Rapid Prototyping of Rapid Prototyping Tools: Cross-Disciplinary Experiences

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Abstract
Both practicing digital fabrication and designing digital fabrication tools requires cross-disciplinary system integration. We outline how our interdisciplinary collaboration (in electrical engineering/computer science/mechanical engineering/design/architecture) for machine building led to a cardboard machine construction kit for rapid prototyping of rapid prototyping machines.

Author Keywords
Digital fabrication; Automation; Advanced Manufacturing; Machine Building; CNC; CAD/CAM; Controls; Crossfab; Engineering Education; Making

ACM Classification Keywords
J.6.b [Computer-aided manufacturing (CAM)]: Computer-Aided Engineering; H.5.2.j [Prototyping]: User Interfaces; H.5.2.o [User-centred Design]: User Interfaces

Introduction
Digital fabrication machines require cross-disciplinary system integration. Ranging from digital design, to controls, to firmware, to human-machine interfaces, the range of fields required to make machines that make is broad. However, digital fabrication offers access to precision and complexity that is hard to achieve without automation. Making digital fabrication machines is therefore highly desirable. How can

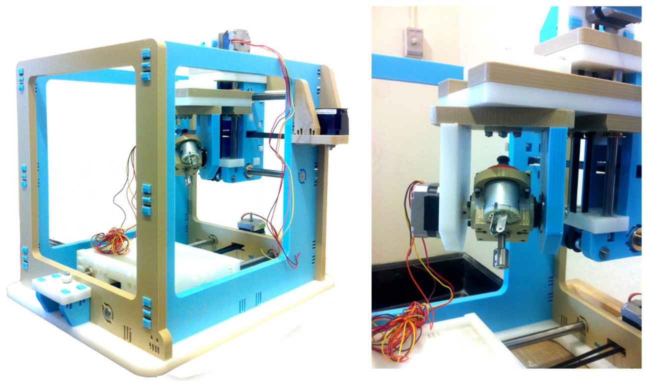

Figure 1: The 5-axis milling machine from HTMSTMAA in 2012.

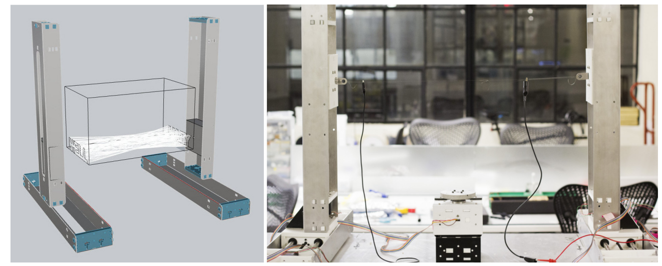

Figure 2: A 5-axis (4-axis wire control, 1 rotary table) hot-wire cutter made with the m[MTM] machine parts.

we make it easier to build custom digital fabrication tools?

How to Make Something that Makes (Almost) Anything

HTMSTMAA is a class at MIT on designing rapid prototyping machines both authors took in the spring of 2012. Coleman was in the Architecture and Mechanical Engineering departments, and Peek was in Media Arts and Sciences. We were forced to work together when the course professor, Neil Gershenfeld, suggested that Coleman would use the networked controls Peek was developing at the time to control the 5-axis tabletop mill he was working on (figure 1). Like many class projects before, we produced several demo machines (a 5-axis mill, a 3-axis mill, and a multi-purpose fabrication machine that folded into a briefcase) that were of little utility after the class. The work envelope of the machine was too small, and there were limitations to the toolhead and machine frame. Even though we released the design files of the machines under open source licenses, few other users replicated or built upon our work.

Modular Machines that Make

Based on the limitations we encountered in our respective class projects, we started working on a series of machines parts with which we could quickly prototype motion and different work envelopes. Instead of designing machines monolithically, we developed a series of linear and rotary stages (see figure 2) that could be used with different end effectors for machine prototyping [6, 1]. They used updated networked controls that incorporated source routing and could be configured on the fly [4, 3].

However, the full system integration was still not that fast– we had to design interfaces between each toohead and the stages, and we were limited by the number of stages we had. We wanted prototyping in machine building to be more like writing a hello world in code, or making a mock up of a physical design in foam core. We wanted it to be faster, and easier to iterate.

