FoldMecha: Exploratory Design and Engineering of Mechanical Papercraft

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ABSTRACT
We present *FoldMecha*, a computer-aided design (CAD) system for exploratory construction of mechanical papercraft. FoldMecha enables students to (a) design their own movements with simple mechanisms by modifying parameters and (b) build physical prototypes. This paper describes the system, as well as associated prototyping methods that make the construction process easier and more adaptable to widely different creations. The paper also discusses a week-long workshop that we held with six teenagers using FoldMecha. The teens successfully designed and built their own mechanisms, and adapted them to a variety of creations. Throughout the workshop, they progressively achieved an advanced level of skill and understanding about mechanical movements.

Author Keywords
Computer-aided design (CAD); tangible learning; learning by making; exploratory construction

ACM Classification Keywords
H.5.2 [Information interfaces and presentation]: User Interfaces – Input devices and Strategies, Interaction styles; K.3.1 [Computers and Education]: Computers Uses in Education

INTRODUCTION
What distinguishes tangible interaction from screen-based interaction is physical embodiment. Many instances of tangible interaction employ sensors and actuators embedded into pre-existing physical objects or environments, and therefore require little expertise in physical design and construction. In many others, on the other hand, the design and construction of the physical embodiment is essential to the interaction.

Conventional CAD tools are well-suited to designing physical embodiments of simple and static objects–e.g., embedding electronics into an object of furniture. However, when the device itself has mechanical behavior, conventional tools challenge even experienced designers. Despite the reduced burdens of calculation, modeling, and hand skills that current CAD tools provide, designing and building mechanical models still remains demanding. It requires understanding mechanical movements, visualizing relationships between component mechanisms, and accurately predicting the behavior of these mechanical systems.

We developed *FoldMecha*, an experimental software system to design movements for mechanical papercrafts. Exploratory construction is a springboard for creative learning [16], and the FoldMecha tool is intended to support this type of playful construction. Using FoldMecha, beginners can (a) design movements by modifying individual components; (b) download parts to cut, (c) build mechanical prototypes using the assembly instructions, and (d) apply those prototypes in their own creations. Our mechanisms are implemented in paper because paper is lightweight, malleable, aesthetically appealing, and inexpensive, and it can be worked with simple craft tools. In developing FoldMecha and associated fabrication methods, we considered accessibility (whether students can use FoldMecha and the methods) and adaptability (whether the tool and methods are sufficiently open to support novel and original designs).

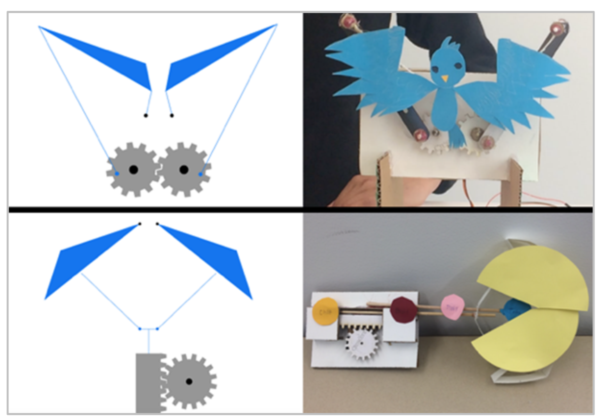

Figure 1. FoldMecha supports users to design mechanical movements by changing parameters, construct the physical models using the parts and folding nets the system generates, and adapt the movements to implement their creative ideas.

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In the remainder of this paper, we first describe design and fabrication using FoldMecha, and the philosophy behind its development. We then describe a mechanical papercraft workshop with six middle school girls in which we evaluated the accessibility and adaptability of the system and prototyping methods. We conclude with findings from the workshop and reflect on how the tool and methods support our design goal.

RELATED WORK

In developing FoldMecha we draw on three areas of related work: computer-aided design for crafting, construction kits, and learning by making. We describe prominent work in these fields that influenced the design of FoldMecha.

