3D-Printing the History of Mechanisms

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Abstract

Physical models of machines have played an important role in the history of engineering for teaching, analyzing, and exploring mechanical concepts. Many of these models have been replaced today by computational representations, but new rapid-prototyping technology allows reintroduction of physical models as an intuitive way to demonstrate mechanical concepts. This paper reports on the use of computer-aided modeling tools and rapid prototyping technology to document, preserve, and reproduce in three dimensions, historic machines and mechanisms. We have reproduced several pre-assembled, fully-functional historic mechanisms such as early straight line mechanisms, ratchets, pumps, and clock escapements, including various kinematic components such as links, joints, gears, worms, nuts, bolts, and springs. The historic mechanisms come from the Cornell Collection of Reuleaux Kinematic Models as well as models based on the work of Leonardo da Vinci. The models are available as part of a new online museum of mechanism, which allows visitors not only to read descriptions and view pictures and videos, but now also download, 3D-print and interact with their own physical replicas. Our aim in this paper is to demonstrate the ability of this technology to reproduce accurate historical kinematic models and machines as a tool for both artifact conservancy as well as for teaching, and to demonstrate this for a wide range of mechanism types. We expect that this new form of 'physical' preservation will become prevalent in future archives. We describe the background and history of the collection as well as aspects of modeling and printing such functional replicas.

Keywords: Reuleaux-Voigt models, kinematic models, rapid prototyping

Introduction

The use of physical models in engineering has had, until the last quarter century, a long and useful history. This is especially true in machine design and engineering. Filippo Brunelleschi (1377-1436), the architect and engineer of the Duomo in Florence is known to have created construction models, including machines. In later centuries Christopher Polhem (1661-1751) in Sweden created a ‘mechanical alphabet’ of models for machines. Robert Willis (1800-1875) of Cambridge was also known for his kinematic teaching models though few have survived. Franz Reuleaux (1829-1905) of Berlin created the world’s largest collection of kinematic models at the Technical University of Berlin with over 800 models. Most of this collection was destroyed in the second world war, though there are 60 in the Deutsches Museum in Munich. However Reuleaux authorized and supervised the reproduction of approximately 360 mechanisms by the model maker Gustav Voigt in Berlin. J. Schroeder of Darmstadt also created kinematic models based on the books of Reuleaux, and Redtenbacher, which were later produced by the model works of Peter Koch. Some of the models of Schröder and Voigt are in collections in Europe, North America and Japan. A recent conference on the history of machines and mechanisms contains several papers related to Reuleaux (Ceccarelli, 2000). The second author (FCM) has published two reviews of Reuleaux’s ideas and use of kinematic models (Moon 2003a,b). Descriptions of some of the models may be found in Reuleaux’s books, published in English translation: *Kinematics of Machinery* (Reuleaux, 1876) and *The Constructor* (Reuleaux, 1893). The earlier kinematic models of Robert Willis (1841-1870) also show the use of kinematic models.

Cornell University was fortunate to have purchased a substantial part of the Voigt-Reuleaux models in 1882. A history of this collection (Moon, 2003a) shows that these models were used for teaching machine design up until the 1970’s. A new generation of academics has again found these models useful for teaching and research. Also a number of scholars, engineers and artists have begun to travel to Ithaca to see the Reuleaux Collection. As a result, Cornell University has decided to document and make the Collection available on the World Wide Web as part of the US National Science Digital Library (NSDL). The kinematic collection comprises 220 models from the Voigt catalog, a dozen models from the Schroeder works and a Robert Willis model made in Paris (Moon, 2003b). Cornell also has models and artifacts from Robert Thurston, who was an expert and historian on the steam engine. The University Library has a substantial collection of original 19th century machine design books of Willis, Laboulaye, Reuleaux, Rankine, Redtenbacher, Burmester, Kennedy, Thurston and others along with earlier so-called 'theatre of machines' books by Besson (1569), Ramelli (1588), Bockler, and Leupold (1724) as well as facsimiles of the notebooks of Leonardo da Vinci. The combined collections of both physical kinematic models and rare books on the history of machines at Cornell is a unique combination of resources matched only by larger institutions such as the Deutsches Museum in Munich and the Smithsonian Institution in Washington D.C.

Cornell has recently created an online museum that contains a sampling of Reuleaux models with mathematical and historic annotation, pictures, movies, animations, and simulations[1]. Many of the above-cited historic books are digitized and referenced in the relevant web portal page of each of the kinematic models. Each of the models contains descriptive and historical text. To see the models in action, we also created animations of many of the models. A special goal was to create the opportunity for the web site user to interact with the models through simulations, such as offered by Kyoto University Museum collection of 19 Voigt-Reuleaux models, which were modeled in a CAD program and animated with the multibody dynamics code (Shiroshita *et al*, 2001).

What cannot be experienced with a web collection, however, is the physical handling of the models. Although physical models of machines were prevalent in early exhibitions and universities, their use has been largely replaced today by CAD models and simulations. These computational models are more versatile and of lower cost, but they lose the physical embodiment that is essential for an intuitive appreciation of many critical concepts of motion and force, such as friction, hysteresis, compliance, geometric

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[1] See www.explore.cornell.edu (search for "kinematics")

tolerances, and dynamics. However, new rapid-prototyping technology allows reintroduction of physical models as an intuitive and simple way to demonstrate these fundamental mechanical concepts. We now use the web to integrate both these textual and artifact collections on the history of machines and mechanisms. Besides reading textual descriptions, viewing pictures and videos, and interacting with simulations, visitors may now also download, 3D-print and interact with their own fully functional physical replicas. We expect that as rapid-prototyping becomes more commonly available, such forms of documentation will become increasingly prevalent.

3D Printing of Kinematic Models

To document the Reuleaux models, CAD models of several mechanisms were made. The models were constructed as assemblies of parts constrained by kinematic and geometric interference. Besides exporting these models as drawings, rendered 3D images and animations, they may be exported for printing on rapid-prototyping fabricator as a file in STL format. This file describes the surfaces of the object as a tessellation of triangles.

