

Computer-aided design of mechanical automata:

Engineering education for children



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ABSTRACT

With decreasing numbers of engineers graduating from undergraduate institutions in the United States, the importance of developing children's interests in engineering is increasingly apparent. In this paper we discuss an approach to engineering education based upon the design of mechanical toys and automata. In implementing this approach we have created a software system, Machine Shop, for the design of automata; Machine Shop facilitates the design of mechanical elements, and their fabrication in wood or plastic on a desktop laser cutter. In this paper, we describe both our software and its place in a larger portrait of engineering education. We also present a case study highlighting the design process of one ten year old student as he designed and constructed his first mechanical automaton, and draw some general observations from our ongoing testing with children in elementary and middle schools.

1. Introduction

Engineering education in the United States currently faces severe problems: it may not be an exaggeration to refer to the situation as a crisis. During the last two decades of the twentieth century the number of incoming university freshmen in engineering continuously decreased; and fewer than half of those students graduated with an engineering degree. Clearly, improvements in early mathematics and science education are warranted in response to this situation; but by the same token, this research must include, or be complemented by, efforts to introduce children to the intellectual core of engineering—namely, design and construction.

There have been a variety of attempts to deal with this problem of early engineering education. Some efforts have focused on integrating engineering into mathematics and science curricula; others have presented engineering topics in simplified forms; still others have made use of readily available construction kits. While these efforts are worthwhile, they also exhibit a profound limitation. In particular, there is little in the way of personalized design in these activities: children solve hypothetical problems or work with demonstrations, but they have little experience of engineering as a means of individual expression. Engineering thus becomes something of a “classroom subject”: something that one might do in school, but that is otherwise removed from the creative life of the child.

This paper presents an alternative approach to engineering education in which elementary- and middle-school children employ computational design tools and novel

fabrication devices to create their own, never-before-seen mechanical automata. We have created a software application, Machine Shop, whose purpose is to permit children to design an endless variety of mechanical sculptures and toys; and the elements of these fascinating machines may then be directly printed out in a variety of

materials on a computer-controlled laser cutter. Machine Shop thus represents an approach toward educational computing in which the desktop computer is not the sole technological element, but is instead combined with a powerful output device (i.e., the laser cutter) to extend the range of children's creative activities with physical materials. While the work presented here is small in scope, we believe that it illustrates a powerful and promising approach toward early engineering education.

The remainder of this paper is organized as follows. In the second section we briefly describe the domain of mechanical automata, and the approach we have taken to make it accessible to children; and we outline the Machine Shop application. In the third section we take a closer look at the design activities associated with Machine Shop how these activities reflect the practice of professional engineers, and how they embody important mathematics and science content as well. The fourth section presents a sketch of our pilot-test work with elementary-school children. Finally, in the fifth section, we conclude with some general observations and a look toward the future.

2. Mechanical Automata and Machine Shop

2.1 Automaton Design and Mechanical Engineering

The history of mechanical automata in the West can be traced back at least as far as the first century A.D. and the work of Hero of Alexandria . The ensuing centuries saw a continuation of this early work in the creation of clockwork and timekeeping figures; by the eighteenth century, mechanical automata and sculptures had become showpieces designed by brilliant artists. While interest in mechanical artwork has waned over the past century, there is currently a healthy (indeed, a revived) tradition of artistic mechanical devices. The artists at the Cabaret Mechanical Theatre are prominent modern-day practitioners of automaton design: Figure 1 shows two

representative samples of these artists' work. The contemporary style exemplified by the Cabaret artists combines engineering sophistication with elements of humor, whimsy, and fantasy.



Figure 1. Work by Cabaret Mechanical Theatre artists. *Barecats* by Paul Spooner (left) and *The Runners* by Peter Markey (right).

2.2 Automata and Children's Engineering

The virtues of contemporary automata suggest advantages for children's engineering as well. The components employed (cams, gears, levers) are central to undergraduate mechanical engineering curricula; a wealth of beautiful constructions may be created using simple combinations of these components; and automata can make these components, and their operation, visible for inspection. Perhaps most important, unlike many design activities, these objects have a strong aesthetic and expressive component. While automaton building is thus appropriate for children, it involves skills representative of engineering at all levels. In the course of building automata, one encounters notions such as the roles of forces and friction; the need to choose appropriate materials; the need to reason about components and their combination; the role of mathematics in

practical design; and the pleasures and frustrations of experimentation in solving a physically realized problem.

