Models of mechanisms for teaching and experimental activity

Marco Ceccarelli - Department of Industrial Engineering, University of Roma "Tor Vergata" - marco.ceccarelli@uniroma2.it

Abstract: This illustration-based paper is focused on mechanism models that were used and still can be used in design, teaching, and experimental activities not only on research and development of mechanical systems by analyzing the functioning they are based on. A conceptual procedure is outlined for the development and use of mechanism models mainly at reduced scaled size. Different types of models are discussed both from historical viewpoints and structure aspects through illustrative examples that are based on author's experience. Those examples are reported also to show the value of Cultural Heritage that mechanism models and corresponding developments may have as worthful for preservation and understanding of past achievements.

Keywords: History of Mechanical Engineering, History of Mechanisms, Mechanism Models.

1. Introduction

Why models of mechanisms for teaching and design validation? This paper presents a survey with historical evolution and practical issues with the aim to justify and motivate still today a use of models of mechanisms that can be useful for several activities. They can be used to explain concepts either in teaching for formation and education or in validating solutions in research and design. They can be produced as drawings, mechanical products, and today virtual designs for applications in many fields, not only for technological interests.

In the literature, models are considered part of an elaboration of a study or design and they are often not considered as a central topic. In fact, in the history of engineering and science, mechanism models are not addressed specifically but they are considered as part of the activities either in research, or design, ore teaching. The history of science and technology is also explained by using them both in encyclopedic works, like for example in (Singer *et al*. 2012; Capocaccia 1973), and in specific works in conferences and journals, like for example in papers at the HHM symposia like (Zhang, Ceccarelli 2019), as well as in didactic activities, as for example with LEGO packages.[1]

---

[1] See https://education.lego.com/en-gb.

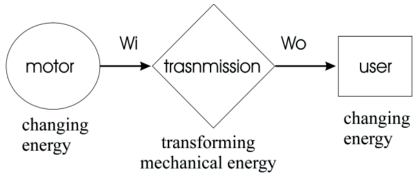

Fig. 1. A conceptual scheme of a mechanical system with transmission mechanisms.

This paper is an attempt to give proper specific considerations to mechanism models both In historical evaluations and technical developments with the awareness that the topic and model applications are much wider than in the proposed presentation in this paper.

2. History of mechanism models

A mechanism is a mechanical system whose aims is to transmit motion and force, (IFToMM 2003). Fig. 1 shows a general application of a mechanism as a key component of a system converting energy to perform a user's task with a desired level of mechanical energy (Lopez-Cajùn, Ceccarelli 2013). In such a scheme, it is also possible to recognize a modelling of a mechanism not only for design purposes but also for explaining the functioning of the whole machine and specifically the operation as intended task.

In general, mechanism models are aimed and included in a variety of activities for teaching, study, research, design, demonstrative illustrations and presentations, simulation, validation operation characterization, experimental check, and even promotion or market exhibition. They are used not only for developing mechanical systems, but even as means or part of systems in activities in other disciplines, with similar aims or complementary purposes as for example indicated in (Ceccarelli 2012).

Today, mechanism models can be developed as sketches or drawings (by hand or by computer-graphics tools), mechanical constructions either in scaled sizes or prototype structures, and virtual designs as based on different type of software and visualization with or without human interaction. Fig. 2 summarizes the evolution of mechanism models from historical viewpoints and technical constructions as linked to achievements and technological means.

The first level of a model can be recognized in a graphical representation that since in Antiquity it has been emphasized with drawings from schematic scratches up to schemes containing lot of details. Still today the first ideas are sketched with drawings (either by hand or by graphics software) that can be used as first step of an activity either in explaining or in designing mechanical systems or for activities in developing concepts and solutions. A graphical figure of a drawing model can have different formats as well as different levels of accuracy, not only in terms of graphical representation and it is used in many disciplines other than mechanical design.

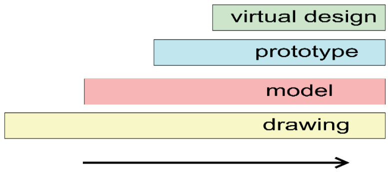

Fig. 2. A diagram of historical and conceptual evolution of mechanism models.

The second level as a mechanical model in Fig. 2 refers to a mechanical construction that can lead to a prototype solution for a machine design or an experiment whose phenomenon is to be investigated. Historically, model constructions were widely used before proceeding to further activities and today such a physical experience have regained significance, mainly with prototypes with full features that are used before final constructions.