There are several rapid prototyping technologies, including laminated object manufacturing (LOM), selective laser sintering (SLS), photo polymerization (stereolithography, SLA), and fused deposition modeling (FDM). The FDM process was used in this study to reproduce several Reuleaux-Voigt kinematic models[2]. The process creates a sequence of thermoplastic layers from a filament wound coil that is heated and extruded through a nozzle. The trajectory of the nozzle is derived from the triangle mesh, so as to raster-scan and fill solid volumes. In order to create functioning mechanisms, a second, water soluble release material is placed in the gaps between the movable parts. The basic material used was Acrylonitrile-Butadiene-Styrene (ABS). Information on these materials can be obtained from Montero *et al* (2001) as well as from the manufacturer.

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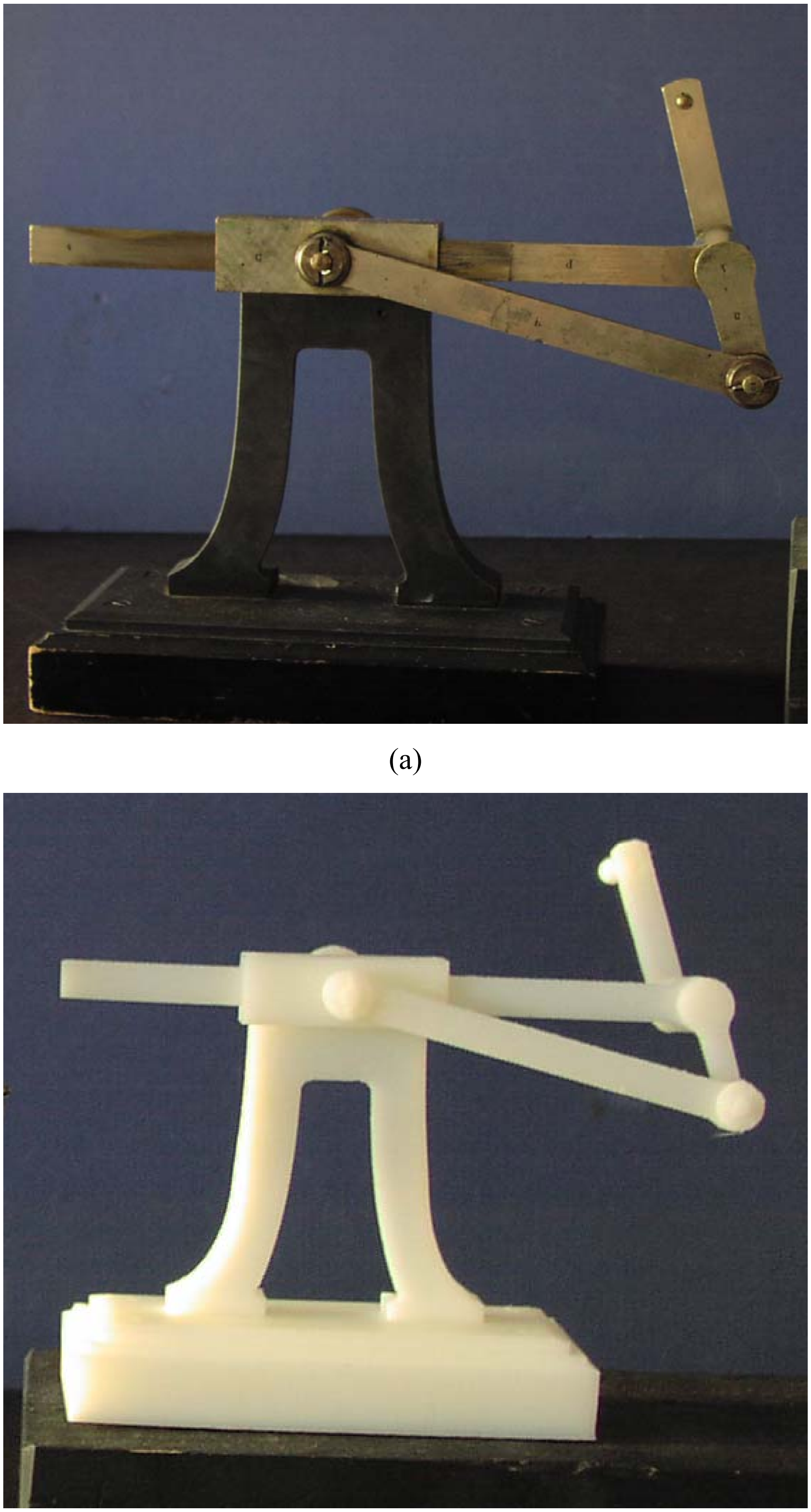
[2] The specific system was a Stratasys FDM 3000

Kinematic mechanisms such as a Geneva mechanism and a planetary gear device have been created before and featured on manufacturer’s web site. Similarly, simple joints and preassembled robot morphologies have been printed before (Lipson and Pollack, 2000; Mavroidis *et al*, 2001). Our aim in this paper is to demonstrate the ability of this technology to reproduce accurate historical kinematic models and machines as a tool for both artifact conservancy and for teaching, as well as to demonstrate the applicability to a wider variety of mechanisms. We have reproduced several pre-assembled, fully-functional historic mechanisms such as early straight line mechanisms, ratchets, pumps, and clock escapements, including various kinematic components such as links, joints, gears, worms, nuts, bolts, and springs.

The following different models are shown in Figures 1-6:

- A slider crank allowing multiple inversions,
- A double slider crank,
- A ratchet mechanism with three spring-loaded stoppers,
- A worm-gear transmission
- A double-chamber leaf pump
- A clock escapement



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(b)

Figure 1. Slider Crank. (a) Original Reuleaux model, (b) Rapid prototype model,

(a)

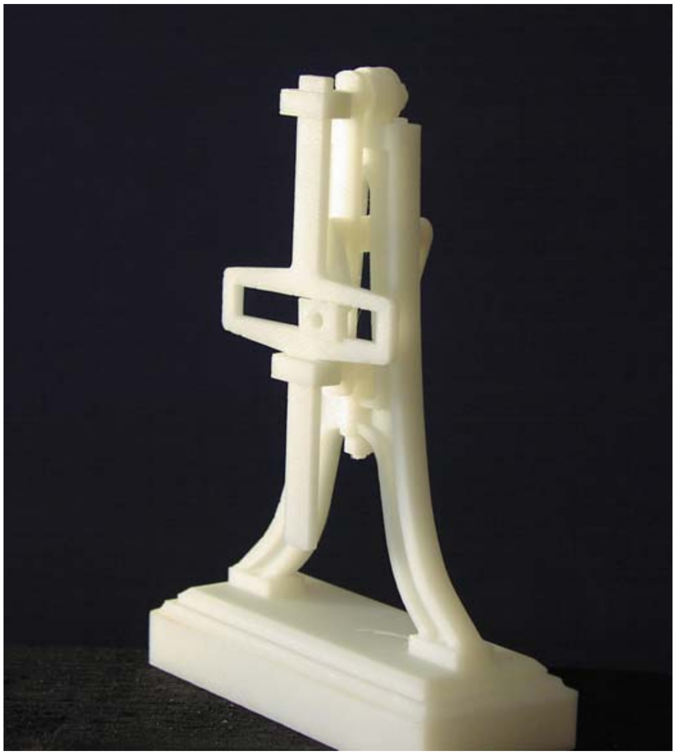

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Figure 2. Double slider crank. (a) Original Reuleaux model, (b) Rapid prototype model

