3-D Printing the History of Mechanisms

Hod Lipson
e-mail: hod.lipson@cornell.edu

Francis C. Moon

Jimmy Hai

Carlo Paventi

School of Mechanical and Aerospace Engineering,
Cornell University, Ithaca, NY, 14853, USA

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 (RP) technologies are now allowing reintroduction of physical models as an intuitive way to demonstrate mechanical concepts. This paper reports on the use of RP to document, preserve, reproduce, and share in three dimensions, historic machines, and mechanisms. We have reproduced several preassembled, fully functional historic mechanisms from the Cornell Collection of Reuleaux Kinematic Models, and made these available as part of a new online museum of mechanism: Not only can visitors read descriptions, view pictures and videos, and interact with simulations of machines, but they can now also download and 3D-print their own physical functional replicas. We expect that this new form of "physical" preservation will become prevalent in future archives. [DOI: 10.1115/1.1902999]

1 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 models in the Deutsches Museum in Munich. However, Reuleaux authorized and supervised the reproduction of approximately 360 mechanisms by the model maker Voigt [1]. Another model maker, 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 [2]. We have published two reviews of Reuleaux's ideas and use of kinematic models [3,4]. Descriptions of some of the models may be found in Reuleaux's books, published in English translation [5] and *The Constructor* [6]. The earlier kinematic models of Willis also show the use of kinematic models [7].

Cornell University was fortunate to have purchased a substantial part of the Voigt–Reuleaux models in 1882. A history of this collection [3] 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 U.S. National Science Digital Library (NSDL). The kinematic collection comprises 230 models from the Voigt catalog, a dozen models from the Schroeder works and a Robert Willis model made in Paris [4], as well as various other instruments. 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 [8], Ramelli [9], Bockler [10], and Leupold [11], 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.

To share this collection, Cornell has recently created an online museum that contains most of the Reuleaux models with mathematical and historic annotation, pictures, movies, animations, and simulations [12]. 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 the Kyoto University Museum collection of 19 Voigt–Reuleaux models, which were modeled in a CAD program and animated with the multibody dynamics code [13].

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, damping, backlash, compliance, geometric tolerances, surface finish, 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.

2 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.

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Fig. 1 Sample printed models. (a) Original models (left) and printed reproduction (right). Top: slider crank; Middle: Scotch–Yoke mechanism; Bottom: A ratchet mechanism with three spring-loaded pawls. (b) Original models (left) and printed reproduction (right). Top: Worm gear mechanism; Middle: A double-chamber leaf pump; Bottom: A clock escapement mechanism

There are several rapid prototyping technologies, including laminated object manufacturing (LOM), selective laser sintering (SLS), photopolymerization (stereolithography, SLA), and fused deposition modeling (FDM). The FDM process was used in this study to reproduce several Reuleaux–Voigt kinematic models. 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, 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 as well as from the manufacturer [14].

Various kinematic components have been created before and even featured on some manufacturers' web sites. Similarly, simple joints and preassembled robot morphologies have been printed [15–19]. Our aim in this paper is to demonstrate the ability of this technology to reproduce complete, functional, preassembled, and 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 preassembled, 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.

Some models are shown in Fig. 1: 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, and a clock escapement.

Other models are available online at the Kinematic Machines for Design Digital Library [12].

3 Reproduction Challenges and 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 boasted 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 students 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). Providing a less expensive reproduction method in cheaper materials, such as thermoplastics, is a fine goal. However basic limitations of the rapid prototyping process leads to certain necessary compromises. Specifically, we strived to make every model printable as a single, preassembled unit, so that it is fully functional right out of the printer. This necessitates careful consideration and, in some cases, redesign of some features of the model. We thus sacrifice some dimensional authenticity for functional authenticity.

3.1 Clearance between Moving Surfaces. One of the major differences between the preassembled printed copies and the originals is the clearance between moving parts. The printing process cannot directly leave the tight mating between parts. Instead the process either leaves an air gap, if possible, or puts in waste support material: This material is later dissolved, melted, etched, or blown away. 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 backlash 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.