2.3 The Machine Shop System

The previous paragraphs argued that automaton building is in many ways a remarkably promising area for children's engineering. Nonetheless, it has one apparent critical disadvantage: the ability to fabricate mechanical components, repeatedly and with precise dimensions, is beyond the ability of most young children. Consider—to take one example—the task of creating a gear.

Traditionally, to make a working gear, a child would have to have a high degree of skill in working with wood, plastic, or metal; while paper is the typical medium of children's construction, it simply isn't sturdy enough to form the substance of a working gear. But if the child then decides to work in (say) wood, she finds that creating a gear requires exceptional precision: it isn't the sort of thing that an inexpert woodworker could reasonably attempt. It is hardly surprising, then, that few children never have the experience of fabricating a gear, or other machine elements: they haven't the skills. Professional automaton builders have spent years acquiring these skills; but children can hardly be expected to make the necessary pieces for even the simplest of automata. This is the essential role, then, of the Machine Shop system: it may be considered a Computer Aided Design and Manufacturing (CAD/CAM) software tool for the engineering of automata, and a means by which children can gain early experience in creative engineering and design.

The CAD component of Machine Shop provides software tools for designing, manipulating, storing, retrieving, and assembling the mechanical components for an automaton as well as facilities to help users explore some of the possible motions that they can produce. The CAM component currently employs a computer controlled carbon dioxide laser cutter, although any number of computer controlled machine tools (mills, lathes, routers, rapid prototyping systems, etc.) could also conceivably be

used. The laser cutter takes files created in the software—files that describe the physical characteristics of the component—and quickly and accurately fabricates the component from a number of materials that the user can choose.

2.3.1 CAD Software

Drawing on the practice of professional automaton makers, Machine Shop's design tools allow users to specify the motion or behavior that they wish their automata to have. The software converts this specification into a component whose parameters provide the desired motion. For example, the lift and duration of cam lobes is specified by manipulating graph points which describe how the cam's follower will move, as shown in Figure 2.

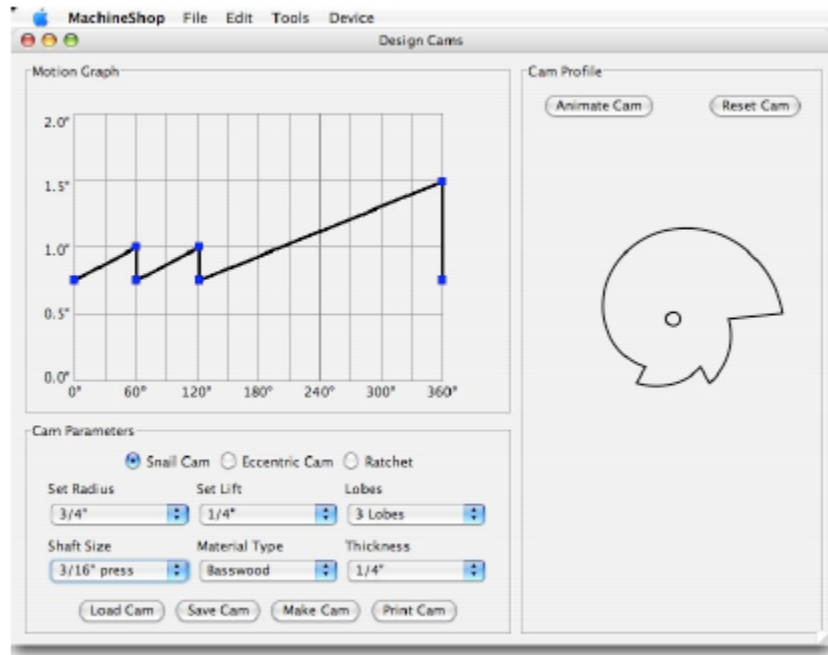


Figure 2. The cam design window in Machine Shop. The user has created a 3-lobed snail cam with two rapid, short rises in the cam follower motion followed by a longer and taller final rise.

This has proven to be a natural way to approach mechanism design since children already have a motion in mind when they come up with an automaton concept. The upper left pane in Figure 2 contains information about the cam's motion; this is where the user manipulates the graph by clicking and dragging key points to create the motion she desires. Once the user has dragged the various points to their desired position, the software generates a cam outline for that motion which is then presented at right. The lower left pane contains controls to choose which of the three basic types of cams (snail, eccentric, or ratchet) is desired; controls to set base cam parameters; controls to select options for the material the cam will be made from; and a variety of buttons to load and save cams to and from the library, print cam profiles, and create fabrication files for the selected CAM device. The right hand pane contains a representation of the current cam profile; this representation is regenerated whenever the user moves key points in the graph at upper left. Once the outline representation has been created, the user can animate it to watch its action.