A mechanical model can be developed from a drawing model to emphasize some aspects and features of a structure or operation even without attention to a full solution. A prototype can be understood as a third level when it is considered a full solution of a mechanical model and likewise it can be developed in reduced scale yet.

Since those constructions of mechanical models and prototypes require lot of efforts both in manufacturing and cost, the advent of Computer Science provide alternatives with virtual designs that can be developed, operated, and tested with different level of virtuality from simple CAD solutions up to haptic-sensed 3D systems. The virtual models are today extensively used but they can be still considered as developed after an activity which is based on previous levels of modelling. This level of modelling emphasizes not only the deepening of functionality analysis in models but also the aspects concerning with the durability ad economic convenience of models for a multidisciplinary towards and integration of different purposes for study, design, and teaching.

As an example of the strict connections among the different levels of mechanism modelling, Fig. 3 (left) shows the classification of mechanisms not only as machine components but also as descriptors of motion categories, that have been developed in the 19th century with a drawing-based classification in a table, (Lanz, Betancourt 1808), and Fig. 3 (right) shows a collection of scaled mechanical models as specifically addressed as a synthesis of the gained knowledge in the field of Mechanism Science (Ceccarelli 2004). This example that today is represented also with virtual models even just duplicating what is in Fig. 3 (right), is also an example of the interesting content that those models may have in the Science and Technology as well in the History of Mechanical Engineering with a value of Cultural Heritage whose products are worthful to be preserved to show the historical evolution of knowledge and to be used as inspiration for further developments.

Mechanism models have been and are still developed in different formats for different aims and frames of applications. In general, they can be considered with one or more levels as summarized in Fig. 2 for activities in teaching, analysis, design, experimental activity and historical investigations.

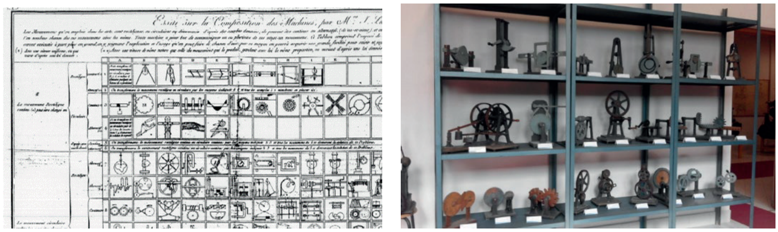

Fig. 3. Classification of mechanism models. Left: table with drawings. Right: a catalogue with mechanical samples.

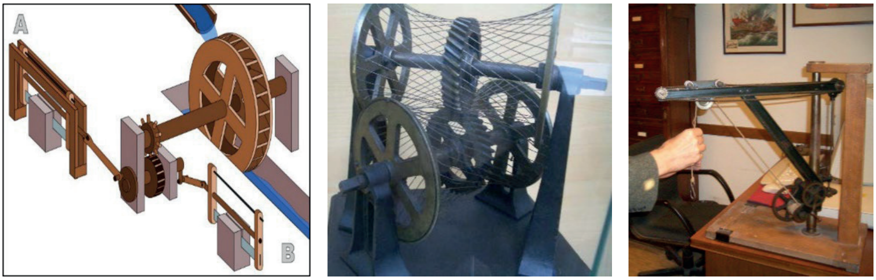

Fig. 4. Examples of developments of mechanism models. Left) reconstruction design. Center) research design. Right: scaled machine design.

Fig. 4 shows mechanism models corresponding to the levels in Fig. 3 as examples of their contents and aims. In particular, Fig. 4 (left) is an example of virtual model that is based on CAD elaboration for a virtuality design reconstruction showing the operation of a Roman stone sawing machine. Fig. 4 (center) is a physical mechanical model of the hyperboloid motion with theoretical aspects in representing the generator lines for identification of the axis of the instantaneous motion. Fig. 4 (right) is a scaled prototype of a crane for checking the operation feasibility of a real-scale design.

3. Procedures for mechanism models

Fig. 5 summarizes activities that can be recognized as necessary in the development of mechanism models for teaching or experimental activity, not only with today modern procedures.

While a general process can be outlined with common steps, as indicated in the central stream line of the flowchart in Fig.5, the peculiarities of the aims and uses may require specific attention to different aspects as indicated in the side blocks that are different for teaching or experimenting activities.