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

Etching pathways. Most rapid prototyping processes require a secondary process for removing support material, by dissolving, melting, blowing, or etching or by manual removal. 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 precision instruments, these gaps will make a mechanism inoperable and must be compensated for. For example, Fig. 2 shows a horizontal shaft under load. If the shaft is printed horizontally with gaps filled with support material [Fig. 2(*a*)], then the shaft will lose its alignment once the support material is removed [Fig. 2(*b*)]. To ensure that the shaft remains horizontally aligned after support materials are removed, the geometry must be compensated in advance, for example as shown in Fig. 2(*c*). Similar but more complex compensations need to be carried out for more elaborate mechanisms.

3.2 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.

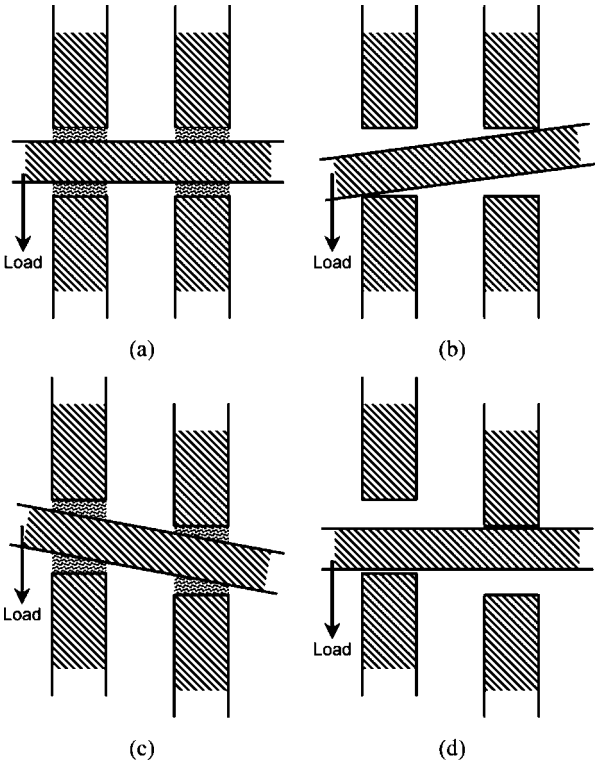


Fig. 2 Misalignment caused by large gap requirements: (*a*) A loaded shaft printed with gaps filled with support material; (*b*) will misalign when support material is removed; (*c*) shaft misalignment is precompensated so that (*d*) final functioning model will perform properly. More complex compensations need to be carried out for more elaborate mechanisms

Warping: Thermoelastic warping may occur during cooling of the material after deposition, leading to warping and misalignment that is especially noticeable on planar surfaces. Reinforcement brackets, fillets, and ribs are often needed to be inserted to counteract these effects.

Deposition pattern. Because the deposition processes is layered and, with some 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 material 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 problem 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 length and width needed to be adjusted to produce the proper functionality [Fig. 3(*b*)].

Weight: In some models the difference in weight between the original model and the printed replica may cause functional discrepancies, especially when dynamic behavior is involved. For example, the pendulum of the clock in Fig. 1 is too light, as printed, to sustain momentum; it must be enlarged (or printed with other materials) to be functional.