A similar tool for the design of spur gear trains is shown in Figure 3. Here, the student selects from a variety of gear ratios, and chooses (among other parameters) whether she wishes to create a two- or three-gear train. Once more, Machine Shop animates the desired train in the right pane. Another editor (not shown) focuses on the design of levers of first, second, and third order. In addition to these design tools, the software contains browsable libraries of components and mechanisms that have been designed in the software. These components and mechanisms are stored in XML format making them both machine and human readable. Additionally, there is a movement exploration tool that allows users to specify an input motion and an output motion and then presents her with a list of motions that meet her criteria. She can choose any one from the list and is presented with a text description of the why and how of the motion as well as a QuickTime movie which shows the mechanism in action.

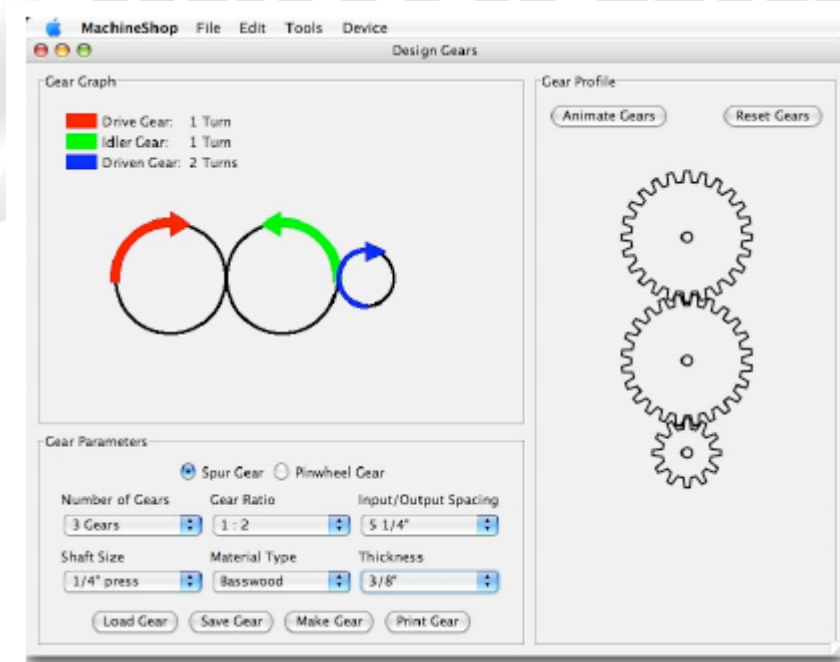


Figure 3. The gear editor presents the user with controls to set the parameters of the gear set (lower left), a symbolic representation of the direction, speed, and force delivered by each gear in the set (upper left), and the profiles of each gear in the current gear set (right). The gear profiles can be animated to simulate the motion of the finished gears.

Figure 4 shows an example: here, the user has asked to see an example of a mechanism in which circular input motion is converted to an oval output motion; one of the available examples presented is an eccentric cam with a ring follower. This tool, while not designed to be a tutor per se, does provide a quick reference for both novice and more experienced users.



Figure 4. The movement explorer window. The user is looking at an eccentric cam with a ring follower used as a crank-slider.

Finally, to help the user create a complete mechanism from individual components there is an assembly tool (still in development) where supporting frameworks will eventually be created and components placed to check their fit before final fabrication occurs.

2.3.2 CAM with a Laser Cutter

Designing the components is only part of the process of creating the finished products that will be assembled into an automaton. The second step takes the fabrication files created in the software and uses them to create the cams, gears, and levers the user will need. While many kinds of computer controlled machines tools could be used with Machine Shop, we are currently using a 30-watt, carbon dioxide laser cutter (figure 5). This machine has a number of advantages in this domain: it is compact, highly precise, fast in operation (components are printed in seconds), increasingly affordable (though not yet as cheap as we would like), compatible with commercially available drawing software, and capable of cutting and etching a wide variety of materials including wood, plastic, cardboard, paper, and fabric. In our experience, then, the laser cutter is an excellent alternative to traditional cutting tools like knives and saws in engineering education; it allows children to avoid the frustration that they would inevitably encounter in trying to fabricate automata using traditional methods.



