Paper Mechatronics: Present and Future

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ABSTRACT
Creative iterative development over the past several years has generated an extensive set of computational tools, learning resources, and materials in the realm of paper mechatronics – an educational craft and design approach that weaves computational and mechanical elements into established traditions of children's construction with paper. Here, we both reflect upon our past and recent work of paper mechatronics, then look to the near- to medium-term future to speculate upon both the emerging trends in technology design and expanding learning potential of this medium for children along material, spatial, and temporal dimensions. We summarize lessons learned through various children's workshops with our materials; and we use these lessons as a foundation upon which to create a wide variety of novel tools and activities in educational papercrafting. We speculate upon the frontiers of this work based on current convergences and shifts in tangible creative computational media.

Author Keywords
Paper mechatronics; craft technology; educational papercrafts

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INTRODUCTION
Paper Mechatronics is a term that we use to denote the integration of mechanical, computational, electronic, and artistic techniques within children's papercrafts, all in the service of promoting creative design and engineering education. We aim to provide an extensible kit that incorporates both "high" and "low" technological elements, along with learning resources that can meet the needs of novice designers and appeal to the interests and abilities of a wide range of users.

Briefly, this newly emerging genre of paper mechatronics results from the blending of familiar craft materials with embedded sensors and computational elements, digital fabrication devices (e.g., desktop paper cutters, laser cutters) and similar emerging technologies to create imaginative objects that can be animated with light, motion, sounds, sensors, and cameras using Arduinos and similar microcontrollers. Although this high/low mixing—and the everyday nature of its core materials—may at first glance seem simplistic, it is actually far more than merely arbitrary. Rather, the design supplies a carefully selected mix, marrying an inherent approachability and flexibility with graduated pathways into experiential and technological depth. The familiar craft materials provide intuitive starting points for young learners and novice designers; these materials can then be progressively augmented and enriched with a variety of "smart" computational and electronic elements. The process of developing projects within this medium, scaffolded by powerful but low-threshold design software, provides accessible entry points into engaging, personalized projects that place learners at the center of an engineering design process that deepens subtly over time while remaining tractable throughout. The materials of paper mechatronics are extremely low-cost; and the projects employing these materials can appeal to diverse learners and genders with an extraordinarily wide variety of interests and backgrounds.

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RELATED WORK
For well over a century, papercrafts have been a staple of children's constructive work. In the early 1800's, Friedrich Froebel included paper folding and cutting activities in his development of the kindergarten system [4]; and even before Froebel, in the late 1700's, some children's books had begun to include flaps or cut-out pieces [8]. In the last half century this genre of work has blossomed in a variety of directions and educational domains [2, 6, 16, 19]

More recently, traditional paper crafts have been augmented and integrated with computational, digital, and novel material technologies. A survey paper [12] presents a thorough introduction to a variety of paper-based sensors and electronic elements: foldable transistors, paper-based energy storage (making use of embedded conductive carbon nanotubes), paper-based strain sensors (in some cases making use of the piezoresistivity of light conductive material deposited on the surface), paper surfaces that can deform under the influence of an electric field, and so forth. (It should also be noted that the review paper itself–like material science research more generally– ignores scenarios that involve children.)

The technological enhancement of educational papercrafting can be seen as an instance of a larger historical pattern: namely, enriching children's experience by blending traditional craft activities with novel materials and technologies. The pattern is perhaps most striking in the realm of textiles: for instance, children can now use conductive threads in conjunction with the LilyPad Arduino device [5] to create programmable clothing and accessories. Likewise, the traditional realm of children's construction with clay has been augmented with inexpensive "conductive dough" that can be incorporated into electronic projects. [9] Paper mechatronics is thus consistent with a broader movement of designing tools and materials that extend the creative and educational range of children's work.

This paper is intended both as a discussion of the *present* state of paper mechatronics–a reflection on the development and workshop assessments that we have completed thus far–and as an exploration of plausible near-future directions for children's papercrafts. The following section focuses on the current "state of the art" in paper mechatronics. The concluding section describes our notions of leaning and "adaptive expertise"–ideas that motivate the educational goals of paper mechatronics–and how those notions might be realized in the future development of paper mechatronics.

PAPER MECHATRONICS: PRESENT

Over the past four years, our goal has been to develop the foundations–both computational tools and supporting materials–to enable children to do creative, artistic engineering in the medium of paper. In this section we summarize this work.

