great difficulties, by the institution's budget. In the first years, 1881 and 1882, fifty two kinematics models were bought. From 1881-82 till 1894-95 one hundred and thirteen kinematics models were bought (table 1).

TABLE 1 — ACQUISITION OF THE KINEMATICS MODELS OF *ACADEMIA POLYTECHNICA DO PORTO* (PRESENTLY FEUP – *FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO*)

Year	*Models Class*	*Total*
1881 and 1882	A – Lower Element Pairs; B – Higher Element Pairs; C – Simple Kinematics Chains; D – Crank Mechanisms; E – Eccentric Slider Cranks; F – Crank Chamber Mechanism; G – Simple Gear Trains; H – Pedestals	52
1885	I – Chamber Wheel Mechanisms, K – Complex Slide Crank Mechanisms; L – Positive Return Cams	69
1886	M – Screws	78
1888	O – planetary Gear Trains	83
1889	P – Jointed Couplings	88
1890	R – Spherical Cycloids	93
1891	R – Rolling Models; U – Plane Guides; N – Rachet Mechanism (1 mod.)	98
1892	Crank Mechanisms	102
1894	N – Ratchet Mechanism (3 mod.)	113
?	Schröder Cardano's Coupling	114

An application for Government funds to buy the N Class models was made in 1888, and in the next year the Government funded the publication of a book by Professor Joaquim de Azevedo Albuquerque [5] — a kind of catalogue of the Reuleaux Collection with some personal considerations. This book was dedicated by Professor Joaquim de Azevedo Albuquerque to Franz Reuleaux — as "*the creator of modern Kinematics and as testimony of the introduction of his admirable scientific system in the higher*

education in Portugal".

With the creation of the *Gabinete de Cinemática da Academia Polytechnica do Porto* (Kinematical Unit at the Polytechnical Academy) and its equipment, during fourteen years the Reuleaux System had a great importance not only in the teaching of the *Academia Polytechnica do Porto*, but also in the dissemination of knowledge in the *Sociedade de Instrução do Porto* (Porto Instructional Society). In the Society headquarters, in 1884, Professor Joaquim de Azevedo Albuquerque promoted three public conferences — "*The Machine and the World*" — where, with the support of the kinematics models, he presented the modern Mechanisms Theory due to Franz Reuleaux.

In the middle of the eighties of the nineteen century the Kinematics teaching in the 3rd Chair occupied a small part of the syllabus (eleven out of seventy lessons). The course had a small number of students — three in 1897-98; two in 1898-99; seven in 1899-90, zero in 1900-1901 and nine in 1901-02.

After 1909, when the professorial career of Professor Joaquim de Azevedo Albuquerque comes to a close, also ends the reference to the teaching of Reuleaux Method [7].

But the didactic instruments that formed the Reuleaux Collection were carefully conserved and, despite the institutional evolution of the *Academia Polytechnica do Porto* into School of Engineering of the University of Porto (1911), Technical Faculty of the University of Porto (1915) and Faculty of Engineering of the University of Porto (1936), this collection is today still carefully preserved and available in the *Faculdade de Engenharia da Universidade do Porto*. There, some models are occasionally presented in the tutorials of Mechanics courses of the Mechanical Engineering degree, and recently some of them have been used in students' assignments in the context of the Computational Modeling and Simulation course.

MODELING AND SIMULATION

Some models of the Reuleaux Kinematical Collection of the Faculdade de Engenharia da Universidade do Porto have been used in the last three years as study/project cases included as assignments in the Computer Aided Design and Manufacturing course. This semi-annual course is a part of the third year curriculum of the Mechanical Engineering (ME) degree or part of the curriculum of the fourth year of the Management and Industrial Engineering (MIE) degree of FEUP (both degrees are 5 year degrees). Every year approximately 140 students follow this course, consisting of two hours of practical classes and two hours of tutorials per week during one semester. The current teaching staff includes the coordinator Dr. João Manuel R. S. Tavares and Eng. Joaquim O. Fonseca, assisted by Mr. José F. C. Saldanha (only those involved so far with Reuleaux models are mentioned).

The aims of the Computer Aided Design and Manufacturing course are:

- to provide students with the capacity to handle geometric and non-geometric information, in the production area;
- to implement computer programs that allow the processing of the information retrieved from commercial software;
- to identify and use the diverse characteristics inherent to the drafting programs and numerical control machines.