3.3 Preassembled Fasteners and Markings. From a peda-

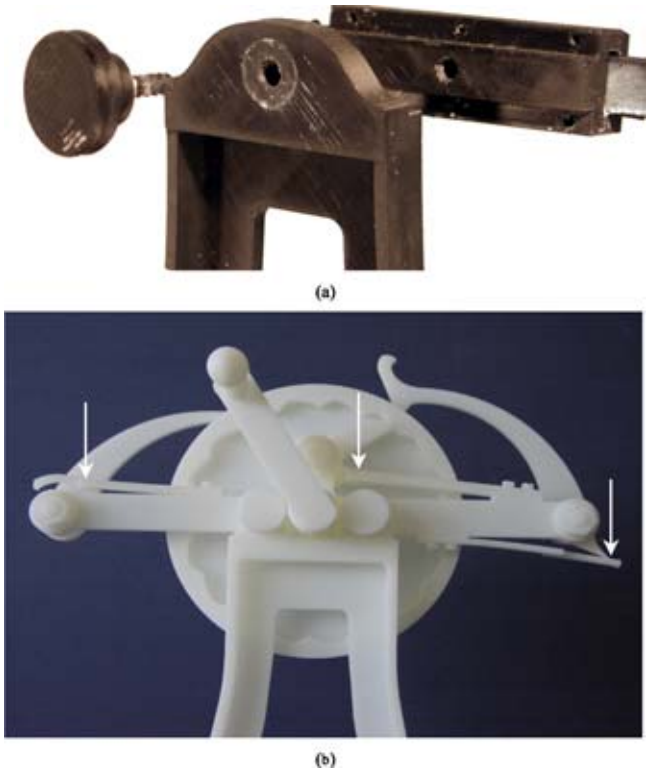


Fig. 3 Closeup of components: (*a*) screw with thread and nut in prismatic joint; (*b*) three loaded ratchet springs. All parts printed preassembled in one pass.

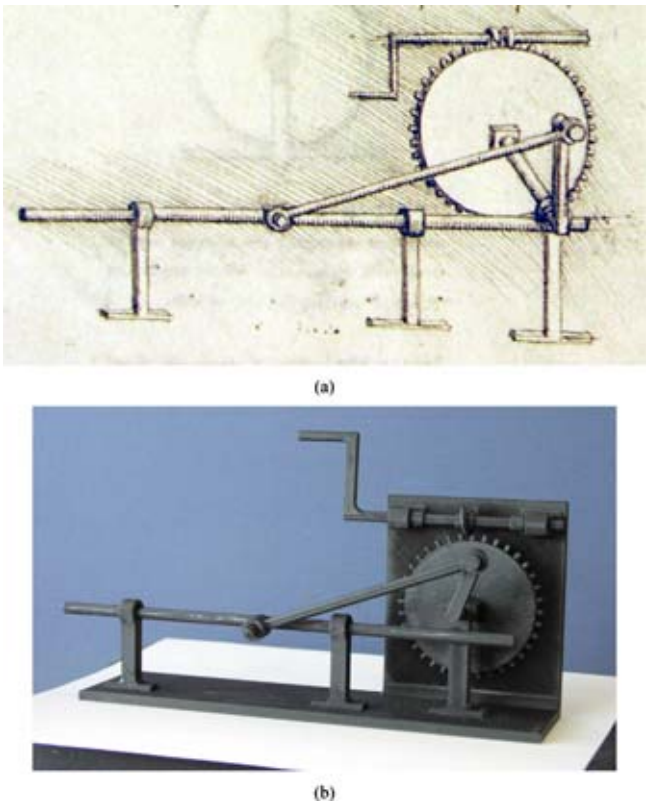


Fig. 4 Leonardo da Vinci's version of a slider crank and endless screw: (*a*) Original drawing; (*b*) rapid prototype model

gogical 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. 3(*a*)].

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 Fig. 1. 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 h in the FDM machine (Stratasys FDM 3000). A full scale model took substantially more time, over 40 h. 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 many of these caveats to largely disappear in the future as the printing technology improves.

3.4 Model Sharing Challenges. The current market of rapid prototyping equipment has not yet reached the level of maturity that would enable a single file to be made suitable for all varieties of rapid prototyping processes. The current de facto industry standard for exchange of rapid prototyping data is the STL file format, which is a relatively information-poor representation of the target model, omitting many important functional and material aspects of the target object. We have found that the greatest varying factor among current machines, relevant to our application, is the minimal allowable gap size, and so we typically provide several model files with varying gap widths among moving surfaces. We expect that future file rapid prototyping formats and automated process planning will allow for specifying much of this information in a technology-independent way, and have the rapid prototyping equipment itself adjust the model and process automatically [20,21].

4 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 preassembled, 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, not only can visitors read descriptions, see pictures and watch movies of mechanisms, but they 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. Though the objects demonstrated in this paper were replicas of existing Reuleaux models, the potential scope is clearly much broader: One can realize many historical concepts

that exist only on paper, such as Leonardo da Vinci's slider crank mechanism (Fig. 4) [24–26], as well as other models that exhibit more contemporary concepts from aerodynamics to molecular biology. Independent of the specific fields of applications, the increased accessibility of these models through electronic sharing, dissemination, and rapid prototyping greatly increases the incentive for designing them.

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 multimaterial functional freeform fabrication, we expect that incorporation of elastomers, lubricants, actuators, and sensors, electronics and power devices [22,23] will allow faithful replication and electronic sharing of an ever-increasing scope of physical models and artifacts.

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