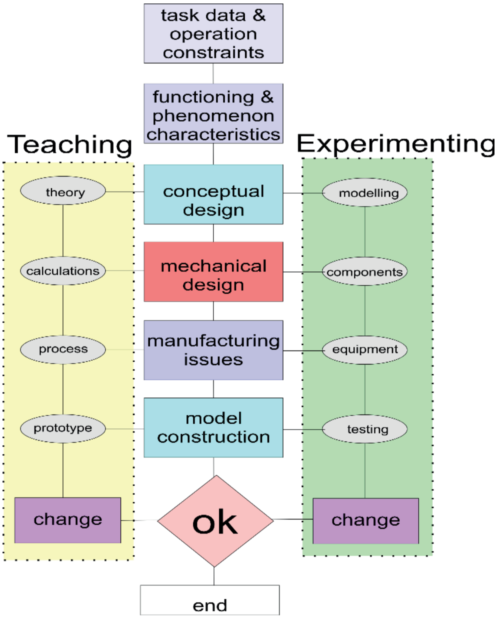

Fig. 5. A flowchart of procedures for design and construction of mechanism mechanical models.

A design procedure can show common steps as proceeding from a definition of design requirements in terms of constraints and task characteristics that can be expressed in the solution for the model construction and its final check after computations and developments from a conceptual design as characterized by details in the mechanical design and manufacturing plans. Significant difference can be recognized in models when they have content mainly for explanation purposes like in teaching or for physical experiences for demonstrations. Thus, in teaching necessary could be to consider theoretical aspects that a model should represent, and very likely calculations as based on mathematical for-mulation would be necessary to properly identify those characteristics that give a prototype solution with the expected teaching aims. Similarly, in experimenting activity a first step could be planned in a design model useful to identify the components and equipment that are necessary for testing activity.

In any case each step of the side activities in Fig. 5 can be influential in the process towards a solution for the model construction. Final check may require considering some aspects previously not included and it may require reiterate partially or the whole process.

Fig. 5 is reported with the above general considerations to indicate the fact that whatever type or level a model is planned, its design and construction require a complex procedure.

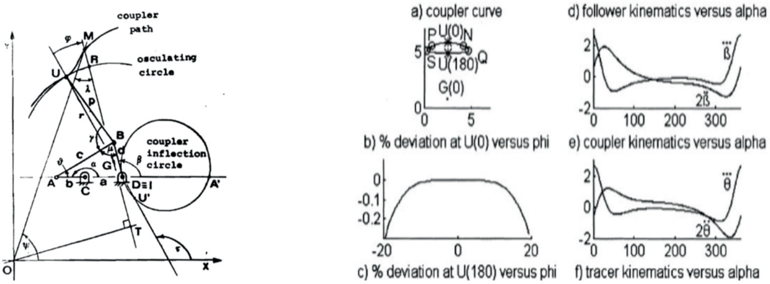

Fig. 6. An example of teaching model. Left: a four-bar linkage with its kinematic loci. Right: computational results of the coupler curve characteristics.

4. Examples of mechanism models

In this section examples are introduced and discussed from the direct experience of the author to illustrate the content and significance that mechanism models can have in different frames and with different formats as per the levels in Fig 2 and referring to the fields of teaching, design, research, experimental activity, and history investigations.

In Fig. 6 an example of drawing model of a four-bar linkage is illustrated together with kinematic properties both for analysis and design purposes. It can be used to explain and teach basic kinematic properties with theoretical contents and how to identify them in a mechanism as well as to formulate then in a design algorithm that is based on them.

The drawing model is completed and supported by the computation results that can be obtained from it, as it is shown in this example with the plots of numerical characterization of the linkage kinematics in term of coupler path and its evaluation (Ceccarelli, Vinciguerra 2000).

Figure 7 is an example of a mechanism model in design and research activity on a finger exoskeleton that staring form a conceptual kinematic scheme has been further developed in a CAD solution and then in a prototype for testing (Gerding *et al*. 2018). The model is designed by combining a drawing with a virtual CAD design that are used in research activity also through numerical simulation of the virtual prototype with the aim to characterize its design and operation before a final construction of a prototype model for experimental validation as per an application of finger motion assistance either in exercising of elderly people of in rehabilitation therapies for injured patients.