The work done during the tutorials with a Reuleaux model consists of:

- the characterization of the model, with a kinematical analysis and a definition of the model's components [8];
- dimensioning every component of the mechanism (with a special care on the use of the correct measuring instruments);
- three dimensional modeling of each component with a parametric CAD software [9];
- computational assembling of the model components;
- computational animation of the digital model;
- reporting of the work and presentation of the computational representation.

During the course, reference is made to the 3D rapid-prototyping techniques of model reproduction as a possible advanced application of the digital model [10].

The different stages of the work can be materialized in Figure 3, where the computational modeling of the *Equilateral curve–pentagon in square* model (of the 'Higher element pairs' series) [11] is illustrated.

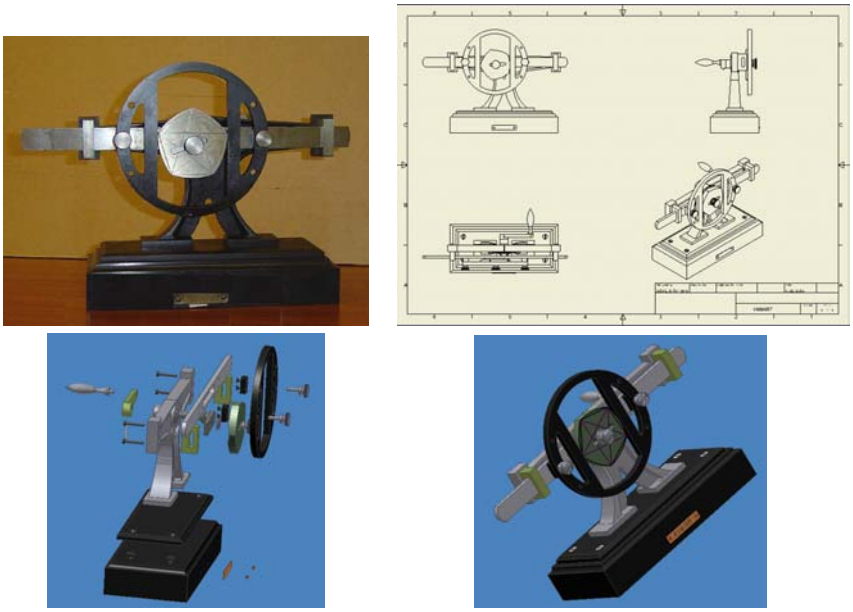

Fig. 3 - Parts of the modeling work for the Equilateral curve–pentagon in square model (of the Higher Element Pairs series) [12]

The resulting CAD model can be used as a case study concerned with the kinematics characteristics of the original Reuleaux mechanism, in a Kinematics or Design of Machines course.

Three examples suggesting the relevance of this type of students' assignment are concisely presented in the following paragraphs.

- **The Exploded Drawing** — an exploded view of the mechanism can be very important for the analysis of a mechanism, or for other purposes, *e.g.* marketing. The components of a mechanism are modeled and afterwards an exploded view can be obtained using appropriate software. One Reuleaux

model can be used as a case, as in the simple example of Figure 4, where the mechanism has a pair of elements — worm drive composed of worm wheel and endless screw [13]. Of course, the need to display the mechanism adds some more components whose form, dimension and liaisons can be very well visualized in the exploded drawing.

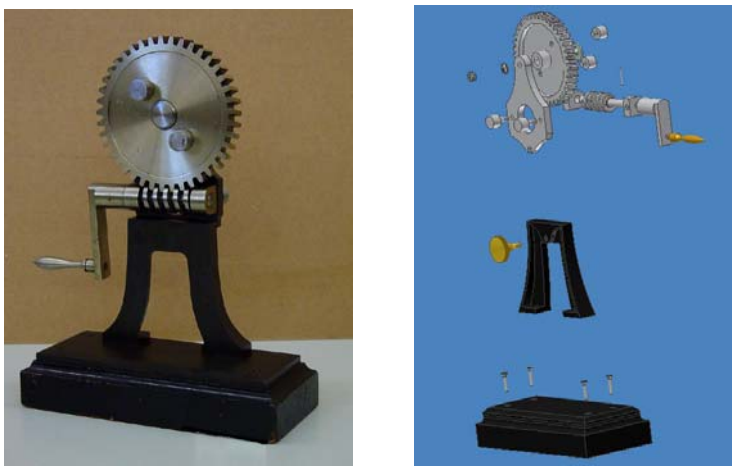

Fig. 4 - Exploded view from a pair of elements — a worm drive [14]

- **The Universal Coupling or Cardano's Coupling** — The Faculdade de Engenharia da Universidade do Porto has in its Reuleaux Collection two models of the Cardano's Coupling constructed by two different Germany manufacturers: Schröder of Darmstad and Voigt of Berlin.