Computer-aided design for crafting

Working with physical materials—learning "through one's hands"—need not be opposed to computation [4]. In the area of mechanical crafting, researchers have built computational tools to both elicit and support a designer's intent by simulating a (presumed) target construction on the screen, and by producing materials for the physical, hands-on phase of construction. A widely used approach is automatic (computer-driven) configuration of mechanical designs. For instance, to synthesize motions into mechanical toys, Zhu *et al*. [23] enabled users to simulate mechanical toys. The user specifies geometry and motion of the toy, then the system selects an appropriate configuration of assemblies from its library to optimize part parameters. In a similar vein, Megaro *et al*. [9] and Coros *et al*. [3, 20] helped users to create a design by drawing the desired movement as a 2D curve on the computer screen. Other software like AutoGami also supports users in selecting movement types to apply to movable papercraft design. The system then actuates the papercraft using shape memory alloy wire and selective inductive power transmission [22]. In these automatic-configuration systems, users *specify* desired behaviors, and the system *generates* a mechanism to produce that behavior; the designer need not be concerned with how the behavior is produced. In contrast, in developing FoldMecha, we aimed to support open-ended creative work, where novice users explore and understand the relations of various local components that generate a mechanical movement, and then incrementally specify their design. In this sense, our system is a bottom-up system that does not automate synthesis but assists the experimental design and learning process. FoldMecha can be seen as an application (in the mechanical realm) of the ideas of Schulz *et al*. [19], whose system enabled users to select a 3D model from an expert-authored database and customize it by modifying parameters. Although FoldMecha similarly supports beginners by providing a set of parameterized templates, we focus on mechanical craft applying certain movements. Whereas previous work simulated static objects, in FoldMecha interactive simulations animate how the movement changes by varying local components.

Construction kits

Diverse construction kits enable designers to experiment with or—as Schön poetically puts it—to engage in a "reflective conversation with the materials of a design situation" [18]. For instance, fischertechnik [5], Capsela [2], MOSS [10], and Tinkerbots [21] afford direct manipulation of the components of a mechanical assembly. A designer can configure components of a mechanism and investigate the behavior of the ensemble. When the parameters of the kit components match the designer's goals, construction kits are an effective way to work. Yet the very features of a construction kit that make it a fast and easy way to explore a design space also make it suboptimal for some tasks. Components are of specific sizes and functions; they assemble only on a modular grid and the kit is a closed system. In this sense, making mechanical movements with a construction kit is a devil's bargain: designers can quickly build complex configurations as long as they stay within the system, but they cannot customize the kit of parts. FoldMecha addresses this issue by supporting users at a more fundamental level. In FoldMecha, users design their own mechanical behavior and generate parts to build and customize it using craft tools and materials.

Learning by making

The iterative process of design and engineering–in short, making–enables one to imagine, play, create, tinker, share, reflect, and learn relevant concepts. Ratto [15] described "critical making" as a theoretical and pragmatic method to connect critical thinking and physical making. He stated the importance of bridging bodily experience with abstract knowledge—wrestling with technical prototypes and exploring various configurations and alternatives. Keune *et al*. [7] also highlighted how material artifacts promote learning. They described the flexibility of artifacts, which is linked to pliability, accessibility, and mobility and is important to support boundary crossing. Similarly, Resnick and Rosenbaum [17] presented design guidelines for tinkerable kits: immediate feedback, fluid experimentation, and open exploration. They described tinkering as a playful style of designing and making things (regardless whether physical or virtual) to learn to improvise, adapt, and iterate. Inspired by these frameworks, and to enable open-ended exploration, we developed the FoldMecha software, in which users design mechanical movements by changing parameters in order to imagine and build various physical creations. We believe that this process can provide opportunities to understand the basics of mechanical movement, but also support creative learning.

FOLDMECHA DESIGN AND FABRICATION PIPELINE

FoldMecha is a bottom-up computational system to support interactive exploratory design and engineering for moveable mechanical paper crafts. Figures 2 and 3 summarize the FoldMecha workflow.