Website and Computational Tools

The "home base" for our work is a website of learning resources (http://www.papermech.net). This includes a computational design simulator and tutorials of prototyping techniques, along with documentation of diverse creations made by workshop participants (see Figure 1). The website contains three sections, which support each stage of building paper mechatronics: (1) design, (2) learn, and (3) explore. First, the 'design' section provides an interactive design simulator. Users can select one of twelve different mechanical movements, design their own movement by modifying local parameters (see Figure 2), and download files to cut the parts and folding nets. Then in the 'learn' section, users can watch video tutorials to assemble the parts to build the physical model, which they designed (see Figure 3). Then for the final stage of adapting the movement model into their creative ideas, they can use the 'explore' section to see the projects that others have developed and shared.

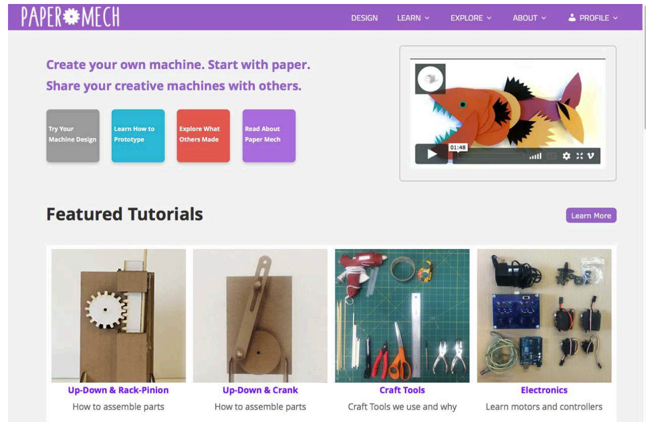

Figure 1. Our website provides a design simulator, prototyping tutorials, and a gallery to display users' creations.

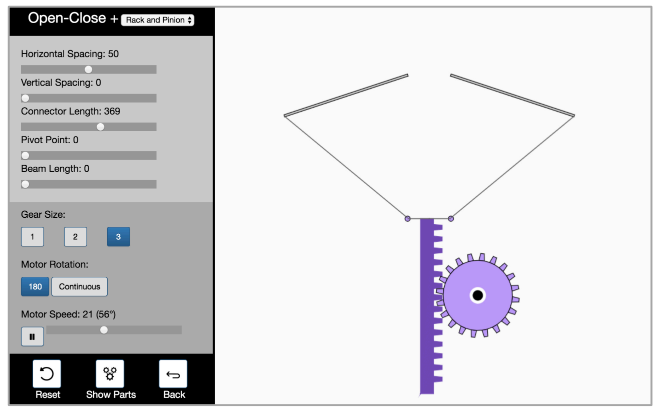

Figure 2. In the 'Design' section, users can choose a movement type and develop their design by changing local parameters.

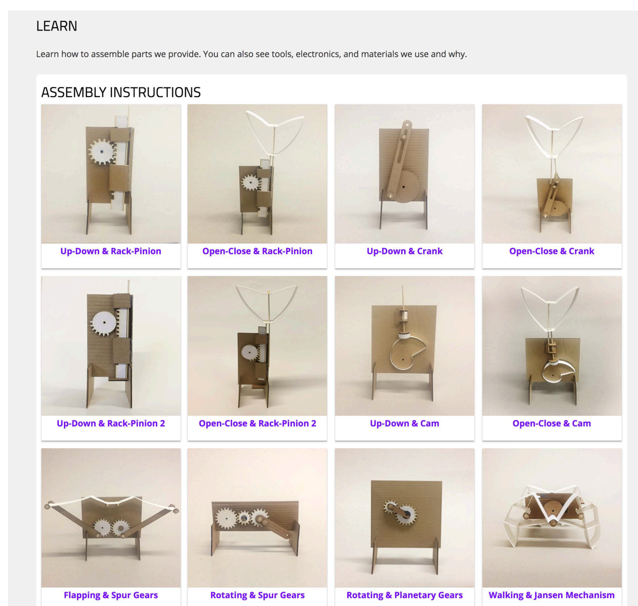

Figure 3. In the 'Learn' section, users can watch video tutorials to learn assembly techniques using the parts and folding nets generated from the 'Design' section.