  The universal coupling is known by different names, and in Portugal it is named the Cardano's Coupling. This coupling has a mathematical treatment [5], [15], where the final expression depends of the angle of the two convergent axes. An experimental study of the coupling work can be made with the model.

  - **The Schröder Model** — is a very simple model with the possibility to change only the angle between the axes. The computational model made by the students was accurate, and as a pedagogical detail it was modeled with several and bright colors (Figure 5).

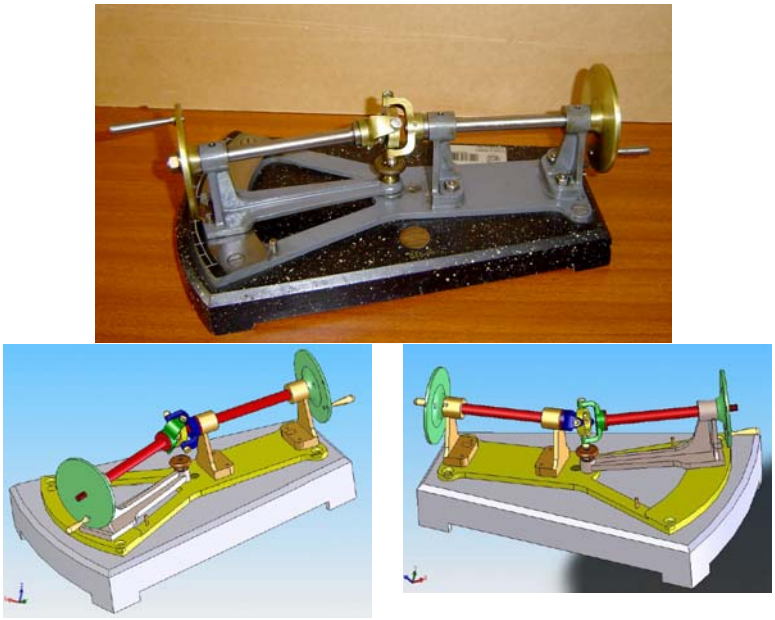

Fig. 5 - Modeling of the Schröder model of the Cardano's coupling [16]

- **The Voigt Model** — it is a complex model with more possible forms and the possibility of various angle measurements and adjustments (Figure 6).

Fig. 6 - Modelling of the Voigt model of the Cardano's Coupling [17]

- **The Paddle Wheel Propeller** — a very important mechanism in the second half of the nineteenth century, the paddle wheel propeller is a mechanism with a somewhat intricate constitution and operation, where the link between the components and the paddle movement is not obvious. As Professor Joaquim de

Azevedo Albuquerque wrote in 1893: *"The articulated paddle system avoids this inconvenient: the paddles enter and exit the water in a vertical position"* [5]. The inconvenience mentioned above is the existence of a vertical component of pressure exerted by the paddles on the water, when they are oblique to the surface of the water, detrimental to the movement of the ship.

The four paddle wheel are oriented by an Oldam's mechanism that permits that the paddles are rolling with a precise rotational movement, while each of the four arms that sustain the paddles are driven by the steam motor (Figure 7).

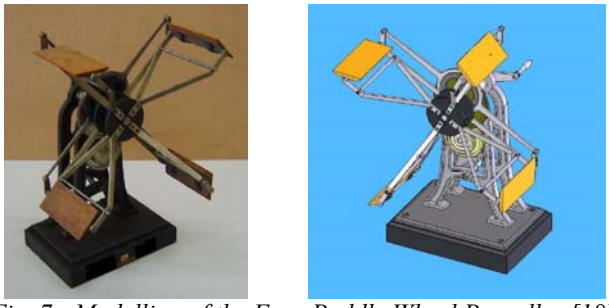

Fig. 7 - Modelling of the Four Paddle Wheel Propeller [18]

In the case of this mechanism, a picture of this three dimensional body in a two dimensional surface is insufficient to visualize its operation due to the complexity and interconnections of the moveable parts, but a digital simulation – animation – provides a modern way to understand the complicated interrelated paddle movement (Figure 8).