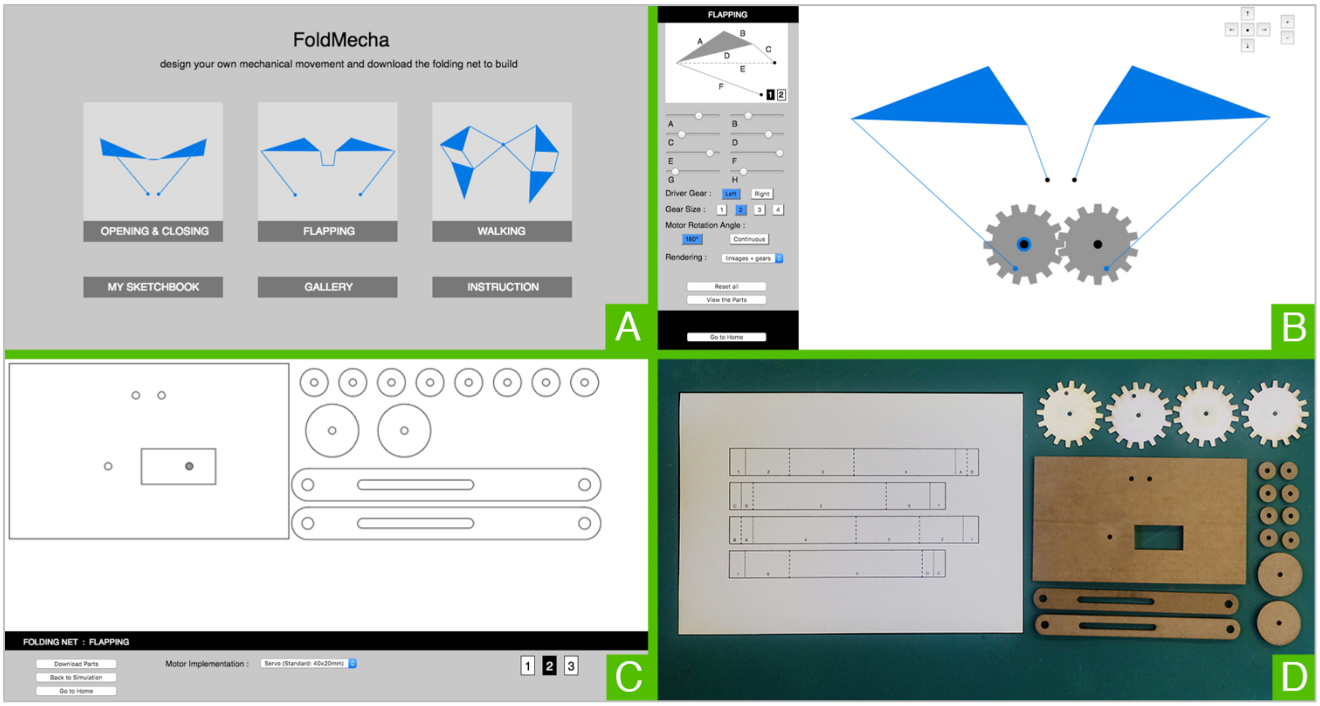

Figure 2. User workflow in flapping movement: (A) The splash page catalogs individual movements; (B) Simulation interacting with local parameters; (C) System-generated parts (D); Cut and printed parts and folding net for physical construction.

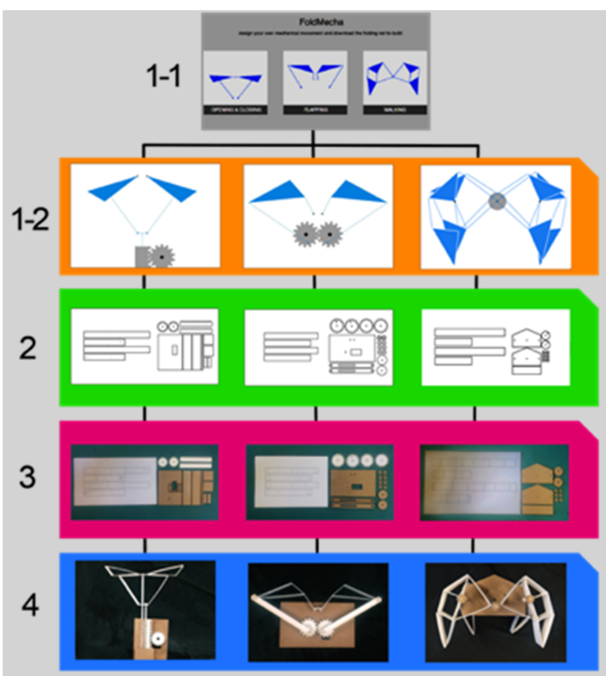

Figure 3. Steps in making a paper machine: (1-1) select a movement; (1-2) change parameters; (2) customize parts; (3) print and cut the files; (4) build working prototypes.

1. Parameterized individual movements

FoldMecha's splash page (figure 2-A) shows an animated catalog of three individual movements: opening-closing, flapping, and walking. Choosing one brings a user to that movement's design page, which shows a parameterized simulation, with options and parameters on the left panel (figure 2-B). The opening-closing movement is made with linkages connected to a rack and pinion mechanism, a pair of gears that convert rotation into linear motion. The flapping movement is made with linkages connected to two identical interlocking gears that turn in opposite directions. The walking movement is a variant on Theo Jansen's 'Strandbeest' mechanism [6]: a strut configuration comprising two triangles and two quadrilaterals.

Users can explore a variety of designs for arms (opening and closing), wings (flapping), or legs (walking) using sliders to vary geometric parameters of the linkages. In the walking movement, users can add pairs of legs, which the Jansen mechanism uses to generate a crab-like motion. In specifying each movement, users select a gear size from 1 to 4 by pressing buttons. Larger gears generate more dynamic movement. The user can also add a motor to drive the mechanism, leading to further options. For instance, in the opening and closing movement, the user must select the motor type (continuous or alternating 180° rotation), which adjusts the gear design (see Figure 4). The continuous rotation version has teeth removed from the pinion gear, allowing the rack to drop suddenly on each full turn when the untoothed section of the gear comes around. In the flapping movement, which includes two gears, users must specify which gear drives and which is driven; this determines a location to embed a motor in the following step. In all movements, users can also set rendering parameters (whether to display both gears and linkages, only gears, or only linkages).