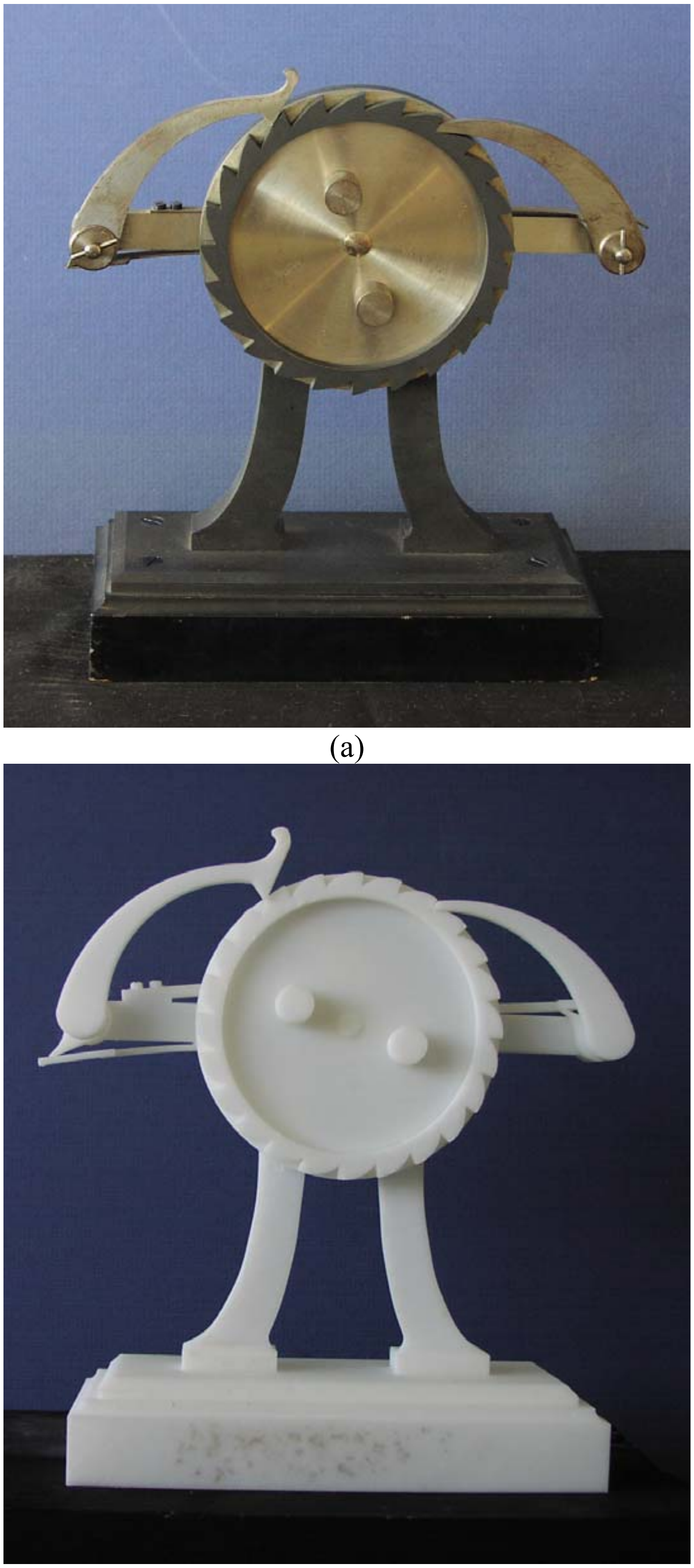
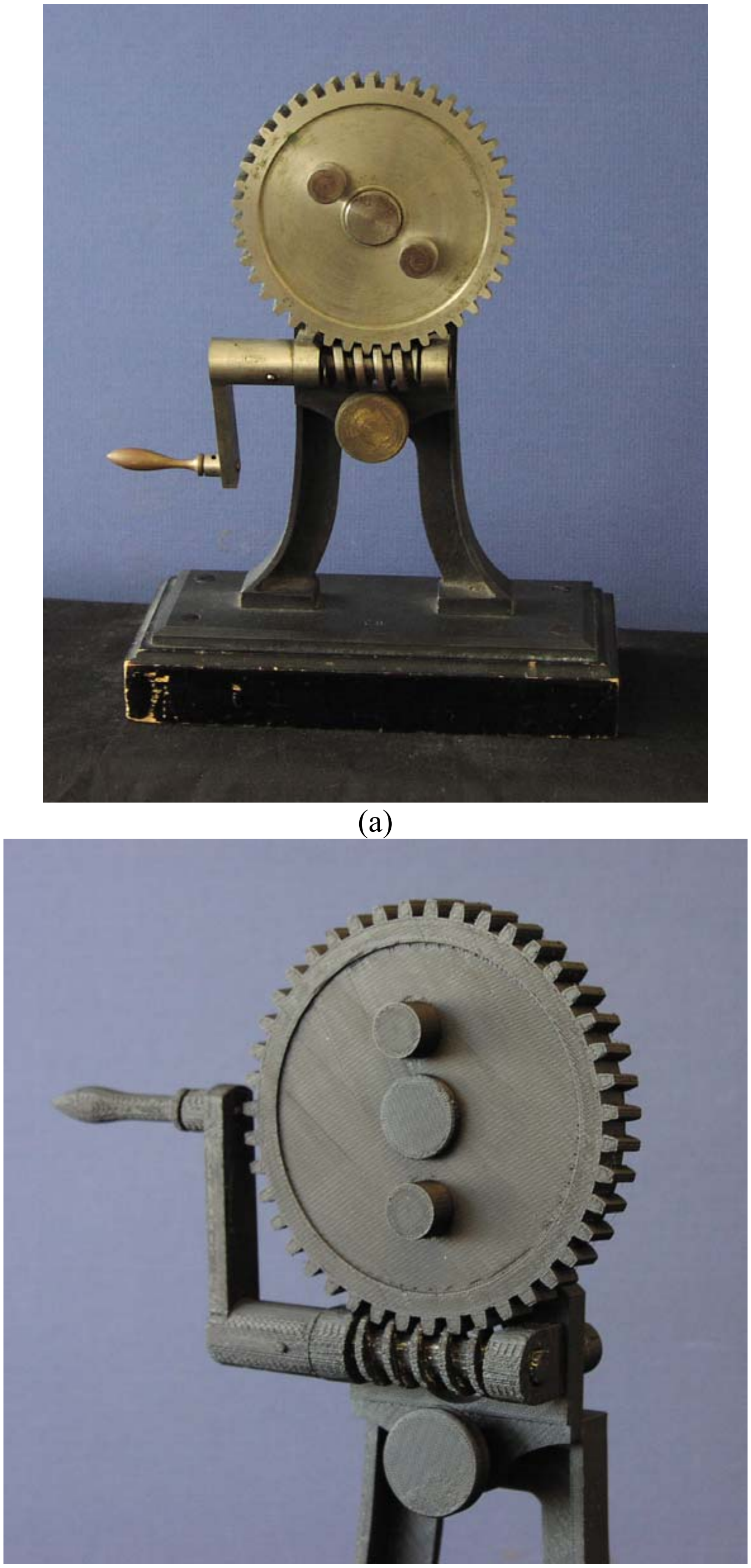