Fig. 8 shows mechanism models in the form of mechanical prototypes in research activity for a humanoid robot with new structures as based on parallel manipulator architecture (Ceccarelli *et al.* 2017). The models are used to investigate and to prove the feasibility and advantages of those parallel mechanisms in this challenging area of Robotics.

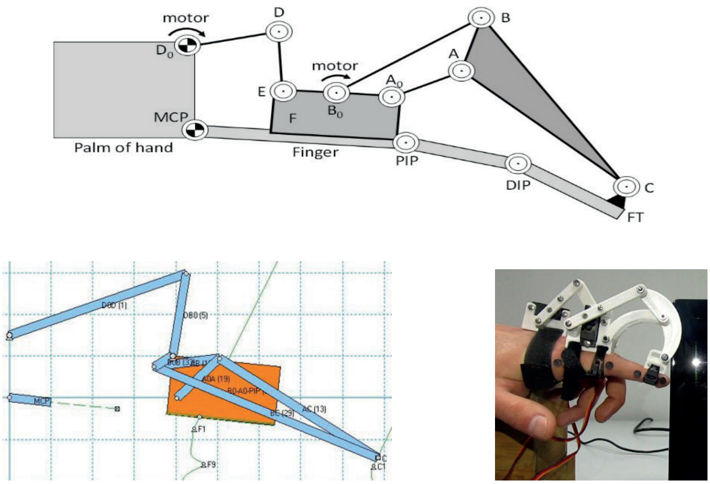

Fig. 7. An example of mechanism model for design purposes. Top: a drawing of a finger exoskeleton. Bottom, left: a CAD design for simulation. Bottom, right: a prototype for testing.

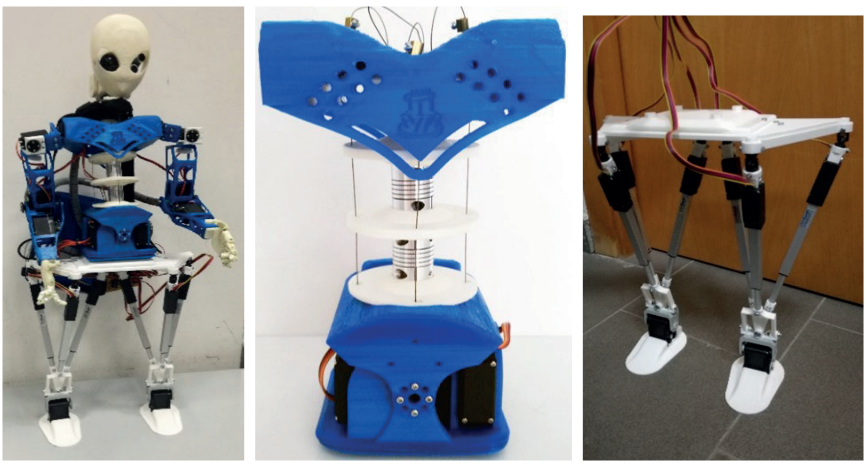

Fig. 8. An example of mechanism designs used in research. Left: LARMbot humanoid prototype. Center: a trunk design. Right: a leg system.

The built prototypes models in LARMbot humanoid are constructed as the kinematic models to emphasize the peculiarities of the conceptual designs in the models also in practical implementations.

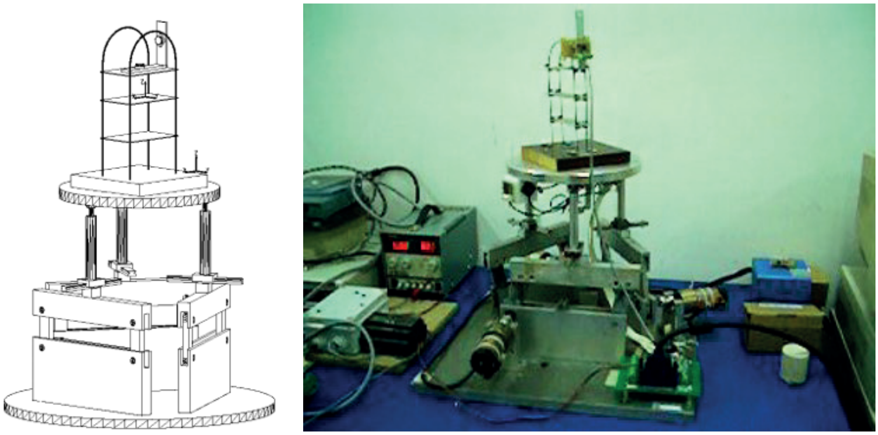

Fig. 9. An example of mechanism model in experimental activity. Left: a drawing design of a building structure in attesting platform. Right: the prototype for experimental activity.