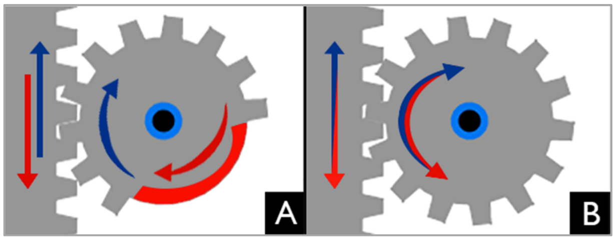

Figure 4. Motor type affects gear design. Depending on the motor, FoldMecha changes the simulation and parts: (A) continuous rotation (B) 180° alternating rotation of gears.

2. Customize the parts and folding net

After selecting and parameterizing, users view the parts and folding net by pressing "View the Parts" (see Figure 2-C). Here, users specify conditions for construction and modify the parts and folding net, deciding about motor implementation, motor size, and thickness of linkages (arms, wings, or legs). Specifying the opening and closing movement entails setting the number of linkages, which modifies the bottom part of the arms. For instance, choosing three linkages makes the bottom figure an equilateral triangle; choosing five produces a regular pentagon.

In order to simplify construction, we produce paper folding net templates. Once the design is done, FoldMecha generates a drawing of folding net strips with marked folding locations. Then users print, cut, and fold the strips following instructions to build the basic linkage modules [11, 12]. Figure 5 shows the folding instructions to form paper strips into an arm, a wing, and a leg.

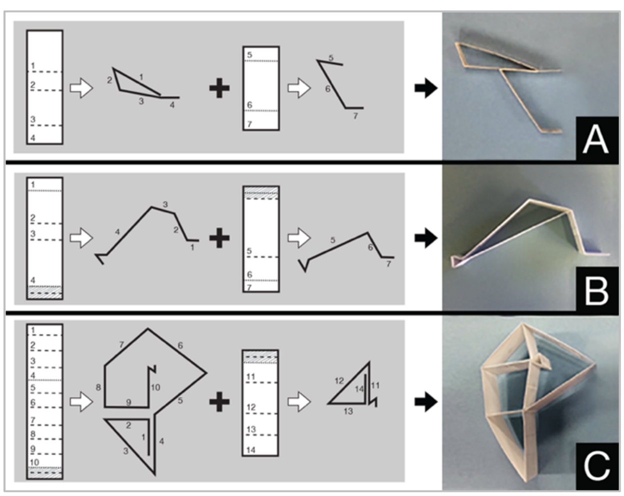

Figure 5. Dashed and dotted lines indicate mountain and valley folds respectively. Folding generates moving joints and unfolded faces become linkages: (A) an arm for opening and closing, (B) a wing for flapping, and (C) a leg for walking.

3. Print and cut PDF files

Once all parts have been specified, the user requests PDF files by pressing "Download Parts". The system generates three separate files: gears for 'high resolution' rigid material such as mat board that can be accurately cut; parts and stands for any rigid material such as cardboard; and stick figures of the folding net to create linkages using foldable paper. After creating the PDF files, the user can cut parts using a laser cutter or a hobbyist paper cutter such as the Silhouette Cameo. For the latter, hand skills are needed to attach layers of gears carefully as these machines do not cut rigid paper or cardboard (see Figure 2-D).

4. Assemble the parts to build working prototypes

The critical part of building mechanical crafts lies in setting moving and fixed joints. To assemble parts and folding nets generated in FoldMecha, the user employs simple craft tools and materials such as lollipop sticks (or wood dowels). The assembly instruction provided as part of the accompanying learning materials explains how to adjust lollipop sticks in multiple places to connect the various parts and the stand. For instance, the assembly instruction for the flapping movement suggests applying lollipop sticks to stand to connect linkages and other parts to connect with gears and linkages, and to attach gears to the stand (see Figure 6). Also, the assembly instruction suggests attaching two layers of gear parts to strengthen the gear teeth. Especially in building gears for flapping and walking movements, this sandwich structure helps to add a space to attach lollipop sticks to gears. Even with these instructions, students still found opportunities to play and tinker with their papercrafts and make adaptations and refinements to their originally conceived idea.