Figure 3. A ratchet mechanism with three spring-loaded stoppers (a) Original Reuleaux model, (b) Rapid prototype model



(a)

(b)

Figure 4. Worm gear mechanism (a) Original Reuleaux model, (b) Rapid prototype model

Figure 5. A double-chamber leaf pump (a) Original Reuleaux model, (b) Rapid prototype model

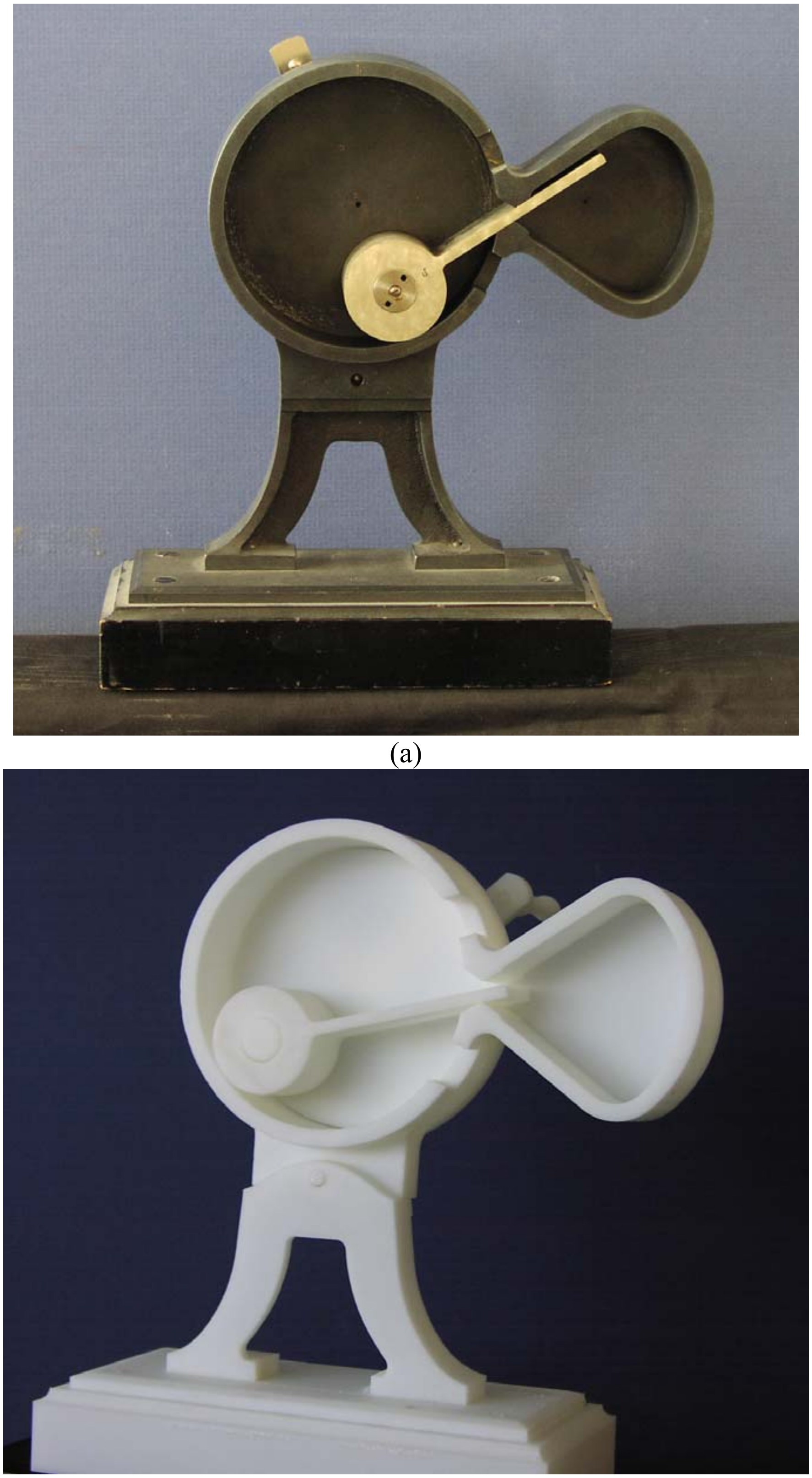


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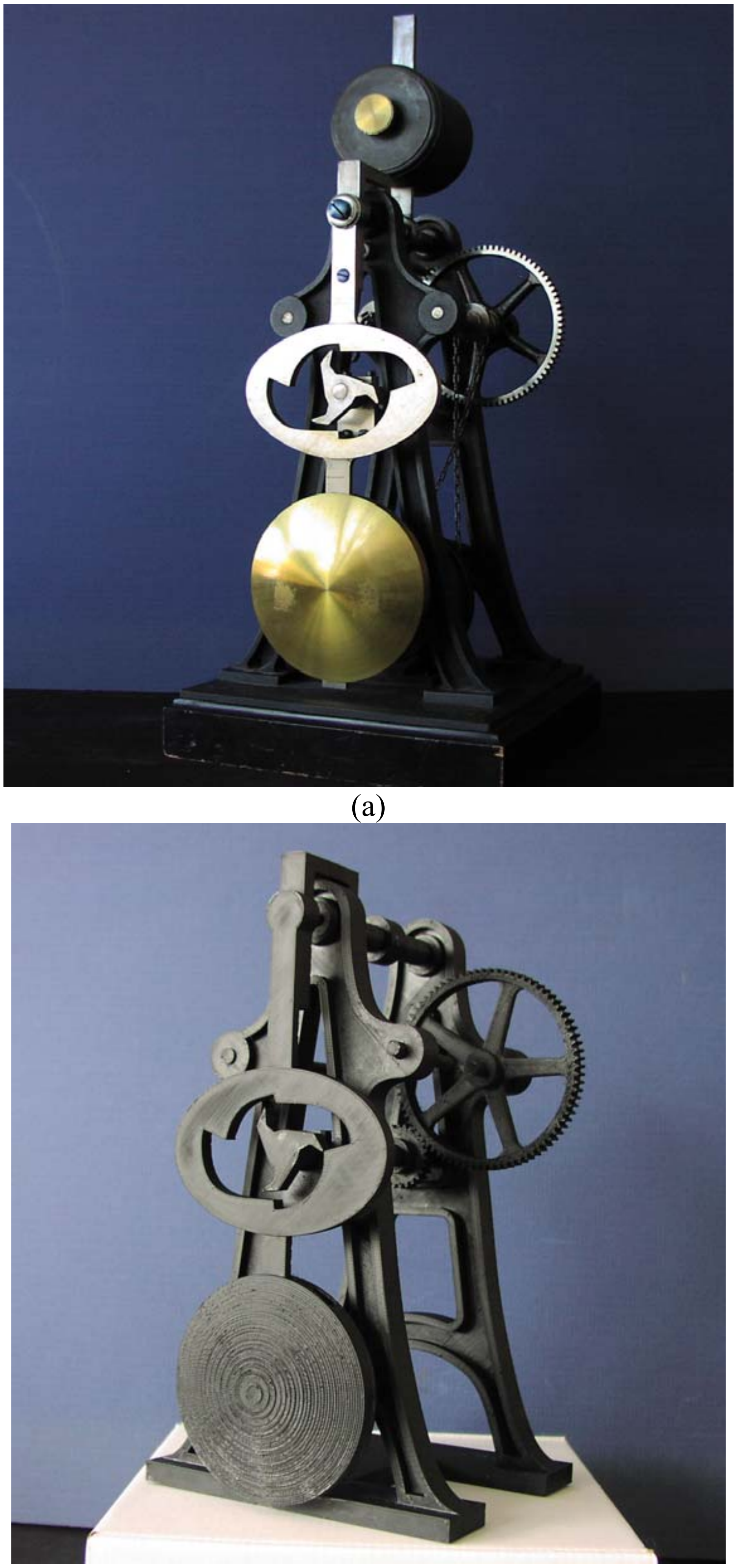
Figure 5. A double-chamber leaf pump (a) Original Reuleaux model, (b) Rapid prototype model



(a)

(b)

Figure 6. A clock escapement mechanism (a) Original Reuleaux model, (b) Rapid prototype model

Prototype Model Authenticity

It is clear from viewing and handling the Reuleaux models that they were carefully designed to follow his ideas of kinematics theory. Reuleaux's major contributions to kinematics includes the notion of lower and higher kinematic pairs, kinematic chains, inversion of mechanisms, rolling centrode curves, aesthetics in machine design and kinematic synthesis and invention. The models made by Gustav Voigt were inscribed with letters and numbers of the links and the joints corresponding to the diagrams in Reuleaux's classic text on the Kinematics of Machinery in 1875/1876.

Many of the models were designed such that one could fix different links in the kinematic chain and obtain three or four kinematic inversions. In some models, such as the curves of constant width or the positive return cams, the centrode pairs are inscribed on glass plates fixed to the mechanisms. Reuleaux designed the pedestal of each model according to aesthetic principles outlined in his other classic text on machine design, The Constructor (1854-1893). In this work he advised the designer that the choice of smooth aesthetic curves will likely bring the machine element closer to an optimum constant stress design. Thus the pedestals in the Reuleaux models exhibit beautiful flowing curves. Finally, Reuleaux chose materials of brass and cast iron that have stood the test of time with very little wear and rust. He boosted in his letter to the President of Cornell University of 1882, that he had a special heat treatment method that would protect the iron from the perspiration of many student hands.