Workshops as Contexts for User Studies

In conjunction with the website development, we have also conducted a series of hands-on workshops (1) to gauge the usability of our materials (the design simulator and prototyping techniques), (2) to understand design processes and challenges for children, and (3) to study the potential of building paper mechatronics as an expressive learning medium. These studies served as guides in refining our materials; they also enabled us to study the potential of paper mechatronics as a learning medium by observing the workshop participants' engagement and progress. The phrase "learning medium" here is associated with the notion of *adaptive expertise*–a topic that we will explain in greater depth in the following section. Briefly, our focus is on how workshop participants develop a deeper understanding of (and interest in) practices of mechanical design or paper engineering, as opposed to specific facts or a domain-specific curriculum.

Time	Subject	Participants	Program
2014 Fall, Three Saturdays	Design template	32 teenagers (ages 14-18)	Out-of-school program
2016 Summer, Five weekdays	Design simulator, assembly techniques	6 teenagers (ages 11-14)	University-based summer camp
2017 Summer, Two days	Website	12 teenagers (ages 13-15)	Summer apprenticeship program

Table 1. Our workshop details

From 2014 to 2017, we have conducted three workshops with fifty children (See Table 1). The first workshop answered preliminary questions regarding the craft itself: are children engaged in, and capable of building paper mechatronics projects? Can a movement-specific design template enable and encourage students to explore their own ideas and adapt their constructions in personalized ways? In the second workshop, we studied the usability of our design simulator and assembly techniques in depth. Can our materials really support children in their design and learning? How can we improve the design simulator and prototyping tutorials to support more fluent and productive design and engineering experience? Finally–once we had a complete website that contained the updated design simulator, video tutorials, and a gallery to browse other creations–we conducted the last workshop. Can children navigate the website without difficulties and use the necessary materials? Are they engaged in the design and engineering of paper mechatronics? What more might they need?

First workshop

Our first workshop in 2014 recruited high school students and consisted of three consecutive Saturday sessions in a studio-like setting. More details can be found in [14].

This first workshop focused on our "big picture" questions for paper mechatronics as a creative learning medium, specifically with regard to the utility of a suite of design templates. As it happened, students built working models successfully and modified the models to personalize their creations. Moreover, the final outcomes were diverse. For instance, several teams applied a "petal structure" (for a sort of open-closed movement) to produce a related movement, such as the flapping of a bird's wings or the motion of the leaves of a plant. Some teams made even more substantial changes to the structure to produce innovative movements. This encouraged us to consider developing a computational tool including more design templates to support a greater mechanical range in building paper mechatronics.

Second workshop

In 2016, using an extended beta-version of the design simulator, we conducted a week-long workshop with six middle school students. More details can be found in [15].

Because this workshop lasted five days, it enabled us to observe the gradual progression of students' understanding about mechanical movements and construction skills along with computational thinking. They not only started describing the movements which they planned to build in more detail–employing demonstrative poses and gestures along the way–but they also illustrated how to implement these movements mechanically, and adjusted the speed or angle of the motion by changing the computational code. Their accuracy in presentations and enhanced confidence led us to consider these children ready to move on to a more advanced level of design experience. They also actively shared feedback on our materials such as requesting video (rather than printed) tutorials for a wider variety of movements (our beta version included three movements).

Third workshop

The final workshop in 2017 recruited twelve students for two days (6 hours in total). Using our website, students designed their movements and ideas, watched video tutorials to learn assembly instructions, and shared ideas exploring the gallery. This workshop went more smoothly than previous ones since students were able to navigate the various resources they needed in each stage of the activity. As they were using the project website, students also often searched Google to find related images and watched YouTube videos in the brainstorming session.

The workshop outcomes were diverse and rich. Having more movement modules widened the scope of inspiration and ideation for students' projects. Their creations were evocative and original, adapting a variety of detailed, playful, and poetic stories, from crazy ducks swimming in a pond to clapping hands to capture a butterfly (Figure 4&5).

Figure 4. Students' work from the third workshop.