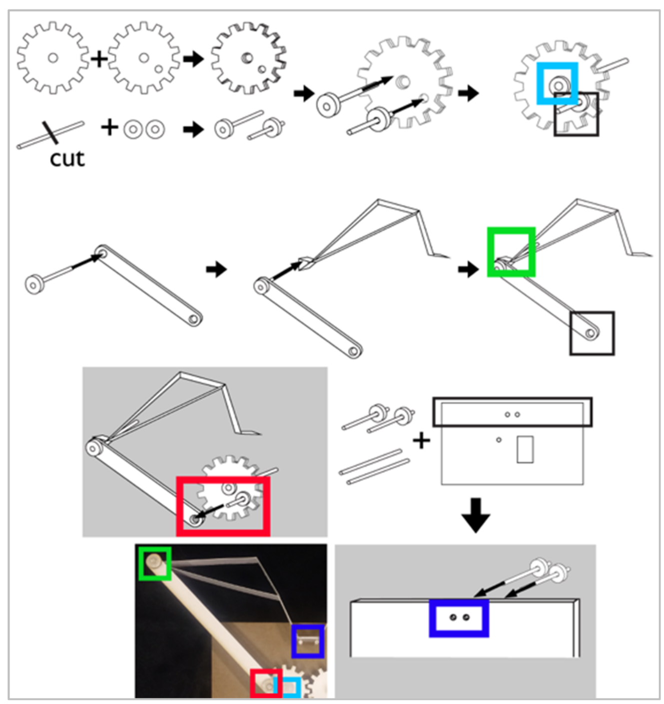

Figure 6. Craft-friendly materials enhance accessibility and adaptability. Lollipop sticks connect gears and linkages.

Design rationale

Our goal is to develop a design tool and methods to support exploratory construction of mechanical papercraft for beginners. To this end, our design decisions respond to two questions of accessibility and adaptability:

1) *Accessibility*: Can students use FoldMecha to construct mechanical papercraft?
2) *Adaptability*: Can they use FoldMecha to be inventive and go beyond examples they are given?

FoldMecha to see the big picture of movements

We wanted users to explore and understand relationships between component mechanisms and their impact on the whole movement. Therefore interactive simulation is a key strategy to engage and support the users. In addition, by providing parts and folding nets for construction, FoldMecha reduces the burdens of calculating and modeling. We also considered generality (abstractness) of movement modules to be applied to widely different ideas.

Prototyping methods to ease and diversify constructions

We tried to simplify the construction process to reduce any barriers to hands-on prototyping, for example, printing paper strips with marked folding lines to generate linkages. We also considered easy manipulation by craft tools and materials. This availability of the craft materials is essential to support iterative construction and encourage active integration with individual and personal creations.

MECHANICAL PAPERCRAFT WORKSHOP

We conducted three workshop sessions with six middle school girls to evaluate the accessibility and adaptability of FoldMecha and associated prototyping methods. We recruited students (ages 11-14) from a university based summer camp program. None had relevant previous experience in mechanical design. In prior workshops, a “rhythm board” was provided to control the speed of servos and solenoids without the need for prior knowledge of electronics or programming [13]. In this workshop basic Arduino coding was introduced and included in the workshop lessons.

Workshop structure

Our workshop met on five consecutive days in 4-5 hour sessions. On the first day we showed examples of mechanical papercraft to introduce the week-long curriculum and engaged students in a warm-up exercise learning to control a 180-degree range servo motor using a microcontroller and to change the speed and the rotation range by modifying example code in Arduino [1]. Then on each of the following two days, we introduced a specific movement theme: open-close movement using a rack and pinion mechanism—a pair of gears that convert rotational motion (by a pinion gear) to linear motion (by a rack gear), and flapping movement using two identical interlocking rotational gears. Then for the last two days, students designed their own machines, combining movements they learned. We included only 180-degree-range servomotors. After each session we asked students to reflect on what they learned, how their creations work, their inspirations in applying each movement to their own creations, and challenges they faced.

We divided the studio into several stations: A design station with laptop computers to design parts in FoldMecha and program microcontrollers in Arduino to control servomotors, a glue-gun station, and a cutting-station. A shared material table provided various craft materials (color papers and pens, tapes, wood dowels, glittery glues, et cetera). We also provided a wireless ink-jet printer, a white board and a projector connected to the instructor’s desktop computer.

During the workshop, participants used individual laptops, with FoldMecha and Arduino installed. After finishing the design of their movements, participants transferred files to the instructor’s computer, which we printed on A3 paper. Each file showed the file names and the selected gear size; we provided the selected gears (which we had precut). Then participants attached their case and parts to cardboard, and cut their parts by hand; they also cut and folded the printed linkage paper files. We provided printed instructions to assemble each movement (both open-close and flapping) as well as video instruction only for flapping movement.