These qualities of the models in this collection guarantee that their reproduction in today's market would be very expensive. (The Cornell set of approximately 250 models cost $8000 in 1882 American dollars. Using a straight forward inflation factor in today's currency would make these models very valuable.) Providing a less expensive reproduction method in cheaper materials, such as thermoplastics, is a fine goal. However basic limitations of the FDM process leads to certain necessary compromises. Specifically, we strived to make every model printable as a single, pre-assembled unit, so that it is fully functional straight out of the printer. This necessitates careful consideration and, in some cases, redesign of some features of the model.

Clearance between moving surfaces

One of the major differences between the FDM copies and the originals is the clearance between moving parts. The printing process cannot directly leave a zero-width gap. Instead the process either leaves an air gap, if possible, or puts in waste material: Water-soluble material that is later washed away, or for stereolithography processes, wax material that is melted or etched away, or unsintered particles in selective sintering processes. The clearance between parts is on the order of 0.4 mm in our case, a rather large gap – an order of magnitude greater than the originals. The large gaps affect the rigidity of the mechanism, add hysteresis effects, and become detrimental when tight surfaces are critical for functionality, such as in pumps. This necessity for large gaps originates in several reasons:

Release: Ensuring the surfaces do not fuse together while printing.

Warping: Because the prototype is built up of many layers, each originating as a molten liquid, there is the problem of thermo-elastic warping. Thus maintenance of plane surfaces in the case of joints with tight clearance is a problem.