Figure 5. The 30 watt carbon dioxide laser cutter in our lab. The laser cutter (left) shares a desk with the computer that controls it.

3. Basing an Engineering Curriculum on Automaton Design

A surprising number of books and videos are available describing the art of the automaton maker. The process is similar in most respects to the design and construction of any mechanical object. The following rubric reflects this tradition of professional practice, tailored to our own experience in mentoring children's projects:

1. An initial idea is conceived. For children, these ideas come most often from their experience and interests. Favorite activities and animals often find their way into automata.
2. A design is created. Children can have a difficult time separating this stage from the initial idea until they are asked to think not only about what the automaton will look and act like, but how those actions will be accomplished.
3. Prototypes are iteratively built and tested. Our users have initially seen this as a wasted step until they start to see their design coming to life in cardboard and paper. Having a physical object that they can view from any angle and quickly modify then becomes one of the longest stages in the process.

4. A final object is fabricated and assembled. This stage is another that children want to hurry through. In most cases they have not been taught careful assembly methods or the need to build subassemblies before final assembly.

It should be noted here that this is not an activity that our test subjects engage in alone. One member of our group with experience in these types of activities works individually with each test user. He acts as resource center and mentor to assist the users when they encounter new challenges. He also helps the users convert their ideas and sketches for the figures and decoration of the automata into files that the laser cutter can use. It should further be noted that this role could easily become one of peer

mentoring, as two of the six test users in our experiments are on the cusp of having sufficient experience and insight to provide this level of support to other users given continued support from the researchers as their skills increase.

During the course of this activity we also take care to make explicit the math and science that the children are using. Careful measurement and placement of components requires the ability to perform operations on both fractional and decimal numbers. Changing speed in gear trains or multiplying force with levers requires an understanding of ratios. Dwell values for cams require that users work with angular measurements in degrees. Gears, cams, and shafts all have radius values.

Understanding forces becomes important when a small input effort must cause a much greater output effort. Friction becomes important when choosing materials that will either slide or grip. Material strength determines how appropriate a given material is for its intended purpose. All of

these are important pieces of domain knowledge and understanding and as a user becomes familiar with them her engineering skills increase.

4. Work with Children and a Case Study

The previous sections have described both the Machine Shop software as well as a portrait of children's engineering that employs that software. In this section, we discuss our still-early experiences with children in building automata with Machine Shop. To date, we have conducted pilot tests with six children, both girls and boys, aged 10 and 11 years. These pilot tests have taken the form of individual meetings (generally of about one hour) on an approximately weekly basis, lasting for a period of from 4 to 9 months; this corresponds to the creation of one or two major automata. In this section we will focus primarily, though not exclusively, on our experience with one student as an illustration both of how children work with the software and of our own approach toward engineering education.

Dylan was aged 10 years and 6 months at the time he began designing automata. His previous experiences designing and constructing physical objects involved model rockets, construction toys such as Lego bricks, and the occasional creation of trains and cars from found materials. (This experience is at the high end of that found in our other test users.) Dylan was interviewed to assess his level of mechanical reasoning and his knowledge of mechanisms; these were consistent with his age and experience. During his initial meeting with the researchers he was shown example automata created in our lab that are similar to those found at Cabaret Mechanical Theatre. This was his first and only exposure to contemporary automata. He was asked to bring an idea for an automaton to the next session.

His first automaton was inspired by an event that occurred while he was camping with other students from his middle school; a group of his compatriots had come across a mountain lion (fortunately, with no ill results). Dylan felt he would have liked to have seen the lion and decided to create a “leaping lion” automaton. The specific requirements were

1. The lion would move forward in an arc moving up in the middle of the arc and down at the end.
2. The lion would not be allowed to leap backwards.
3. At the completion of each leap the lion’s mouth would open and would close again as the leap was repeated.

Each of these requirements was flagged as a mechanism specification and worked on in the above order.

The leaping behavior was inspired by one of the automata that Dylan had seen during the previous session, a winged bison that moved in an elliptical path as it “flew”. This

machine used an eccentric cam and ring follower, but Dylan was intent on finding a different mechanism that provided the same motion. Having observed some examples of simple mechanisms, Dylan finally chose to work on a prototype including both a ratchet (to satisfy requirement 2) and a disk with an offset pin acting as a crank (to satisfy requirement 1). He deferred the problem of opening and closing the lion’s mouth while prototyping the lion’s overall motion. Some time spent searching online finally produced an African lion profile that Dylan felt was close to what he had envisioned. This image was converted to a vector outline for cutting. While producing a prototype in cardboard, Dylan decided that the 3 inch long version he had originally decided upon was too small and the overall length of the lion was doubled to about 6

inches. A ratchet, pawl, and disc were designed in Machine Shop, cut from cardboard, and attached to a larger piece of cardboard to determine some of the basic mechanism parameters. It was at this time that Dylan had an insight.