Results

First session: building an open-close movement

During the first (open-close movement) session every participant used FoldMecha to design a movement. Five students among six built working mechanical papercrafts and four applied the movement to make wings, mouth or leaves; two students struggled to imagine and find an application for the open-close movement.

Second session: building a flapping movement

Likewise, in the second session, all participants started by designing movements in FoldMecha. Students took more time in design than in the first session as they started thinking about what to build (how to apply the movement). Some students started by selecting a gear size and modifying linkage proportions to reflect a specific machine they planned to build. Every participant built a working mechanical papercraft.

In the workflow of the second session, participants were more confident and fluent in using FoldMecha and craft tools (box-cutters, glue-guns, etc.). Also, in the second session we provided video instruction along with the printed instructions (building a flapping movement) and minimized individual explanations. The video instruction was more helpful, as students watched it at their own pace.

Third session: inventing your own machine

For the last two days, students invented, designed and built their own machines by combining mechanical components. Figure 8 shows what students built. Machines A and B are complete and machines C, D, E, and F are works-in-progress. In (A) a fish swims in the sea: as the motor-driven pinion gear turns, the rack gear produces linear motion that makes the fish’s fins connected to linkages move back and forth. In (B) a Tyrannosaurus-rex opens and closes its mouth as its baby jumps up and down: the rack produces

Figure 7. Participants applied movements to working mechanical papercraft: (A) open-close, and (B) flapping.

linear motion, using linkages to open and close the T-rex's mouth while the baby T-rex attached to the other side of the rack jumps. Machine (C) is a pterodactyl, animated by a rack gear connected with two pinion gears and two additional gears one for each side. (The student planned to add a pair of wings to the two bottom rotational gears and attach the head of the pterodactyl to the rack). Machine (D) is a big bird: the student planned to add a pair of wings to the flapping movement and attach the rack and pinion at the front to combine up and down motion with flapping. (E) is a woman waving her arms: two identical gears interlock with arms attached to the linkages. (The student planned to attach the body to the center). In the Dancing Ballerina (F): the motor-embedded pinion gear produces linear motion on the right side rack while another pinion gear rotates in the opposite direction, triggering another linear motion on the left side. (The student planned to attach the body of the ballerina on the center with arms on each rack moving up and down.) Throughout the two days, students were deeply engaged in the design process and presented presented their ideas confidently. In the reflection interviews, those who didn't complete their constructions emphasized that the they were presenting work in progress and explained the rest of their ambitious plans.

WORKSHOP FINDINGS

Open-close is a better designed module than flapping

FoldMecha aims to support beginners to design and build their own constructions by adapting and applying mechanical movements. Therefore, the range of outcomes was the criterion to gauge adaptability, whether each movement module was sufficiently flexible to diverse designs. By this criterion, the open-close movement is a better module than the flapping movement. Students interpreted the open-close movement in more ways than the flapping movement (see Figure 7). Five students applied the flapping motion as wings and made a kind of bird (bat, gull, owl, etc.) whereas students interpreted the open-close movement into more dynamically different ways such as a Pac-man mouth, angel wings or a bluebird. That is, abstractness of a movement was linked to creative interpretations.