Friction: The FDM models do not have any lubrication, so a large gap helps minimize friction. This is especially true for processes that have low surface finish.

Etching pathways. Most Rapid prototyping processes require a secondary processes for removing support material, either using solvents, melting, blowing or etching. If gaps are too tight, these solvents cannot reach the material to be removed and/or the dissolved material cannot flow out. Consequently, the design is typically modified to allow easy pathways for removal of release materials.

Large gaps typically result in loose fits among parts. In some cases, these gaps will make a mechanism inoperable and must be compensated for. For example, Figure 7 shows a horizontal shaft under load. If the shaft is printed horizontally with gaps filled with support material (Fig 7a), then the shaft will lose its alignment one the support material is removed (Fig 7b). To ensure that the shaft remains aligned after support materials is removed, the geometry must be compensated in advance, as shown in figure 7c. Similar but more complex compensations need to be carried out for more elaborate mechanisms.

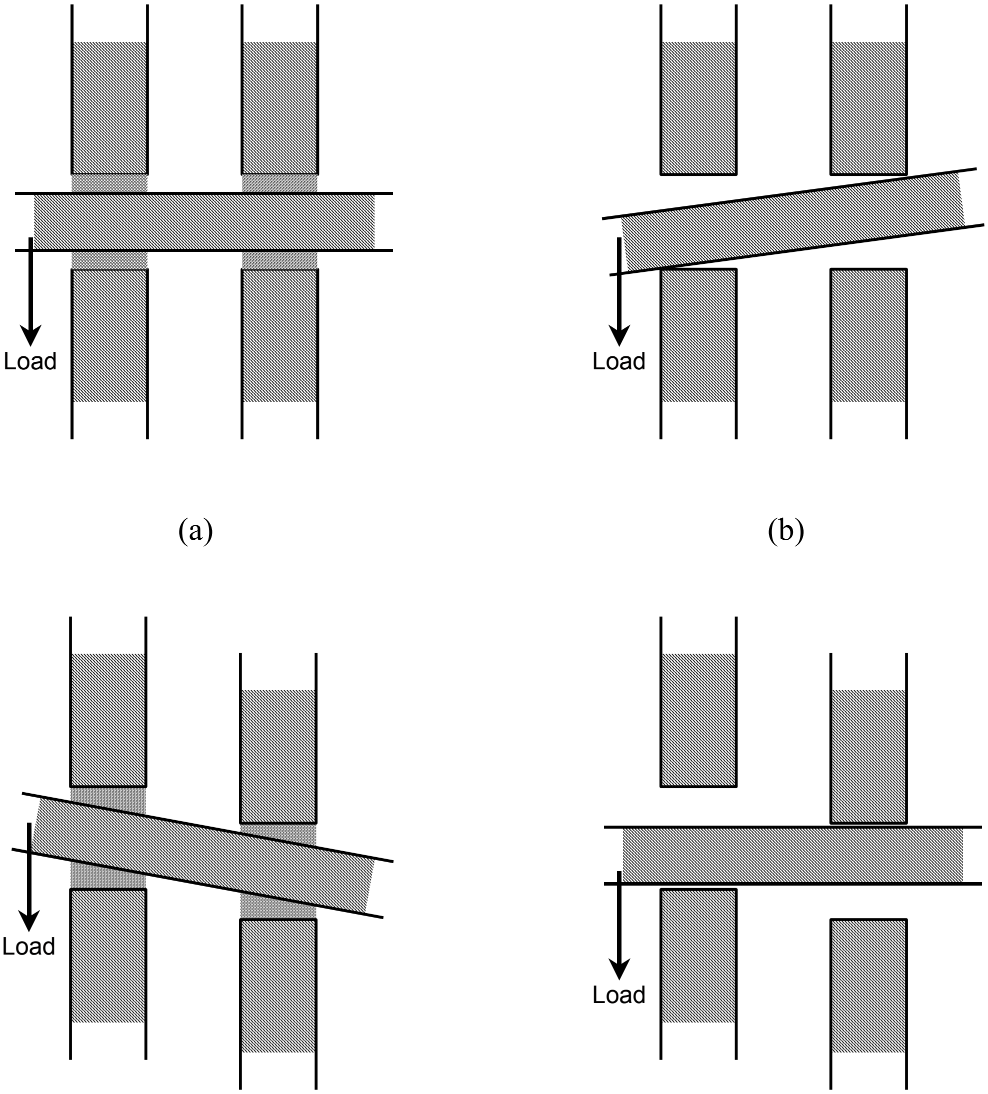
Strength and compliance

Another issue is the strength of the rapid prototyping material itself. For example, Reuleaux's brass handles on his models have a beautiful shape that is fragile in the ABS plastic. Several aspects affect the strength of the printed mechanism:

Material: Various materials can be used, affecting the durability of the resulting mechanism. A typical ABS product is far weaker than the original. Weak points and stress concentration points may need to be reinforced.

Deposition pattern. Because the deposition processes is layered and, with FDM processes also fibered, the material's mechanical behavior approximates laminated material (e.g. composites) or fibrous material (e.g. hardwood) more than it does a solid material. Thus the original material properties specified by the manufacturer may be somewhat deceptive, and the true properties end up being largely dependent on the orientation of the part and exact deposition pattern. It is therefore desirable to set the mechanism at a state such that it may be printed with fibers along the length of load gradients. New materials and deposition processes may alleviate this need in the future.