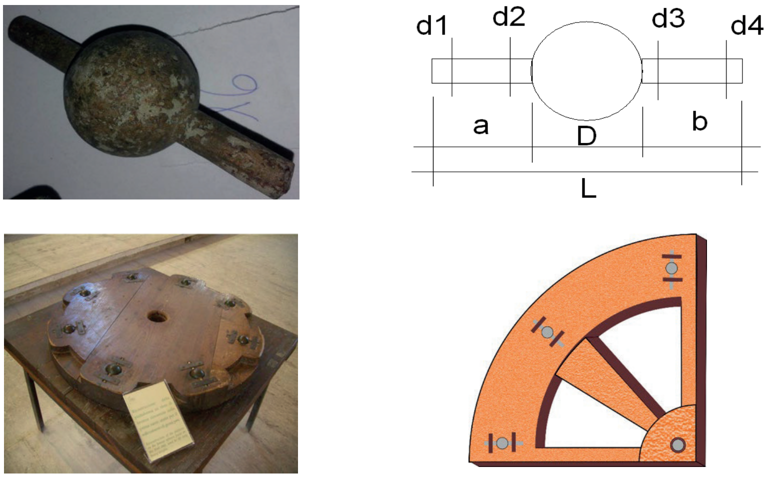

Fig. 10. An example of mechanism design used in study of history of machines. Top, left: Roman bronze ball bearing of 1st century A.D. Top, right: a drawing model. Bottom, left: a reconstruction model of a circular platform with ball bearings. Bottom, right: a CAD design model of a circular module of a guide with ball bearings.

A direct use of mechanism models with their schematic structures is shown in Fig. 9 where the model of a civil structure of a building in concrete is made of small-beam model with the essential geometry of the concrete structure in order to investigate its response to seismic motion that is simulated by a movable platform of a parallel manipulator prototype (Ceccarelli *et al.* 2002).

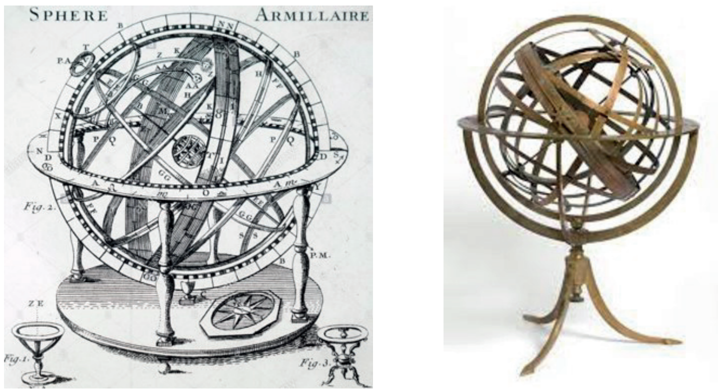

Fig. 11. An example of armillary mechanism design used in study of history of astronomy. Left: a drawing model. Right: a prototype**.**

Figs 7 to 9 are examples of how much the models in their different formats and levels can be useful in research and design activities in very different areas with or without the today overestimated victual models.

Models are also used extensively in studies of history of machines both to describe and understand the structures and their contents as historical achievements in evolution of machine technology. Examples are reported in Figs. 10 to 12 referring to different periodical periods and different machine applications.

In Fig. 10 the models of drawing and reconstruction prototype are used to explain the technical value and machine application of the archeological remains of Roman ball bearings of 1st century A.D. from Roman imperial ships discovered in the lake of Nemi, (Ceccarelli *et al*. 2019)

Fig. 11 shows examples of armillary mechanisms that were used in Ancient and past time with very similar design with respect to each other with the aim to study astronomy and to represent planet motion in the solar systems both in research activity and exhibitions. The models were made by drawings and mechanical prototypes. A drawing of those systems is a model representation of a mathematical model and the mechanical design was used as practical application both for illustrations and entertainment purposes and explanation of the planet motions for calculation of astronomical time (Aterini 2019).