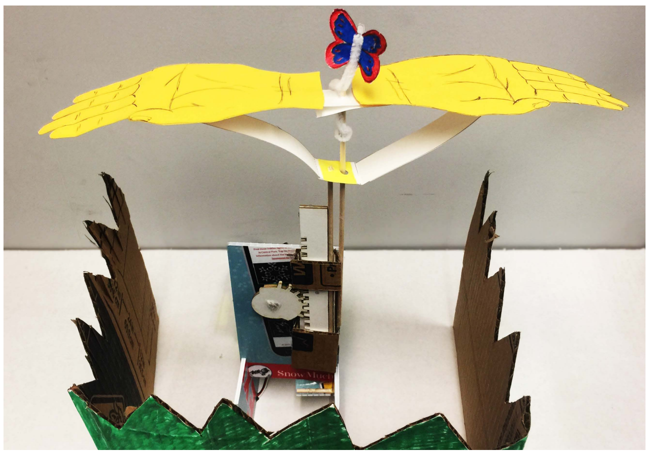

Figure 5. A 14-year-old boy spent almost 3 hours to draw the hands in the real size. His team proudly presented the work at the classroom with the title of "Hands of Life"

Reflections on Workshops: Central Themes of Paper Mechatronics as a Design Medium for Children

Given the aesthetic, expressive, and mechanical range of the workshop projects, we have become confident both in the potential of paper mechatronics as a creative learning medium, and in the utility of our materials in supporting and engaging children. Here we share our reflections on the main factors that contributed to these encouraging results.

The theme of things that move

Not surprisingly, children like making things that move, and this theme increases engagement. Many students developed detailed, personalized stories based on the movements of their creations, such as "a kid holding parents' hands and swinging arms." A recurring theme was that their goals were expressed in terms of generating particular motions (rather than learning some mechanical concepts). In other words, the participants saw their work as personalized creation, as opposed to advancement through a particular curriculum or body of subject matter.

Easy-to-handle, familiar, and recycled materials

Paper is easy to cut and attach using common craft supplies such as scissors or glue. The accessibility of paper enabled children to eliminate or change portions of mechanical designs, and attach them to other parts or objects to develop a new structure. Unlike many self-contained construction kits (in which the materials are generally assumed to be limited to a specific set of parts) paper lends itself to informal combinations with a range of other materials: our workshops included supplies such as plastic bottles, beads, and googly eyes to encourage experimentation. In addition, not all materials need be new: we observed that people showed more active exploration with recycled (rather than pristine) cardboard. Recycled materials can support a playful environment (cf. the discussion by Ackermann [1]) in which people feel free to "mess around" with ideas without fear of failure. So we devoted attention to the scope and types of exploratory materials in our workshops.

Familiarity with diverse papercrafting methods

Papercrafting lends itself to an enormous variety of physical techniques–folding, pleating, bending, crumpling, tearing, to name a few–and paper itself, as a substance, can take many forms from tissue paper to origami paper. Students enjoyed and were familiar with playing with various paper materials, which also contributed to the diversity of their creations. In addition, paper accommodates decoration through drawing and coloring. In our workshops, children used color pencils, pens, and paints to draw certain images to add details to their creations. Many participants tried to assign specific identities and unique elements to their creations: for instance, even if two students built the same basic object, their final products were stylistically distinct.

Tinkering-friendly and beginner-friendly design tool

Working with children without technical backgrounds helped us develop tinker-friendly and beginner-friendly technologies. The primary considerations reflected in the design tool and prototyping techniques were adapted from Resnick and Rosenbaum's design guidelines for tinkerable kits: immediate feedback, fluid experimentation, and open exploration [18]. We developed the simulator to enable users to customize the parameters of mechanical movements without worrying about failures; the simulator's animations follow parameter changes, providing a means to improvise, and to experiment with mechanical designs. Moreover, in our workshops, we noticed that some students showed concerns when they encountered technical, domain-specific languages such as "rack and pinion gears" or linkages. This finding motivated us to modify the design simulator to employ simpler, more "motion-specific" words such as up-down, open-close, or flapping.

A gallery to get inspired by peers

From the first two workshops, we learned the importance of showing examples to widen children's perspective for creative thinking. Children showed particular excitement in response to similar projects developed by other children to imagine their own design possibilities. So in the gallery of the website, we display students' work along with their show-and-tell presentations (with their approval) instead of showing only the outcomes. Our sense is that students are empowered not only by seeing great work developed by peers, but also by thinking that their work can be presented to others as both an inspiration and example of excellence.

Learning co-operation and collaboration

In many cases students had to co-operate to share tools such as a glue gun or a straight edge for cutting cardboard. On collaborative team projects, students had to negotiate and come to consensus on the concept of the project, which movements to select to incorporate into the design, the overall narrative of the piece, and other design decisions. These practices during design compromises, sharing tools and ideas, as well as learning to work together were a common pattern that emerged during paper mechatronic construction. The design medium also served as a context to exchange different kinds and levels of expertise held by facilitators and peers, whether students were crafting materials together into their shared visions, and/or troubleshoot coding scripts or mechanisms. These kinds of co-operative and collaborative interactions were evident in workshops, and consistent with what other researchers are finding in community-oriented makerspaces [3,20].