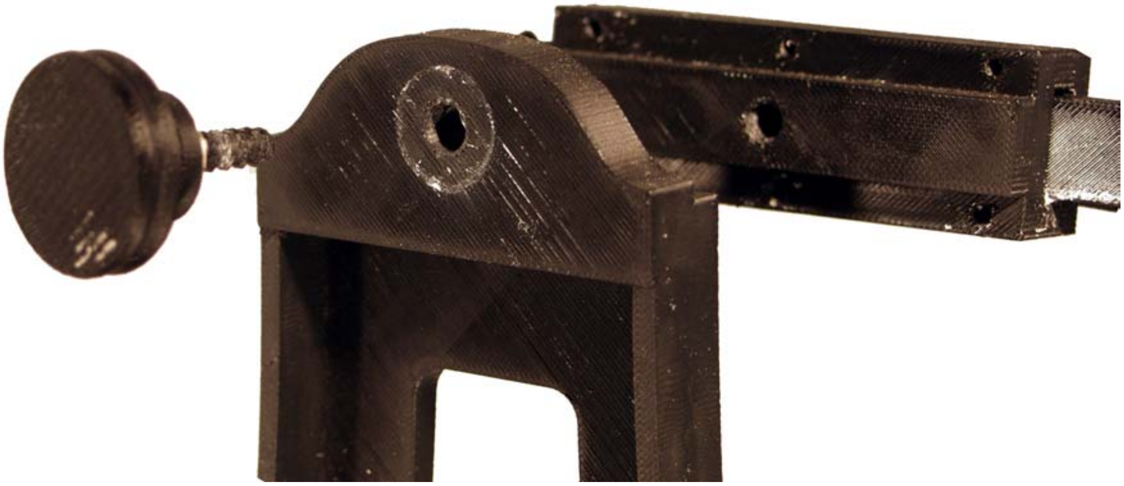
Compliance. The elasticity of the material may be useful when printing compliant mechanisms such as springs. However, in such components the geometry interacts with the material properties, so that the geometry must be changed to achieve certain kinematic behavior. This is demonstrated in the printing of the spring loaded-ratchet mechanism, in which leaf-springs lengths and width needed to be adjusted to produce the proper functionality (Fig 8b).



(a) (b)

(c) (d)

Figure 7. Misalignment caused by large gap requirements: (A) A loaded shaft printed with gaps filled with support material, (b) will misalign when support material is removed. (c) Shaft misalignment is pre-compensated so that (d) final functioning model will perform properly. More complex compensations need to be carried out for more elaborate mechanisms.



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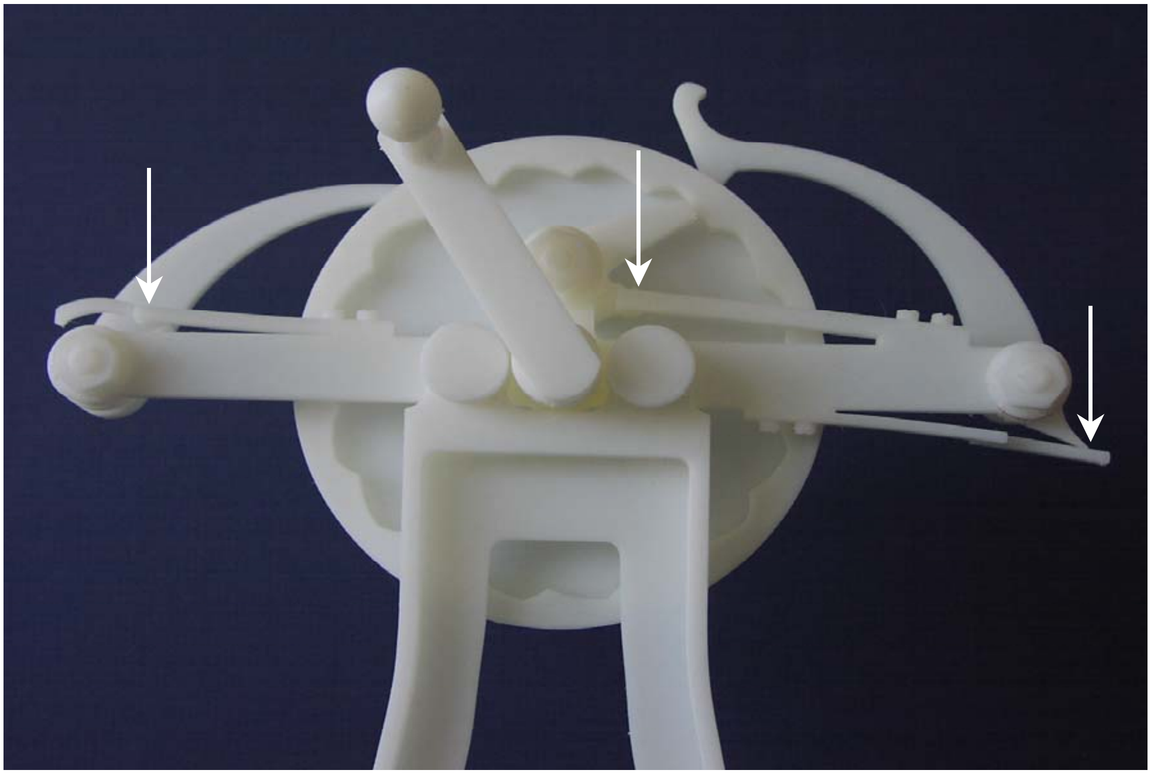

(c)

Figure 8. Close-up of components: (a) screw with thread and nut in prismatic joint, (b) three loaded ratchet springs. All parts printed preassembled in one pass.

Pre-assembled fasteners and markings

From a pedagogical point of view, many of the Reuleaux models can be demounted so they can be remounted with another fixed link to form an inversion. The Voigt models have fine screws for demounting the mechanism from the pedestal, which are difficult to replicate in the plastic with their original diameter and pitch, again because of the large gaps necessary between movable parts. To replicate these fasteners and inversion capabilities, we modeled fasteners with an enlarged diameter and pitch (Fig 8a).

Many of the models have links and bearings inscribed with numbers and letters. This is difficult to replicate because of the digital nature of the layering process which sometimes produces a fine stepped finish; however, depending on the orientation, sufficiently large fonts have been reproduced.

Putting these caveats aside however, the FDM produced copies of the Reuleaux models are remarkably visually true to the originals as shown in a comparison in Figures 1-6. The models are fairly robust to use and move. The cost and time to produce one is a fraction of that necessary to manufacture a traditional copy in iron and brass, but require several days to model and adjust for printing. A half scale model of the slider crank took approximately 10 hours in the FDM machine. A full scale model took substantially more time, over 40 hours. Some time and material can be saved however if one designs in some cavities in some of the parts such as the base and the pedestal. We expect these caveats to largely disappear in the future as the printing technology improves.

3D Printing Leonardo da Vinci's Machines

The Leonardo da Vinci scholar L. Reti, who translated the Codex Madrid notebooks, wrote several articles in which he claimed that Leonardo had intended parts of the Codex Madrid to be a text on basic machine elements (Reti, 1974). To make his case Reti compared Leonardo's drawings of basic machine and kinematic elements with the basic list of 'constructive elements' found in Reuleaux's Kinematics of Machinery (1876).