Fig. 12 refers to models that have been developed to reconstruct the structure and to explain the operation of the archaeological remains of the Antikytera mechanism that after several studies with several graphical and mechanical models like the ones in Fig.12 has been recognized to be a gearing system for astronomic calculation (Koetsier 2012). The drawing models is the theoretical basis of the interpretation with a sort of design that have completed the machine structure form the remained few parts that were discovered with unclear geometry. The reconstruction prototype is a model to show the feasibility of the interpretation and a means to further study the level of mechanical knowledge at the Antiquity both for manufacturing and theoretical mechanics of gears.

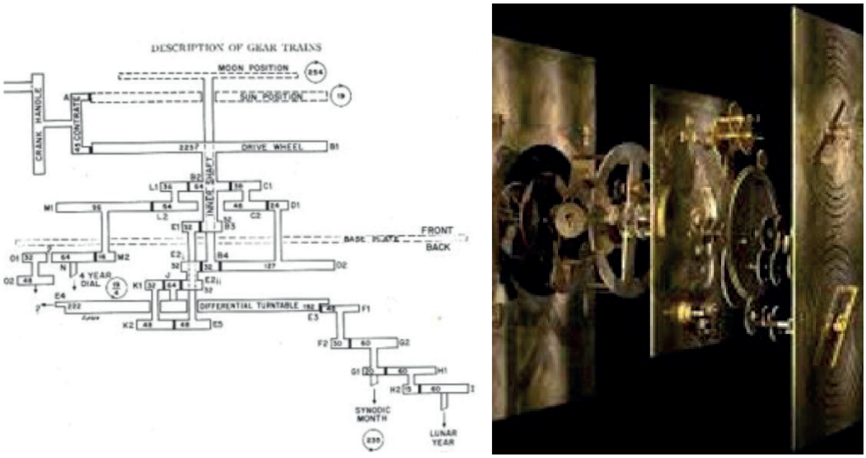

Fig. 12. An example of mechanism design used in study of history of machines. Left: a drawing model of Antikytera machine. Right: a reconstruction via a prototype.

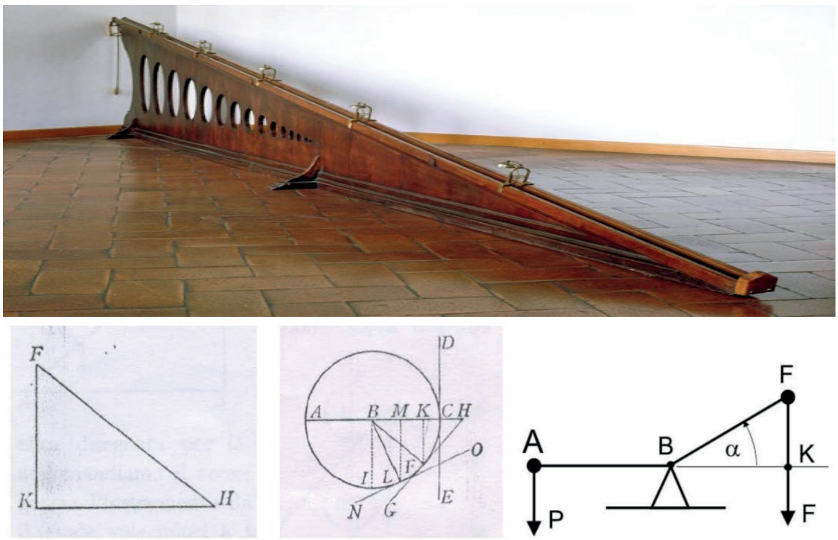

Fig. 13. An example of mechanism design used in study of history of machines- Top: the wood model by Galilei for inclined plan. Bottom: graphical schemes of its mechanics.

Fig.13 and 14 are examples of the value of Cultural Heritage that models of mechanisms may have. Fig 13 (top) refers to the wood model that Galilei built for his experiments to prove the effect of gravity by using his modelling of the inclined plane (Ceccarelli 2006). The wood model is of museum value as tangible product of Cultural Heritage that is exhibited at Galilei Museum in Florence, while the graphical models in Fig.13 (bottom) refer to the corresponding mechanics both in the book of the Galilei's lecture notes and a modern interpretation of them.