A Cardboard Construction Kit

We decided to make a cardboard construction kit for building digital fabrication machines. Using off-the-shelf components, custom networked controls, and laser cut folded

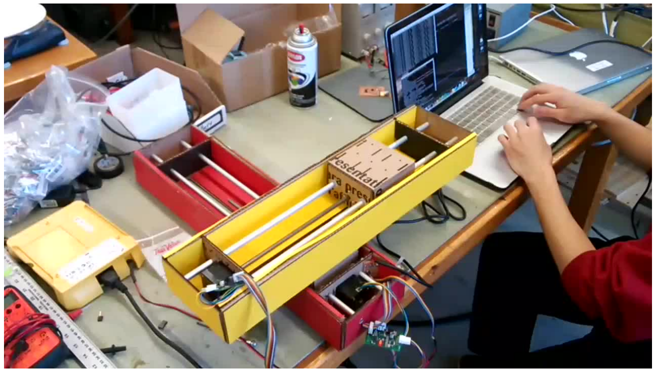

Figure 3: The mMTM cardboard stages in a classroom setting.

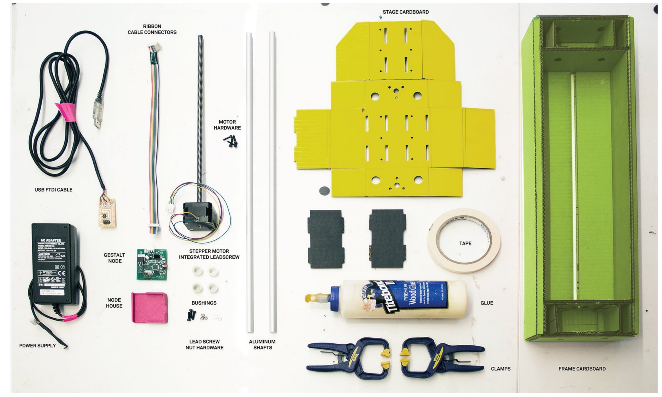

Figure 4: All the parts needed for one cardboard mMTM stage.

cardboard, we constructed a new design for the modular machines that make. Cardboard was an ultimately mutable material, as no one could wonder how it might be modified. We made the networked controls as cheap as possible, so that adding an extra degree of freedom wouldn't be hampered by cost. We documented example machines (in mechanical design, control software, and machine interfaces), created classroom curriculum, and taught workshops [5, 7].

More than 100 machines were made based on the cardboard construction kit, some of which we have documented in [8]. They include 5 axis mills, sand gardening machines, 3d scanning machines, and vegetable cutting machines. While some of these machines may seem frivolous, making machine building so easy it could be frivolous was the point of the construction kit. Novice fabricators were going straight for 5-axis control, because the historical limitations of machine design and control were not present.

A large part of the success of the cardboard machine kit was due to its extensive documentation [2]. To be able to communicate clearly with each other, both authors being experts in different fields, we needed to document our work meticulously. This allowed the next users who might be experts in some but not all of the fields required for digital fabrication to easily participate as well.

Rapid Prototyping of Rapid Protoyping Machines

The goal of the machine building projects we worked on together was to make all aspects of machine building more accessible. By reducing the complexity of the mechanical design work with the modular components, reducing the complexity of the control systems with networked controls, and reducing the complexity of creating software interfaces by developing virtual machine interfaces, we made it easy to make initial prototypes of machines. Without combining our respective expertises into a holistic system though, we would have made little progress. If we were both architects, we would have never worked on networked control infrastructure. If we were both electrical engineers, we would have never considered building a cardboard CNC stage.

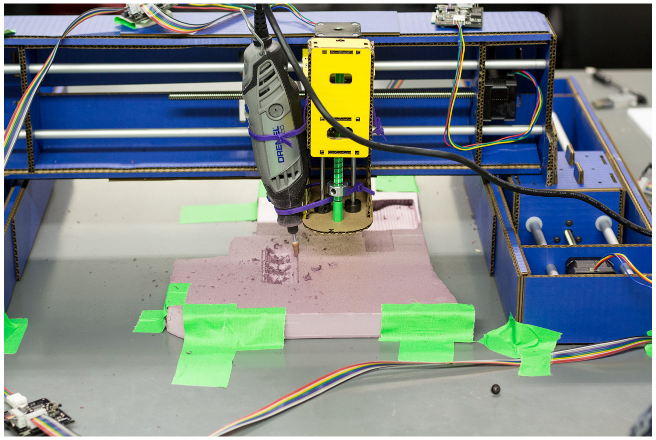

Figure 5: Workshop participants test the mechanical limits of the cardboard plotter they have just developed by turning it into a CNC mill.

There is still a lot left to do– the next step after cardboard machine prototypes could also use some help. But we don't think it'd be possible without interdisciplinary collaboration.

The cardboard construction kit has so far been a great educational tool for machine building. But the modular and reconfigurable concepts for digital fabrication extend beyond education. How can we enable custom automation even at industrial scale? We continue to work together on making machines that make– both the infrastructure for digital fabrication, and larger and larger machines.

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