PAPER MECHATRONICS: FUTURE

The previous section described the current state of our paper mechatronics work, and the cumulative workshop experience upon which our design judgments are based. At the same time, we acknowledge that workshops in general–while informative–represent only a limited format in which to explore the possibilities of a creative medium. Workshops are of necessity limited in *time*: they provide little basis for thinking about projects that might take weeks or months to complete. They are limited in *space*: a medium like paper mechatronics could conceivably lend itself to projects at large scale, or occupying multiple sites, but a workshop is confined to a single confined location. And finally, workshops are limited in the sorts of *material* or *technological* experiments that they can accommodate; there is no occasion to experiment with untried technologies or unusual novel materials because these may constitute a distraction from the goal of assessing the current state of the still-evolving "core" medium.

As a prelude to discussing these future directions, however, we feel that it is incumbent upon us to first step back and describe the notions of learning that seem best supported by a creative construction medium such as paper mechatronics. That is, both our current development and future speculations for this medium are based on an idea of *what children can or should gain* from working with materials such as these. The goal is not to, for example, embody, through our materials, a stepwise approach to a specific curriculum (which is the style, for instance, of some commercial science or electronics kits). Rather, the goal is to develop the intellectual identity or persona of a fluent, creative maker/practitioner. The following subsection elaborates on this notion; afterward we incorporate this notion of learning in our exploration of future directions.

Adaptive Expertise: Learning via Making

A small, but growing number of researchers study learning in the context of making, and its connection to engineering design [3, 10, 17] A critical strand of research within the Learning Sciences and related fields is how people solve problems that arise under uncertainty, and how learners flexibly adapt their knowledge and problem-solving skills to new situations. *Adaptive expertise* describes this ability to develop knowledge, dispositions, and practices when faced with a new problem–with a particular emphasis on experimentation and being resourceful [7,11].

Adaptive expertise can be developed and addressed by creating learner-centered environments. These environments–our paper mechatronics site can be seen as at least a prototype within the genre–provide opportunities to make students' thinking explicit, provide contrasting design cases, model expert problem solving strategies, and demonstrate expert techniques [13].

The notion of adaptive expertise is, as we've suggested, particularly germane to a medium like paper mechatronics. We believe paper mechatronics can provide a rich context for learning the practices of modern engineering design, permitting learners to develop adaptive expertise to better approach and tackle open-ended problems with confidence and creativity. We anticipate that, because of the unique combination of the projects' intensive and personalized nature, the approachability and flexibility of the medium, and the ever-deepening nature of the technological and engineering design experiences that span the digital and tangible, young who engage repeatedly with our paper mechatronics experiences will deepen measurably in adaptive expertise. Moreover, we believe that the expertise developed has not only an intellectual but also an agentive and affective component: a certain willingness to play with untried possibilities, to challenge oneself (after all, adaptive expertise is about tackling *new* problems), and to feel a certain growing "professional" confidence in one's own creative capacities and identities as a capable maker.

It is because we have such goals in mind that the workshops described in the previous section have seemed encouraging to us: without overstating the case, or the (still modest) scale of our current efforts, it does appear that a medium like paper mechatronics can provide a context for developing adaptive expertise. (A perusal of the students' documented projects, and their own descriptions of and reflections upon those projects, is in keeping with the definition of the idea introduced above.) At the same time, part of the spirit of adaptive expertise as a genre of learning is to continue to expand creative boundaries. It is to this goal–looking beyond the limitations of the workshop experience–that we now turn.

Beyond Workshop Projects: The Temporal Dimension

Engineering and artistic projects in all sorts of media frequently take shape over a period beyond that of the typical workshop. Indeed, many creative projects have barely begun to be conceived in a period as short as a weekend or two. Some projects, by their very nature, require or encourage a greater time commitment than afforded by the typical workshop schedule.