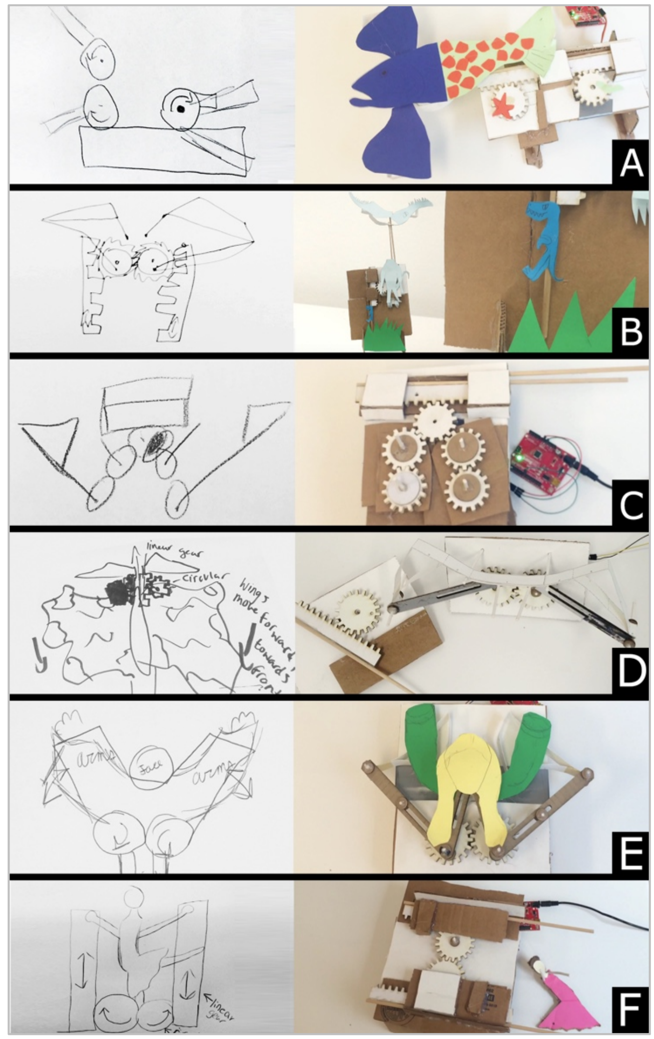

Figure 8. The third session combined multiple mechanical components to create their own mechanical inventions: idea sketches (left) and the workshop outcomes (right).

Craft materials enhance accessibility and adaptability

The material properties of mat board (used for gears) and cardboard enabled students to experiment as they built their own mechanical movements; this was important especially in the third session. Students cut and glued mat board and cardboard, modifying the parts in order to build the movement, which was more complicated than the first two movements and lacked assembly instructions. For instance, one student, an 11-year-old girl, realized that the given rack gear was too short to interlock two rotational gears (see Figure 8-A), and attached two rack gears next to a long wood dowel and cut it to the length she needed. Also students who employed two rack gears (Figure 8-B, 8-F) needed to customize the case to add a track to keep a rack gear in position to interlock with a pinion gear. Both students successfully built the movement by attaching extra cardboard to match the height of gears.

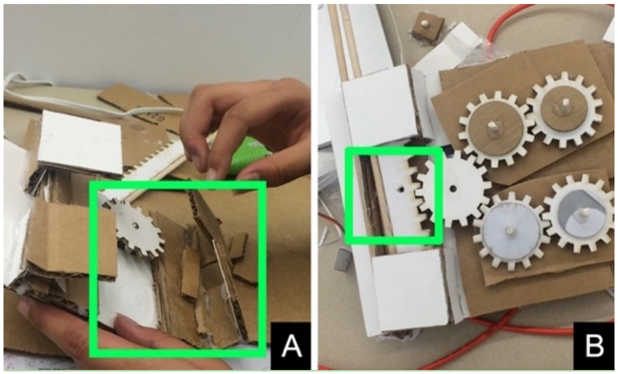

Figure 9. Craft materials encouraged tinkering to build mechanical movements: (A) adding a track by attaching small cardboard pieces to interlock two rack gears with the center pinion gear, and (B) adding another hole to set a wood dowel.

Expressivity of craft materials increases adaptability

Our FoldMecha workshop on building mechanical papercraft aimed to integrate mechanical design with rich crafting expression. Student integrated mechanical movements with drawing (Figures 10-A, E, F), decorating (Figure 10-B), outlining with glittery glue (Figure 10-C), and attaching to other objects made of tape with beads (Figure 10-D) or wood dowels (Figure 10-F). As their expressive explorations were closely linked to the tools and materials available in the studio, we expect that providing more tools and materials would have increased the spectrum of expressivity of the outcomes. Also, the one-week workshop format could limit student opportunities to mix, combine, and adapt multiple movements to create even more expressive forms and thus we plan to explore longer periods of design exploration.

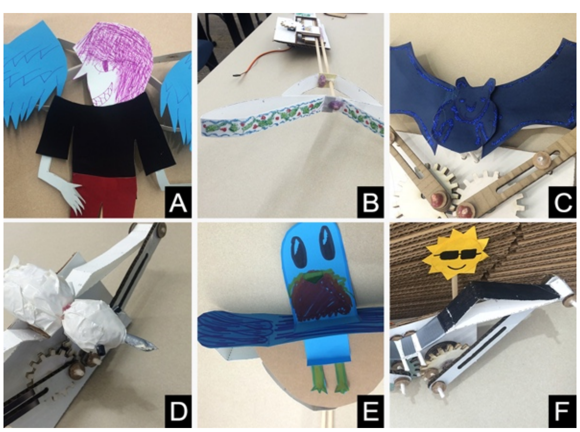

Figure 10. Craft materials invite expressions such as drawing, coloring, cutting, and attaching additional objects.