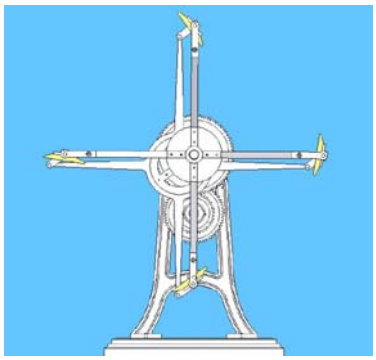

Fig. 8 - Digital simulation of the Four Paddle Wheel Propeller [18]

These few examples of modeling and simulation made by students show how, nowadays — one hundred and twenty five years after the purchase of the Reuleaux Collection of Kinematical Models — the Reuleaux Models are still a valuable and useful complementary means of teaching at the Faculdade de Engenharia da Universidade do Porto.

CONCLUDING REMARKS

In 1875 the study of Kinematics had an evolution due to the creative work of Franz Reuleaux, then presented as definitive. The new method of study — Reuleaux System — was adopted. But its abstract nature and the importance of the deductive method

created the need for models of the mechanisms. With those models the students could visualize the concepts and acquire the knowledge that they would later use in their professional practice.

The *Academia Polytechnica do Porto*, despite severe budget constraints, bought in a period of fourteen years starting in 1881 a models collection of 113 items from the Voigt Catalogue. The models were used as didactic instruments till 1909, and after that year they had been occasionally presented in the tutorials of Mechanics courses of the Mechanical Engineering degree.

The collection. although integrated in the FEUP Museum – a project seeking the conservation and study of the important historical heritage of FEUP – is located at the premises of the Department of Mechanical Engineering and Management of FEUP.

Nowadays some of the models are used in the Computer Aided Design and Manufacturing course, as cases (among assignments concerning other mechanisms or machines) where they are modeled and their movement is simulated through digital animations. Examples of these assignments performed by third year Mechanical Engineering and fourth year Management and Industrial Engineering degree students of *Faculdade de Engenharia da Universidade do Porto* were presented in this paper.

NOTES AND REFERENCES

1. Franz Reuleaux, “Theoretische Kinematik. Grundzüge einer Theorie des Maschinenwesens”, Berlin, 1875. Traduit par A. Debize: “Cinématique – Principes Fondamentaux d’ une Théorie Génerale des Machines”, Lb. F. Savy, Paris, 1877.
2. L.-B. Francoeur, “Traité de Mécanique Élementaire”, Paris, 1825.
3. Ch. Laboulaye, “Traité de Cinématique ou Théorie des Mécanismes”, Librairie de Lacroix, 1861
4. Edm. Bour, “Cours de Mécanique et Machines – Cinématique”, 1865
5. Joaquim de Azevedo Albuquerque, “O Gabinete Cinemático da Academia Politécnica do Porto — Sistema Reuleaux”, Typ. Occidental, Porto 1893 (in Portuguese)
6. Th. Beck, “Bemerkungen zu F. Reuleaux’s Kinematik über die Frage: Ist Reibung ein Kraft oder ein Widerstand ?”, Darmstad, 1876
7. Manuel Vaz Guedes, “Ciência ou Técnica: uma Colecção de Instrumentos Didácticos da Faculdade de Engenharia da Universidade do Porto”; *in*: P. M. S. T. de Castro, ed., “Memórias da FEUP”, Edições FEUP, Porto, 2001, pp. 148-185
8. This part of the modeling work is made with the precious help of the Reuleaux Collection Curator — Mr José F. C. Saldanha — whose efforts and interest have contributed to the survival of the FEUP Reuleaux Collection in very good shape.
9. The parametric CAD software used has been the commercial Autodesk Inventor (www.autodesk.com)
10. H. Lipson, F. C. Moon, J. Hai, and C. Paventi; "3D Printing the History of Mechanisms" ASME J. Mechanical Design, Vol. 127, pp. 1029-1033, September 2005
11. Franz Reuleaux, “The Kinematics of Machinery”, §29, pp. 139-146, Dover Publications 1963
12. As presented by the MIE-2004/2005 student João Serrenho
13. Franz Reuleaux, “The Kinematics of Machinery”, pp. 82-83, Dover Publications 1963
14. As presented by the MIE-2004/2005 students Ângela Fagundes and Marina

Vasconcelos
15. Franz Reuleaux, “The Kinematics of Machinery”, pp. 331, Dover Publications 1963
16. As presented by the ME-2004/2005 student José Alves Ferreira
17. As presented by the MIE-2004/2005 students Isabel Sousa and Maria Pereira
18. As presented by the ME-2004/2005 student Dário Fonseca