Models are developed also today in such a solution that can have values of tangible products of Cultural Heritage. Fig.14 shows examples of recent models of machine mechanism for tracking the machine evolution and teaching purposes including the explanation for a large public. The examples in Fig. 14 (left) refer to wood models of 1960s that is preserved at University of Rome "La Sapienza" and to a collection of metal models, including 19th century construction and recent one, that is exhibited at "Politecnico di Torino" (Ceccarelli 2004).

The reported examples in Figs. 7-14 give a sample window of a very rich variety of models with different levels and aims as summarized in Fig. 2, also as an attempt to stimulate a better consideration of mechanism models form perspectives other than the ones from technical engineering viewpoints.

5. Conclusions

This paper shows that mechanism models can be recognized of interest for design and analysis purposes but also for experiences in teaching and experimental activities not only in the fields of mechanical engineering. Since Antiquity mechanism models were used to check and to explain concepts in understanding systems and phenomena as well as in designing machines. Still today they are used to clarify research and innovation as based on concepts and achievements that can clearly represent. In addition, when considering the historical evolution, mechanism models can be also considered of Cultural Heritage value with the content of tangible and intangible products that track the science and technology developments.

Fig. 14. An example of mechanism models as Cultural Heritage tangible products. Left: a wood model of 1960s. Right: a collection of iron made models of 19th and 20th centuries.

References

Aterini B. (2019). The Astrolabe: A Mechanism for Reading the Stars, in Zhang B., Ceccarelli M. (eds.), Explorations in the History and Heritage of Machines and Mechanisms. Cham: Springer Nature.

Capocaccia A. (ed.) (1973). *Storia della Tecnica – Dalla preistoria all'anno Mille*. Turin: UTET.

Ceccarelli M. (2004). *Classifications of mechanisms over time*, in *Proceedings of International Symposium on History of Machines and Mechanisms HMM2004*. Dordrecht: Kluwer.

Ceccarelli M. (2006). "Early TMM in *Le Mecaniche* by Galileo Galilei in 1593". *Mechanisms and Machine Theory*,41 (12), pp 1401-1406.

Ceccarelli M. (2012). *An Outline of History of Mechanism Design in servicing Science*, in *Physics, Astronomy and Engineering: critical problems in the History of Science and Society*, Siauliai: Scientia Socialis.

Ceccarelli M. *et al.* (2019). *Analysis and reconstruction of a platform with ball bearings in Roman ships of Nemi lake*, in Zhang B., Ceccarelli M. (eds.), *Explorations in the History and Heritage of Machines and Mechanisms*. Cham: Springer Nature.

Ceccarelli M., Cafolla D., Russo M., Carbone G. (2017). "LARMBot Humanoid Design Towards a Prototype". *International Journal of Applied Bionics and Biomechanics,* 1 (2), p. 00008.

Ceccarelli M., Ottaviano E., Galvagno M. (2002). *A 3-DOF Parallel Manipulator as Earthquake Motion Simulator*, in *Proceedings of the 7th International Conference on Control, Automation, Robotics and Vision – ICARCV 2002*. Singapore: IEEE.

Ceccarelli M., Vinciguerra A. (2000). "Approximate Four-Bar Circle-Tracing Mechanisms: Classical and New Synthesis". *Mechanism and Machine Theory*, 35 (11), pp.1579-1599.

Gerding E.C. *et al.* (2019). *Design of a Finger Exoskeleton for Motion Guidance*, in B. Corves B. *et al.* (eds.), Proceedings of the EuCoMeS 2018 Conference. Cham: Springer.

IFToMM (2003). "Standardization and Terminology". *Mechanism and Machine Theory*, 38.

Koessier T. (2009). *Phases in the Unraveling of the Secrets of the Gear System of the Antikythera Mechanism*, in Yan H.S., Ceccarelli M. (eds.), *Proceedings of the International Symposium on History of Machines and Mechanisms*. Dordrecht: Springer.

Lanz J.M., Betancourt A. (1808). *Essai sur la composition des machines*. Paris: Baichelier.

Lopez-Cajùn C.S., Ceccarelli M. (2013). *Mecanismos: Fundamentos cinematicos para el diseno y la optimizacion de la maquinaria*. Ciudad de Mexico: Trillas.

Singer C. *et al.* (eds.) (2012). *Storia della Tecnologia*, Volume 2. Turin: Bollati Boringhieri.

Zhang B., Ceccarelli M. (eds.) (2019). *Explorations in the History and Heritage of Machines and Mechanisms*. Cham: Springer Nature.