Digital tool for a big picture of mechanical movement and physical prototyping to strengthen understanding

Different media supported learning in its own affordances. As author Malcolm McCullough [8] writes, "Whereas hands feel their way one piece at a time, eyes see wholes, and compare many objects simultaneously" (p. 31). Design with interactive simulation in FoldMecha initiated understanding mechanical movements by modifying local parameters that impact the whole movement. Physical prototyping specified and strengthened this understanding. Using FoldMecha, students observed how varying gear sizes or linkage lengths affects the movement and this influenced their design decisions. Specifically, during the second (flapping movement) session, a 13-year-old girl who decided to build a bat selected size 4 gears and designed a long linkage. She said that she made design decisions "to make the bat fly more dynamically" like the bats that she saw on her family vacation. At the same time, some students did not quite understand the relation between pulling and pushing in the physical world: A common mistake on the first day was to attach the rack to the case, and then wonder how to make it move. As students built physical movements by hands-on prototyping, they returned to the FoldMecha application and compared their prototypes to the simulation. One 12-year-old girl who built a Pac-man figure using the open-close movement on the first day reflected, "I might have needed to select a bigger gear to be able to entirely close the mouth of the Pac-man."

Gradual shift from beginning to advanced level

The weeklong workshop enabled students to gradually attain an advanced level of skill. They not only started describing the movements, which they planned to build in more detail by confidently taking specific poses and gestures; they also illustrated how to implement these movements mechanically. Reflecting on the third session, one student described her project by distinguishing forward from vertical flapping and illustrated how she planned to connect the linear movement by a rack and pinion to the flapping movement to create a bird-like flying forward and up-and-down movement (See Figure 11-A). Another girl, a dancer, presented a machine to make a ballerina jump and take a stretching arm pose (Figure 11-B). Another made rotational hand-gestures to describe how she made the arms of her construction wave, and talked about how she wants to add more gears to connect the legs (Figure 11-C).

Overall, this progress influenced students to spend more time planning and to stick with their initial ideas. In the first two sessions, rather than change their mechanical design structure to build what they planned, they instead changed their ideas to use the mechanism they had chosen. However, in the third session they designed the completed movement more quickly and avoided drastic modifications to the basic movement structure.

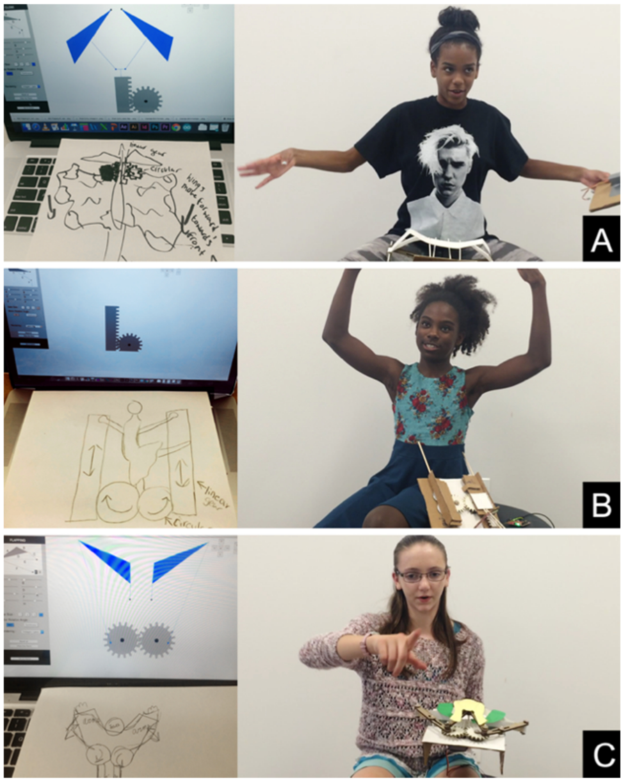

Figure 11. In the final session students presented project ideas more accurately by taking specific poses and gestures to describe the machines they designed.

CONCLUSION

FoldMecha is a computer-aided design system that supports exploratory construction of mechanical papercraft. It enables beginners to design their own movements by varying component parameters and build physical prototypes using the system-generated parts and folding nets. We developed simple folding nets to build linkages and employed craft materials for the parts to make the prototyping process easy to follow and tinker. This accessibility also increased adaptability to be integrated with various expressive creations. We conducted a week-long workshop with six middle school students to test the accessibility and adaptability of the FoldMecha design tool and its prototyping methods. Students were highly engaged in the design process and successfully designed and built their own mechanical papercrafts and actively adapt to a variety of creations. They also showed gradual progression on their understanding about mechanical movements.

We believe that consciously designed tools and methods can widen the gate of exploratory construction that ultimately promotes "powerful ideas" (in Papert's [14] famous phrase) for young learners. This paper presents our progress in developing FoldMecha and associated prototyping methods, to address how to lower the burdens of design and engineering for novices (accessibility) and how to extend the diversity of creations (adaptability).

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