One such comparison is the slider crank mechanism. Leonardo da Vinci drew several designs of slider cranks and also appeared to understand the nature of kinematic singularities through these drawings. One design shown in Figure Z, uses a combination of an endless screw and a slider crank. A CAD drawing was made using the proportions shown in the Codex Madrid (da Vinci, 1493) and an FDM model was produced as shown in Figure 9. Although Leonardo was a consummate artist, he did not seem to carry this aesthetic over into machine design. Thus to be faithful to his style in machine drawing, the pedestal was made with rectangular shaped elements unlike that of Reuleaux who seemed to abhor rectangular elements in design.

Although Vasari vaguely makes mention of Leonardo making models, there is no evidence that he ever made 3D models of his machine and mechanism designs. However, in the late 20th century, several model makers in Italy have produced models of Leonardo’s machines (e.g. Heydenreich and Guatelli, 1951). The use of CAD and FDM prototyping however shows that one can realize historic models for a reasonable cost without the services of a master crafts person.

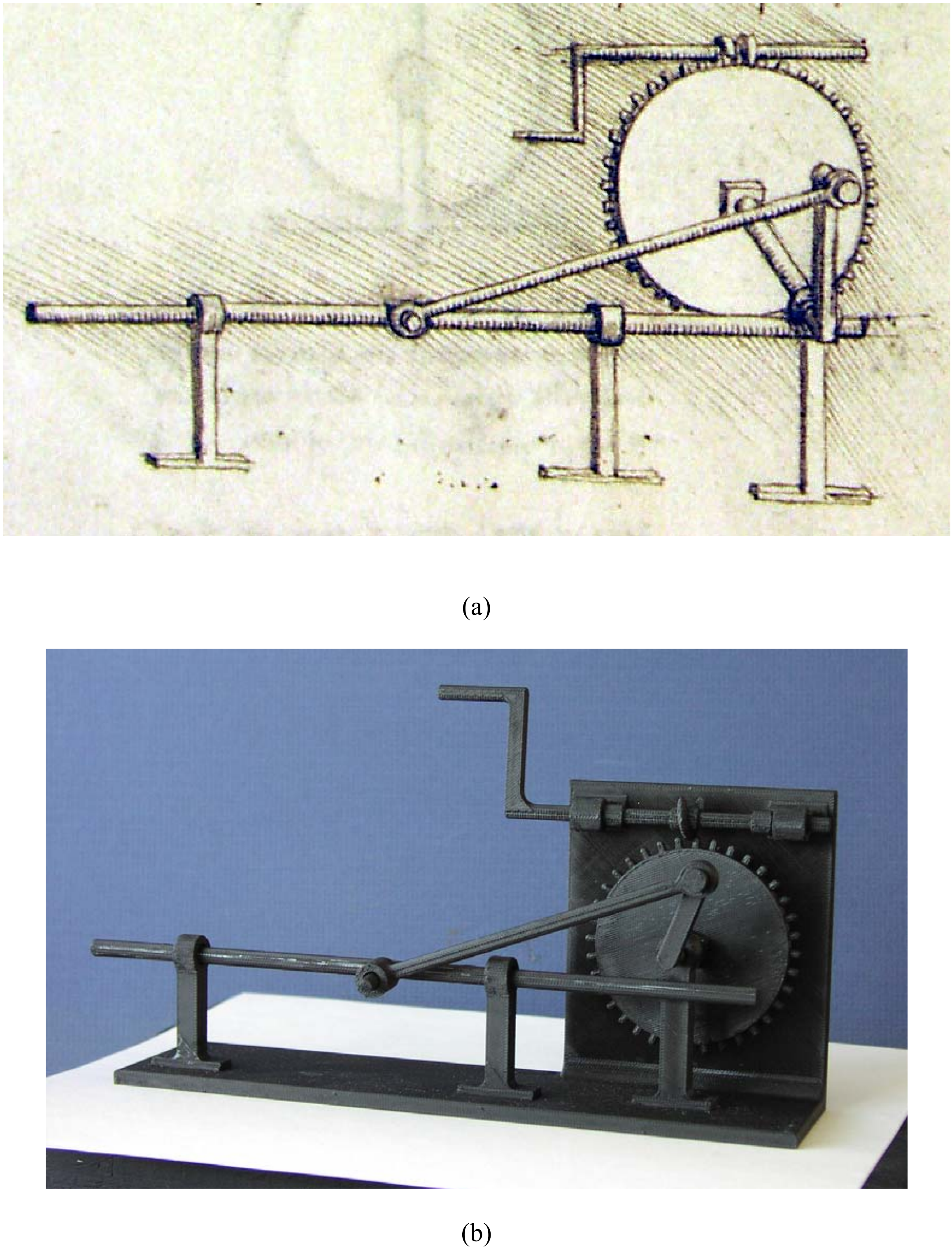

Figure 9. Leonardo da Vinci version of a slider crank and endless screw. (a) Original drawing, (b) Rapid prototype model

Conclusions

Physical models of machines have played an important role in the history of engineering for teaching, modeling and exploring mechanical concepts. Many of these models have been replaced by computational representations, but new rapid-prototyping technology allows reintroduction of physical models as an intuitive way to demonstrate mechanical concepts. This paper reports on the use of computer-aided modeling tools and rapid prototyping technology to document, preserve, and reproduce in three dimensions, historic machines and mechanisms. We have reproduced several pre-assembled, fully-functional historic mechanisms such as early straight line mechanisms, ratchets, pumps, [clock escapements and counting devices], including various kinematic components such as links, joints, gears, worms, nuts, bolts, and springs. In an online museum of mechanism, visitors may now also download, 3D-print and interact with their own physical replicas.

Our aim in this paper is to demonstrate the ability of this technology to reproduce accurate historical kinematic models and machines as a tool for both artifact conservancy as well as for teaching, and to demonstrate is applicability to a wide range of mechanism types. We expect that this new form of 'physical' preservation will become prevalent in future archives. As research in rapid prototyping advances to allow for more durable materials and more accurate, faster and cheaper production, more elaborate machines may be printable by a growing community around the world. Moreover, as new research leads to multi-material functional freeform fabrication, we expect that incorporation of elastomers, lubricants, actuators and sensors will allow faithful replication of an ever-increasing scope of artifacts.

Acknowledgments

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