Instead of having a disc and a ratchet, he asked if the offset crank pin could be applied directly to the ratchet to eliminate the disc. This change was incorporated into all subsequent versions and the mechanism for moving the lion came together quickly. The issue remained of how to make the jaw move. The eventual solution—using a free floating rod with stops above and below the framework to open and close the jaw at the extreme points in the lion’s movement—was a suggestion made by the researcher, emerging from brainstorming discussions taking place over several weeks. The researcher and Dylan made a cardboard mock-up as a proof of concept and, when satisfied, proceeded to cut all of the necessary pieces from wood. Time was then spent dry fitting the pieces and making assembly sketches and alignment marks before carefully gluing together subassemblies, cutting shafts and rods, drilling holes to the proper size, and final assembly. The finished automaton was left to dry for a week, tightly trussed in rubber bands and clothespins. After Dylan had finished painting and decorating the lion he was asked to describe what he had done and how his automaton worked.



Figure 6. Dylan's finished lion (left) and a view showing the jaw mechanism (right). The body and mechanical elements are laser cut from basswood. The grass is laser cut craft foam and the tail is a ballpoint pen spring with kite string. The lion on the right is a duplicate of the original and has one side cut from clear acrylic to show the internal mechanism.

In the course of his work, Dylan clearly exhibited a growth in familiarity with the components in the lion's mechanism. Where he had used terms like "thing" only weeks before he now correctly used the proper names for the components. He was quite comfortable describing the purpose of each component and how they worked together to create the finished motion. He was able to explain the dependencies in the mechanism. He showed no reluctance to make sketches to support his explanations where before he would only sketch when specifically asked. To see how much transfer there might be in this new knowledge, the researcher showed him a poster of an automaton much more complicated than any he had previously seen and asked him to explain how it worked. His explanation was thoughtful and in most aspects correct. He also showed an increased appreciation for the process that he had followed and was very anxious to make another automaton.

Dylan's lion automaton is a delightful piece of engineering, but not unique in that respect among the constructions of our students. Figure 7 shows several other original automata created by our pilot Machine Shop subjects. These examples display a variety of levers, cranks, and cams in their construction; all reflect the advantages of precise design and construction made possible by the combination of design software and a laser cutter for fabrication.



Figure 7. A sampling of other student projects from our pilot work with MachineShop. A dragon (left), an evil juggling cat (center), and a trio of commuters (right).

5. Ongoing and Future Work

In our view, Machine Shop represents an approach toward educational computing which runs counter to the exclusively “virtual” emphasis of many efforts in the field. Children who use Machine Shop are working with both “bits” (when working at the screen) and “atoms” (when working with materials); and each of these distinct aspects of the engineering task complements the other. Interestingly, the students who have worked with Machine Shop have also—unanimously and without encouragement from their adult mentors—elected to keep their constructions after completion. This suggests an interesting theme highlighted by a style of educational technology that produces tangible results: namely, that students appear to have a positive affective relationship to the results of their work. While purely virtual artefacts simulations or programs—rarely attain the status of souvenirs, physical artefacts (such as automata) easily take on such a role.

On the pedagogical side, our experience with the Machine Shop system has convinced us that the best approach to teaching engineering to children cannot consist solely of software development and dissemination. Rather, our approach combines the use of novel software tools with a longer-term process of mutual discussion and brainstorming between an adult (or student) mentor and student engineer. Rather, then, than view software as a replacement for adult tutoring, we see a tool such as Machine Shop as a necessary but far-from-sufficient adjunct to something approaching an informal apprenticeship. As to the software itself, it remains a work-in-progress: among other additions, we plan extensions to allow the design and creation of additional types of components. We also intend to use the software to create a series of historical mechanisms in the style of such revered engineers as Leonardo da Vinci. Going beyond these immediate goals, this work suggests that still other engineering disciplines—electrical engineering and architectural design, most prominently—could likewise be transformed into expressive domains for children given the right support materials and curricular design.

IGNITED MINDS
Journals

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