We could envision ambitious student projects in the paper mechatronics medium: perhaps a group of students might create a full-scale story or pop-up book [16] with paper mechatronic elements. A large-scale collaborative project, such as a paper mechatronic "mural", might likewise require a long-term effort from a group of students; the construction of such a project could well play out over an extended period, with the population of contributors and creators changing or evolving over time. A similarly challenging project might involve creating movies or stop-action animations featuring paper mechatronic creations; this would involve incorporating paper figures into projects based in yet another (video-based) creative medium.

Yet another possibility would be to create paper mechatronics projects whose activity itself plays out over a longer period–as opposed to typical workshop projects whose movements occur over a period of seconds at most. One might create mechatronic designs that operate in discrete steps–and the number of such steps could be large (as in the modeling of some long-term computational processes), or the steps might occur with extended gaps or at irregular intervals.

In short, paper mechatronics lends itself naturally to a variety of projects that could challenge children well beyond the temporal scope of a workshop (or even a typical classroom project).

Beyond Workshop Projects: The Spatial Dimension

Workshops take place in spaces that organize tools, materials, and activities around accomplishing tasks and work. Thus, such settings may constrain projects to tabletop-sized creations and miss other specific properties of the space (e.g., high ceilings, large windows, and so forth). Another avenue of exploration for paper mechatronics is expanding into specific settings. The murals mentioned earlier might be realized on a large wall, or in a hallway or lobby; there might be similar efforts to create a sort of "mechatronic wallpaper" design, or to create projects that have some sort of aerial component (machines that hang or move along strings or constructive threads suspended from a high ceiling, or paper mechatronic mobiles). Still other creations might involve multiple, physically distinct elements that communicate over a distance. A paper machine could incorporate parts that communicate over short distances using infrared or RFID signaling; or still grander projects could involve multiple sites, with elements that communicate remotely over the web.

Beyond Workshop Projects: The Material/Technical Dimension

One of the more striking aspects of paper mechatronics is its material and technological flexibility: again, the medium is not conceived as a tightly-interwoven collection of pieces (in the spirit of a classic construction kit), but rather as a medium that can be combined and integrated with all sorts of other "stuff". It is this ecumenical nature that allows paper mechatronics to be freely mixed, in varying proportions and forms, with other (either "low tech" or "high tech") materials, devices, and creative media.

To take an initial example, one might create a machine or automaton using both "traditional" materials (wood, plastic, metal) in concert with paper. Such a machine might be conceived as an object in which the paper mechatronics element acts only as one portion of a much larger or more elaborate effort. If a machine needs to be designed according to a variety of criteria, such multi-material methods might be called for: the portions of the machine that involve durability and ruggedness might be created from metal or wood, while more delicate or decorative elements might be created from paper. Yet another possibility would be incorporating modular or replaceable paper elements (e.g., "butterfly wings" of different designs, or paper pinwheels that can be inserted and removed) as portions of a larger creative project.

Perhaps a bit more futuristically, a medium like paper mechatronics affords creative opportunities for combination with "high-tech" developments as well. One could view paper devices as components in larger projects generally associated with the "Internet of Things" (IoT) label. A decorative paper machine could act as a visual output device for sensory input derived from distant locations, or data repositories accessed via the Web. Still another possibility would be to combine paper mechatronics creations with innovative or novel projection systems: a movable paper device could be used as a sort of "mechanical shadow puppet". Graphical scenes, data visualizations, or animations might be projected onto the surfaces of a paper mechatronics creation. Or–to take yet another possibility–one might experiment with computationally controlled projection systems (see, for instance, Dynamicland.org) in combination with paper mechatronics creations project.

The purpose of this sort of speculation is to view the medium of paper mechatronics not as a rigidly-defined body of subject matter–nor as a particular existing set of tools or projects–but rather as a still-growing medium of expression for children's creative construction. We look forward to continuing our own work in this medium, and to the (still unforeseen) creative contributions of children, hobbyists, and other researchers in the exploration of still more uncharted territory in computationally-enriched papercrafts.

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SELECTION AND PARTICIPATION OF CHILDREN

Parents of children enrolled in an existing youth program offered by an out-of-school learning program (e.g., library, summer program, afterschool) were invited to participate via email, a PDF flyer, and verbally in person. Children were also recruited via email to their teachers, educators, and parents and via subscribers to community list-serves. (e.g., Bay Area Maker educator's group, university-run Makers Collective). Email was also sent to teachers and program leaders of out-of-school programs for posting to their lists and networks of families with children. Participants were selected based on their availability, interest, and assent from children themselves and the consent from parents and adults.

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